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Solid wall heat losses and the potential for energy saving

Literature review

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Date: 29 May 2014

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Notes

This review of the literature on solid wall heat losses and the potential for energy savings was conducted in the summer and autumn of 2013 and the first draft was completed on 29 November 2013. Therefore any relevant literature published since that date will not have been included in this report. The project under which this review was conducted will continue to review the latest literature in this area and will periodically compile lists of any new literature. These will be made available on the project web site (see http://www.bre.co.uk/swi).

Acknowledgements

This review was co-ordinated and by collated by Andrew Gemmell at BRE.

BRE would like to thank the team of authors from Cardiff University lead by Professor Tweed for their contributions to the review.

The principle chapter authors were:

- Sean Doran (BRE) – Heat loss measurement and calculation methodologies
- Gabriela Zapata and Christopher Tweed (Cardiff University) - Predicted performance compared to actual savings
- Christine Suffolk (Cardiff University) - Occupant behaviour
- Timothy Forman and Christopher Tweed (Cardiff University) - Unintended consequences of solid wall insulation
- Gabriela Zapata and Christopher Tweed (Cardiff University) - Heritage and conservation
- Andrew Gemmell (BRE) – Summary report

We would also like to thank BRE's experts and subject leaders: Sean Doran, John Henderson, Matt Custard, Andrew Gemmell, Colin King and Tim Yates.

Summary

Overview of the review findings

Below is a general overview of the findings of the review, this is followed by a more detailed summary of each section of the report.

How is the heat loss through solid walls typically measured and calculated?

Heatflux sensors, thermocouples and infrared thermography are all widely used both in the field and in laboratories to test the thermal performance of a variety of wall types and components. Hot boxes, environmental chambers and transient techniques are all used for testing samples of walls under laboratory conditions. Infrared thermography is also used to identify inhomogeneities, confirm qualitative results and assist in the visualisation of heat fluxes at surfaces. Whole house heat loss is typically measured using a co-heating test, although ventilation heat loss can be assessed using an airtightness test.

The calculation of U-values can be done through three-dimensional thermal modelling programs, such as Trisco, or other simplified methods. The reliability and accuracy of U-value calculations, however, hinge on knowledge of the materials within the construction. Conventions do exist, however these are aimed at ensuring a unified approach for U-value calculations rather than achieving the best possible accuracy.

How much energy is saved as a result of insulating solid walled properties?

Quantifying the savings that can be attributed to the installation of solid wall insulation (SWI) can be difficult. The majority of recent studies have tended to investigate the aggregated consequences of a combination of retrofit strategies, one of which could be insulation of walls, and most have not looked at solid walled properties. However, the research available consistently shows that the actual savings achieved are far less than those predicted.

How can the gap between predicted and actual savings be explained?

The primary reasons for the gap between the predicted and actual savings, identified by the review are;

1. Inaccurate assumptions regarding the baseline performance of the building envelope and the temperatures the homes are heated to prior to installation;
2. Errors in the installation of the insulation and poor workmanship;
3. Changes in occupant energy use behaviour once the insulation has been installed.

Calculation tools may include erroneous assumptions about occupant behaviour, assuming that all homes are heated to a standard temperature, regardless of occupancy or income. In addition, changes in occupant behaviour following the energy efficiency improvement have been estimated to typically be account for between 30% and 60% of the reduction in the predicted space heating savings.

The review has found that simulation-based and calculation methodologies tend to be based on a standard approach that may not be appropriate for materials with variable properties. Steady-state methodologies may fail to represent the thermal performance of some materials accurately because of the limitations in the assumptions made, misrepresenting the construction quality and the energy consumption prior to the retrofit. The use of *in situ* measurements and surveys to collect input data should improve the quality of the baseline scenarios.

What are the potential unintended consequences of installing solid wall insulation?

The main unintended consequences identified from the review can be categorised into two areas: 1) the risk of overheating in buildings with SWI and 2) changes to the distribution of moisture in a building following an intervention. Both of these can have severe effects on occupants' health, as well as the building itself. The research suggests installing external rather than internal insulation can help to moderate the excesses of internal temperature swings. However, poor installation of either can lead to problems with water ingress, condensation, and mould growth. The majority of the unintended consequences observed, have been linked to shortfalls in the quality of the workmanship, as well as mistakes in the initial assessment of the buildings when assessing their suitability for the application of wall insulation.

What additional considerations need to be taken when insulating heritage buildings?

Heritage buildings are considered to be complex systems that exhibit a delicate equilibrium between thermal mass, air leakage, building envelope properties and heating regime. Many traditional buildings were built to be 'breathable' and so installing impermeable insulation materials and vapour barriers increases the likelihood of moisture problems. Natural insulation materials (such as cellulose or sheep's wool) may prove more suitable. Both external and internal wall insulation may be unsuitable for heritage buildings due to the loss of historic detail.

Chapter summaries

More detailed summaries of the key findings, conclusions and recommendations from each review chapter, are given below.

Heat loss measurement and calculation methodologies

Heat flux sensors, thermocouples, thermistors and infrared thermography are all widely used both in the field and in laboratories for testing the thermal performance of elements and components. Typically, hot boxes, environmental chambers and transient techniques are all used for testing samples of wall under laboratory conditions.

The literature suggests that infrared thermography is a valuable aid in identifying inhomogeneities, confirming qualitative results and assisting in the visualisation of heat fluxes at surfaces. BS EN 13187:1999 describes the use of infrared thermography for the qualitative detection of thermal irregularities. Three-dimensional thermal modelling programs, such as Trisco (produced by Physibel), are invaluable tools for the interpretation of measured heat fluxes and measured temperatures.

Heat flux sensors can either be mounted on the surface of an element being tested, or they can be embedded within it. Some research suggests that embedding a sensor could lead to greater accuracy than surface-mounting it. Depending on the nature of the experiment, temperature sensors (typically thermocouples or thermistors) can be mounted on the surface or within the air adjacent to the element under test, or they can be embedded at strategic locations within the solid material.

The reliability and accuracy of U-value measurements can be especially sensitive to the difference in temperature between the warm and cold environments. Transient methods, involving sudden changes in temperature, of the order of several °C, can potentially reveal thermal information in a matter of minutes rather than hours or days, through examination of the transit time of the heat pulse and the shape of its profile after transit, and although the concepts have been considered for several decades, more research is needed in this field in order to develop the reliability of such measurements. Heat pulses can be provided either by heating elements, which in some cases can be embedded, or through bursts of heat radiation. At present, there are questions about the accuracy and reliability of heat pulse techniques for walls which are non-homogenous, as well as for walls which incorporate insulation materials. Conducting tests on moisture content can benefit the interpretation of results.

Calculation of U-values can be done using thermal modelling tools such as Trisco, using the method in BS EN ISO 10211:2007, or through the simplified method described in BS EN ISO 6946:2006. Reliability and accuracy of U-value calculations, however, hinge on knowledge of the materials within the construction. Conventions do exist, and are published in papers such as BR443 and CIBSE Guide A3, however these are aimed at ensuring a unified approach for U-value calculations rather than achieving the best possible accuracy.

The heat loss for a whole house can be measured using a co-heating test. The method provides a measure of the heat loss coefficient attributable to heat conduction through the fabric of the dwelling.

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Predicted performance compared to actual savings

The review compiled evidence about the following aspects of the calculation of performance pre- and post-retrofit:

- Baseline performance of the envelope
- Design and construction aspects related to the retrofit work that affect performance
- Limitations of simulation-based methodologies in terms of:
    - Differences in the predictions by calculation tools (SAP, RdSAP, NHER, SBEM)
    - Erroneous baseline U-values
    - Misrepresentation of occupant factors

The literature review for this topic has found that the majority of previous studies have investigated the aggregated consequences of a combination of retrofit strategies, one of which could be insulation of walls and that few have monitored a sufficiently large sample for a sufficient length of time for statistically robust comparisons to be made.

The baseline performance of the building envelope could be determined by laboratory-based studies and *in situ* measurements. The weakness of laboratory-based studies is that they often fail to capture the complexities of hygrothermal and maybe other behaviours of the materials in real settings. This is particularly relevant for pre-1919 dwellings and traditional materials where the lack of accurate data about the properties of the materials and the variety of materials used reduces the certainty of baseline U-values that are not based on *in situ* measurements. For example, the uneven distribution of moisture in a wall could lead to increased scatter in comparisons of measured and calculated U-values. Analysis for this project should consider this.

Studies have suggested that:

- the behaviour of walls in existing dwellings could differ from the standard performance of materials;
- methodologies used for determining the U-value of materials may not be able to accurately represent the baseline performance of materials of pre-1919 dwellings and traditional buildings;
- datasets of materials obtained under laboratory conditions may fail to consider the influence of moisture content on the baseline performance; and
- common industry standards used for the appraisal of moisture content of building elements may be limited in representing the dynamics of moisture transport within and across the wall build-up which is particularly relevant for the performance of pre-1919 solid walls.

The construction quality of the retrofit work can also affect the performance achieved after the retrofit as can the quality and suitability of the design. Studies have found the following errors in the construction process: poor workmanship, poor standards on site, gaps in the insulation, changes in the specifications, poor execution of details at junctions and poor site care to reduce thermal bridges. The quality and suitability of the specification at the design stage will also have a major impact on performance achieved after the retrofit. Poor design and errors in installation are likely to undermine the post-retrofit performance and jeopardise the achievement of the anticipated savings. This project should pay particular attention to the process of any installations of solid wall insulation. It is not enough to assume that achieved performance matches the designed performance *in situ*.

Concerning simulation-based methodologies ability to predict the savings, the literature suggests three causes of discrepancies: differences between results of calculation tools, despite the use of similar input data (potentially due to embedded calculation methods); the erroneous representation of baseline U-values and incorrect assumptions about occupancy. It will be recognised that simulation-based methodologies can never fully take account of all factors that affect energy use, particularly given the requirement for non-intrusive surveys of limited duration, so there will always be some divergence.

Simulation-based methodologies tend to be based on a standard approach that may not be appropriate due to the lack of understanding of the performance and users' practices to achieve comfort. Steady-state methodologies may fail to represent the thermal performance of some materials accurately, misrepresenting the construction quality and the energy consumption prior to the retrofit. For some materials it is necessary to consider moisture content and air movement and to recognise that there will be variations and ranges of uncertainty in the baseline thermal performance of materials. The use of *in situ* measurements and surveys to collect input data could improve the quality of the baseline scenarios.

With occupants' behaviours, it has been found that the occupants of poorly insulated dwellings tend to underheat their homes, however, baseline modelling scenarios assume the same temperatures are achieved in all dwellings, regardless of the existing thermal performance. In the cases where householders maintain lower temperatures than expected, it has been found that after the retrofit there is usually an increase in the indoor temperature. The improved thermal comfort benefit reduces the savings.

An aspect that has not been explored in detail is the choice of metric to assess the retrofit saving, such as end-energy use, heating demand, energy cost or thermal comfort (indoor temperature, temperature differential within the dwelling). It should be noticed that the discrepancies between the predicted and measured performance in different studies can depend on the metrics they use for the comparison.

In summary, this survey of the literature has highlighted that the gap between predicted and actual performance is affected by three main elements. The first; baseline estimates, occurs because of what could be summarised as overly simplistic assumptions about the thermal performance of the walls. More information about the wall, coupled with more resolution in the sources of information about standard performance assumptions, can lead to better baseline estimates. Related to this is how walls are represented in simulation tools. More information needs to be collected in order to allow more sophisticated assumptions to be made within the software. Other explanations are that the insulation system does not perform as expected because of its installation and the behaviour of the occupants may not (or is unlikely to) match the standard assumptions used in most models. The literature has shown that the occupant factors are likely to be misrepresented before and after the retrofit.

The main findings of specific relevance for this project are:

- It is important to collect detailed data on internal temperatures alongside U-value measurements (i.e. in several rooms, not just at the point of the U-value measurement). This will be particularly useful if obtained both before and after solid wall insulation.
- Data on moisture content of the wall is likely to be important for some construction types, so this should be routinely collected as part of this and future studies of U-values.
- Occupant behaviour, especially with regard to the control and use of heating systems, gives rise to significant modelling uncertainty, so by survey or otherwise, it is important to capture data about this during the remainder of the study.
- If possible, attempts should be made to determine whether design and construction errors have been made during the application of solid wall insulation and the consequences of those defects evaluated.

Future directions of research include the calibration of simulation-based methodologies and standards on the basis of *in situ* U-value measurements and the creation of a comprehensive database of traditional materials to improve the quality of U-value baseline performance. Both aspects could be embedded in the tools to estimate the baseline performance of existing dwellings for retrofit programmes such as the Green Deal. Combining user profiles and heating patterns in relation to the energy efficiency of the dwelling may improve the occupancy assumptions embedded in simulation-based methodologies. A clearer understanding of construction defects and common sources of on-site error could lead to the creation of confidence or safety factors to account for the construction quality likely to be delivered during retrofit work.

Occupant behaviour

The idea that energy efficiency improvements might increase rather than decrease energy use is not new, as it was proposed as far back as 1865. There is an agreement in the research literature about the existence of the rebound effects; however, there is not a consensus on the size of the effects or a definitive definition. Rebound effects can be classified into three main categories: direct, indirect and economy-wide. It is recommended that this project should focus on direct rebound effects which occur when energy efficiency improvement in one type of energy or energy service increases the consumption of the same energy or energy service.

The review suggests that there are an insufficient number of suitably monitored and analysed projects to thoroughly assess rebound effects. In addition, the methodological quality of most research using before and after measurements is relatively poor. It is, therefore, important that any pre- post monitoring trials proposed for this project are carefully designed to ensure any rebound effects can be confidently quantified. Many of the trials conducted to date have failed to take account of some key variables that may influence the size of any rebound effects, such as income, household demographics, occupant attitudes and behaviour, and the cost of fuel. Researchers have suggested that a control group could be used on trials of this kind, to control for changes in external temperatures, fuel costs and other extraneous variables which might influence consumption rates over the trial period. The forthcoming field trial conducted as part of this project should include a sample of control properties. The control group should act as a 'baseline'. This will ensure that any difference found after the intervention, can be confidently attributed to the wall insulation, rather than other variables such as new government policy or energy prices etc.

For space heating, the rebound effect is estimated to be around 30% on average (30% of the potential savings are taken back through increased consumption). However, others estimate the percentage to be as high as 60%. *Income, time since installation* and the *internal temperature* before energy efficiency improvements are carried out are all thought to contribute to the size of the rebound. Future trials should monitor energy consumption for sufficient time post insulation, to monitor changes in behaviour over time. Internal temperatures should also be measured for a sufficient period, before and after the intervention, to allow the potential relationships between internal temperatures and the size of any rebound effects to be measured. Currently, the lack of suitable research studies conducted at a large enough scale hampers the development of the sophisticated understanding likely to be necessary to inform the design of successful retrofit programmes.

As well as rebound effects, *prebound effect* and *behavioural spillover* are also factors which are likely to contribute to the difference between the predicted and actual energy savings achieved, but research is needed to explore this further. The prebound effect is found when the actual energy use in the homes, prior to the installation of insulation, is actually lower than modelled or predicted. Energy efficiency improvements cannot save energy that is not being consumed in the first place; therefore the expected savings are overestimated. Research suggests that the worse a home is thermally, the more economically the occupants tend to behave with respect to their space heating. Low efficiency and low consumption go hand in hand, as do high efficiency and high consumption. Therefore this overestimation of the consumption prior to insulation is likely to be greater for more inefficient homes.

It is suggested that energy efficiency policies need to work collaboratively with policies aimed at eradicating fuel poverty, since it can be argued that the causes of the prebound effect should not be isolated from the energy efficiency policies. We recommend that the field trial proposed under this project should look at the differences between the predicted energy consumption prior to the installation of the wall insulation as well as after, so that any prebound effect can be quantified reliably.

Behavioural spill-over occurs when the adoption of certain pro-environmental behaviours have a knock-on (or 'catalyst') effect, which leads to the adoption of a broader range of other pro-environmental behaviours. Research suggests that having refurbishment work carried out could strengthen a pro-environmental identity and thereby increase the likelihood that these people will adopt other pro-environmental behaviours. However, research by Defra (2011) suggests that there is no clear catalyst behaviour or behaviours that can be relied upon to lead to the uptake of multiple pro-environmental behaviours. Research also suggests that these effects are likely to be observed in only a relatively small number of cases.

Unintended consequences of solid wall insulation

Two main unintended consequences were identified from the review: 1) the risk of overheating in buildings with SWI; and 2) changes to the distribution of moisture in a building following an intervention and the damage this may cause to the building and its occupants. More research is required to address the gaps in existing knowledge. Future research needs to be rigorous and based on the assessment of actual properties. Many of the existing studies are based on modelling using computer software rather than careful studies of actual buildings in sufficient numbers.

Unintended consequences of installing insulation on solid walls identified by the review include; thermal bridges (leading to heat loss and mould growth), various moisture problems resulting from greater airtightness and inadequate ventilation, interstitial condensation, overheating during hot weather, and a less durable wall surface. As well as the health problems associated with damp and mould, overheating in bedrooms could be a risk to health, particularly given the urban heat island (UHI) effect and climate change projections.

The review found that the influence of thermal mass on post-insulated buildings is not well understood and needs to be studied in greater detail. It also needs to be considered alongside orientation and fenestration to assess the risk of overheating. There is conflicting evidence on the role of thermal mass and particularly on the best place to put insulation to avoid overheating. However, there is a clear preference for external insulation so that the existing mass of the external walls can moderate the excesses of internal temperature swings.

A thorough and extensive review of buildings that have been insulated with EWI is suggested, to endeavour to identify causes of unintended consequences. The current arguments are based on limitations in different numerical models (Glaser / Wufi). Although Wufi encompasses more parameters (wind-driven rain, water ingress, and local climate data) than Glaser, it is still a numerical model, with serious limitations on the materials and climate data bases within the tool. Much support is given to undertaking this type of modelling, but it is both costly and impractical on a mass roll-out of supported / funded insulation schemes.

Although at an early stage in this project, there are already indications that the areas of weakness in the EWI process could be categorised into three main causes of unintended consequences: the initial assessment of buildings, systematic problems, and factors relating to occupancy. There is already a growing list of these that need to be considered, and ranking these by risk and effect will help focus the minds of the people involved in making the decision whether to insulate or not.

The literature examined as part of this review points to several factors which can lead to the unintended problems often observed. These factors include:

- Inadequate assessment of the condition of the building before improvement is considered,
- The limitations in assessing realistic climatic conditions,
- Incorrect installation methods being used.

All of these factors have the potential for considerable risk in the implementation of large-scale external wall insulation projects such as the Green Deal or ECO, and in particular when external or internal insulation is applied to walls that are of solid construction. Many factors are influential in this early deterioration but poor detailing on junctions and penetrations in buildings appear to be major factors.

Heritage and conservation

Heritage buildings are complex systems that exhibit a delicate equilibrium between thermal mass, air leakage, building envelope properties and heating regime. The literature review reveals many unknowns and uncertainties about the interconnections between these aspects and their individual and combined effect on the performance of the buildings. Some of the knowledge gaps identified by the review include:

- limited validity of many current standards and models—specifically, BS 5250, BS EN 13788, and the Glaser method—to assess the hygothermal performance;
- uncertain and varying values of thermal conductivity for traditional materials (the discrepancies between the U-values measured *in situ* and values embedded in the databases of traditional materials used by models to determine the building performance);
- air permeability and ventilation rates in heritage buildings and how the pre-existing ventilation conditions are related to the specific hygrothermal characteristics of the envelope (U-values, breathability, moisture transport within and throughout wall build-ups);
- the role of occupants in the creation of internal moisture and the effect on the overall moisture balance in heritage buildings; and the relation between heating regime and energy consumption have not been explored in depth;
- uncertainties about the medium and long-term consequences of applying insulation to solid walls made of traditional materials—the change in the performance of the envelope could lead to changes in the whole building performance (balance of moisture, hygrothermal performance), in the indoor environment conditions and in the overall building condition (decay and damage).

The guidance and the research presented here highlights the need to understand the pre-existing conditions and characteristics of heritage buildings when proposing energy efficiency retrofits to ensure compatibility between the existing and the new and to prevent damage and deterioration. This is particularly relevant for the implementation of insulation on solid walls due to the complexity of moisture transport within and across the wall, the hygrothermal performance of traditional materials, the breathability of the envelope and the relation to the overall performance and physics of heritage buildings.

There is a need to consider how the knowledge gained about the *in situ* performance and post-retrofit monitoring studies could inform and improve the standards, performance models, methods and guidelines used by the building industry for determining the performance of the building and building elements; and, enhance the data about traditional materials embedded in databases. From the few detailed *in situ* studies that exist, the review finds that there are enough warning signs to suggest that insulating external walls either externally or internally can lead to undesirable consequences. Further studies are needed before a large scale roll-out of wall insulation for heritage buildings can be recommended.

Finally, the review finds that retrofit work should balance the different aspects concerning heritage buildings. These include: conservation principles, an improvement in energy performance and the indoor environment, the role of occupants in energy consumption reduction, and a reduction of existing decay and damage. Therefore, research on the performance of heritage buildings should be disseminated to the building industry, planning and building control authorities to increase their knowledge about the considerations and risks associated with retrofit works.

Table of Contents

Introduction

This literature review was completed as part of a larger research project conducted by BRE and funded by the Department of Energy and Climate Change (DECC). The key aims of the project are to better understand the properties and performance of solid walls in the UK and to quantify the impacts of installing solid wall insulation on domestic properties.

Improving the energy efficiency of Britain's housing stock forms a major part of the Government's energy and climate change policy. Energy efficiency programmes developed over the last two decades have focused primarily on a number of major measures, including boiler replacements, insulating hot water cylinders, roofs and wall cavities. Progress in these areas has been significant, primarily as a result of Government programmes such as CERT, Warm Front and their predecessors. The current Green Deal and ECO programmes continue where the previous programmes left off. However, the remaining potential for these measures is now reduced, and these new programmes will now have to start addressing some of the more challenging energy efficiency improvement measures if the efficiency of the housing stock in Great Britain is to be improved significantly in the future.

Insulating the solid wall housing stock is one of the greatest challenges for energy efficiency policy. It potentially offers significant savings, as there are more than 7 million solid wall dwellings in Great Britain. It is important, therefore, to better understand the properties and performance of solid walls as they stand now and to quantify the impacts of installing solid wall insulation on domestic properties.

The literature review

The aim of the literature review was to identify and describe relevant research conducted over the last 20 years and beyond. The review outlines the current understanding and highlights the relevance of the work conducted thus far to the project. It identifies where there are gaps in the existing understanding and where further research is needed. It also highlights key lessons learnt from the previous research studies which are relevant to the design of the current project and the planned field trials.

This document was not intended to be an analytical review of the existing literature. The aim was not to challenge the existing understanding at this stage of the project. Instead, the objective was to identify, outline and describe existing research, measurement and modeling methodologies, and current accepted practices.

BRE worked with the Centre for Sustainable Design of the Built Environment, at the Welsh School of Architecture, Cardiff University, to deliver the literature review. BRE was responsible for the co-ordination and management of the literature review and Cardiff University led on the literature searches and production of the report. The specification for the review was developed by BRE in conjunction with DECC. BRE worked with Cardiff University to identify all relevant sources of information. A team of reviewers at Cardiff University, led by Professor Chris Tweed, then produced the report chapters. These were reviewed and supplemented with further input from assigned expert subject leaders at BRE.

The material for this review was sourced from a wide variety of literature including peer-reviewed scientific journals, grey literature sources, relevant conference proceedings, guidelines and other published material. Databases of academic journals were used to conduct systematic searches relating to each of the key subject areas covered in this review. Databases used for searches were Web of Knowledge, the Construction Information Service, Elsevier Science Direct, Google Scholar, and JSTOR. Sources of grey literature included Sustainable Traditional Buildings Alliance (STBA), Historic Scotland, English Heritage, the Building Research Establishment (BRE), the National House-Building Council (NHBC), the Welsh body Cadw, Department of Environment for Northern Ireland, The Ulster Architectural Heritage Society (UAHS), and the Energy Saving Trust (EST). International sources were also reviewed including the Fraunhofer Institute for Building Physics (Germany), the Oak Ridge National Laboratory (USA) and the Building Science Corporation (USA).

The reference list at the end of this document provides lists of all the relevant papers and documents identified for each of the subject areas.

The review was split into the following five chapters:

1. Heat loss measurement and calculation methodologies
2. Predicted performance compared to actual savings
3. Occupant behaviour
4. Unintended consequences
5. Heritage and conservation

The sections below provide some background and contextual information around the key topics and concepts discussed in the review chapters.

UK Stock Profile and Context

History of Construction Methods in the UK

To understand the make-up of the existing building stock in the UK, it is important to understand the evolution of construction in the UK. Prior to the 1930s in the UK, house building was undertaken using a variety of solid wall techniques and construction forms, known as frameless structures, with the external façade acting as the loadbearing wall.

Most frameless loadbearing external walls consist either of a structure made in the form of an assembly of prefabricated units – bricks, blocks or slabs of natural stone, fired clay, concrete or calcium silicate – or in the form of site-cast slabs of concrete. Generally the units were regular and rectangular shape and will be bonded together with a mortar, but large units were built without mortar. These walls are required to support their own dead weight plus the dead weight of any floors, partitions, ceilings, roofs and claddings which bear onto them or are fixed to them over the height of one or more storeys.

Traditionally for this period, lime mortar was the most common bonding unit, but other similar materials were used. The aggregate in the mortar was always very dependent on local resources and available materials, such as sand, crushed rock, pulverised ash, and coal dust.

The walls were typically one solid layer of material, although even in the pre-1930s cavity walls were in existence. As a general rule, the older the property, the more likely it is to have solid masonry walls, with nearly two thirds of all dwellings built before 1918 having solid walls. Historically, by far the most common material used in solid masonry walling around the late 1800s and early 1900s was clay brickwork, nominally 230 mm thick. However, a range of masonry materials and thicknesses were used including stone, in-situ cast dense and no-fines concrete, and lightweight concrete blockwork. Some of these materials may present their own technical and buildability issues when considering thermal upgrading. In addition, stock condition surveys typically do not distinguish between brick and stone, and thus when considering opportunities for improvement starts to make the process more difficult and complex. Consideration will need to be given where there may be problems in achieving appropriate fixing or adhesion to the masonry substrate, should the risk analysis indicate that thermal upgrades are suitable.

Current Knowledge of UK Stock Profiles

An estimated 7.7 million UK dwellings have solid walls while a further 1.75 million or so have cavity walls which are not suitable for cavity wall insulation (for example because the cavity is too narrow or the wall covering prevents straightforward injection of insulant). Improving the thermal performance of these dwellings has enormous potential to reduce carbon emissions and fuel poverty, whether it is undertaken using external or internal insulation techniques. Many of the UK's fuel poor live in these types of properties which are defined in the UK as Hard to Heat Homes (HTH) Measures to improve their performance will be essential to lifting many of these residents out of fuel poverty, and to meet the EU and UK targets for CO_2 reductions.

Although not a common form of modern building construction, solid masonry walling makes up a sizeable proportion of the current housing stock, and Wales has the highest proportion of housing stock with solid walls of various constructions, in the region of 34% of its total housing stock is of solid wall type. The majority of solid wall properties are low-rise (two-storey) detached, semi-detached or terraced homes.

Detailed breakdowns of the UK housing stock can be found in appendix A

Heritage buildings

When endeavouring to define heritage buildings it is important to look at a number of criteria

- Value as a historical architectural work
- Value for its construction engineering
- Value as cultural heritage
- Value to the settlement history, neighbourhood and environment

Value as a historical architectural work

The invisible attributes of architecture and places are often as important as the visible. Knowing that an artefact or place has a history and knowing something of that history alters the way in which it is perceived. There have been heated debates in cultural heritage about the importance of authenticity. Interpretations of authenticity also vary with culture. In the Far East, for example, a timber structure such as a temple of shrine may be regarded as thousands of years old because there has been a building on the site for that period of time. The actual building may only be two hundred years old. The fact that the present building is not the same building as the original seems to have little impact on the authenticity of the relic. Conservationists, and particularly preservationists, in the West are less flexible in their allowing authenticity, which is applied as an honorific term of approval.

There is justifiable reason for this as the physical form, scale and layout of the building embodies the architectural history of the building and the way it was built reflects societal and cultural values and knowledge of that period. Many interesting facts about our past can be determined from, for example, the contents of thick stone walls.

Value for its construction engineering

All traditional/historic buildings can contribute to present quality of life by reminding us of our past and adding visual interest to the environment. Traditional buildings are of historic interest because they reflect the lives and achievements of our predecessors. Traditional buildings are usually constructed from locally sourced materials that are rarely used in the majority of buildings constructed today. Also, traditional construction puts a value on all historic buildings in terms of cultural heritage and as an irreplaceable resource. With sensitive alterations and repairs, the resource continues to be useful and fulfils a new role as a cultural object. An important value of such buildings is how they represent the abilities of the crafts people of a particular time and the knowledge and skills they possessed. The engineering of traditional buildings is often a function of the available tools and technologies too. Thus, they tell us more about those times than about the building alone.

Value as cultural heritage

Historic/traditional buildings differ greatly in how much they can be changed without losing their specific interest. Some buildings are sensitive to the slightest alteration, especially when done externally. Others may have changed drastically several times during their life and can adapt to changes quite comfortably.

Before deciding upon a refurbishment measure for any building, it is important to identify to what extent the building is sensitive to alteration. What are the important elements that are significant to that building in term of the special character and the interest of the building? Sufficient surveys, investigation and studies of the physical, documentary and cultural value should be done in advance of design work to ensure that the building is well understood before proposing any alteration work. It is important to identify the characteristics that are significant at local, regional and national scale. Some features may not be important at regional and national level but are very important at a local level. They could be the most valuable elements within a local context and have particular value to local stakeholders. It may be the local representative of its own period and local cultural heritage.

Most existing residential buildings are capable of describing their period by having special characteristics or features from their era. These help us to understand those periods in greater detail (such as Victorian, Edwardian etc). When proposing refurbishment, it would also be appropriate to include the help from specific interest groups with specialised knowledge of the period to make sure that the sense of place and that period is not lost.

Value to settlement history, neighbourhood and environment

The historical settlement, townscape and the environment of the area or town reflects the local identity of that place. The special architectural features of the traditional building or conservation area give a character to the building or the area. To enhance the character and appearance of the building or the settlement either for aesthetic reasons or to meet the changing needs of the occupiers, there should be complete understanding of the importance of a building’s character and its originality which reflects the history of its settlement. With external wall refurbishment the particular focus should be on the selection of the external materials and their densities. Building lines and corner features should relate to the neighbouring buildings and should be sympathetic to the local area. The landscaping and the external boundary and surface treatment should be included as an integral element of the overall design of the proposal. Proper refurbishment of the external wall will maintain the valuable environmental and cultural unity of the area and will form systematic landscape scenery.

Internal and external insulation

Since solid walls do not have a cavity into which insulation can be injected, they are normally insulated by applying either internal or external insulation.

An alternative to insulation can be a coating, applied to the external surface of the brickwork in order to keep the wall dry, however such coatings will only lead to a relatively small improvement in the U-value.

The application of internal insulation can be carried out by a householder or by a contractor. It can be applied either as a continuous layer of insulation or insulation can be fitted between battens, or it can involve a combination of both.

Examples of internal insulation include the following:

1. Blown fibre injected through holes in the existing internal plasterboard to fill the void between the plasterboard and the masonry

2. A continuous layer of material, such as polystyrene or polyurethane, bonded to the existing internal wall surface using a glue. A system such as this is only suitable for very flat wall surfaces and the insulation will usually be sandwiched to a layer of plasterboard.

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3. Polystyrene, polyurethane or mineral wool (or similar) fitted between battens which are in turn affixed to the inside surface of the existing wall. Once the insulation has been installed, a new sheet of plasterboard is then fitted to the battens. The battens can be made of timber or steel.

External insulation systems normally require a contractor to install. They typically involve a layer of insulation applied to the external surface of the existing wall, and then a render coat is normally added externally. External systems can for example involve mineral wool or polystyrene.

SAP methodology

The Government's Standard Assessment Procedure (SAP) for assessing the energy performance of dwellings was first published by the then DOE and BRE in 1993 and in amended form in 1994. Revised versions were published in 1998, 2001, 2005, 2009 and 2012. SAP is based on the BRE Domestic Energy Model, known as BREDEM. Since the publication of the 1995 edition of the Building Regulations for England and Wales, SAP has been used as a means of assessing the compliance of a dwelling design with regulatory requirements for the conservation of fuel and power.

A SAP rating for a dwelling is based on the predicted energy costs associated with space heating, water heating, ventilation and lighting, less cost savings from energy generation technologies. It is adjusted for floor area so that it is essentially independent of dwelling size, for a given built form. SAP also predicts CO_2 emissions.

The SAP calculation method is set out in the form of a worksheet, accompanied by a series of lookup tables and it is compliant with the Energy Performance of Buildings Directive. Although a manual calculation is possible, the calculation is generally carried out using approved software.

The calculation procedure takes account of a wide range of factors, including:

1. materials used in the construction of the dwelling
2. thermal insulation of the building fabric
3. predicted air leakage and ventilation equipment
4. efficiency of the heating system, and controls
5. solar heat gains through windows and doors
6. the fuel used to provide heating, ventilation and lighting
7. energy for space cooling, if applicable
8. renewable energy technologies

SAP is used to assess the dwelling itself and it takes no account of the actual occupants, nor the way the actual occupants consume energy. With the exception of air conditioning, SAP ratings are not affected by the location of a dwelling within the UK. This allows house builders to standardise their designs with the knowledge that they will meet the regulations regardless of where the dwellings are built.

A variant of SAP, known as RdSAP, is used for existing dwellings, such as pre-1919 solid-walled dwellings, for example. RdSAP stands for 'reduced data' SAP, and the input dataset is based on the information which a surveyor can collect during a non-intrusive survey rather than the full information obtainable from architectural drawings. The RdSAP procedure, therefore, contains a number of assumptions. In particular, RdSAP contains assumptions about wall constructions and uses lookup tables for U-values, where the U-values are estimates based on the age of the dwelling, the generic construction types and the measured thickness of walls. For solid walls, RdSAP estimates of U-values are currently thought to be higher than measured U-values and the present project is seeking to resolve this difference.

Describing the thermal performance of elements (U-values)

U-values are used to describe the tendency of walls to lose heat. It is a measure of the quantity of heat that will flow through unit area in unit time, per unit difference in temperature between the internal and external environment. It is expressed in W/m²K (i.e. watts of heat lost per square metre per degree). An element (e.g. a wall) which is uninsulated or poorly insulated will have a high U-value whereas an element which is well-insulated will have a low U-value.

The rate of heat loss in watts attributable to an element of area A, and U-value U, where the temperature inside the building is T_i and the temperature outside is T_e, is given by Φ, where:

$$\Phi = A \times U \times (T_i - T_e)$$

U-values can be calculated if the dimensions and thermal properties of the layers of a wall are known, and a simplified procedure for calculating U-values is given in BS EN ISO 6046. For existing walls, it is necessary to make assumptions about their composition, and BR443 provides guidance on conventions that should be used.

Established conventions on U-value calculations were used to obtain the published U-values given in Appendix S of the SAP 2012 document. A U-value of 2.1 W/m²K is given for a typical 9-inch solid brick wall. This U-value was obtained by adding together, separately, the thermal resistances of all the layers of the wall, and then taking the reciprocal of the resultant value.

1 Heat loss measurement and calculation methodologies[1]

1.1 Introduction

This section discusses methods used to determine U-values of building constructions, with a particular emphasis on walls. It is subdivided into the following sections:

- measurement of temperature
- temperature contrast
- infrared thermography
- hot box methods
- heat flux sensors
- transient effects and transient techniques
- moisture content
- duration of a U-value measurement
- solar effects
- whole house heat loss
- calculation methodologies
- conclusions and recommendations

A large number of references were examined but only those most relevant to the subject of this literature review are discussed here.

Experimental studies on the heat transfer through building elements have been carried out at least as far back as 1936, when a laboratory for testing walls was constructed at the Building Research Station in Garston, Watford. Since then, a considerable number of research projects have been carried out by various organisations, using a variety of techniques for measuring U-values and other thermal parameters. Much of the research has involved the use of either hot boxes or heat flux sensors, in conjunction with temperature sensors. Some of this work has involved the testing of a wall under laboratory conditions, where each side is subjected to a closely-controlled environment, and there has also been much work involving measurements in buildings in the field, both occupied and unoccupied.

Hot boxes are also often used for the measurement of U-values, particularly in the laboratory environment. Hot box methods, under laboratory conditions at least, tend to give results which are accurate and reliable. Hot boxes are considered to provide the most authoritative test, and, due to their design, the heat transfer across a wall under test can be deduced from the electrical energy which is supplied to the warm side of the wall.

Heat flux sensors, which can be mounted on the surface of an element or embedded within it, are often used in the field as a means of assessing thermal transmittance. They offer a much more practical method for in situ testing of walls than hot boxes, particularly if the building is occupied at the time, since they are much more portable and take up much less room. Heat flux sensors can also assess heat flux densities at positions of particular interest, and can be used to show the variation in heat flux at different points on a wall.

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[1] Author: Sean Doran (BRE)

When measuring U-values, reference is frequently made to the term 'heat flux'. Heat flux is the heat flow (in watts) divided by area (in square metres). Under steady state conditions, the U-value of a wall (or other building element) is equal to the heat flux divided by the difference in temperature between one side of the building element and the other.

ISO 9869:1994 sets out the in situ method for measuring U-values using heat flux sensors, as well as the method of analysing the measurement data. It also offers optional methods for correcting for thermal storage, although measurement errors due to thermal storage effects become minimal provided the period of measurement is sufficiently long. ISO 9869 also describes techniques for averaging readings, including a method which some authors, e.g. Desogus *et al* (2011), refer to as the 'mean progressive method'. Baker (2011) and Rye (2010) provide an illustration of the progressive averaging of data, showing a U-value gradually stabilising as the period of monitoring increases, shown here in Figure 1.

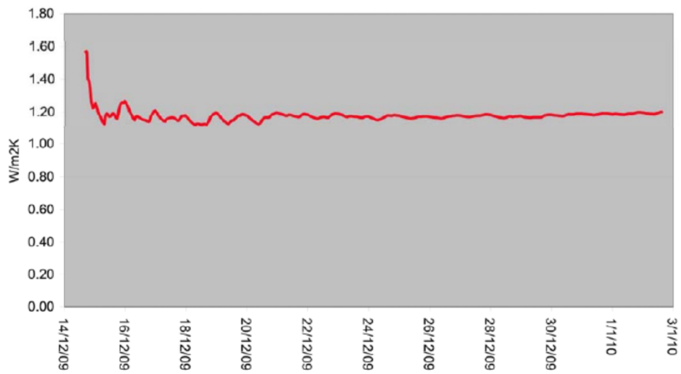

Figure 1: An illustration of a resulting U-value gradually stabilising as the period of monitoring increases, from Rye (2010), giving a broad-brush indication of the accuracy which is achievable for a given duration of measurement.

It is notable that the error in the U-value in Figure 1 is very high during the first few days and then it quickly decreases, as indicated by the shape of the line. It has to be added, however, that the data in Figure 1 appear to show an example of very stable conditions, and in practice the U-value would usually take longer to stabilise than the graph in Figure 1 suggests, at least in the case of occupied housing

Appendix B of BRE report 78132, reproduced here in Figure 1B, illustrates the level of fluctuation in the measured U-value, when the U-value is obtained from 5 days of continuous data, and it shows a significant fluctuation even after basic thermal storage corrections have been applied. The solid line in the figure shows the '5-day' U-value without thermal storage corrections and the dotted line shows the '5-day' U-value with thermal storage corrections.

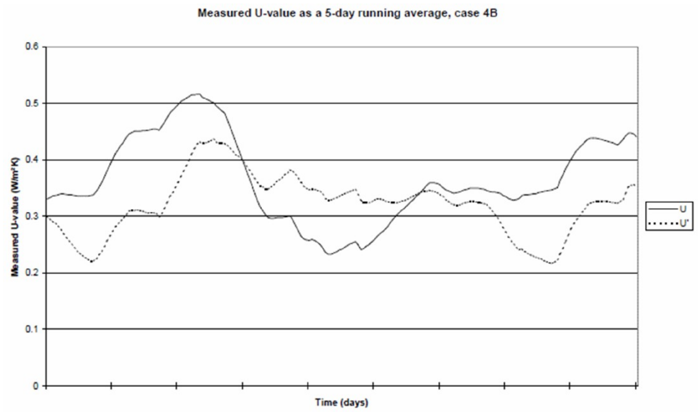

Figure 1B: An illustration of the fluctuation in the U-value with time, where the U-value for each point on this graph is based on 5 days of data. The uncorrected U-value is shown as a solid line and the U-value corrected for thermal storage (using the method in ISO 9869:1994) is shown as a dashed line.

Ward (1993) and Senior (1984) conducted extensive U-value measurements during the 1980s and 1990s on a variety of wall types, using heat flux sensors, and were able to conclude that U-values for insulated walls tend to be higher than a simple U-value calculation would suggest. Their method involved the use of disc-shaped heat flux sensors which incorporated multiple thermocouple junctions within a central active area, embedded in plastic, and a surrounding guarding area, also composed of plastic. Ward used two sizes of heat flux sensor, one being 50mm in diameter and the other 100mm in diameter, both being 3mm thick. Ward was concerned about the inhomogeneity in the thermal conductivity of the heat flux sensors and used a metal disk, of the same diameter as the heat flux sensor, in order to compensate for the inhomogeneity. Ward also paid close attention to the surface roughness, and developed a technique to accommodate the undulations in the surface. This research also made extensive use of thermal imaging in order to identify the positions on the walls that were most representative of the wall as a whole. Attention was also paid to the differences between surface temperatures and air temperatures, as well as the impact of different types of surfaces upon measurement accuracy and air movement within wall cavities. Overall, Ward estimated an error of 15% in the measured U-values, a level that was sufficient to demonstrate that there was a discrepancy between measured and calculated U-values for some types of insulated walls. In order to resolve the problem of radiative versus air temperatures, Ward covered the heat flux sensor with a matt black surface so that its temperature would approach the black body temperature which was also monitored using a black-painted temperature sensor.

Yesilata and Turgut (2007) give a helpful overview of techniques for assessing thermal resistances, although the emphasis in this paper is on laboratory measurements rather than field measurements. It includes a discussion of the hot box technique (illustrated in Figure 1c of their paper) and transient dynamic methods involving thermal waves as a means of determining thermal properties of materials.

Desogus *et al* (2011) publish a comparison between different measuring methods to determine the thermal resistance of building fabric, including a test wall incorporating an array of measuring points, which was tested in an environmental chamber. This paper also compares a 'destructive' method which involves drilling the layers and measuring their thickness and thermal properties, with non-destructive approaches, and succeeds in obtaining good agreement between the two methods. This would appear to suggest that if the properties of the materials within a wall construction are precisely known, then the calculated U-value, using the method in EN ISO 6946, can agree well with the measured U-value of the wall, using the method in ISO 9869, at least for the type of wall which they examined.

The following sub-sections will examine a number of aspects of U-value measurement, providing an overview of the methods that have been used, both in the laboratory and in the field.

1.2 Measurement of temperature

In order to measure the U-value of a building element or component, it is necessary to measure temperatures, or temperature differences, in order to interpret the resulting heat flow or heat flux and thereby determine the U-value. Temperature sensors can be located either in the air adjacent to a building element, or on the surfaces of the element. In addition, particularly where a detailed understanding is being sought, they can also be embedded within the element at various depths.

In most of the research involving the measurement of U-values, temperatures are measured using thermocouples or thermistors, and in some cases differential thermocouples are used, where one thermocouple is in the warm environment and one in the cold environment, within a single thermocouple circuit.

In some research, temperature sensors have been embedded at strategic depths within the solid material (e.g. Tomas and Rees 1999) to gain a much more comprehensive understanding of the heat distribution. Thomas and Rees (1999) use an array of temperature sensors in a ground floor. This research also provided a good understanding of the temperature distribution beneath a ground floor through the use of many embedded thermocouple sensors arranged at various positions and depths, and in particular they were able to conclude that there is a definite boundary region below the perimeter of a ground floor where temperatures and humidities show dramatic change. The distribution of soil types was investigated in order to assist in the interpretation. Thomas's mapping was not confined to temperatures – in their research a neutron probe was used to map moisture content in the soil. Their research suggests that mapping an element which is being tested can lead to a better understanding of the heat transfer mechanisms that lead to the overall U-value.

Desogus *et al* (2011) note the importance of the accuracy of temperature sensors in obtaining a U-value which is both accurate and reliable, although it is likely that the sensitivity of temperature sensors could be less important when the contrast in temperature is high. Additionally, the use of differential thermocouples could potentially offer a way to achieve more accurate U-values. Interestingly, Desogus *et al* measure both the surface temperatures and the air temperatures in order to gain a fuller picture of the measurement.

Figure 2: Examples of temperature sensors, sensing both the surface and the air temperature, Rye 2010.

For the present project, accurate measurement of temperature is crucial if accurate U-values are to be obtained. This is the case both for in situ measurements and for testing under laboratory conditions, as well as for any whole-house heat loss measurements that may be carried out.

The use of embedded temperature sensors may be worth considering as a means of gaining a better understanding of the heat flow patterns within solid walls, as they may help to reveal which parts of the wall structure offer the highest or lowest resistance to the flow of heat, however there would be practical difficulties in the use of embedded sensors and the installation of such sensors could distort the temperature distributions within a wall.

1.2.1 Temperature contrast

The contrast in temperature between the inside and outside of a building element or between the two sides of a sample of building envelope, in a laboratory situation, can have a very significant impact upon the accuracy of a U-value measurement.

Nicolajsen (2005) noted that under Danish conditions, U-values and moisture contents can vary seasonally and that the difference in temperature between inside and outside can significantly influence the measured U-value. Nicolajsen also commented that it is best to measure U-values in winter, a view which would probably be expressed by most authors.

Desogus *et al* (2011) note that the temperature difference between the inside and outside environments must be at least 10 K in order to provide sufficient accuracy.

1.2.2 Infrared thermography

Thermal imaging, while largely a qualitative rather than a quantitative technique, can be an invaluable aid to accurate U-value measurement. It can complement both laboratory measurement and field measurement as it can map the temperature distribution across a surface. It shows the degree of temperature variation across a surface and it helps in the identification of suitable (i.e. representative) locations for U-value measurement, as well as giving a general assessment of spatial inhomogeneity. Zalewski *et al* (2010) for example, describe some work which makes extensive use of thermography to complement other investigations.

Zalewski *et al* (2010) carried out laboratory tests on a section of steel-frame wall which was instrumented with thermocouples and heat flux sensors, and located between two environmental chambers. The paper discusses comparisons between the monitored results, thermograms and thermal simulations using Trisco software. Zalewski *et al* note the usefulness of the thermography in visualising heat losses and further suggests that thermography is an invaluable tool in finding the zones which are most thermally representative of the whole building envelope. Zalewski *et al* (2010) use the Trisco simulations (Standaert, 2002) as a means of interpreting the measurement data. It is noted that Zalewski's apparatus uses unusually high temperatures, however, with a warm environment of 42°C. Attention was paid, in the measurements, to the air temperature and radiant temperature, and surface thermocouples were used. Heat flux sensors with surrounding guarding were used to monitor the heat flux at various positions on the steel frame construction. Zalewski concluded that there was good agreement between the measured results and the thermal model predictions.

Infrared thermography is a vital part of the present project as it will provide a measure of the homogeneity of walls and will provide an indication of how representative a particular location of a wall is for measuring a U-value.

1.2.3 Hot box methods

A hot box approach is often used, particularly in the laboratory environment, as this provides a mean heat flux over an extensive area of wall. Total heat flow is determined by the current and voltage supplied to the heating elements at the warm side of the specimen.

In most hot-box arrangements, the temperature within the hot box is the same as the temperature outside of the hot box, so that the heat generated within the hot-box is equal to the heat that is conducted through the section of wall that is adjacent to it. Since the heat generated within the hot box is determined by the supply current and voltage to its heating elements total heat flow can be quantified.

Yesilata and Turgut (2007) give an overview of laboratory methods for testing materials and building structures, including a description of the hot box technique and transient methods. In the hot box method, a steady-state equilibrium is to be achieved, where near-constant temperatures are achieved, and the U-value is determined from the electrical power consumed in the heaters.

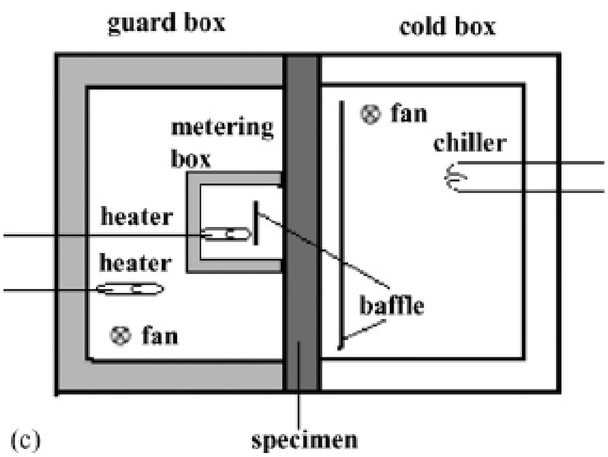

Figure 3: An outline description of a hot box arrangement under laboratory conditions, from Yesilata and Turgut (2007), involving an environmental chamber on either side of the wall specimen, electric heaters, chillers, baffles to minimise radiative effects and appropriate metering of electrical energy as a means of quantifying the total heat flow.

A variation of the hot-box approach was used by Lee *et al* (1999). In their approach, a test panel was placed against one surface of the wall, and corrections were made for lateral heat loss. This approach has some merits, as it helps to keep the surface temperatures constant; however this method requires prior knowledge of the thermal properties of the materials in the wall in order to apply corrections and the accuracy of such corrections will depend upon the accuracy of the prior knowledge.

Unlike other methods of measuring U-values, hot boxes avoid many of the problems associated with calibration. The heat transfer through a wall will be determined by the supply voltage and current to the hot box and by the measured temperatures to the warm and cold sides of the wall. A hot box can therefore be used as a means of testing other methods of U-value measurement, such as heat flux sensors where calibration might be an issue. Hot box testing is therefore a very important component of the present research programme as it provides a means of verifying aspects of the experimental methodology which is used in the field.

1.2.4 Heat flux sensors

Heat flux sensors are extensively used both in laboratory conditions and for field testing. Sensors can be either surface-mounted (e.g. Baker 2008, Ward 1993, Rye and Hubbard 2012) or embedded (e.g. Nicolajsen 2005, Desogus *et al* 2011). When used in the field, they require surfaces that are sufficiently flat and smooth, although substrates can be used to compensate for roughness (Ward, 1993). Thermography is often used as a means of ensuring that the location of measurement is representative of the element (e.g. Rye 2010, Ward 1993), as well as providing a qualitative measure of spatial inhomogeneity.

Figure 4, Figure 5 and Figure 6 illustrate the use of heat flux sensors in buildings.

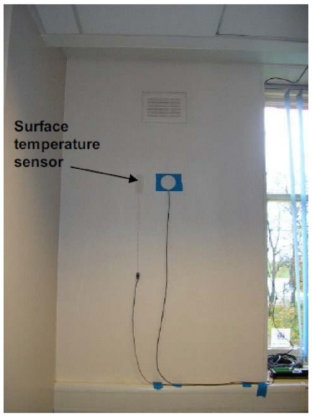

Figure 4: A surface-mounted heat flux sensor and a surface-mounted temperature sensor (Baker 2008).

Figure 5: A surface-mounted heat flux sensor and temperature sensor (Rye 2010).

Figure 6: An embedded heat flux sensor being placed behind the interior gypsum board, from Figure 4 of the paper by Nicolajsen (2005).

Owing to their portability, heat flux sensors are particularly useful for in situ measurements of U-values, particularly within occupied housing where compactness of size is crucial. For the present project, heat flux sensors will provide the main method of measuring U-values in housing.

1.2.5 Embedded sensors

Nicolajsen (2005) concluded that embedding a heat flow meter behind the plasterboard led to a much lower measurement error than placing the heat flow meter on the indoor surface. Nicolajsen's estimated error, when embedded, was only 1% whereas when surface mounted Nicolajsen estimated an error of the order of 5%.

Desogus *et al* (2011), like Nicolajsen, appear to be in favour of embedding heat flux sensors rather than mounting them on the surface of the wall, and they state that "heat-flux meters need to be plastered on the surface or embedded in specimens". Desogus *et al* also argue that the alteration in the heat condition of the surface due to the heat flux sensor "will lead to a change in temperature fields in the specimen and around the heat-flux meter." They conclude that "the best way to evaluate the in situ R-value of buildings is by direct measurement with a heat-flux meter".

Thomas and Rees (1999) used an array of 11 embedded heat flux sensors in a floor and obtained good agreement with the expected result for the U-value of the floor, at least in the case of a dense concrete floor, suggesting that the use of embedded heat flux sensors can lead to a considerably improved understanding of the patterns of heat transfer.

Whilst embedded sensors could lead to a better understanding of the temperature and heat flow distributions within solid walls, there are practical difficulties that would need to be overcome. The implantation of sensors could affect the wall construction being studied and, in addition, there could be problems obtaining consent from occupiers.

1.2.6 Accuracy

Nicolajsen (2005) notes that heat flow meters offer an approach to measurement which is unaffected by the overall air tightness of the building. Nicolajsen concluded that with the use of heat flux sensors an overall measurement error of around 7% is achievable (section 7.1 of the paper). The main sources of error, according to Nicolajsen, can be attributed to the calibration of the heat flux sensor (5%) and the accuracy of the temperature sensing (5%). Nicolajsen estimated the error due to contact resistance to be around 5% as well, but in this case managed to avoid this source of error by embedding the sensor rather than mounting it on the surface. Through the minimisation of measurement errors, Nicolajsen was able to conclude that measured U-values, obtained through heat flux sensors, were around 10% lower than corresponding calculated U-values (Table 2 of the paper).

Ward's research (Ward 1993) also provided an error analysis, giving the calibration error as 5% (the same as Nicolajsen), the temperature error as 3% (slightly lower than the 5% value quoted by Nicolajsen), and the repeatability of the system as 5% (similar to Nicolajsen's estimate of error from contact resistance), and as a result Ward's error was 15%, although this measurement error was certainly still sufficient to draw some conclusions about the performance of insulation in his study. The method of combining the errors was different in the two papers – Ward used simple addition of errors while Nicolajsen combined the errors in quadrature. The errors are summarised in Table 1.

Table 1: Errors associated with sensors

Summary of errors	Nicolajsen, 2005	Ward, 1993
Calibration of heat flux sensor	5%	5%
Accuracy of temperature sensing	5%	3%
Error due to contact resistance	1%*	-
Correction for in situ use		2%
Repeatability of system	-	5%
OVERALL ERROR quoted in paper	7%	15%
Method of combining errors	quadrature	addition

*According to Nicolajsen this error would have been of the order of 5% if the heat flux sensor were surface mounted, but estimates an error of only 1% because the sensor which Nicolajsen used was embedded.

1.2.7 Spatial inhomogeneity

Heat flux sensors can be used to observe the spatial inhomogeneity in the U-value of a wall, and the use of several different measurement points can lead to a fuller picture of the behaviour of a building element such as a wall. For instance, Nicolajsen (2005) observed that the measured U-value of a timber frame construction varied spatially on the same wall and the standard deviation in the measured U-value was found to be 0.01 W/m^2K (Table 1 of Nicolajsen's paper).

Although ISO 9869 requires a minimum of two heat flux meters per wall, this would not be enough to provide a quantitative measure of the spatial inhomogeneity of the U-value of a wall (although thermal imaging will certainly provide a qualitative measure of this). Having more than two heat flux meters, however, could lead to a better indication of how much the U-value of a wall varies spatially, and would provide an indication of the level of confidence in U-values that are measured.

1.2.8 Affixing sensors

Doran (2001) discusses the affixing of a heat flux sensor to a wall, and the importance of guarding (inactive area) around the sensor, in order to reduce the edge effects where heat may try to bypass the edges of the sensor when it is surface-mounted. His approach was based on that taken by Ward, 1993, and the arrangement by Ward, is shown in Figure 8. In that research, a substrate of modelling clay was used, whereas more recent research by the same author (Doran, 2008) used petroleum jelly as a substrate (Figure 9).

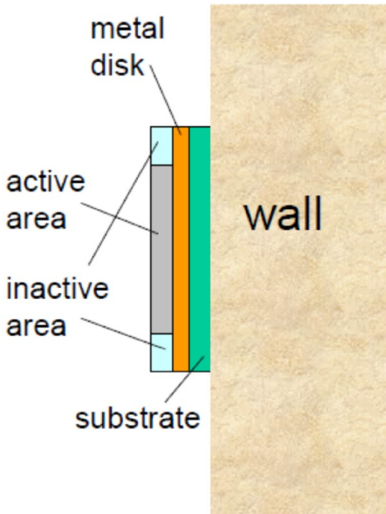

Figure 7: A sketch showing the positioning of a heat flux sensor on a wall (Doran 2001).

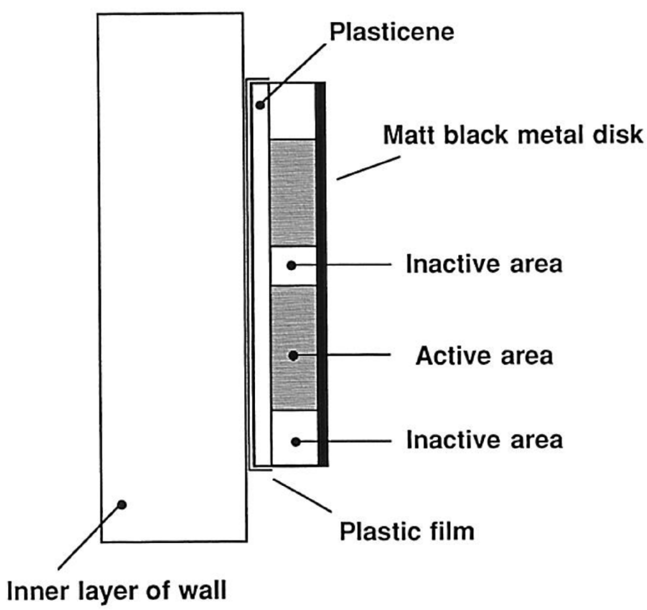

Figure 8: A heat flux sensor arrangement used by Ward (Ward 1993).

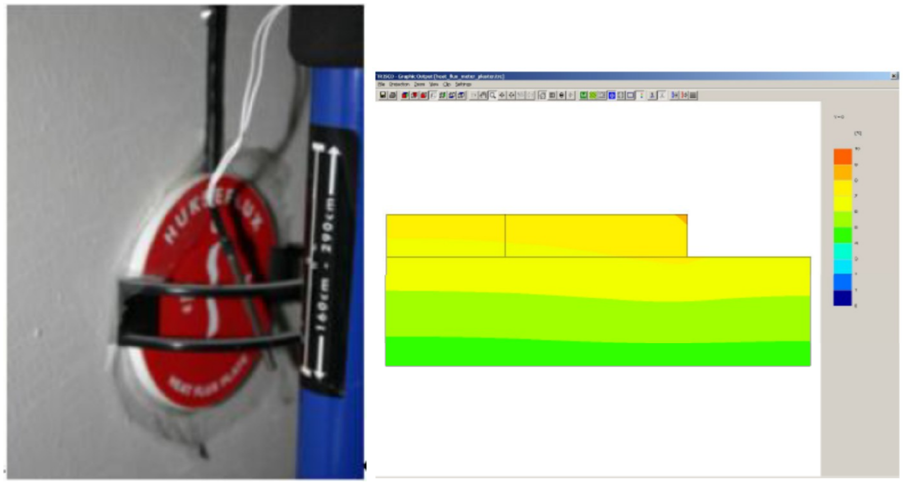

Figure 9: A heat flux meter arrangement, and thermal model of the expected temperature distribution (Doran 2008).

In the heat flux meter arrangement, a thin plastic sheet was used to prevent the petroleum jelly substrate from staining the wall, and a thermistor was placed roughly 1cm away from the heat flux meter to monitor indoor temperature. Note that in the thermal model, only half of the disc is shown, laid over the innermost layers of a wall, with a line separating the central active area of the disc from the surrounding inactive area.

Previous research appears to indicate that surface-mounted heat flux meters can lead to a slight distortion of temperature distributions, leading to a possible systematic error. It is also apparent that thermal modelling techniques can be used to predict such distortions and thereby derive correction factors to allow for them. Less clear, however, is how best to minimise or allow for contact resistances, such as the contact resistance between a heat flux meter and the wall which it is being used to test, and evaluating contact resistances would appear to be outside of the scope of thermal modelling calculations.

1.3 Transient effects and transient techniques

1.3.1 Amplitude time lag and amplitude decrement

In addition to U-values, other parameters have been measured in walls. Pratt (1969) considers the fundamental time lag and amplitude decrement. Fundamental time lag represents the time delay between temperature variation at the inner surface and a sinusoidal temperature variation (24 hour) applied at the outer surface. The amplitude decrement is the ratio of peak values of temperature at the inner and outer surfaces. These parameters are related to thermal mass and are connected with the thermal parameters of a building element.

Although Pratt (1969) includes results for 73 measurements, only the first four results actually relate to traditional 9" solid brick walls. The solid wall results in this paper point to a typical U-value of 2.2 W/m^2K for a 9" plastered solid brick wall, close to the value assumed for current RdSAP calculations. Curiously, the presence of render or plaster appears, in Pratt's work, to have only a very small effect upon the U-value, suggesting that render has little effect upon the thermal properties of the brickwork which it is protecting. In particular, this would appear to suggest that render does not protect brickwork from the wetting effects of rain and has negligible effect upon U-values.

1.3.2 Transient techniques

Transient techniques, which involve the use of pulses of heat, or step changes in temperature, offer the possibility of rapid measurement of some of the thermal properties of materials, but research in this field has yet to provide a reliable and accurate approach which could be used to assess whole walls. They can be used both in the field and under laboratory conditions, and some techniques, that of Pilkington and Grove (2012), for example, involve a heated object, such as a needle, or a pulse of radiation – to measure thermal diffusivity or thermal conductivity.

Yesilata and Turgut (2007) give an overview of laboratory methods for testing materials and building structures, including a description of the hot box technique and transient methods. Their paper includes a description of transient dynamic methods, typically involving thermal waves to determine thermal properties. In this approach, a heat pulse (or heat flux) in the form of a step-wise function is produced in order to generate a dynamic temperature field. The wave or pulse of heat can be generated by a short intense 'flash' of radiation on the specimen or by an embedded electric heater. This technique typically leads to a measurement of thermal diffusivity and from this the thermal conductivity may be calculated. As part of the process, temperatures are measured at strategic positions within the specimen and temperature-time graphs are produced for each location, in order to evaluate the thermal properties of the materials under test. They warn that more work is necessary to increase the utilisation and standardisation of their technique, and therefore their work is unlikely to benefit the present solid walls project directly.

Pratt and Lacy (1965) present a mathematical treatment of a sinusoidally-varying heat flow through a homogeneous masonry wall. The equations are detailed but they show that it is possible to calculate thermal diffusivity from the time delay in the temperature profile of the wall. Their derivation indicates that information can be gleaned from monitoring the temperatures at both surfaces. Experimental results are presented for various wall types, including a Fletton brick wall. While the approach is of considerable interest, it does not appear to lead to rapid U-value measurements which could conveniently be carried out in-situ.

Pilkington and Grove (2012) examined the use of pulses of heat through guarded needle probes as a way of measuring the thermal conductivity of a homogeneous isotropic insulation material (see Fig 3 of their article which shows a good example of such a needle probe). They concluded that there are good prospects for measuring thermal conductivity using this method but that existing solutions for probe length to radius ratios need revision before reliable results can be consistently achieved, at least as far as insulation materials are concerned.

Other approaches to transient methods have also been examined. De Gracia *et al* (2011a), for example, describe a transient method involving heated and cooled copper coils as a means of testing properties of material samples. De Gracia shows that their technique can be used to evaluate a range of thermal response characteristics of composite wall samples, including evaluation of U-values and thermal mass under laboratory conditions,

Although much of the work in this field involves the development of techniques and devices which are not yet fully established, transient techniques show promise for the future assessment of materials, including composite materials, which could potentially be an invaluable aid in improving our understanding of solid wall constructions. At present, however, caution is advisable with regard to the use of transient techniques as some of the existing techniques are still at a development stage and their use in testing solid walls might not lead to conclusive results.

1.4 Moisture content

Moisture content can strongly influence the thermal conductivity of masonry, and both BS EN ISO 10456 and CIBSE Guide A3 provides algorithms to adjust for moisture content. Understanding a U-value, therefore, necessitates some consideration of the likely moisture content in the building element being tested.

The CIBSE Guide A3 indicates a typical moisture content of 5% for 'exposed' brickwork and a typical moisture content of 1% for 'protected' brickwork, and recommends that the brickwork in solid walls be considered 'exposed' even where they have been rendered.

The amount of moisture present in the fabric of a building has long been recognised as an important factor in influencing a U-value, and interpretation of a measured U-value is often accompanied by a measurement of moisture content. CIBSE provides recommended thermal conductivity values for both 'exposed' and 'protected' bricks, where a value of 0.77 W/m·K is recommended for 'exposed' bricks and a value of 0.56 W/m·K is recommended for 'protected' bricks. This difference in thermal conductivity can have a significant influence on the U-value of a typical nine-inch solid wall. For instance, a typical solid wall might be expected, using current calculation methods, to have a U-value in the region of 2.1 W/m²K, but if the same wall was composed of 'protected' bricks it's U-value would be expected to drop to around 1.8 W/m²K.

Pratt's approach, when analysing U-value measurements carried out on walls (Pratt 1969) was to normalise the U-values in order to allow for moisture content, and to report the U-value that would be reached had the walls been in position long enough for the materials to have lost their initial water of construction. The adjustments to the U-value which Pratt used to allow for moisture content drew upon results published in another paper (Pratt 1964).

Pratt considers 'normalised U-values' which represent the measured U-value adjusted for moisture content, based on the ultimate moisture content that a wall would be expected to have once they have lost their initial water of construction. In practice, the ultimate moisture content is often considered to be 5% and it will, of course, be influenced by environmental conditions and the presence of hygroscopic salts. Pratt (1969) does not describe how the U-values are measured.

Nicolajsen (2005) noted that, under Danish conditions, U-values and moisture contents can vary seasonally but reports that moisture content, at least in the case of timber-framed walls, has less influence than other factors such as temperature difference.

In the case of solid walls in the UK, the application of insulation systems is likely to impact upon the moisture content of brickwork, and a full understanding of the change in the U-value expected from insulation will necessitate consideration of changes in moisture content. In the case of external wall insulation, where the insulation is likely to protect the existing brickwork from rain, the moisture content of the brickwork may well fall to a fraction of its former level, leading to an increase in the thermal resistance of the existing brickwork.

1.4.1 Duration of a U-value measurement

It seems likely that temperature stability, thermal storage and temperature difference are all very important factors in determining how long a wall needs to be monitored before a reliable U-value can be obtained. For occupied housing, a period of two weeks is normally considered necessary in order to obtain sufficient accuracy. In laboratory conditions, under tightly-controlled conditions, a much shorter period is likely to be sufficient.

Owing to the influence of thermal capacity, it is usually necessary to monitor heat flux and temperatures continuously over a period of time, even under closely-controlled laboratory conditions. The importance of ensuring that the duration of measurement is sufficient is even higher when measurements are carried out in the field, where the external temperature cannot be controlled and there are limits to how precisely the indoor temperature can be controlled.

Nicolajsen (2005) carried out some tests on timber-frame buildings in Denmark where the indoor temperature and indoor relative humidity were controlled, and examined 14-day integration times (i.e. running averages) as a means of analysing the heat flows and temperatures. They had the combined advantage of low external temperatures, a north facing façade, consistently high indoor temperatures and a relatively long period of measurement. Perhaps as a consequence of these factors, they were able to achieve a high level of accuracy in their measured U-values.

1.5 Solar effects

As a general rule, authors were aware of the complications imposed by sunlight, and in some cases they tended to carry out experiments on facades that were facing away from the sun (e.g. Pratt 1969, Nicolajsen 2005). None of the authors appeared to look at the possibility of shading or baffling sections of south-facing wall as a way of mitigating radiative effects. Although there is little published about the influence of compass direction on the accuracy of U-values, preliminary work by BRE, under the present project, suggests that there is little correlation between measured U-value and compass direction, suggesting that U-value measurements can tolerate some sunlight.

It was recognised, for the tests reported by Pratt (Pratt 1969), that solar effects would tend to complicate the analysis of the results and therefore the measurements in Pratt's paper were generally carried out on north-facing elements.

Nicolajsen notes that measurement accuracy is better for north-facing facades due to the avoidance of sunlight (Section 7.1 of Nicolajsen 2005).

1.6 Whole house heat loss

Leeds Metropolitan University has developed a methodology, known as a co-heating test, which can be used to assess the whole-house heat loss. It is a method which has been encouraged by TSB for certain projects, such as the recent AIMC4 project. It involves providing a known quantity of heat to a dwelling whilst monitoring indoor and outdoor temperatures, solar radiation and ventilation. The method leads to a measure of the heat loss coefficient attributable to heat conduction through the fabric of the dwelling. This heat loss coefficient is expressed in watts per degree, and indicates the heat loss in watts (via the building fabric) divided by the difference in temperature between inside and outside.

The heat is normally provided by electrical resistive heating, as this provides 100% efficiency and therefore leads to no ambiguities regarding the quantity of heat that is supplied. Air is circulated using fans in order to minimise temperature stratification, and thermostats are used in order to maintain a steady temperature (thereby minimising thermal storage effects). The house is normally unoccupied and locked during the co-heating test in order to prevent anyone losing heat through opening any doors. A minimum temperature difference (between inside and outside) of 10 K is normally required. The May 2010 specification, published by Leeds Metropolitan University, gives a duration of measurement, once indoor temperatures have stabilised, of at least one week, but it recommends two or three weeks of continuous data in order to arrive at satisfactory accuracy. It also recommends an indoor setpoint temperature of 25°C.

Ventilation heat loss is normally assessed either using tracer gas decay (e.g. CO_2 decay measurement) or through airtightness testing. The former appears to be preferred by Leeds Metropolitan because it offers a direct measure of air exchange, and, in effect, takes full account of both wind speed and air tightness.

Typically, when a co-heating test is conducted, a graph is plotted of the relationship between the heat input and the difference in temperature between inside and outside, where the heat input has been corrected for solar gain and ventilation-related heat loss. Such graphs are usually scatter plots of daily means.

1.6.1 Adjacent dwellings

Sarah Birchall of BSRIA advises that any heat loss through any construction elements that are shared with adjacent dwellings must be considered, either through achieving the same mean internal temperature as the test dwelling, so that heat loss to/from adjacent spaces will be eliminated, however if access to adjacent dwellings is not permitted then compensation for heat loss can be achieved by installing heat flux sensors on the internal surface of the test dwelling and measuring the heat flux through construction elements[2].

1.7 Calculation methodologies

BS EN ISO 6946, in conjunction with BR443 (Anderson 2006), is the accepted method for architects and surveyors to use to calculate U-values of masonry walls. The RdSAP methodology also uses these documents as the basis of its own calculations. The method in BS EN ISO 6946 involves calculating an 'upper limit' and a 'lower limit' of thermal resistance. The 'upper limit' is calculated as the thermal resistance that would ensue if heat could only flow in straight lines running perpendicular to the wall surface. The 'lower limit' is calculated as the thermal resistance that would ensue if heat could flow freely, in directions parallel to the wall surface. The overall thermal resistance is considered to be halfway between the 'upper limit' of thermal resistance and the 'lower limit' of thermal resistance. The U-value is then the reciprocal of the overall thermal resistance. The approach in BS EN ISO 6946 is considered accurate when the materials making up the wall are of similar thermal conductivities.

While BS EN ISO 6946 is considered to be an accurate method of calculating U-values for most wall types, questions have been raised about its accuracy when materials (or air spaces) of widely differing conductivities are present in the wall construction, and as a result some constructions lie outside of the scope of this standard (e.g. walls where metal bridges an insulating layer). Where there may be doubt regarding the accuracy or applicability of BS EN ISO 6946, an alternative standard calculation procedure is described in BR497 (Ward and Sanders 2007) and BS EN ISO 10211. BR497 and BS EN ISO 10211 are usually associated with thermal bridging calculations, but they can also be used for calculating U-values. BR497 sets out conventions for calculations and BS EN ISO 10211 sets out the method of calculation, which involves detailed simulation calculations and in practice necessitates the use of specialist thermal modelling software such as Physibel's Trisco software (Standaert 2002). In practice, BS EN ISO 10211 is seldom used as a way of calculating U-values of traditional wall constructions owing to the effort and costs involved in the calculations.

Whether U-values are calculated using BS EN ISO 6946 or BS EN ISO 10211, it is necessary to obtain reliable thermal conductivities for the materials making up a wall construction. BR 443 (Anderson 2006) gives a standard thermal conductivity for 'protected' and 'exposed' brickwork, based on values given in the CIBSE A3 Guide and BS EN ISO 10456. Furthermore, BS EN ISO 10456 provides methods to allow for the actual densities and moisture contents where they are known. It therefore offers a means of 'normalising' U-values in order to express the U-values which would be expected for a standardised or long-term-average moisture content.

[2] Presentation by Sarah Birchall, Graduate Engineer, sarah.birchall@bsria.co.uk, BSRIA.

1.8 Summary

A range of papers has been published, showing various techniques for measuring the thermal performance of building elements and building materials. They show that:

- Heat flux sensors, thermocouples and infrared thermography are all widely used both in the field and in laboratories for testing the thermal performance of elements and components.
- Hot boxes, environmental chambers and transient techniques are all used for testing samples of wall under laboratory conditions.

Published research also notes the following:

- Infrared thermography is a valuable aid in identifying inhomogeneities, confirming qualitative results and assisting in the visualisation of heat fluxes at surfaces.
- Three-dimensional thermal modelling programs, such as Trisco, are invaluable tools for the interpretation of measured heat fluxes and measured temperatures.
- Heat flux sensors can either be mounted on the surface of an element being tested, or they can be embedded within it. Some research suggests that embedding a sensor could lead to greater accuracy than surface-mounting it.
- Depending on the nature of the experiment, temperature sensors (typically thermocouples) can be mounted on the surface or within the air adjacent to the element under test, or they can be embedded at strategic locations within the solid material.
- The reliability and accuracy of U-value measurements can be especially sensitive to the difference in temperature between the warm and cold environments.
- Transient methods, involving sudden changes in temperature, of the order of several °C, can potentially reveal thermal information in a matter of minutes rather than hours, through examination of the transit time of the heat pulse and its shape of its profile after transit, and although the concepts have been considered for several decades, more research is needed in this field in order to develop the reliability of such measurements. Heat pulses can be provided either by heating elements, which in some cases can be embedded, or through bursts of heat radiation. At present, there are questions about the accuracy and reliability of heat pulse techniques for walls which are non-homogenous, as well as for walls which incorporate insulation materials.
- Conducting tests on moisture content can benefit the interpretation of results (e.g. the measurement of moisture in soil using neutron probes can assist the understanding of a ground floor).
- The heat loss for a whole house can be measured using a co-heating test. The method provides a measure of the heat loss coefficient attributable to heat conduction through the fabric of the dwelling.

2 Predicted performance compared to actual savings[3]

2.1 Introduction

To be able to accurately predict the running costs of a dwelling it is necessary to have good estimates of the behaviour of its occupants and the performance of each of the elements of that dwelling. Key elements of the latter include the fabric elements (walls, roof, floor, windows etc.), the air-tightness of the dwelling and its heating system. There is some evidence from the literature, discussed in this chapter, that current assumptions underestimate the thermal performance of walls (and in particular solid walls). Deficiencies in these assumptions will lead to inaccurate predictions of running costs. When looking at the savings due to energy efficient retrofitting of these dwellings these errors will lead to inaccurate predictions of the savings resulting from the efficiency upgrades. Assumptions about how the dwelling is inhabited by its occupants will also have a bearing on the accuracy of predictions however these are primarily discussed in chapter 3.

Estimation tools also have to make assumptions about the performance improvements of solid walls following efficiency upgrades. For example, the resultant U-value will tend to be assumed as complying with calculations using the product specifications and it will be assumed that the performance of materials and quality of workmanship are of a high standard. In reality this may not always be the case. Changes in occupant behaviour post retrofit are also material but these are discussed in the next chapter.

The gap between predicted performance (as estimated by models) and actual performance (as measured in the dwelling) is of concern to energy efficiency and retrofit programmes that are focused on existing buildings, for example, the Green Deal[4] and ECO[5]. The discrepancy between predicted and actual performance creates uncertainty concerning the potential benefits and savings of energy efficiency measures applied to solid walls. Current programmes, in particular Green Deal and ECO, apply 'in-use factors' to reduce the savings estimated from improvements. These factors are designed as a catch all to align predicted savings with empirical evidence of actual savings. In Green Deal and ECO they range from 10% to 35% and are based on best estimates from current research and information. They are of course unsatisfactory compared with a correctly configured model, as they are not identified with any specific causes or factors which may in reality vary depending on the situation. In a correctly configured model this variation is taken account of so that the results are in general good estimates of the energy use and savings found in the field.

Early figures of the potential savings of insulating solid walls were estimated by Milbank (1981) and Southern (1980). They used the 1976 United Kingdom housing stock statistics and cost information from 1979 to calculate the savings from installing insulation on solid walls in existing dwellings. Southern (1982) estimates that improving the U-value of the nation's solid walls to 0.6W/m^{2}K could achieve an

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[3] Principal authors: Gabriela Zapata and Christopher Tweed (Cardiff University).

[4] The Green Deal is a UK government programme that aims to facilitate and encourage the installation of energy efficiency measures to reduce the impact of fuel price rise; increase the comfort level; and, achieve fuel savings.

[5] ECO places legal obligations on energy suppliers to deliver energy efficiency measures to domestic energy users, and operates alongside the Green Deal, with a particular focus on vulnerable consumer groups and hard to treat homes.

annual primary energy saving of approximately 80PJ (equivalent to about 22TWh). A further improvement to 0.3 W/m^{2}K would save an additional 17PJ per year (~4.7TWh). While the figures are broad approximations, they show the magnitude of the potential savings due to the insulation of solid walls.

The difficulty in rolling out a successful national retrofit programme is exacerbated by the scale of the problem (Kelly, 2009). Based on figures from the UK's Department of Energy and Climate Change (DECC) (2012): 9.2 million homes (40% of those with lofts) have yet to be insulated with more than 125mm of insulation in the loft; 7.7 million homes (41% of those with cavities) have yet to receive cavity wall insulation; and more than 7.6 million homes with solid walls (98%) have yet to be insulated.

Solid walls are categorised as harder to treat than most cavity walls. Solid wall dwellings tend to have been built before 1930s (though this varies regionally) of masonry material and have a width greater than or equal to 9 inches (Hulme and Beaumont 2008). Heat losses from solid walls, together with roof losses if poorly insulated, are the most significant routes to heat escaping from the dwelling. Other important factors include the efficiency of the space and water heating systems.

This section focusses on the energy performance estimation of existing dwellings and discusses the differences between predicted performance before the application of the energy efficient retrofit and the achieved performance after the retrofit. Some of the themes discussed overlap with other sections of the literature review, reflecting the complexity of the issues and their interconnectedness. While the main focus of this review is "solid wall insulation", it should be noted that the majority of retrofit studies are unlikely to focus solely on the installation of insulation. In general, the studies apply a combination of retrofit measures such as the replacement of windows, wall and loft insulation and replacement of boilers and heating systems. Hence, the direct benefits of solid wall insulation on the reduction of energy demand are unlikely to be estimated alone.

A note of caution needs to be added about existing retrofit studies. Sorrell (2007) identified four main problems in using their results:

- low statistical power due to small samples;
- high variance in results and failure to present error analyses of estimates;
- large variation in relevant independent variables within and between studies (for example the participants received different combinations of measures); and
- a short monitoring period deemed insufficient to capture seasonal variation in energy usage.

These limitations undermine the possibility of making comparisons across studies and highlight the need for more research with larger samples. The review returns to Sorrel's work in the discussion of the "rebound effect" in Section 3.

The remainder of this section has been divided into the following sub-sections:

- baseline performance of the envelope;
- construction aspects of retrofit that compromise the performance;
- limitations of calculation methodologies to predict the savings; and
- conclusions and recommendations.

2.2 Baseline performance of the envelope

The baseline performance of the building envelope refers to the anticipated performance of the solid wall (and other elements) before the application of the energy efficiency measures. It provides the datum against which savings are measured. It is therefore important to have the most accurate baseline figures possible if they are to inform decisions about large scale programmes of energy retrofits. Standardised assessment tools are generally used to estimate baseline performance.

2.2.1 SAP/RdSAP

The main tool used for estimating the performance of dwellings is the Standard Assessment Procedure[6] (SAP). The indicators of energy performance are energy consumption per unit floor area, an energy cost rating (the SAP rating), an Environmental Impact rating based on CO_2 emissions (the EI rating) and a Dwelling CO_2 Emission Rate (DER).

SAP is a particular application of the BREDEM methodology (BRE Domestic Energy Model). SAP uses standardised assumptions for characteristics such as size of household, heating patterns and location so as to allow comparison of dwellings. BREDEM is more flexible; allowing the user to input specific parameters and adjust these factors. In SAP, dwellings are rated according to the cost (using standard fuel price assumptions) of heating the home (space and water), ventilating and lighting the home (less savings from energy generation technologies). Appliance and cooking costs are excluded (though a full BREDEM calculation includes these). Fuel type is an important variable as the SAP rating is a cost based measure, though the fuel does not itself affect estimates of the performance of the dwelling envelope. Rather, it is the physical properties of the envelope (U-value, ψ- value, etc.) that determine its actual performance. For example, two identical dwellings; one with mains gas as its main heating fuel and one with bulk LPG, would have significantly different SAP ratings because of the relative costs of these two fuels. Carbon emissions however would be very similar. This would be shown by the Environmental Impact rating which is based on the same energy end uses as described above, but using standard carbon emission factors to convert the energy end uses. (The DER is a similar indicator to the EI rating and is used in relation to compliance with Building Regulations).

The performance of existing dwellings requires the collection of data using a non-intrusive survey. A system has been developed which formalises the collection of data and the inferences made where data are not collected when it is not possible to collect all of the information required for a full SAP calculation. This is known as Reduced Data SAP or RdSAP. RdSAP uses approximations based on known properties of the features of the house to approximate a rating. RdSAP will normally assume a U-value for a wall based on its age and category of construction (for example solid brick, cavity, stone, etc.). In some instances, the baseline performance of the envelope might not be ‘standard.’ The thermal properties of materials assumed by methodologies such as RdSAP are likely to be derived from laboratory tests that might be unable to represent the performance of the envelope in ‘real settings.’[7] For example, in existing dwellings, baseline performance is likely to be affected by moisture content variations and moisture transport through and within the solid wall (Senior 1984; Ward 1993; Rye 2010; Baker 2011).

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[6] The Standard Assessment Procedure (SAP) is the methodology used by the Department of Energy & Climate Change (DECC) to estimate the energy performance of dwellings for the purposes of energy and environmental policy compliance. SAP is the tool for the appraisal of energy consumption and carbon emissions in dwellings with standard comfort levels, services provision and occupation patterns.

[7] The expression ‘real settings’ refers to the field conditions that existing dwellings are exposed to; for example, weather, seasonal variations, differences between outdoor and indoor environment, etc.

2.2.2 Baseline performance of materials

The values used in RdSAP were established over a number of years and represent typical U-values for particular wall types. They were based largely on measured thermal conductivity and thickness of constituent parts of the wall, combined together in a calculation of the U-value using standard physical principles of heat flow. Of course, in reality, solid stone and solid brick walls vary in thickness and thermal conductivity, being affected by factors which include the materials, density, rendering, internal finish, air gaps, moisture content, local climate and exposure. The values in RdSAP were derived from best estimates of thickness and thermal conductivities considered typical at the time they became established. However, given the variety of factors and large variation of each in reality in the field, and the limited data available, it was unlikely that these could have correctly represented an average U-value for the stock of these wall types. This section describes laboratory-based studies of the baseline performance of materials and *in-situ* studies measuring the same performance.

Datasets containing the standard properties of the material are created and used to estimate the baseline performance of the envelope of existing dwellings. However, it is important to consider the applicability and limitations of laboratory-based datasets to outline the performance of the envelope of existing dwellings in real settings. Clarke *et al* (1990), for example, investigated fourteen datasets of the physical properties of building materials. They found that the datasets contained insufficient information about the empirical studies conducted to deduce the properties. Few databases explained how the production process of the materials may affect their properties. The lack of rigour in reporting the data increased the uncertainty and the difficulty in comparing and merging the data. The study found that materials testing organisations were focused on thermal conductivity in steady-state conditions. Vapour resistivity was assessed by two-thirds of the research participants. It was found that, at most, two results at different conditions were obtained which was deemed insufficient to evaluate the behaviour of hygroscopic materials. Longwave emissivity and shortwave absorption properties were rarely included in databases. The authors recommend the identification of “robust methods of risk assessment that implicitly accept the inherently uncertain nature of building material property values” (Clarke *et al* 1990). This study highlights the potential limitations in the application of standardised datasets, especially when the conditions of the study and the context of the analysis are not clear. It also suggests that, although these datasets may suggest alternative values to those in BS EN ISO 10456, CIBSE A3 and BR443, it is difficult to justify using them because of the problems highlighted. Taking a risk based approach to defining performance characteristics, such as applying ranges, would not be practical for most common applications of tools such as SAP. It is for this reason that RdSAP uses a single U-value for each type and age of wall.

Laboratory-based studies have drawn attention to the effect of moisture on the thermal performance of materials. Variations in moisture content and the dynamics of moisture transport that develop over time within a wall could also affect the baseline performance of the envelope (Pratt, 1964). For a damp specimen, the steady-state measures an ‘apparent’ conductivity that may be less than the value for the specimen containing the same amount of moisture but uniformly distributed throughout its bulk. Due to the long-term exposure of existing dwellings to the weather, the envelope could present a heterogeneous distribution of moisture content, creating zones within the same construction that exhibit variations in thermal performance. This could lead to an increased scatter in the U-values. It could also lead to an increased mismatch between measured U-values and calculated U-values for example in instances where the U-value is measured upstairs but drill samples and core samples are taken downstairs (for safety reasons).

The performance of materials is often evaluated under controlled conditions. Thorsell and Bomberg (2011) state that the thermal resistance of dry materials which represents behaviour under steady-state conditions is limited in its usefulness for evaluating performance of constructions under field conditions. They suggest the use of hygrothermal models and *in situ* testing to verify performance on site, though this is likely to be impractical on a large scale.

In summary, the laboratory-based studies suggest that there can be variations between the performance of a material determined in laboratory conditions and the one observed in real settings due to the effect of

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moisture content and moisture transport that are experienced in existing dwellings. Equally, the datasets that summarise the properties of materials are likely to refer to standard values, but the actual materials may differ from these. Variables such as difference in construction, relative proportions of components, exposure to weather conditions and cyclical seasonal variations and the presence of moisture within and through the wall might affect the baseline performance of the envelope of existing dwellings as compared to the typical performance of the material found in a laboratory setting.

While the research outlined above addresses the derivation of baseline U-values from laboratory measurements, *in situ* studies have measured the performance of solid walls of existing dwellings. They have found gaps between the actual baseline performance of existing walls and the standard performance anticipated for that material. It has been found that a single wall may present a range of U-values and variations in moisture content across the wall surface.

When discrepancies were found between the predicted and measured performance, Senior (1984) analysed the potential factors that might have caused the discrepancies and adjusted the U-values of the elements on the basis of a detailed *in situ* survey. The consideration of variation in the properties of the wall (moisture content, width, differences between the specifications and the materials in the build-up and, where insulated, defects on insulation) helped to improve the accuracy of the U-value calculation.

Table 2 shows the description of the walls with the estimated, measured and adjusted U-values. The estimated value is the one initially calculated with information obtained from the building plans while the adjusted value accounts for variations found on the detailed survey. The gaps between estimated and measured U-values were as high as twice the expected performance or more (walls 1, 3 and 5). It was also found that there was a range of variation in the U-value of a single wall in the order of 50 to 220 per cent (walls 1 and 8). One of the walls performed better than expected (wall 8). This study shows the difficulties of using standard calculations to determine the baseline performance of walls in existing dwellings and the value of detailed surveys in detecting factors that may affect the performance.

Table 2: Comparison of estimated baseline performance of walls, actual in situ measurements and adjustment of the U-value (based on Senior 1984)

	Description of the wall	**Estimated U-value (W/m^2K)**	**Measured U-value**	**Adjusted U-value**	**Adjustments on the baseline estimation**
1	Timber wall panelling and mineral wool insulation with plasterboard on battens	0.88	1.01-3.64	0.99	Variation in U-values across the wall, cold spots were detected, variation in insulation width
2	Timber infill panelling wall with plasterboard on battens	0.88-1.131	0.92		
3	Cavity wall, block wall-hard plastered internally directly onto wall	0.96	2.57	2.35	Consideration of moisture content and air infiltration
4	Wall with plasterboard on battens	1.18	1.40	1.48	Update of different elements in the build-up (differences between plans and actual build-up)
5	Standard cavity wall with bricks on both sides	0.64	1.28-1.42	1.25	Consideration of moisture content and block density
6	Standard cavity wall with bricks on both sides, internal plasterboard on battens	1.08	1.48	1.42	Consideration of air infiltration, ventilation rate and temperature of the cavity
7	Standard brick, foam, brick wall with plasterboard on dabs	0.51	0.51-0.56		
8	Standard insulated timber infill panel wall	0.88	0.50	0.63	Conductivity of the mineral wool and thickness
9	Standard brick, foam, brick and plaster on brick	0.57	0.77-1.03		Defects on the foam (cracked and shrunk)

Research (Senior, 1984; Ward, 1993) suggests, therefore, that U-values can be treated as three types:

- Standard (calculated on the basis of building plans);
- Adjusted (Ua, accounting for the actual properties of the wall build-up according to a more detailed on site survey of the properties) and
- Measured (Um, obtained in situ).

In these studies, the measurement error was in the order of +/- 20% due to calibration of the heat plates, position of the plates, corrections for *in situ* use, accuracy of temperature difference and repeatability of the system. One third of the measurements lay within the estimate error range of the measurements. The remaining two-thirds of the measurements were outside the range, showing a discrepancy of at least 100% above the predicted U-value. The mean ratio *Um/Ua* was 0.89, 11% lower than expected.

The gaps between the standard performance of the material and the actual performance found *in situ* may be greater in the case of traditional buildings[8]. These are discussed in detail in Chapter 5.

The *Sustainable Traditional Buildings Alliance* suggests that there are no comprehensive data for the assessment of the performance of the materials of traditional buildings. *In situ* studies of the thermal performance of traditional buildings have found that the baseline U-values of traditional materials are likely to be overestimated when using the calculation methods embedded in BR 443 and the U-value calculation tool *BuildDesk* (Rye 2010; Rye and Hubbard 2012). In other words, the *in situ* U-values were lower than those predicted by the calculation method, suggesting that the performance of these walls was considerably better than anticipated. Figure 10 illustrates the performance of pre-1919 solid walls, comparing the value calculated by BR 443 and the *in situ* measurement. Notice that the calculated value tends to underestimate the actual performance, and thus may suggest greater energy savings. Traditional buildings and built heritage are discussed in detail in Section 5. This section only discusses the variations in baseline U-values found in this category of building.

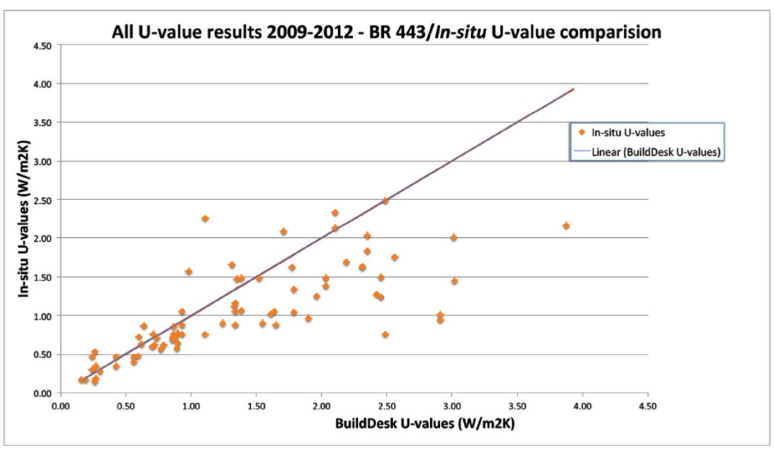

Figure 10: Comparisons of U-values obtained *in situ* and by *BuildDesk* (After Rye and Scott, 2012).

[8] English Heritage defines traditional buildings as those built pre-1919, made of solid walls, and with materials that are permeable to moisture (English Heritage 2012a; 2012e)

An example of the gap is the case of stone and brick walls. According to RdSAP appendix S, the U-values are 2.3 and 2.0 for stone walls in England, 1.9 and 1.6 for stone walls in Scotland and 2.1 for pre-1919 brick walls in England and Scotland.

The studies by Rye (2010; 2012) suggest an average *in situ* value of 1.51 for solid stone walls while Baker (2011) found *in situ* values between 1.1 and 1.5 for solid stone walls in Scotland and an average U-value of 1.4 for solid brick walls in England. These studies suggest that it is the calculated estimate and its underlying assumptions about the properties of the materials with which the walls are constructed that are the source of greatest error. However, measurement is also subject to error, primarily due to an insufficient temperature difference between inside and outside when the measurements are made, and uncertainties over the build-up of the wall (Baker, 2011). Further work on *in situ* measurement of U-values is needed to quantify these errors as most of the existing measurement studies have been conducted under controlled laboratory conditions.

2.2.3 The effect of moisture on thermal performance

Moisture content and moisture transport within and across the solid wall are known to influence heat flow. The building industry standards that outline the evaluation of moisture in buildings are:

- BS 5250: 2011 Code of practice for the control of condensation in buildings;
- BS EN 13788: 2002 Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation; and
- BS EN 15026: 2007 Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation.

BS 5250:2011 refers to BS EN 13788: 2002 in relation to the Glaser method that uses the vapour pressure differential and the average monthly external temperature to estimate the occurrences of condensation within or on the interior surface of the fabric. May and Rye (2012) suggest that the Glaser method is limited because it only considers the critical surface humidity and interstitial condensation without covering other moisture factors: ground water, precipitation, built-in moisture and moisture convection. While BS 15026 is an alternative standard to assess the hygrothermal properties of the building components, May and Rye (2012) draw attention to the fact that the physics of moisture behaviour are not fully understood which could lead to unanticipated hygrothermal behaviour.

BS EN 15026 considers the non-steady state so it includes moisture behaviour, specific material properties and the local environment of a building over time, provided the availability of the corresponding climate data set for that location. This standard informs the WUFI™ model which is recommended for the evaluation of as-built performance in retrofitting cases, especially for traditional buildings. WUFI is an advanced hygrothermal model distributed by the Fraunhofer Institute in Building Physics that solves the coupled heat and moisture transport equations for building envelope systems. However, one of the limitations in the use of WUFI, at least in its standard form, is that it is a one-dimensional calculation method and does not consider heat transfer and moisture transfer caused by air movement (Building Energy Software Tools Directory). Although a 2D version is available and may be more accurate to represent the dynamics of moisture, it is not widely used. Thus there is a dilemma to resolve: hygrothermal modelling is important to the prediction of performance and yet the tools available to do this are too complex for many practitioners to understand. The solutions are (1) to provide training in this area of building physics and/or (2) to develop simpler hygrothermal modelling tools that retain the necessary rigour.

The misrepresentation of the baseline performance could lead to the selection of inappropriate strategies to reduce the heat loss. The over-insulation of the building fabric might result in unanticipated consequences[9] such as overheating, reduction of indoor air quality, condensation, damp and other problems. The understanding of the baseline performance and pre-existing characteristics of the wall to be retrofitted should inform the selection of the type of insulation and the adequate levels of improvement. Post-retrofit performance is likely to be affected by the type of insulation applied to the solid wall, whether it is external or internal. A report by *Changeworks* (2012) compares external and internal wall insulation, summarised in Table 3 below. External wall insulation is considered to present less risk of moisture and condensation problems. Internal wall insulation increases the potential of retention of moisture from the exterior, which could reduce the building structure quality and affect the occupants' health. The dampness could increase the heat loss of the wall. Internally insulated walls tend to have a faster response to heat as the external layer does not get heated. Although the externally insulated walls warm up more slowly, they retain heat for longer because of their higher thermal mass. This report suggests the need to understand the implications and differences between external and internal wall insulation so as to propose a robust and sustainable strategy that contributes to energy savings without posing risks to the building fabric or their occupants.

Table 3: Advantages and disadvantages of external and internal wall insulation (extracted from Changeworks 2012).

	External wall insulation	**Internal wall insulation**
Advantages	Lower risk of moisture build-up and condensation Slower heat loss because the walls retain heat Improvement of the structural integrity of building Less disruption to occupants and no need for decanting Potential to improve the exterior appearance	Cheaper if done by the occupants (DIY) Application could be done on individual rooms or a single room at a time Fast heat response Enhancement of the interior finish of the building Fewer restrictions to the type of properties where it can be applied (i.e. conservation areas, high-rise blocks, terrace houses)
Disadvantages	More expensive Not applicable where the building is to retain the original appearance or in multi-occupancy properties Restrictions on execution of work (e.g. weather) Neighbours' agreements should be obtained in joined properties which could be difficult in blocks of flats	Possible problems with moisture build-up and condensation Cold bridges Issues with services accessibility Loss of room size Complex fittings could present problems with fixings internally

The effect of moisture content and weather variations in the performance of internal wall insulations solutions is likely to vary by location because of different climates (May, 2012). The data demonstrate that locations such as Swansea and Liverpool present a higher risk of moisture content than London. The moisture content increases with the insulation thickness. In Swansea, for example, the orientation seems to affect the moisture content to a higher degree than in London. Moisture content could vary from 25-33 kg/kg in insulation elements whose thickness varies from 60-100mm for southwest orientations while for north orientation the moisture content is within the range of 14-15 kg/kg for the same range of insulation

[9] Covered in Chapter 4 of this review

thickness variation. In London, for the north and southwest orientations, the variation of moisture contents is of the order of 10-11kg/kg for insulation thickness between 40-100mm.

May (2012) warns that best practice and guidance do not differentiate between different types of buildings (thickness, capillary qualities, construction type), location, orientation nor types of insulation. The industry guidance on energy efficiency tends to prescribe or advise a pre-determined U-value to be achieved on the retrofit intervention without addressing the possible effects of over-insulation on the fabric and human health. May (2012) advocates sensitivity analyses of the appropriate and cost effective levels of insulation.

There are few long term studies of the hygrothermal behaviour of retrofitted external walls. A small study has been conducted by the BRE Centre for Sustainable Design of the Built Environment in the Welsh School of Architecture at Cardiff University. The study monitored five buildings with thick stone walls before and after the application of insulation using five different types: internal insulation (non-breather), internal insulation (breather), external insulation (non-breather), external insulation (breather) and external rainscreen. The buildings are all located in the harsh climate of North Wales, where there is a high incidence of driving rain for much of the year. This research was carried out as part of the broader SUSREF (Sustainable Refurbishment of Building Facades and External Walls) project funded by the European Commission under its FP7 programme of research (Peuhkuri *et al* 2012; Uriarte *et al* 2011; Vares *et al* 2012).

The main findings of this work were:

- the primary source of moisture in the walls was from rain penetrating the exterior surface;
- the main route for water through the wall was provided by the mortar joints between the stones;
- rain penetration and moisture content in the external wall diminished after insulation was applied to the external surface;
- internal insulation solutions appear to promote a build-up of moisture close to the internal surface of the original wall, regardless of whether the construction is considered to be breathable or not;
- explanations for changes in hygrothermal behaviour even across this small sample are tentative because of the number of variables involved; and,
- the outcomes resulting from insulation interventions can vary considerably within the same property because of differences at the external (solar access, prevailing wind) and internal (heating regime, occupancy effects) boundary layers.

The results from SUSREF confirm the non-homogeneity of the seemingly simple construction of stone walls recognised by Baker (2011), and the importance of recognising this in the design of SWI solutions.

The studies discussed in this section include laboratory and *in situ* studies to determine the baseline performance of walls. The gaps found between the predictions and the *in situ* values suggest:

- the behaviour of the walls in existing dwellings, especially solid walls, is likely to differ from the standard performance of materials;
- methodologies used for determining the U-value of materials may not be able to represent the baseline performance of materials of pre-1919 dwellings and traditional buildings;
- datasets of materials obtained under laboratory conditions may fail to consider the influence of moisture content on the baseline performance; and

- common industry standards used for the appraisal of moisture content on building elements may be limited in representing the dynamics of moisture transport within and across the wall build-up which is particularly relevant for the performance of pre-1919 solid walls.

2.3 Construction aspects of retrofit works that affect performance

The quality of construction delivered during the energy-efficiency interventions and the standards on site are likely to affect the post-retrofit performance of the dwelling. Poor workmanship, lack of experience, poor knowledge or unwillingness to adopt adequate construction practices can undermine the energy performance of the dwelling (Reeves, 2009). In a laboratory study, Trethowen (1991) analysed the convective heat loss caused by edge gaps around insulation by measuring the heat transfer through insulated walls and ceiling cavities. The loss through walls could be 10% or greater when there is a 1% gap width. Gaps of less than visible width (~1mm) could compromise the insulation value.

An empirical study by Leeds Metropolitan University compared predicted and actual savings on the retrofit of a house (Miles-Shenton *et al* 2010; Miles-Shenton *et al* 2011; Stafford *et al* 2011; Wingfield *et al* 2011). Although the study was not focused on solid wall insulation, the findings are relevant because they identify construction quality as a source of gaps between predicted and post-retrofit performance. These publications suggest that unidentifiable construction defects, lack of uniformity in the U-value performance of the fabric and human modelling errors could result in the misrepresentation of the baseline performance. During construction, standards on site and unanticipated construction problems may lead to differences between as-designed and as-built performance.

Miles-Shenton et al (2010) describe a two-stage retrofit process in a house located in York in partnership with the Joseph Rowntree Housing Trust (JRHT). It provides a useful insight into some of the problems that can occur in a retrofit project. The retrofit was developed in the same house in two sequential phases: firstly, a standard retrofit; and thereafter, a radical retrofit. The research team was involved in the construction process, providing professional advice, observing the intervention and measuring the pre and post-intervention performance. The standard retrofit comprised measures that could be afforded by the householder while the radical retrofit sought to increase the standard of the house to current regulation standards. The following tests were conducted before and after each of the phased interventions: airtightness tests, co-heating tests, infra-red thermography tests.

The initial performance was better than predicted, as shown in Table 4 below. The measured heat loss was anticipated to be 341.4 W/K but it was found to be 324.7 W/K. The heat loss parameter was approximately 5 per cent better than anticipated (Table below). The gap between expected and actual baseline performance may be explained by an insufficient understanding of the existing construction and characteristics that may have not been identified on the initial survey. The initial survey followed the procedures outlined for the Green Deal programme and included a visual inspection, an air pressurisation test and thermal performance predictions by SAP.

The standard retrofit strategies consisted of insulating the cavity wall using blown-in fill, insulation around the integral garage and loft, improvement of airtightness, reduction of the thermal bridges, installation of a condensing boiler and the use of low energy light fittings.

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Table 4: Comparison between the modelled performance of 67 Temple Avenue before and after the retrofits (extracted from JRHT 2012).

67 TEMPLE AVENUE	EXISTING CONDITION	STANDARD RETROFIT	RADICAL RETROFIT
ESTIMATED FUEL COSTS PER YEAR (DECEMBER 2009) £/yr			
HEATING	612	285	87
HOT WATER	136	84	22
LIGHTING	55	54	54
SAP BAND A-G	D	C	B
SAP SCORE 0-100	59	77	89
ESTIMATED CARBON DIOXIDE EMISSIONS PER YEAR $kgCO_2/yr$	5751	3121	1269
DWELLING EMISSION RATE (DER) $kgCO_2/m^2/yr$	62.22	30.69	13.11
PREDICTED HEAT LOSS W/K	341.4	238.7	107.2
PREDICTED HEAT LOSS REDUCTION W/K	n/a	102.7	234.2
PREDICTED HEAT LOSS PARAMETER W/m^2K	3.05	2.13	1.15
MEASURED AIRTIGHTNESS $m^3/(h.m^2)$@50Pa	15.76	9.83	5.42
MEASURED HEAT LOSS W/K	324.7	249.2	159.0
MEASURED HEAT LOSS REDUCTION W/K	n/a	75.5	165.7
MEASURED HEAT LOSS PARAMETER W/m^2K	2.90	2.22	1.42

Thermographs, combined with endoscope and heat flux investigations, detected gaps in the cavity wall insulation, possibly due to the poor quality of inner leaf of brick and debris in the cavity and obstructions not detected on the survey. A gap was also identified in the roof insulation. After a standard retrofit the airtightness was $9.83m^3/hm^2$ at 50Pa, the predicted heat loss reduction was designed to be 102.7W/K but the measured one was 75.5.

The radical retrofit was intended to increase the performance of the house to the current standards of the prototype houses newly built by JRHT. This type of retrofit required a high capital investment which was likely to limit its wide application: external wall insulation (EWI), ground floor insulation, use of mechanical ventilation and heat recovery (MVHR), the use of triple-glazed argon-filled windows, solar water heating and further improvements to the airtightness. There were some problems with the installation of the EWI, presenting discontinuities around the existing entrance and patio doors. The installation also posed problems at eaves and windows. The research team could not assess the interface between the installation of windows and EWI because the team did not have access to the construction documentation to conduct the analysis. The estimated, improved U-value due to EWI was predicted to be 0.15 W/m^2K. Measured values were in the order of 0.23-0.24 W/m^2K.

The standard retrofit achieved 73% of the predicted improvement and the radical retrofit achieved 71% of predicted improvement. Table 4 shows that baseline heat loss and heat loss parameters (existing condition) predicted by SAP are higher than those measured before the retrofit. After the retrofit, both aspects as calculated by SAP are lower than the ones measured on site. These aspects do not imply an error in the SAP calculations but highlight the difficulties in using standard thermal modelling assumptions embedded in tools used to evaluate the performance of existing dwellings. If assumptions about the properties of materials and their construction could be improved it is likely that estimates of savings would be significantly improved in turn. This highlights the challenges faced by the surveyor undertaking a non-intrusive survey.

Similar studies highlight the discrepancies caused by deviations in as-built retrofits (Hopper *et al,* 2012a). They report problems with on-site execution of external wall insulation, changes to details for the windows, and increased thermal bridging. A preliminary review of the programme *Retrofit For The Future*[10] (TSB 2013) states that, of the 37 projects included, three achieved 80% of the predicted reduction and 23 projects achieved a reduction of between 50% and 80% of what was predicted prior to the retrofit in terms of CO_2 emissions, primary energy requirement and annual space heating demand. Site management and training of site staff to understand the expected standards are recommended to ensure good construction quality.

Hong (2011) describes the Warm Front Scheme where houses occupied by older people and families with children were retrofitted. The measures included draught proofing, insulation and central heating. It was found that after the retrofitting work, the mean indoor temperature increased by 1.6°C. Central heating produced an increase of 2.3°C. Insulation produced a mean saving of 9%. Hong (2011) compares the pre-intervention predictions and the post-intervention savings, finding that the insulation achieved 74% to 84% of the expected savings. Some of the reasons for the shortfall[11] may be the overestimation of the air leakage modelled prior to the intervention and the construction quality (the insulation was missed in some areas of the walls).

The studies presented in this section have identified some of the problems in delivering the energy efficiency measures on site such as poor workmanship, lack of knowledge and experience in delivering details and *ad hoc* design changes. These studies present some of the barriers that emerge during construction which possibly lead to gaps between predicted and actual post-retrofit performance. Attention is drawn to the difficulties of achieving the assumed standards on site because of poor care when executing retrofit work (installation of the insulation), poor detailing, lack of care in delivering the junctions and critical details; and changes to the as-designed details during construction phases. The studies concerning construction quality highlight the importance of ensuring adequate construction standards and workmanship to decrease the risk of post-retrofit underperformance.

It must also be noted that in addition to the installation workmanship, the quality and suitability of the original design (particularly the detailed design) will have a significant impact on post refurbishment performance. Identifying the most suitable materials to use and where they should be installed is key to the relative success of the retrofit. For more information, the Temple Avenue report (Miles-Shenton et al 2010) referred to above, includes a substantial discussion about design issues.

2.4 Limitations of calculation methodologies to predict the savings

Many studies addressing energy-efficient interventions use simulation-based methodologies to estimate the performance before and after the retrofit; for example, the Eaga study conducted by the Centre for Sustainable Energy (CSE) to determine the impact of solid wall insulation in dwellings located in South West England (Morris 2010). The savings predicted were based on SAP modelling before and after intervention. Strube *et al* (2012) analysed solid wall insulation using a simplified steady state heat loss model for assessing the fabric based on CIBSE Guide A and U-values from RdSAP. The results are compared to the PassivHaus Enerphit standard. The study looks at various measures of achieving target U-values. The strategies comprise: solid wall insulation (SWI) only; SWI plus loft insulation; and full fabric retrofit. While the paper outlines the challenges in implementing external and internal insulation, it does

[10] The review does not report on the field trials in detail. That information had not been published at the time of writing this work.

[11] The reasons outlined in this section correspond to construction quality. Other factors that may have reduced the post-retrofit savings such as occupation are addressed in Section 3 of this report.

not state which strategy is assumed in the insulation measure. Difficulties occur with more sophisticated simulation tools as well (Clinch *et al*, 2001; Aisheh, 2010; Emekwuru *et al*, 2012). Simulation-based methodologies are prone to embed uncertainty in the results from:

- the specific assumptions and calculation methods underlying the energy performance appraisal—even when using similar input parameters, different calculation tools may present variations in the predicted performance;
- the baseline scenario—the anticipated performance of the envelope based on standard values that may not be applicable to existing dwellings;
- the assumptions of simulation tools tend to correspond to typical scenarios of occupation and energy usage that may not be representative of the existing pattern of occupation—specific user practices to achieve comfort, variations in heating regime and unexpected comfort practices may influence the energy performance prior and after the retrofit

In general terms, predictive methods to estimate performance use standardised assumptions with limited applicability for the analysis of the performance of existing dwellings that have solid wall insulation. Clarke *et al* (1990) argue that the 'predictive methods concerning the behaviour of buildings and their components operate within a probabilistic context'. It should be acknowledged that there are intrinsic limitations in a predictive approach purely based on simulation scenarios. Galvin (2012) suggests that existing buildings are being modelled using the same approaches as for new buildings. Consequently, errors in modelling the baseline scenarios are likely to occur. As noted in Section 1 above, the *Sustainable Traditional Buildings Alliance* (STBA) suggests that modelling techniques could misrepresent the performance due to human error and incorrect modelling assumptions (STBA, 2012). Gentry et al (2010), quoted in STBA (2012) argues that there is a lack of adequate data for the correct representation of some building physics phenomenon. Additionally, the existing calculation methodologies may not represent adequately the hygrothermal behaviour of buildings, as discussed in the previous section.

Salmon and Tye (2000) also found variations in the performance of insulation materials obtained from laboratory-based studies. They conducted studies to determine the thermal properties of reference materials produced by the National Physical Laboratory, UK (NPL) (Salmon and Tye 2000; Tye and Salmon 2002). They compared expanded polystyrene (EPS), extruded polystyrene (EXPS) and Rockwool; materials commonly used for insulation. The study found differences in the range of 2 and 3 per cent in the thermal conductivity of materials, possibly due to the type and source of calibration. In all cases, the laboratory measured values of thermal conductivity were lower than those supplied, which could lead to lower predicted savings following insulation. The findings of this paper lead the author to conclude that manufacturers' data may be unreliable, even to the detriment of their own claims.

The following sections discuss three factors that could affect the quality of the predictions of calculation methodologies:

- differences in the predictions by simulation-based methodologies;
- misrepresentation of baseline U-values; and
- challenges in representing the occupant factors.

2.4.1 Differences in the predictions by calculation tools

Studies which have compared the results of simulation-based methodologies have found variations in the results despite the same input data being used (Barnham *et al* 2008; Heath *et al* 2010; Deurinck *et al* 2011a and 2011b; Hong 2011; Deurinck *et al* 2012). Barnham *et al* (2008) compare the results of calculations using National Home Energy Rating (NHER) and the Standard Assessment Procedure (SAP). The study analysed different versions of NHER: auto-evaluator, surveyor and evaluator. It was found the calculation methodologies produced different results even when the same case was being evaluated. An NHER calculation is always performed in the same way irrespective of which version is used; it is the level of detail in the inputs that varies. The same holds true for RdSAP and SAP. Heath *et al* (2010) compare the predicted CO_2 savings by SAP, RdSAP, NHER: Stock Assessor and Plan Assessor, Simplified Building Energy Model and Building Simulation Model by ESP-r, dynamic thermal simulation tool. The authors analysed the performance pre- and post-retrofit of a traditional dwelling in Scotland; Garden Bothy Dumfries House, a pre-1919 construction made of solid walls. Heath *et al* (2010) compare the results of the calculation methodologies in relation to the energy consumption for space heating, water heating and electricity, CO_2 emissions and running cost. The results are summarised in the tables below.

Table 5: Performance prior to retrofit -annual figures (extracted from Heath et al 2010).

Software programme	kWh / m²	Total kWh	CO_2 / m² (kg)	Total CO_2 (kg)	Fuel costs
NHER Plan Assessor	1,406	88,806	434	27,421	£4,337
NHER Stock Assessor	1,167	73,762	355	22,455	£2,743
NHER RdSAP only	1,068	67,501	268	16,962	£2,746
RdSAP	989	62,485	247	15,605	£1,887
SAP	1,879	118,698	491	31,306	£2,197
SBEM	1,002	69,138	328	22,625	n/a
BSM	1,194	82,386	353	24,347	n/a
Averages	1,244	80,397	354	22,960	£2,782

For the baseline performance, differences were found between the results of the calculation methodologies. For space heating consumption, the lowest value was predicted by RdSAP (989 kWh/ m²) and the highest by SAP (1879 kWh/ m²), twice as high as the RdSAP estimation.

Table 6: Performance after the retrofit - annual figures (extracted from Heath et al 2010).

Software programme	kWh / m²	Total kWh	CO_2 / m² (kg)	Total CO_2 (kg)	Fuel costs
NHER Plan Assessor	309	24,639	33	2,106	£1,118
NHER Stock Assessor	545	34,456	36	2,262	£1,374
NHER RdSAP only	460	29,065	16	994	£1,375
RdSAP	429	27,107	17	1,074	£873
SAP	398	25,117	15	963	£519
SBEM	477	32,913	118	8,135	n/a
BSM	n/a	n/a	n/a	n/a	n/a
Averages	436	28,883	39	2,589	£1,052

After the intervention, the lower value was predicted by NHER Plan assessor (309kWh/m²) compared to 545kwh/m² predicted by NHER Stock Assessor.

The table below compares the energy rating pre- and post-retrofit obtained using each of the calculation methodologies. Heath *et al* (2010) argue that RdSAP has fixed U-values that cannot be tailored with survey data which is a limitation in representing the baseline performance. It should be noted that RdSAP is meant to be a simplified methodology for assessing the performance of existing dwellings with a limited amount of survey information, such as for Green Deal evaluations (DECC 2012b).

Table 7: Energy efficiency ratings before and after the retrofit obtained from SAP, RdSAP and NHER (extracted from Heath et al 2010).

SAP		
	Pre-improvement	Post-improvement
SAP 2005	-28	44
NHER Plan Assessor	1	46
Notes:	The pre-improvement SAP rating is considerably lower when modelled using SAP 2005. The post-improvement SAP rating is very similar with both programmes.	

RdSAP		
	Pre-improvement	Post-improvement
RdSAP (ECMK)	2	40
NHER Stock Assessor	1	37
NHER RdSAP only	1	37
Notes:	All predictions are similar. However, the slightly higher post-improvement prediction generated by the ECMK programme would raise the property into a higher SAP band, which would be reflected in any EPC. This is covered in more detail in section 7.2.	

SAP band		
	Pre-improvement	Post-improvement
SAP 2005	G	E
NHER Plan Assessor	G	E
RdSAP (ECMK)	G	E
NHER Stock Assessor	G	F
NHER RdSAP only	G	F
Notes:	All programmes rated the property at G pre-improvement. However, the post-improvement predictions range from E to F. The potential impacts of this variation are covered in more detail in section 7.2.	

NHER		
	Pre-improvement	Post-improvement
NHER Plan Assessor	0	4.4
NHER Stock Assessor	0	2.8
NHER RdSAP only	0	2.8
Notes:	All programmes rated the property at 0 pre-improvement; this is the lowest rating possible. However, Plan Assessor gave a significantly higher post-improvement rating than the other programmes.	

Heath *et al* (2010) suggest the differences in the results for RdSAP could be caused by the efficiency assumption for a biomass boiler system (60% assumed from table 4a of the SAP booklet versus 92% actual); embedded assumptions in the tools about the U-value, fuel type, occupancy and heating pattern, actual air temperature. It has been found that occupants can achieve comfort next to heat sources and therefore, the actual air temperature might differ from the standard baseline assumptions. Heath *et al* (2010) recommend monitoring the achieved reductions after the intervention and undertaking *in situ* monitoring to calibrate the software and quantify the gap between predicted and achieved post-intervention performance.

The studies by Leeds Metropolitan University, suggest there could be a misrepresentation of the baseline performance by calculation methods such as SAP due to human error, inaccurate assumptions about occupation and heating patterns and standardised scenarios of comfort practices that fail to represent the use factors in dwellings made of solid walls (Miles-Shenton *et al* 2010; Miles-Shenton *et al* 2011; Stafford *et al* 2011; Wingfield *et al* 2011).

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In summary, the literature highlights potential discrepancies between the results obtained by different calculation methodologies based on simulation models that embed standardised assumptions about parameters that affect the energy performance of dwellings. As with any prediction, there are limitations to what a theoretical scenario is able to represent and whether it reflects the phenomenon that occurs in reality. In the case of existing dwellings the predictions by simulation models could be undermined by erroneous baseline U-values and the misrepresentation of use factors before and after the retrofit (heating regimes, comfort preferences, users' practices).

2.4.2 Erroneous baseline U-values

The investigations discussed earlier have conducted *in situ* measurements of walls in existing dwellings and compared these to the estimations by calculation methodologies. The *in situ* thermal performance investigations have found that BR 443 and *BuildDesk* underestimated the thermal performance of pre-1919 materials due to the lack of accurate thermal performance data on traditional materials (Rye 2010; Baker 2011; Rye and Hubbard 2012; Rye and Scott 2012).

Rye (2010) found discrepancies between *in situ* measurements and the predictions by *BuildDesk*, a tool to estimate the U-value of building components, as shown in Figure 11. The heat loss was overestimated in 77% of the samples. The differences were greater for stone walls.

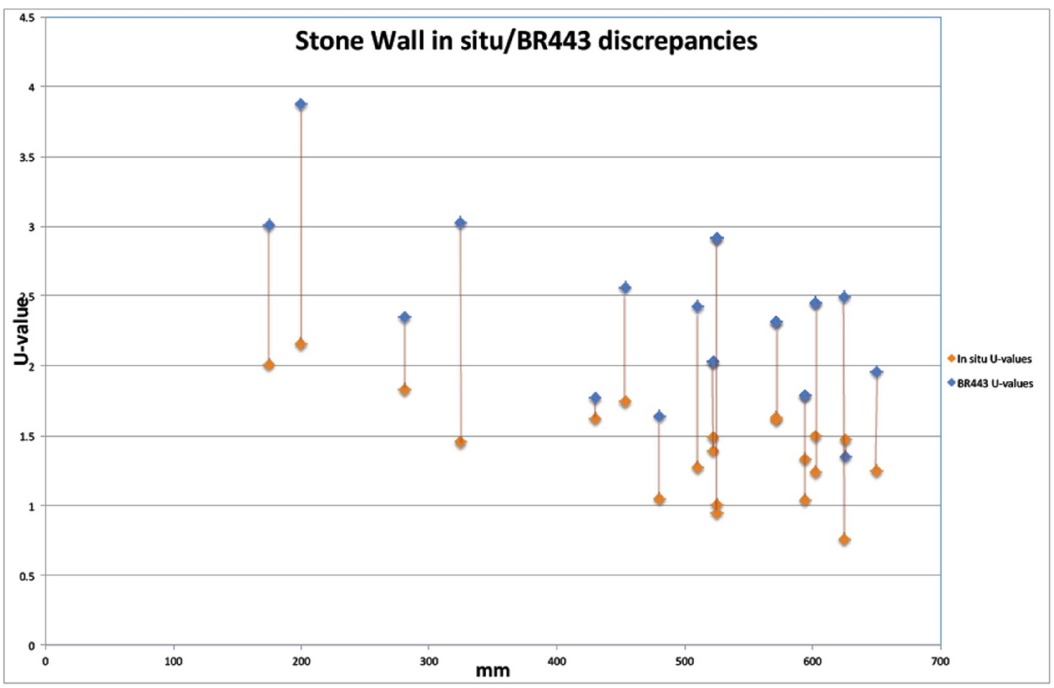

Figure 11: Discrepancies between U-values obtained in situ and by *BuildDesk* for stone walls (Extracted from Rye and Scott 2012).

Only two out of 16 values presented a close agreement between measured and *BuildDesk* figures. Rye and Hubbard (2012) claim there is a lack of baseline thermal conductivity data for most UK vernacular buildings. The problem of lack of data is aggravated by the variability of vernacular materials whose properties are likely to differ per geographical location.

As shown by these studies, the U-value baseline could be misrepresented in calculation methodologies. It may be necessary to use *in situ* measurements to inform existing datasets and understand better the performance of traditional materials and the variations within similar materials so as to embed that range in predetermined datasets.

2.4.3 Misrepresentation of occupant factors

This topic is discussed in Chapter 3 of the literature review. The discussion here focuses on the inadequate assumptions about occupancy embedded in the calculation methodologies.

Occupants have an influential effect on energy consumption. Heating consumption can vary by a factor of 3 in technically identical houses (Larsen et al 2010). Occupants' idiosyncrasies and pre-existing habits to achieve thermal comfort in existing dwellings may be complex to translate to standard occupancy data used as modelling input. The occupation parameters embedded in the pre-retrofit performance estimation model may be misrepresented by the calculation methodologies. A number of studies have demonstrated that the baseline indoor thermal characteristics of poorly insulated houses tend to differ from the assumptions of the models (Cornish 1975; Uglow 1983 and 1984; Ward 1987; Shipworth 2011; Hong 2011). Moreover, householders' practices to achieve thermal comfort in poorly insulated dwellings (window operation and thermostat settings) could be maintained after the intervention, affecting the expected savings. In terms of heating, Sorrell (2007) suggests that there could be a shortfall in the savings due to wrong assumptions about the temperature to which the dwelling is heated before and after the retrofit and the behavioural patterns (preferences of internal temperature, window operation and user-related variables).

Cornish (1975) describes a study on houses of a Scottish local authority where the fuel consumption patterns were compared between well and poorly insulated houses. The study classifies building occupants as high, low and average heat users. The study found that in well insulated houses, the 10% highest heat users used 2.5 times as much fuel as the 10% lowest users. In the poorly insulated houses the 10% highest users used 6.5 times as much fuel than the 10% lowest users. The average heat users in well insulated houses used 20% less fuel than in houses with half their insulation value. Cornish (1975) suggests that the average heat-users might take half of the benefits of increased insulation in fuel savings and half in temperature. The study shows that the 10% highest users of increased insulated homes took 75% of the benefits in fuel savings. For the 25% lowest heat users, the fuel usage was not affected by the improved U-value, suggesting it was all taken as improved comfort. These figures show the degree of variation within and between groups. Such variations are unlikely to be captured on standard occupancy profiles used to predict the performance.

When comparing the simulation predictions and the measured savings, Cornish (1975) found that instead of the anticipated 35% savings, the average fuel users in well insulated houses used 17% less fuel than those in the poorly insulated ones. The whole house temperature in well insulated houses was 1.6°C higher than the poorly insulated ones (14.7°C versus 13.1°C). The inside to outside difference was 17% higher in the insulated houses with a more uniform temperature distribution within the insulated group.

A number of studies have found that the anticipated savings post-retrofit may not be achieved due to misleading assumptions about occupancy, unanticipated changes (or maintenance) of occupants' practices to achieve comfort and unexpected preferences prior to and after the retrofit. For example, PA Management Consultants (1983) reported on a retrofit intervention. The predictions estimated that the insulation would produce a 19% reduction in delivered space heating energy requirements. However, no savings were recorded. The discrepancies between predicted and actual savings were explained by an underestimation of the baseline U-value and the temperature before the retrofit (2-4°C lower than expected). This suggests that occupant factors may have affected the performance and the savings after the retrofit. Ward (1987) reports on the BRECSU demonstration project in Liverpool. The predicted consumption was compared with the monitored consumptions in the heating season of 1985-1986. BREDEM was found to overpredict the total energy consumption by 12-17GJ/year due to the space heating loads. The tenants were not heating to as high a standard as assumed.

Hens (2010) studies a house built in 1957 which was retrofitted in the eighties by installing insulation. New energy efficiency measures were installed in 2004 (solar boiler) and 2009 (PV panels). The dwelling was monitored from 1978. The study is relevant in that it finds the measured data were consistently less than the predictions:

- the calculations overestimated the energy consumption for space heating by 28%
- hot water use was 33.9% lower than assumed. 50°C was the average temperature assumed in the calculations while the average measured temperature was 35.2°C with peaks around 50°C (29.7% lower than calculations). The temperature of cold water instead of being 10°C as set in the calculation model, ranged from 12°C winter to 18°C in summer. The calculation model underestimated the baseline scenarios.

A recent study for Affinity Sutton (2013) found that a significant number of homes used more fuel following energy efficiency improvements than before. This change could be caused by a number of factors, including changes in occupant behaviour. In three out of four cases SAP over predicted the savings because the complexity of occupancy patterns was not considered.

A number of studies have analysed the limitations of using the typical occupancy factors embedded in simulation models. Deurinck *et al* (2011b) use TRNSYS to calculate the energy savings post intervention. They found that while calculation methods presuppose an internal temperature of 18°C, the existing indoor temperatures in poorly insulated dwellings may be lower. After interventions in poorly insulated dwellings, the indoor temperature will rise even if the heating patterns do not change. Thus, the authors claim that the use of a fixed temperature for all insulation levels leads to inaccurate predictions of energy savings. Aspen *et al* (2012) find that SAP overpredicts the pre-existing temperatures maintained by occupants prior to the intervention. Similarly, Banks and White (2012) evaluate a solid wall insulation programme implemented in fuel poor households in the private sector. They suggest that occupants of poorly insulated low income dwellings develop habits to reach thermal comfort while minimising energy costs. The dwellings with poor fabric experienced a lower temperature than assumed by standards and calculation models. These properties tend to be under-heated, therefore the comfort improvements counterbalance the energy savings as the benefits of the retrofit are used to achieve the desired thermal comfort level.

Heath *et al* (2012) compare RdSAP, SAP and NHER, finding that RdSAP and NHER could differ in relation to heating patterns. The first two presuppose the use of heating nine hours per day on weekdays and 16 hours per day on weekends to set temperatures of 21°C in living rooms and 18°C in the rest of the dwelling, while NHER allows the user to input their own heating pattern. The authors highlight that the longer heating season in northern Britain is not considered in those tools. Sharpe and Shearer (2012) found discrepancies between the SAP predictions and actual savings due to the ways that users achieve comfort in the houses, for example, through the operation of windows to provide fresh air during winter while having the heating system on.

The summarised information about the retrofit of Grove Cottage, contained in the *Retrofit for the Future* database by TSB (2013), shows that the prediction scenarios overestimated the savings. In this case, the PassivHaus calculation tool was used for the predictions. This tool assumes an indoor temperature of 20°C. However, the house was actually heated to 21°C. The predictions suggested a heat demand of 25kWh/m^{2}y against the measured value of 35kWh/m^{2}y.

Table 8, extracted from the Grove Cottage project information on the TSB website, illustrates the differences between forecast and measured performance:

Table 8: Comparison of the performance prior and after the retrofit (forecast and measured) on Grove Cottage (extracted from TSB database http://www.retrofitforthefuture.org/ 2013)

	Before the retrofit	Forecast	Measured
CO_2 emissions	55 kg CO_2/m²yr	22 kg CO_2/m²yr	25 kg CO_2/m²yr
Primary energy requirement	284 kWh/m²yr	108 kWh/m²yr	120 kWh/m²yr
Annual space heat demand	-	25 kWh/m²yr	35 kWh/m²yr

To account for the differences in heating patterns and users' preferences, some studies have proposed the characterisation of types of users and behaviours (Lopes *et al* 2012; Guerra-Santin and Itard 2010; Guerra-Santin 2011; Love 2012; de Meester *et al* 2013)

Lopes *et al* (2012) suggest two types of models to predict occupant behaviour:

- a combination of qualitative and quantitative data, for instance diaries and measurements to characterise different types of users and behaviours; and
- quantitative models based on data mining which could result in the creation of building types that represent energy usage

Guerra Santin and Itard (2010) use a statistical approach to determine the behavioural patterns based on a survey by the OTB Research Institute for Housing, Mobility and Urban Studies in the Netherlands and a Woon survey by the Dutch Ministry of Housing. Although the study is focused on buildings built after 1995, it is relevant in characterising the users according to their behaviours and heating patterns which could inform different profiles of energy use. Guerra-Santin and Itard (2010) suggest that behaviours are likely to be related to demographics. In Guerra-Santin (2011) this is further explored and profiles of energy use and demographics are suggested for the following groups: single families, families with children and elderly. This highlights the need to consider different types of occupation patterns to address the differences in energy uses and occupation profiles that may affect the way that houses are heated.

Love (2012) uses *EnergyPlus* to compare the impact of different occupant heating behaviour in terms of heating time, space and temperature. Love (2012) employs low, medium and high behavioural scenarios combined with three scenarios of building efficiency: inefficient, middle and efficient. The building efficiency refers to the heat loss parameter and the efficiency of the heating systems. By creating different behaviour patterns Love (2012) attempts to address the possible variations found in heating practices and comfort preferences. De Meester *et al* (2013) analyse the impact of occupant behaviour on heating consumption in Belgium. They use TAS (a dynamic thermal simulation program) to simulate seven insulation characteristics and four types of occupancy. After an insulation upgrade in the worst insulated scenario, changes in thermostat settings and occupied area could result in savings 20% to 40% lower than expected. It was found that the more the building is insulated, the more the heating loads are affected by lifestyle.

The literature presented in this section has illustrated the complexity of modelling the factors related to occupancy due to the large variations in heating patterns, users' behaviours and users' practices to achieve thermal comfort. The practices and habits enacted by the occupants enable them to find a balance between comfort and fuel saving before the retrofit, leading them to unexpected responses and behaviours after the retrofit. In summary, the literature shows that there are a number of pre-existing habits to which users adapt in order to minimise energy consumption. Those practices may be maintained after the retrofit in detriment to the energy saving potential. Equally, in homes underheated prior to retrofit, the energy savings are compromised by the comfort-taking post-retrofit. Despite the energy savings not being realised, the occupants benefit from better indoor environment and increased comfort levels.

2.5 Summary and recommendations

The literature review for this topic has found that the majority of previous studies have investigated the aggregated consequences of a combination of retrofit strategies, one of which could be insulation of walls and that few have monitored a sufficiently large sample for a sufficient length of time for statistically robust comparisons to be made (Sorrell 2007). The current project should account for these findings where appropriate, in particular with regard to the length of monitoring.

The review compiled evidence about the following aspects of the calculation of performance pre- and post-retrofit:

- Baseline performance of the envelope
- Construction aspects related to the retrofit work that affect performance
- Limitations of simulation-based methodologies in terms of:
    - Differences in the predictions by calculation tools (SAP, RdSAP, NHER, SBEM)
    - Erroneous baseline U-values
    - Misrepresentation of occupant factors

The baseline performance of the building envelope could be determined by laboratory-based studies and *in situ* measurements. The weakness of laboratory-based studies is that they often fail to capture the complexities of hygrothermal and maybe other behaviours of the materials in real settings. This is particularly relevant for pre-1919 dwellings and traditional materials where the lack of accurate data about the properties of the materials and the variety of materials used reduces the certainty of baseline U-values that are not based on *in situ* measurements. For example, the uneven distribution of moisture in a wall could lead to increased scatter in comparisons of measured and calculated U-values. Analysis for this project should consider this. Studies have suggested that:

- the behaviour of the walls in existing dwellings, could differ from the standard performance of materials;
- methodologies used for determining the U-value of materials may not be able to represent the baseline performance of materials of pre-1919 dwellings and traditional buildings;
- datasets of materials obtained under laboratory conditions may fail to consider the influence of moisture content on the baseline performance; and
- common industry standards used for the appraisal of moisture content on building elements may be limited in representing the dynamics of moisture transport within and across the wall build-up which is particularly relevant for the performance of pre-1919s solid walls.

The construction quality of the retrofit work can also affect the performance achieved after the retrofit. Studies have found the following errors in the construction process: poor workmanship, poor standards on site, gaps in the insulation, changes in the specifications, poor execution of details at junctions and poor site care to reduce thermal bridges. The errors are likely to undermine the post-retrofit performance and jeopardise the achievement of the anticipated savings. This project should pay particular attention to the process of any installations of solid wall insulation. It is not enough to assume that achieved performance matches the designed performance *in situ*.

Concerning simulation-based methodologies ability to predict the savings, the literature suggests three causes of discrepancies: differences between results of calculation tools despite the use of similar input data (potentially due to embedded calculation methods); the erroneous representation of baseline U-values and incorrect assumptions about occupancy. It will be recognised that simulation-based methodologies can never fully take account of all factors that affect energy use, particularly given the requirement for non-intrusive surveys of limited time, so there will always be some such disagreements.

Simulation-based methodologies tend to be based on a standard approach that may not be appropriate due to the lack of understanding of the performance and users' practices to achieve comfort. Steady-state methodologies may fail to represent the thermal performance of some materials accurately, misrepresenting the construction quality and the energy consumption prior to the retrofit. For some materials it is necessary to consider moisture content and air movement and to recognise that there will be variations and ranges of uncertainty in the baseline thermal performance of materials. The use of *in situ* measurements and surveys to collect input data could improve the quality of the baseline scenarios.

In relation to occupants' behaviours, it has been found that the occupants of poorly insulated dwellings tend to underheat their homes however; baseline modelling scenarios assume the same temperatures are achieved in all dwellings regardless of the existing thermal performance. In the cases where householders maintain lower temperatures than expected, it has been found that after the retrofit there is an increase in the indoor temperature. The improved thermal comfort benefit reduces the savings.

An aspect that has not been explored in detail is the choice of metric to assess the retrofit saving, such as end-energy use, heating demand, energy cost or thermal comfort (indoor temperature, temperature differential within the dwelling). It should be noticed that the discrepancies between the predicted and measured performance in different studies can depend on the metrics they use for the comparison.

In summary, this survey of the literature has highlighted that the gap between predicted and actual performance is affected by three main elements. The first; baseline estimates, occurs because of what could be summarised as overly simplistic assumptions about the building elements and in particular the thermal performance of the walls. More information about the wall, coupled with more resolution in the sources of information about standard performance assumptions, can lead to better baseline estimates. Related to this is how walls are represented in simulation tools. More information needs to be collected in order to allow more sophisticated assumptions to be made within the software. Other explanations are that the system does not perform as expected because of its installation and the behaviour of the occupants may not (or is unlikely to) match the standard assumptions used in most models. The literature has shown that the occupant factors are likely to be misrepresented before and after the retrofit.

The main findings of specific relevance for this project are:

- It is important to collect detailed data on internal temperatures alongside U-value measurements (i.e. in several rooms, not just at the point of the U-value measurement). This will be particularly useful if obtained both before and after solid wall insulation.
- Data on moisture content of the wall is likely to be important for some construction types, so this should be routinely collected as part of this and future studies of U-values.
- Occupant behaviour, especially with regard to the control and use of heating systems, gives rise to significant modelling uncertainty, so by survey or otherwise, it is important to capture data about this during the remainder of the study.
- If possible, attempts should be made to determine whether construction errors have been made during the application of solid wall insulation and the consequences of those defects evaluated.

Future directions of research include the calibration of simulation-based methodologies and standards on the basis of in situ U-value measurements and the creation of a comprehensive database of traditional materials to improve the quality of U-value baseline performance. Both aspects could be embedded in the tools to estimate the baseline performance of existing dwellings for retrofit programmes such as the Green Deal. Combining user profiles and heating patterns in relation to the energy efficiency of the dwelling may improve the occupancy assumptions embedded in simulation-based methodologies. A clearer understanding of construction defects and common sources of on-site error could lead to the creation of confidence or safety factors to account for the construction quality likely to be delivered during retrofit work.

3 Occupant behaviour[12]

This section has been divided into six sub-sections:

- Rebound effect – definitions
- Rebound effect – measuring the impacts
- Rebound effect – factors affecting the size
- The prebound effect
- Behavioural spillover
- Conclusion and references

3.1 Rebound effects - definitions

The idea that energy efficiency improvements might *increase* rather than *decrease* energy use was first proposed by William Stanley Jevons in 1865 (Sorrell 2009):

"It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth. As a rule, new modes of economy will lead to an increase of consumption..." (Jevons, 1865).

In his book "The Coal Question," Jevons argued that the energy efficiency improvements made by Watts' steam engine facilitated greater production of lower cost coal in the coal mines. This lower cost coal was used by steam engines for services, such as pumping air into blast furnaces, which increased blast temperatures (for the iron making process). This reduction in the quantity of coal needed to make iron then reduced the cost of iron. The lower cost iron reduced the costs of steam engines, contributed to railway development, lowered the cost of transporting coal and iron, and consequently increased the demand for both coal and iron (Sorrell, 2009), thereby completely negating the energy efficiency improvements.

In the late 1970s and early 1980s, Daniel Khazzoom and Len Brookes independently expanded upon Jevons' argument (The Jevons Paradox), suggesting that increased energy efficiency at the micro-economic level (e.g. individual households) might reduce energy use at this level, but might increase overall, national *or macroeconomic* energy use (Herring, 1999). In 1992, Saunders formalised the hypotheses put forward by Khazzoom and Brookes, as the "Khazzoom-Brookes Postulate." (Saunders, 1992) As predicted by Jevons, it has been argued that this leads to an increase in energy consumption over the long run, rather than a decrease, and this is referred to as 'backfire' (Druckman *et al*, 2011).

Due to raised concerns about global warming, debates about backfire and rebound effects grew more intense during the 1990s (Herring, 1999). Economists such as Michael Grubb and Amory Lovins argued against Khazzoom and Brookes and suggested that, without market barriers, energy efficiency improvements would result in reduced national energy use (Herring, 1999). These debates continue and,

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although there is a consensus in the research literature about the existence of the rebound effect, debates have arisen about its magnitude (Gavankar and Geyer, 2010).

Although there is no standardised classification or terminology and no agreed definition of the rebound effect (Gavankar and Geyer, 2010), the rebound effect is variously defined as:

- A behavioural response to improvements in energy efficiency (Mizobuchi, 2008; Roy, 2000; Druckman et al, 2011);
- An increase in demand which wholly or partially compensates for the theoretical reduction in energy consumption due to the changes induced by improvements in energy efficiency (Peters et al, 2012);
- An increase in consumption (caused by behavioural and/or other systemic responses), occurring as an unintended side effect of a policy, market and/or technological intervention aiming to improve energy efficiency (Maxwell et al, 2011);
- The energy savings that are taken back by consumers and/or the economy in order to satisfy energy needs which were stimulated by the energy efficiency improvements (Gavankar and Geyer, 2010).

As well as there being no definitive definition for the rebound effect, different categories of the rebound effect have also been identified (Alcott, 2005; Madlener and Alcott, 2009: Greening *et al*, 2000).

Maxwell *et al* (2011) suggest that, in general, rebound effects can be classified into three main categories: direct, indirect and economy-wide:

Direct rebound effects occur when the energy efficiency improvement of one type of energy or energy service increases the consumption of the same energy or energy service (Gavankar and Geyer, 2010). For example, if solid wall insulation is fitted in a property, thermal efficiency will be improved. The home will then be cheaper to heat and consequently the occupants might choose to heat their homes for longer periods of time, increase the air temperature and/or heat more rooms in the property (Gemmell, Monahan and Suffolk 2012).

Indirect rebound effects occur when the energy efficiency improvement of one type of energy or energy service increases the consumption of *another* energy or energy service (Gavankar and Geyer, 2010). For example, if solid wall insulation is fitted in a property and thermal efficiency is improved, the home will then be cheaper to heat. From the financial savings made, the occupants might then choose to spend the money saved on a short or long-haul flight for a family holiday, which they otherwise might not have made (Gemmell *et al* 2012).

Economy wide rebound effects occur when energy efficiency improvements enable productivity growth, which leads to increases in economy-wide energy consumption (Gavankar and Geyer, 2010).

These categories are currently the most widely recognised types of rebound effects. For this project, the primary focus should be on the direct rebound effects associated with the installation of solid wall insulation. A field trial conducted as part of this project should look for evidence of direct rebound effects post insulation as well as any evidence of indirect effects.

3.2 Rebound effects – measuring and quantifying the impacts

Difficulties arise when measuring direct rebound effects, since, depending on the boundaries used to describe the rebound effect, the measured behavioural response will also vary (Greening *et al*, 2000).

Druckman *et al* (2010; 2011) define measuring direct rebound effects as:

$$\text{Rebound} = \frac{(\text{Potential saving} - \text{Actual savings})}{\text{Potential saving}}$$

For example, if solid wall insulation has the potential to save 20% of the energy used to heat a property (potential saving), but after installing the insulation, the occupants *take back* some of the potential saving as additional comfort and only save 15% (actual saving), this would result in a direct rebound of 0.25. Rebound is commonly measured as a percentage of engineering savings, and so this would result in a direct positive rebound of 25% (i.e. 25% of the potential savings are taken back).

$$\text{Rebound} = \frac{(20\% - 15\%)}{20\%} = 25\%$$

If however, the same solid wall insulation was installed (with a potential saving of 20%), but after installing the insulation, the occupants used less heating than the potential saving expected and had an actual saving of 22% (this could be due to factors such as radiant temperatures being increased, enabling occupants to feel comfortable at lower air temperatures or if the energy efficiency measures were implemented alongside an educational campaign), this would result in a 10% direct *negative* rebound effect and therefore greater efficiency improvements would have been achieved than expected (Maxwell *et al*, 2011).

$$\text{Rebound} = \frac{(20\% - 22\%)}{20\%} = -10\%$$

If the positive rebound is greater than 100% of the predicted engineering savings, this would result in more energy being used after the energy efficiency improvement than before (Madlener and Alcott, 2009). This *backfire* would have a large impact on policies being implemented to improve energy efficiency.

A large majority of the studies on rebound effects compare post-installation actual energy use, with engineering estimates for pre-installation. However, Greening *et al* (2000) report that when actual measurements of pre-installation energy use were taken, the magnitudes of the rebound effects were smaller (this could be attributed to the prebound effect which will be discussed later).

Haas and Biermayr (2000) suggest that the reason why there is little empirical evidence of the rebound effect is that it is difficult to find a suitable methodology for quantifying it. Milne and Boardman (2000) support this by saying that there are an insufficient number of suitably monitored and analysed projects to thoroughly assess rebound effects.

Haas and Biermayr (2000) identified four methodologies that they suggest are worth considering:

1. Conducting a time-series analysis;
2. Using a cross-section of households, investigating if there is a linear relationship between energy consumption and efficiency;
3. Using a cross-section of households, carrying out a cross-section analysis exploring the impact of prices and efficiency;

4. Analysing energy consumption before and after energy efficiency improvements are carried out and comparing the actual measured savings with the theoretically calculated savings.

In their research carried out in Austria, Haas and Biermayr (2000) found evidence for a direct rebound effect of between 20% and 30% for space heating. They used all of the above methodologies and, although they conclude that all of the above approaches have their weaknesses, they found that similar rebound sizes were found when using the different methodologies.

Sorrell *et al* (2009) provide an overview of the different methods used for estimating the direct rebound effect. In their paper, which specifically focuses on energy use in households, they suggest that the methodological quality of most research using before and after measurements is relatively poor. The majority of the studies do not include a control group and confounding variables are often not controlled for (Sorrell *et al*, 2009). Additionally, they suggest that many of the studies are prone to selection bias, the sample sizes are often small and the monitoring periods are too short.

Taking on board the recommendations from previous research, it is recommended that the best methodological approach to use for the forthcoming field trial would be to analyse the energy consumption for a whole heating season before and after homes are insulated. Actual energy used post insulation should be compared with both estimated and actual energy use prior to the homes being insulated. As recommended by Sorrell, the sample should include a number of control properties which are not insulated during the monitoring period. This should ensure confounding variables are controlled for and that any differences in energy consumption pre and post insulation can be more confidently attributed to the installation of insulation.

Sorrell *et al* (2009) also highlight that there is often confusion between what they describe as:

'Shortfall', which is the difference between the actual energy consumption and the expected energy consumption (based on engineering estimates);

'Temperature take-back', which refers to the change in the mean internal air temperature after the energy efficiency improvements are carried out; and

'Behavioural change', which is the proportion of change in the internal air temperature due to adjustments of heating controls and other variables by the occupant (Sorrell *et al*, 2009).

The temperature take-back is affected by both behavioural change and physical factors. Shortfall is affected by temperature take-back, as well as poor engineering estimates, equipment not performing as required and factors such as poorly installed insulation (Sorrell *et al*, 2009). Behavioural change is therefore not the only factor contributing to temperature take-back. Sorrell *et al*, (2009) also argue that it is misleading to assume that direct rebound effects are solely due to behaviour change, since the energy efficiency improvements might change other variables (such as changes in airflow), which then encourage a behavioural response (such as opening more windows).

To address this, the forthcoming field trial should assess 'shortfall', 'temperature take back' and 'behavioural change' by: empirically comparing actual energy consumption and the expected energy consumption (both pre and post), monitoring the mean internal temperatures both pre and post insulation for a whole heating season, and assessing changes in energy use behaviour post insulation.

When discussing measurements of direct rebound effects, and in particular residential space heating, Greening *et al* (2000) discuss which variables should be measured. They question if it should be the thermostat set point, the thermal comfort of the occupants (which would include attitudes towards thermal comfort, individual activity levels, mean radiant temperature, air velocity and humidity), and/or the space heated that should be measured. They also suggest that some of the available datasets do not include other key variables such as income, household demographics and cost of fuel. The forth coming field trial should (as far as possible) collect the relevant data to assess all of the above variables. Data should be collected through physical monitoring of the building and occupant interviews.

3.3 Rebound effects - factors affecting the size

It is the very economy of its use which leads to its extensive consumption. It has been so in the past, and it will be so in the future (Jevons, 1865).

Although the literature generally agrees about the existence of the rebound effect, contentions arise when exploring and predicting its size. A report produced by Sorrell (2007) assessing the economy-wide rebound effects, points out that the size of both direct and indirect rebound effects varies widely between different technologies, sectors and income groups. This is not surprising when some homes use six times the amount of energy for their heating as other homes with the same energy rating (Sunikka-Blank and Galvin, 2012). The findings from Sorrell's (2007) research suggest that improvements in energy efficiency will not result in the backfire (an overall increase, rather than decrease in energy use after energy efficiency improvements are made) as Jevons and Khazzoom-Brookes postulate. However, the findings highlight that there is substantial evidence supporting the existence of the rebound effect and so it should be considered when planning energy efficiency strategies (Sorrell, 2007).

Sorrell (2007) estimates that the direct rebound effect in OECD countries (Organisation for Economic Co-operation and Development) for household heating and cooling is unlikely to be more than 30%. Therefore energy efficiency improvements should achieve a minimum of 70% of the predicted reduction in energy consumption. The econometric and quasi-experimental evidence reviewed by Sorrell *et al*, (2009) suggests that the direct rebound effect for household heating is around 20%. However, Gavankar and Geyer (2010) suggest that this will range between 30% and 60%, with the higher percentage being occupants who have unsatisfied demand.

Sorrell *et al*, (2009) found that for household heating, temperature take-back ranged between 1.14 degrees Celsius to 1.6 degrees Celsius; half of this was accounted for by the physical characteristics of the dwelling and the remainder by the behavioural change (Sorrell *et al*, 2009). The forthcoming insulation field trial should measure the average internal temperature across the house, pre and post insulation.

In order to quantify the size of any rebound effect associated with changes in occupant behaviour, the forthcoming field trial will need to measure all other factors which could account for any measured changes in consumption post insulation.

3.3.1 Income and internal temperatures

When discussing what affects the size of direct rebound effects, Sorrell (2007) proposes that direct rebound effects are dependent on household income. Gavankar and Geyer (2010) also propose that *income* and *time* are the main factors affecting the size of direct rebound effects and they expand on this by suggesting that:

"*Rebound [effects] will be higher among the lower income groups than in higher income groups*".

They suggest that lower incomes are linked to unsatisfied demand. Increasing energy efficiency then enables lower income groups to satisfy their demand, which they might not have been able to do prior to the energy efficiency improvement.

Sanders and Phillipson (2006) found that the size of any direct rebound effects was linked to energy consumption before refurbishment. There appears to be a clear link between the average internal temperature of a dwelling before the installation of energy efficiency measures and the amount of potential benefit taken as extra warmth. The research suggests that temperature is the main determining factor of the amount of benefit from energy efficient measures taken as an increase in comfort rather than energy savings. It is likely that this is the underlying factor which accounts for the observed differences between different income groups. Rather than the difference being directly related to income, it is likely that those in lower income groups were less able to heat their homes to a comfortable temperature prior to the intervention and therefore took back more of the potential energy savings as increased comfort.

Using studies of real homes that were monitored over a period of time, Milne and Boardman (2000) evaluated the rebound effects in low-income housing. They found that the internal temperature (before the energy efficiency improvements were carried out) was the main determinant of the amount of potential energy savings that is taken as extra warmth. Based on the results from the monitored projects, they suggest that at 16.5°C (the average temperature of housing in Great Britain in 2000), there will be a direct rebound effect of around 30%. However, if the average pre-insulation temperature was at the lower temperature of 14°C, 50% of the energy savings would be taken as a temperature increase. They continue by suggesting that it will not be until whole-house average indoor temperatures are around 19-20 degrees that 80-90% of the potential theoretical savings will be made (Milne and Boardman, 2000). In their research they also found that the average temperatures of local authority housing tenants and owner-occupiers homes were similar, and they argue that there is no reason why the overall amount of rebound between the two groups should differ. This finding suggests there is not a necessity to include owner-occupiers in the forthcoming field trial sample.

Herring (1999) highlights the disadvantages faced by those suffering from fuel poverty when discussing the energy efficiency of new appliances. Since new appliances are often more efficient than older items, people who are able to afford to buy these new items will have higher levels of energy efficiency in comparison to those who cannot afford to buy them. Additionally, by having less efficient appliances, those on lower incomes will need to pay more to achieve the same desired level of energy services as those on higher incomes (with more efficient appliances). In contrast, Schipper and Grubb (2000) suggest that those with higher incomes may not necessarily spend their increased income on energy intensive goods and services, since their needs may be satisfied. They suggest that there is a limit on how much of the same type of energy can be used once an unsatisfied need or comfort level is met (i.e. there is a limit as to how much heat an occupant requires to heat their home to a comfortable temperature).

Due to saturation effects[13], the size of the rebound effect, and in particular the direct rebound effect, may start declining over time. For example if the walls of a property are insulated and the occupants are then able to heat their rooms to a higher temperature, as the thermal comfort increases, the rebound initially induced may decrease.

[13] Saturation effects relate to the reduction in the rate of increase in the level of service required, as the difference between the effective level of service and the comfort level is decreased (Maxwell *et al*, 2011).

bre

3.3.2 Thermal comfort

The idea of a comfort level, or perception of thermal comfort, involves both physiological and psychological factors (Milne and Boardman 2000). In 1970, Fanger derived an equation to express comfort, taking into consideration different physical factors such as air temperature, air velocity, relative humidity and the mean radiant temperature[14] of the surrounding surfaces, plus occupants' clothing and metabolic rate (Fanger 1970, cited in Milne and Boardman, 2000). Sanders and Phillipson (2006) support this by suggesting this is consistent with the steady-state thermal comfort theory which proposes that mean radiant temperature, air temperature, air velocity and relative humidity are the key factors affecting people's perception of thermal comfort. However, Fanger's equation ignores the psychological aspects of thermal comfort.

Energy efficiency measures, such as solid-wall insulation or double-glazing; 1) reduce the amount of energy required to maintain an indoor/outdoor temperature differential, 2) provide an even distribution of warmth throughout the house and 3) once the heating is turned off they reduce the rate at which the house will cool down. However, if the heating remains at the same setting as before the energy efficiency improvements were carried out, the last two of these factors will lead to an increase in the overall indoor temperature (Milne and Boardman 2000). Research has found that indoor temperatures often increase after energy efficiency measures have been introduced. They suggest that there are two separate processes that cause indoor air temperature to rise, the first process is *physical* and the second is *behavioural.*

They point out that the interaction between the physical and behavioural aspects is complex and contributes to possible variations in the size of rebound effects; this can range from all the benefit being taken as energy savings (0% rebound) to all of the benefit being taken as extra warmth (100% or more; rebound and backfire). They suggest that measures such as cavity wall insulation and double glazing, which result in a higher radiant surface temperature, might enable higher levels of thermal comfort to be achieved at lower indoor air temperature levels. Higher radiant surface temperatures allow the occupants to be comfortable at lower air temperatures and so can reduce the amount of rebound by up to 20% (Milne and Boardman, 2000).

As well as changes in people's perception of comfort, there are also changes in how people 'use' their homes. For example, if a home is not warm enough and if the price of creating warmth drops (through energy efficiency improvements), Milne and Boardman (2000) suggest that the occupants might intentionally increase their indoor air temperature beyond the level they would have chosen prior to the energy efficiency intervention, to improve their comfort. In addition, as the occupants are able to heat more rooms in the house to a comfortable temperature, due to more efficient heating systems and improved insulation, the occupants are more likely to use these rooms. If these rooms were previously not heated in order to save money, then this will increase consumption. There will also be an increase in the lighting and appliance use in these rooms (which might not have been used previously), thus contributing to indirect rebound effects (Wright, 2008). These changes must be monitored as part of the field trial monitoring.

3.4 The Prebound effect

In their analysis of Dutch households, Tigchelaar *et al* (2011) found a negative correlation between the technical efficiency of a house and the heating behaviour of the occupants in the household. They found

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[14] The heat that radiates from a warm object is known as thermal radiation. If you were to stand next to a warm radiator in a cold room, you would feel the radiant heat gain from the radiator, even though the air temperature is cold.

that, on average, occupants living in more efficient dwellings (as rated by the Dutch Energy Performance Certificates) have more energy intensive heating behaviours (than the average household) and occupants living in less efficient dwellings have less energy intensive heating behaviours. Although they conclude by suggesting that more research is needed to explore the causality of this relationship, these findings support the idea put forward by Herring (1999) that low efficiency and low consumption go hand in hand, as do high efficiency and high consumption.

This is supported by findings from Sunikka-Blank and Galvin (2012). They examined data from 3,400 German households and analysed both the calculated energy performance rating and the actual measured energy consumption. They found that the actual measured heating consumption could be on average 30% lower than the calculated amount. Further work also showed that, on average, the less energy efficient the building was (as calculated by the energy performance rating), the larger the percentage difference between the measured and calculated consumption (Rosenow and Galvin, 2013).

In general, the worse a home is thermally, the more economically the occupants tend to behave with respect to their space heating. (Sunikka-Blank and Galvin, 2012, p265).

Prebound effect refers to how much less, as a percentage, the measured energy consumption is in comparison with the calculated energy consumption before energy efficiency improvements are carried out (Sunikka-Blank and Galvin, 2012). For example, if a house has a calculated energy consumption of 200 kWh/m^{2}a, but the measured energy consumption is 150 kWh/m^{2}a, it has a prebound effect of 25%. As part of this project, the team should examine the size of any prebound effects through secondary analysis of existing data, as well as collecting detailed primary data through the pre/post insulation field trial. Measuring actual energy consumption prior to the installation and comparing this with the estimated energy consumption, will allow the team to quantify the size of the prebound effect.

The variations in actual consumption compared with calculated energy use could significantly reduce the calculated predicted gains from energy efficiency improvements. The research suggests that the predicted energy consumption prior to energy efficiency improvements is overestimated.

This is shown schematically in Figure 12.

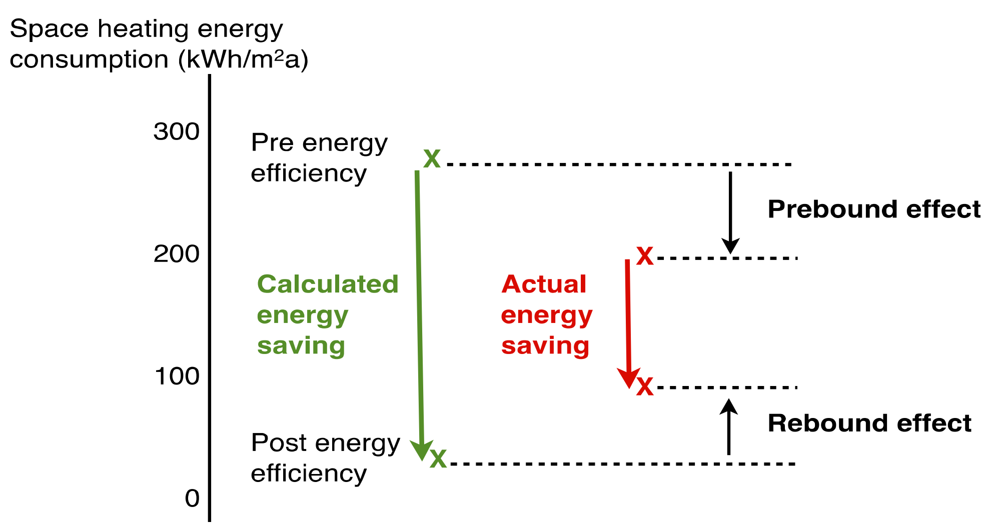

Figure 12: Example of how prebound and rebound effects might reduce predicted energy savings (after Sunikka-Blank and Galvin 2012).

Sunikka-Blank and Galvin's (2012) findings also show a large variation in the heating energy consumptions for households with identical calculated energy performance ratings, but on average they found that the prebound effect was 0% for properties with calculated ratings of 100 kWh/m^2a, 30% for properties with ratings of 220 kWh/m^2a and up to 55% for properties with ratings of 500 kWh/m^2a (Sunikka-Blank and Galvin (2012)). They also found that dwellings with calculated ratings below 100 kWh/m^2a had negative prebound effects and the occupants consumed more energy than the calculated amount.

These findings suggest that energy efficiency improvements cannot save energy that is not being consumed (Sunikka-Blank and Galvin, 2012). However, further research is needed to explore what the causes are, and what factors affect the variation in the size of the prebound effect. For example, it may be that the actual energy used is considerably lower than the calculated amount because the occupants cannot afford to heat their homes to an adequate temperature. This would support the findings of Gavankar and Geyer (2010) described above. If this is the case, energy efficiency policies need to work collaboratively with policies aimed at eradicating fuel poverty, to ensure that thermal comfort is achieved for the fuel poor and that whole house energy efficiency improvements are carried out to maximise the potential energy savings. It could be argued that the causes of the prebound effect should inform more general energy efficiency policies.

It is also important to consider the wider benefits of better insulating solid wall properties other than simply energy savings. The research suggests that a larger direct rebound effect will be observed in households which could not afford to heat their homes to a comfortable temperature prior to the home being insulated. Although this means less energy and carbon saved, the health and wellbeing of the occupants is likely to increase. As BRE research has shown (Davidson et al, 2010), reducing cold and damp in homes and improving the health of the occupants would also result in savings for the NHS.

3.5 Spillover effect

An additional area of interest is 'catalyst behaviour'. This is where 'performing certain pro-environmental behaviours can have a knock-on (or 'catalyst') effect and can lead to the adoption of a broader range of other pro-environmental behaviours.' (DEFRA, 2011). This phenomenon is known as the spill-over effect. There are positive spill-over effects and negative spill-over effects.

An example of a positive spill-over effect would be if an occupant chooses to install loft insulation to save energy (catalyst behaviour), and this then leads the occupant to try and reduce their subsequent energy consumption to maximise the possible savings. These initial actions could also make them consider how else they could save energy and reduce their environmental impact, for example, reducing the amount of time spent in the shower to save water.

Negative spill-over effects happen when the adoption of a pro-environmental behaviour deters other pro-environmental behaviours. An example would be if someone were to install cavity wall insulation to save energy. They then feel they don't need to worry about saving energy in other areas of their life since they believe that 'they have done their bit' and this excuses increased energy consumption associated with other behaviours.

As part of the forthcoming field trial, the researchers should look for any evidence of positive or negative spillover effects that result from the insulation of the homes.

Positive spill-over effects can be better understood in the context of self-perception theories. Bem's self-perception theory (1972, cited in Thøgerson and Crompton, 2009) suggests that people use their own behaviours as 'cues to their internal dispositions', meaning that the behaviours they exhibit inform how they think and feel. Behaving in a certain way can, therefore, strengthen or weaken the way some thinks about something. Thøgerson and Crompton (2009) and Scott (1977) derived a spill-over theory from this, suggesting that engaging in a behaviour might change an individual's attitude towards performing that specific behaviour. Therefore, a change in behaviour leads to a change in attitude (specific to that behaviour) and increases the likelihood of the person repeating the behaviour in the future.

In some circumstances, people feel that it is inconsistent to behave in an environmentally friendly way in one area (such as recycling), while not doing so in another area (such as car sharing). This inconsistency produces an unpleasant affect (or arousal) called cognitive dissonance (Thøgerson, 2004 cited in Thøgerson and Crompton, 2009). It is suggested that acting consistently across pro-environmental behaviours depends on how important it is for the individual to act in an environmentally responsible way (Thøgerson 2004, cited in Thøgerson and Crompton, 2009). However, not all inconsistencies are regarded as being equally important and if the inconsistency is not regarded as being important then cognitive dissonance is unlikely. Thøgerson and Crompton (2009) suggest that positive behavioural spill-over is more likely to occur if the person feels that it is morally important for them to act in an environmentally responsible way (Thøgerson and Crompton, 2009).

Whitmarsh and O'Neill (2010) examined whether pro-environmental self-identity determines consistency across pro-environmental behaviours. Their proposal is that there is a common motivational cause of pro-environmental behaviours. This theory is supported by observational research. Whitmarsh and O'Neill identified clusters of pro-environmental behaviours (i.e. people who display one pro-environmental behaviour tend to exhibit clusters of other pro-environmental behaviours). These clusters represent either similar types of behaviour, different levels of environmental commitment or similar individual characteristics. Three of these types of clusters have been identified by Barr *et al* (2005, cited in Whitmarsh and O'Neill, 2010): 'purchase decisions' (shopping, composting and reuse), 'habits' (domestic water and energy conservation) and 'recycling'. According to Barr *et al*, these clusters relate to different lifestyles (i.e. socio-demographic characteristics and values).

Research in Denmark found that people are reasonably consistent within similar categories of behaviour. The categories include buying organic food, recycling and using public transport (Thøgersen and O'Lander, 2006, cited in Whitmarsh and O'Neill, 2010). There were significant correlations across these categories which can be accounted for by common motivational causes (general environmental values and concerns).This motivational cause is a pro-environmental self-identity.

These findings suggest that if the refurbishment of a dwelling is driven by a pro-environmental self-identity then the likelihood that the occupants will exhibit other types of pro-environmental behaviour is significantly higher. Thøgerson and Crompton's (2009) research suggests that having refurbishment work carried out could strengthen a pro-environmental identity and thereby increase the likelihood that these people will adopt other pro-environmental behaviours. However, this likelihood is tempered by how easy it would be for people to change these other behaviours and how these changes would impact on other aspects of their self-identity. People's behaviour is governed by more than one self-identity as well as the practicalities of behaving in a certain way. For example, their pro-environmental self-identity may lead to a desire to use public transport more; however if this behaviour were impractical or would impact on other aspects of their self or social identity then they would not do it. So, if someone considers themselves to be a car fanatic, perhaps as part of a group of car fanatics, then they would be unlikely to switch from the car to public transport, as this behaviour would not be consistent with their self and social identity as a car fanatic. Similarly, if someone lives in a location that makes the use of public transport difficult and/or impractical, they are unlikely to change their behaviour, despite this action fitting in with their pro-environmental self-identity.

The above examples are based on the premise that the individuals have a pro-environmental self-identity in the first place and the initial decision to refurbish the house is determined, at least in part, by a desire to save energy and the environment. If the decision was not driven by this, then it is very unlikely that this action will result in other subsequent energy saving behaviours. Research by DEFRA (2011) suggests that there is no clear catalyst behaviour or behaviours that can be relied upon to lead to the uptake of multiple pro-environmental behaviours. Whitmarsh and O'Neill (2010) suggest that people do not act consistently across diverse behavioural areas and there is no common motivational basis for pro-environmental behaviours.

The research suggests that encouraging a particular action is not likely to lead to the uptake of further, multiple actions, unless a holistic approach is taken; this needs to include the wider contexts in which actions occur and the processes by which behaviours change (DEFRA, 2011).

3.6 Conclusions and recommendations

The idea that energy efficiency improvements might increase rather than decrease energy use is not a new one, in fact it was proposed as far back as 1865. There is an agreement in the research literature about the existence of the rebound effects; however, there is not a consensus on the size of the effects or a definitive definition. Rebound effects can be classified into three main categories: direct, indirect and economy-wide. It is recommended that this project should focus on direct rebound effects which occur when energy efficiency improvement in one type of energy or energy service increases the consumption of the same energy or energy service.

At present, there are an insufficient number of suitably monitored and analysed projects to thoroughly assess rebound effects. In addition, the methodological quality of most research using before and after measurements is relatively poor. It is, therefore, important that any pre- post monitoring trials proposed for this project are carefully designed to ensure any rebound effects can be confidently quantified. Many of the trials conducted to date have failed to take account of some key variables that may influence the size of any rebound effects, such as income, household demographics, occupant attitudes and behaviour, and the cost of fuel. Researchers have suggested that a control group could be used on trials of this kind, to control for changes in external temperatures, fuel costs and other extraneous variables which might influence consumption rates over the trial period. The forthcoming field trial conducted as part of this project should include a sample of control properties. The sample should be made up of solid wall properties that are not insulated within the monitoring period. The homes selected should be of a similar construction and in similar locations to the insulated properties and include a mix of property sizes and include a range of households. The control group should act as a ‘baseline’. This will ensure that any difference found after the intervention, can be confidently attributed to the wall insulation, rather than other variables such as new government policy or energy prices etc.

For space heating, the rebound effect is estimated to be around 30% on average (Sorrell, 2007), but is also estimated to be as high as 60% (Gavanker and Geyer, 2010). *Income* and the *internal temperature* before energy efficiency improvements are carried out are all thought to contribute to the size of the rebound. Future trials should monitor energy consumption for sufficient time post insulation, to monitor changes in behaviour over time. Internal temperatures should also be measured for a sufficient period, before and after the intervention, to allow the potential relationships between internal temperatures and the size of any rebound effects to be measured. Currently, the lack of suitable research studies conducted at a large enough scale hampers the development of the sophisticated understanding likely to be necessary to inform the design of successful retrofit programmes.

As well as rebound effects, *prebound effect* and *behavioural spillover* are also factors which are likely to contribute to the difference between the predicted and actual energy savings achieved, but research is needed to explore this further. The prebound effect is found when the actual energy use in the homes, prior to the installation of insulation, is lower than modelled or predicted. Energy efficiency improvements cannot save energy that is not being consumed in the first place; therefore the expected savings are overestimated. Research suggests that the worse a home is thermally, the more economically the occupants tend to behave with respect to their space heating. Low efficiency and low consumption go hand in hand, as do high efficiency and high consumption. Therefore this overestimation of the consumption prior to insulation is likely to be greater for more inefficient homes.

It is suggested that energy efficiency policies need to work collaboratively with policies aimed at eradicating fuel poverty, since it can be argued that the causes of the prebound effect should not be isolated from the energy efficiency policies. We recommend that the field trial proposed under this project should look at the differences between the predicted energy consumption prior to the installation of the wall insulation as well as after, so that any prebound effect can be quantified reliably.

Behavioural spill-over occurs when performing certain pro-environmental behaviours can have a knock-on (or 'catalyst') effect, which leads to the adoption of a broader range of other pro-environmental behaviours. Research suggests that having refurbishment work carried out could strengthen a pro-environmental identity and thereby increase the likelihood that these people will adopt other pro-environmental behaviours. However, research by DEFRA (2011) suggests that there is no clear catalyst behaviour or behaviours that can be relied upon to lead to the uptake of multiple pro-environmental behaviours. Research also suggests that these effects are likely to be observed in only a relatively small number of cases.

3.7 Recommendations for future field trials

Based on the findings of the previous research covered in this section, the following recommendations are made for the forthcoming field trial:

- Energy consumption should be monitored for a whole heating season before and after the homes are insulated to ensure fair and meaningful comparisons can be made. This time period would enable to team to monitor changes in behaviour over time and allow any observed changes to settle and stabilise.
- The sample should include a number of control properties which are not insulated. This should ensure confounding variables are controlled for and that any differences in energy consumption pre- and post-insulation can be more confidently attributed to the installation of insulation.
- The trial should assess 'shortfall', 'temperature take back' and 'behavioural change' by: empirically comparing actual energy consumption and the expected energy consumption (both pre and post insulating), monitoring the mean internal temperatures both pre and post insulation for a whole heating season, and assessing changes in energy use behaviour post insulation.
- In order to quantify the size of any rebound effect associated with changes in occupant behaviour, the trial will need to measure all other factors which could account for any measured changes in consumption post insulation.
- The trial should (as far as possible) collect data on:
    - Thermostat set points
    - Use of space heating
    - Occupant thermal comfort
    - Individual activity levels and amounts of clothing
    - Mean temperature and humidity across the house
    - Household income and demographics
    - The cost of fuel
    - Heating regimes
    - Occupant energy use behaviour
- The trial should examine the size of any prebound effects, measuring actual energy consumption prior to the installation and comparing this with the estimated energy consumption.
- Researchers should look for any evidence of positive or negative spillover effects that result from the insulation of the homes.

4 Unintended consequences of solid wall insulation[15]

This section presents a literature review on the topic of solid wall insulation (SWI) and 'unintended consequences'. A broad range of unintended consequences are considered; however, the review focuses mainly on moisture-related problems and the summer overheating risk. Internal wall insulation (IWI), external wall insulation (EWI), and insulation of hard to treat cavities are included in the review.

4.1 Thermal performance

Thermal bridges, air tightness, thermal mass, and placement and distribution of insulation within the wall build-up are important aspects of thermal performance relevant to SWI, and these are all areas that will make up the key findings and learning from this project, in particular the un-intended consequences of undertaking them incorrectly.

Thermal bridging is a critically important phenomenon with impacts on heat transfer and temperature gradients. Recent work has highlighted the effect of not minimising cold bridging. It indicates an elevated risk of condensation and mould growth if not addressed. Guidance on minimising thermal bridging can be found in documents such as Ward (2006), which provides guidance on the assessment of thermal bridges at junctions and openings and their impact on heat transfer, and on numerical modelling techniques and assessment techniques for the prediction of conditions which pose a risk of surface and interstitial condensation; and in DEFRA (2001) which provides useful guidance on detailing for reduction of thermal bridging as well as air leakage. Thermal bridging and penetrations become nearly unavoidable in IWI systems (Al-Homoud 2005); however there is universal agreement on the importance of minimising their occurrences. This area, however, has had little consideration when undertaking refurbishment due to the complexity of assessing the impact correctly.

The effect of thermal mass in buildings is a well-understood phenomenon, but little documented evidence is available on the risks of decoupling this mass by the introduction of internal wall insulation. This phenomenon will need to be considered in the project with guidance produced on possible risks and alleviation strategies. Reviews of knowledge on this topic include Al-Homoud (2005) and Barnard *et al* (2001), which describes the functions of thermal mass in a building as well as best practice guidelines for modelling its performance. Thermal mass significantly reduces diurnal temperature swings when coupled to indoor air (English Heritage 2011; Energy Saving Trust 2010; Gupta and Gregg 2012). In typical temperature cycles only the first 100mm depth of a dense material absorbs ambient heat (English Heritage 2011).

The effect on performance of placing insulation on the inside or outside of a wall (or middle) has been examined by a number of authors in recent years (e.g. Al-Homoud 2005). Stazi *et al* (2013) examined the performances of three traditional wall constructions (1940s to 1980s) in an Italian temperate climate: solid brick ('capacity' type), unfilled brick-block cavity wall ('stratification' type) and unfilled brick cavity wall with 5cm EWI ('resistance' type). Using dynamic parametric analyses facilitated by the modelling software EnergyPlus and CFD Fluent, the authors demonstrate significant variation in the performance of the three envelopes. They conclude that, in summer, the 'capacity' and 'resistance' strategies behaved better than the 'stratification' model. During winter, the 'resistance' strategy outperformed the other models. Their work also indicates that higher levels of insulation coupled with high thermal mass in this climatic

[15] Principal authors: Timothy Forman and Christopher Tweed (Cardiff University).

condition may lead to overheating; however, results suggest that this might be resolved by adopting a ventilated EWI system.

Al-Sanea and Zedan (2011) studied the dynamic thermal characteristics of insulated walls to determine optimum insulation thickness and distribution under steady conditions using Riyadh climate data. Simulating insulation of walls with identical thermal mass (either 200mm-thick heavy-weight hollow concrete block, or two 100mm-thick layers of the same material), the authors examined the use of one, two, and three layers of insulation in varied configurations (all configurations with the same u-value). They determined that the best overall performance was obtained using three layers of 26mm insulation placed at the inside, middle, and outside of the wall. Differences in performance were significant: this insulation configuration produced a time lag for peak energy transmission that was approximately 100% greater than the configuration with the shortest time lag (approximately 12 hours versus six hours). The configuration with the shortest time lag was a 200mm construction insulated with 78mm insulation placed on the inside face. This variation in time lag can be attributed to the difference in thermal mass which is coupled to the indoor and outdoor climates in each configuration.

Kossecka and Kosny (2002) produced similar work for six different US climatic zones, in which they modelled the influence of insulation configurations on massive exterior envelope components which were comprised of heavyweight concrete layers totalling 152mm. The authors conclude that the optimum thermal performance was obtained in all conditions when massive materials are directly exposed to the interior space. This finding is key to the principles of external wall insulation, indicating that the placement of the insulating material is fundamentally more efficient when situated externally. Differences in thermal performance were shown to be significant across all six climates. This project should seek to confirm that this principle is relevant to the UK climate.

Bojic and Loveday (1997) and Ozel and Pihtili (2007) also investigated the impact of insulation distribution. Bojic and Loveday (1997) modelled three-layered constructions using UK climate data while Ozel and Pihtili (2007) modelled the distribution of insulation in walls with various orientations using climate data for Turkey. Bojic and Loveday tried out variations of insulation thickness and distribution in 'insulation/masonry/insulation' and 'masonry/insulation/masonry' configurations; the authors determined that for intermittent heating, the 'insulation/masonry/insulation' configuration saved 32% more energy than the alternative configuration. The opposite effect was found for intermittent cooling, underscoring the reduced thermal lag of insulated inner surfaces as compared to exposed thermal mass. Ozel and Pihtili determined that the time lag and decrement factor were optimal in a configuration of three equal insulation pieces placed at the internal, middle, and external of the wall. The worst performance for two layers of insulation was found for an IWI configuration, while the best was found for a middle and external configuration. The research suggests that EWI may have better performance than IWI in terms of time lag and decrement under the modelled conditions. Al-Homoud (2005) agrees, arguing that winter passive solar heating and summer convective cooling are facilitated by positioning insulation to the exterior of thermal mass; however he suggests this may lower durability by exposing insulation to the damaging effects of the outdoor climate. If adopted in the UK, this would result in a significant shift away from common practice. The lowering of durability is a factor which will need to be investigated, as there is evidence that certain acrylic finishes have not delivered a long term durable solution in the UK, resulting in moisture and water ingress into the insulation layer. This can result in drop in effectiveness of the insulation layers of particular materials, mineral wool being one in particular.

Much of the research in this area is based on modelling studies. There is a need for more field work in this area to check the underlying assumptions of the models. The proposed project should include the collection of new primary data and detailed analysis so that the thermal performance of solid walls can be better understood.

4.2 Durability and robust detailing

Stazi *et al* (2009) and Künzel *et al* (2006) investigated the durability and performance of EWI systems over time. In Stazi *et al* (2009), the thermal and hygrothermal performances of a 20-year old EWI system (40mm expanded polystyrene) were analysed using monitoring and laboratory tests, simulations and parametric analysis. The results demonstrated the efficacy and durability of the system, as well as its mechanical integrity. Cracks, peeling and flaking of the surface finish were reported to correspond to the joints between insulation panels, possibly due to overheating and differential temperature dilations. This damage was greater on the south face of the building. The durability of materials and finishes are a key part of this project when considering un-intended consequences. It points to the necessity of good detailing and a sound understanding being required when choosing insulation systems.

Künzel *et al* (2006) studied a substantial number of multi-storey EWI installations in Germany close to the Bavarian Alps, with relatively severe temperature fluctuations and wind-driven rain. The installations were inspected several times, starting in 1975.

The inspections demonstrated the following:

- Damage or degradation was no more frequent than for conventional rendered masonry walls
- Systems were slightly more susceptible to microbial growth due to rain or condensation
- Costs and maintenance frequency for EWI systems were comparable to those for traditional walls

Noteworthy disadvantages of SWI include less robust interior and exterior surfaces (both IWI and EWI), and vulnerabilities to moisture ingress (EWI). King and Weeks (2010) recommend that insulation and render be regularly checked as part of a maintenance cycle. There is little data to suggest that this is currently undertaken, whether the walls are insulated or not. Energy Solutions (no date) in a summary of knowledge about SWI installation, note the risk of impact damage to EWI, which it suggests may be mitigated by thickening the render at ground level. This principle will need to be considered in this project with particular attention to the risks in high traffic areas such as common areas and entrances. The Energy Saving Trust (2006b) suggests that, to minimise the risk of damage, reinforcement is provided for wet render or dry systems in vulnerable areas (ground floor, near entrances and vehicle access). It also suggests that surfaces can be easily over-painted in the event of graffiti damage. The author notes that dry finish systems with smoother surfaces tend to require less maintenance than wet systems (selection of systems might take into account factors such as orientation and exposure, and the risk of algal growth or staining from general air pollution or specifically from flues or fan outlets).

Recent research on EWI of masonry and wood-framed walls which was funded by the US DOE presents an in-depth review of engineering challenges in EWI (Baker 2013). The report highlights the advantages of improved water management and airtightness which EWI can provide. It argues, however, that the engineering evidence for these advantages is not yet clear enough for streamlined acceptance by (USA) building control. It also highlights the need for more thorough integration of water management and integrations of building components such as windows, doors, decks, and roof-wall intersections. Research conducted by the Building Science Corporation reported in this document aimed to develop baseline analysis to address these gaps. In addition to water management details, the research also addressed wind load resistance capacities, as well as movement and deflection tolerances. Many of the risks of EWI described in this report are familiar from other pieces of similar research. An example is the risk posed by brittle and cracked claddings allowing moisture ingress. The author notes that further research is needed around many topics related to water detailing as well as deflection movement (particularly of heavier claddings in exposed environments). The research produced a range of solutions for attaching thick layers of EWI, as well as detailing around elements and water management. Nevertheless, the challenges addressed by the project call attention to the complexities of installing EWI in highly variable constructions where maintaining watertightness and appropriate vapour control can be challenging. This area of work is one that will need further research, with particular attention being paid to the robustness of industry “standard details”. There is anecdotal evidence of an overreliance on mastic sealant. If this kind of detailing work is not undertaken in appropriate climatic conditions, and with the right level of care, the seal can be compromised resulting in the ingress of moisture behind the insulation layer.

4.3 Overheating

Overheating – particularly during summer high temperatures can be an unintended consequence of installing SWI. A large body of recent research has investigated SWI and the overheating risk in the context of climate change. This is covered later in the chapter. A more general area of inquiry into the risks of SWI and overheating under current climate conditions is presented in this section.

Beizaee *et al* (2013) present what they note is one of the first national scale studies of summertime temperatures in English dwellings. Their research involved interviews and recordings of living room and bedroom temperatures in 207 homes across England during the (cool) summer of 2007. The authors report that mean temperatures during occupied hours in living rooms ranged from 18.9°C to 25.7°C, with an average across all homes of 21.8°C. Mean bedroom temperatures during occupied hours ranged from 18.7°C to 25.8°C and averaged 21.6°C across all homes. The authors call attention to extremes in recorded temperatures in living rooms and bedrooms of 30.3°C. Of note is the fact that bedrooms of homes built prior to 1919 were observed to be significantly cooler ($p < 0.05$). The living rooms of more modern flats were significantly warmer than the living rooms in the other dwelling types ($p < 0.05$). Solid stone walls were associated with cooler indoor summer temperatures. The authors noted potential weaknesses in the study including a small sample size, an unusually cool study period, and potential errors in monitoring or recording. Beizaee *et al* note that this paper builds on the work carried out by Lomas and Kane (2013) and complements that by Kelly *et al* (2012). An important difference from Lomas and Kane is that bedrooms built after 1980 were found to be significantly cooler. This may be due to different ambient temperatures during the research periods. Thus, while modelling studies suggest there is a higher risk of overheating in better insulated buildings, there is uncertainty about the precise impact of insulation levels on overheating risk. As noted above, the role of thermal mass in mitigating the effects of solar gain will be important.

The data collected during the proposed field trial, conducted as part of this project, should significantly add to the body of evidence and provide a greater understanding of occupant comfort levels, heating requirements and typical internal temperature pre and post insulation. Monitoring the air infiltration rates, before and after insulating, will deliver a greater understanding of the possible causes of overheating, and will feed into the unintended consequences learning from the work. Subsequently this should feed into the assessment process of surveying for solid wall insulation suitability.

Other recent work includes Porritt *et al* (2012), who modelled IWI and EWI using EnergyPlus (with jEPlus) to investigate the effect of shading, insulation, and ventilation strategies in UK dwellings. Modelling included four orientations, end and mid-terrace houses, two occupancy profiles, and weather data from the 2003 heat wave; results were compared to monitored data. Interventions which reduce solar gains (including EWI) were shown to be effective at limiting heat gain. This quality is also reported by many other authors, e.g. Gupta and Gregg (2012), Oikonomou *et al* (2012), and by the Energy Saving Trust (2010), which recommends finishing external surfaces with high albedo finishes to reduce solar heat gain. IWI is shown as being less effective and is also correlated to potential overheating by Porritt *et al* (2012). Reduction of radiative cooling, retention of internal heat gains, and poor control of diurnal temperature swings are impacts of IWI discussed by many authors (the Energy Saving Trust, 2010; Porritt *et al* 2012).

The research of Porritt *et al* (2012) highlights the importance of orientation to the ‘IWI or EWI’ question. For instance, EWI on a west-facing living room wall had a much lower effect than on other orientations (20-22% fewer degree hours), while IWI on the same wall increased overheating (+21%) (see Figure 13).

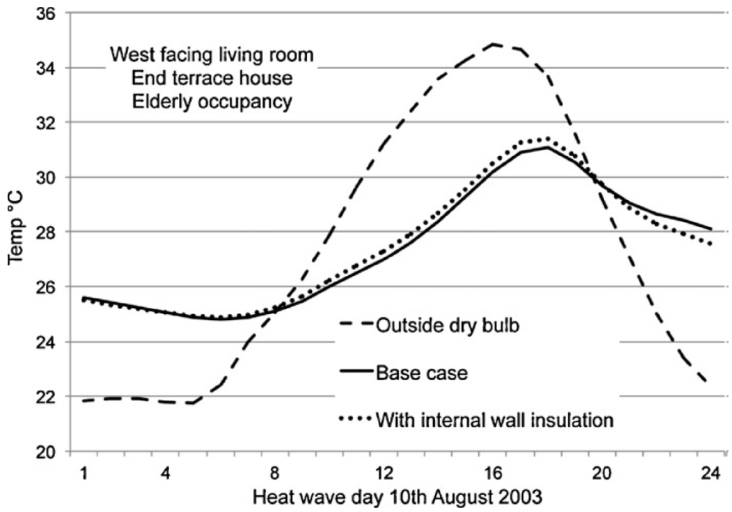

Figure 13: The effect of IWI on an end terrace living room (elderly occupancy) showing how it leads to an increased temperature during occupied hours (Porritt et al 2012, p. 24)

Research by CIBSE (Hacker *et al* 2005), based on modelling and case study analysis, compared a 19th-century house with a new-build medium weight house, as well as with flats, and concluded that higher standards of insulation and lower infiltration rates can be either advantageous or disadvantageous depending on the time of day, which part of the dwelling is being considered, and ventilation strategy. Insulation is noted by the authors as being a 'double-edged sword'. While it can prevent heat loss from a building, it can also potentially increase the overheating risk. Nevertheless, insulation serves an important function in reducing unwanted conductive heat gain through the envelope during warm periods. They found that, where solar shading and ventilation control had been employed, the new-build flat outperformed the others at higher temperatures. This suggests that, above the 28 °C threshold, the higher insulation and airtightness of the flat were of benefit. Oikonomou *et al* (2012) report modelling that indicated that very high or very low insulation standards were most prone to overheating.

The research by CIBSE (Hacker *et al* 2005), also showed that for modelled houses, significant improvements of thermal performance in living-rooms were typically linked to the degree of thermal mass present in a construction. In bedrooms, however, lower mass houses provided the benefit of responding quickly to cool night air. The advantages of thermal mass can be optimised by maximising exposed surface area (English Heritage, 2011). By providing thermal mass (materials with high specific heat capacity) where IWI is installed, (e.g. plastered internal walls, concrete, stone, or clay floors), overheating can be limited. Cross-ventilation and night time purging will encourage heat exchange with thermal mass. (Energy Saving Trust 2010; Hacker *et al* 2005; Gupta and Gregg 2012; Orme *et al* 2003).

Control of heat gains through air tightness (inflow) and ventilation (outflow) is critical to controlling overheating (Energy Saving Trust, 2010; Hacker *et al* 2005). The forthcoming field trial should look at the effect insulating properties has on ventilation and infiltration. A growing body of evidence indicates that ventilation is rarely considered in the assessment stage of considering whether to insulate a property or not.

Recent research released by De Montfort University provides some guidance and a simple tool to provide guidance for reducing the risk of overheating in buildings that are to receive EWI (Porritt *et al* 2011).

They modelled four building types using the tool: 19th century terraced, 1930s semi-detached, 1960s flats, modern detached. The tool presents the effect in bar chart form (in degree hours over 28 degrees) on occupied period overheating of the selected single adaptations (1 of 13 listed below), compared to the unadapted (or base case) dwellings. Two occupancy profiles (daytime occupied and daytime unoccupied) and four orientations can be selected. Overheating can be viewed for the living-room, main bedroom, or both combined (total overheating exposure).

Adaptations assessed:

1. Internal blinds
2. External Shutters
3. Curtains
4. Low-e triple glazing
5. External fixed shading
6. Night ventilation
7. Window rules
8. Upgrade flat roof
9. Solar reflective roof
10. Solar reflective walls
11. External wall insulation
12. Internal wall insulation
13. Cavity wall insulation

The following results were gained from this modelling:

- External shutters are the single most effective intervention for most house types considered, typically resulting in 50% reduction of overheating exposure.
- The exception is the Victorian terraced houses with solid walls, where high-albedo walls or external insulation is often more effective. External insulation consistently outperforms internal insulation, though the latter could be effective as an element of combined adaptations.
- Of the building types studied, 1960s top-floor flats and 2007 detached houses (Tier 2) experience more than twice as much overheating as the other types. Their overheating exposure could not be eliminated using the passive measures tested as could be done for Tier 1 building types (ground-floor flats, terraced and semi-detached houses).
- It is possible to substantially reduce overheating and winter heating energy requirements of Tier 1 buildings at a moderate cost. The costs for retrofitting Tier 2 buildings could be many times higher.
- Overheating exposure can be significantly greater for residents who have to stay at home during the daytime, e.g. the elderly or infirm, who should not, where possible, be housed in the most vulnerable dwellings (Tier 2).

4.4 Climate change: impacts, risks, adaptation

It is widely agreed that climate change poses significant challenges to the built environment. SWI is likely to be affected by climate change in a number of ways, and this is certainly reflected in the growing body of research on this topic. The projections of climate change which are relevant to SWI are presented in this section, along with discussion of its potential impacts and the potential for compounding effects.

4.4.1 Projections and impacts

Likely effects of climate change in the UK include: increased mean temperature (winter and summer), changes in mean daily maximum temperature, changes in precipitation (annual, winter and summer means), and changes in annual mean precipitation (in river basins) (Jenkins *et al* 2009a and 2009b). Projections and assumptions for climate, population, housing patterns, emissions, behaviour, and consumption reduction measures, as well as the implications for SWI performance given various scenarios, can also be found in Hinnells *et al* (2007). De Wilde and Coley (2012) summarise challenges in research on climate change and the built environment, noting:

- Many rules and regulations related to buildings are based on historical climate data
- Existing performance metrics must be used carefully, taking into account human factors such as perception of thermal comfort
- There is a general need for more climate change impact studies addressing a wider range of building types/configurations as well as climate scenarios
- Building maintenance, renovation and repair have an impact on building performance as well as improving the adaptation of buildings to climate change.

De Wilde and Coley (2012) remind researchers to remain critical of the climate projections. They delineate several research gaps in the field:

- Understanding and management of the urban heat island effect
- Investigation of the implications of occupant behaviour
- Consideration of the implications for concepts of flexible and resilient building design, including addressing the concept of long lifetimes of buildings designed to be adaptable to a changing climate
- Innovation in systems such as HVAC, light, and ICT equipment
- Ranking of various mitigation and adaptation strategies.

Risks such as overheating, flooding, and reduced water availability are posed by climate change. Pelsmakers (2012) argues that the UK built environment is poorly suited to confront these risks. For instance, UK housing has few of the features to limit overheating found in Mediterranean traditions (e.g. small shuttered windows on south and west facing walls, exteriors painted white to reflect the heat, courtyards with vegetation and water to moderate the immediate environment). The report notes the importance of improving climate change adaptation.

Walsh *et al* (2007) report results of nine projects which came under ‘The Building Knowledge for a Changing Climate (BKCC)’ programme supported by EPSRC and UKCIP. The authors highlight the importance of understanding the vulnerabilities of engineering systems to make them more robust and resilient and argue that skilled analysis and judgement is not seen in widespread practice. Included in the BKCC programme was the ‘Engineering Historic Futures’ project which was led by Professor May Cassar of the Centre for Sustainable Heritage at the University College London (Cassar and Hawkings, 2007). This project set out to examine characteristics of wetting and drying of historic masonry walls (primarily those constructed of brick or sandstone). The project aimed to deliver a computer model capable of predicting drying time of these walls under varying climatic conditions. Investigation included case study existing buildings, laboratory tests and computer modelling. The authors argue for the importance of maintaining natural ventilation and humidity control measures in traditional constructions. Their research demonstrates that restricting natural ventilation rates can increase the moisture content of indoor air by up to 40%. The research also highlighted the importance of routine building maintenance for preventing moisture ingress (e.g. rainwater goods), and for the importance of protecting historic buildings by managing floods and flood damage. Like many other authors writing about traditional constructions, Cassar and Hawkings argue for the importance of considering the uniqueness of each building and its environment. They recognise that there is great complexity in developing models which are capable of accounting for variations including wind speed and direction, solar radiation, temperature, and wall construction.

Phillipson and Stirling (2004) suggest that with increased severity and frequency of flooding, buildings will need to be capable of being reoccupied more quickly and at lower cost, other documents such as Improving the Flood Performance of New Buildings[16] available on the DCLG website provides some insight into the resilience of particular construction materials which could be useful in the retrofit process. See also Wingfield. J., Bell, M. & Bowker, P. (2005) Improving the Flood Performance of New Buildings through Improved Materials, Methods and Details and the CIRIA[17] website for more information. Technology for rapidly drying buildings is already readily available; however, there has been little study of its use in the context of historic buildings and it may stress building fabric, irreversibly distort materials, lead to structural failure, or cryptocrystallisation[18] within masonry and salt efflorescence[19] (Walsh *et al* 2007).

Phillipson and Stirling (2004) note that traditional construction materials (e.g. concrete, brick, timber and metals) are likely to be susceptible to deterioration during periods of higher temperatures and with longer hotter periods. They may also be subject to new thermal movements as well as more movement in foundations (due to wetter winters, drier summers, and the direct effects of flooding). Such movement may reduce tightness to air, water, and vapour (Al-Homoud 2005) as well as lead to increased cracking in concrete, masonry and finishes (Phillipson and Stirling 2004). Frost damage might be reduced with increasing temperatures; on the other hand, higher levels of driving rain may lead to wetter materials which are more susceptible to frosts. Phillipson and Stirling (2004) also suggest that increased weather-tightness may be required due to more severe winter and rainfall. Resilience strategies such as choosing materials which are not damaged by immersion in flood waters are important considerations and are relevant to SWI (Energy Saving Trust 2010).

A failure to properly detail buildings for changes in climate and to properly assess the likely effects of increases in precipitation on the durability of finishes, could lead to a significant underperformance of insulation measures and early loss of performance and durability. The lack of availability of robust UK weather data is a key limitation in the assessment process for durability, condensation and mould risk. This will need to be prioritised should there be a shift in policy on condensation risk analysis from BS5250 which used EN13788 to EN15026

4.4.2 Climate change, urban heat island (UHI) and overheating

Using thermal simulations, Kershaw and Coley (2009) studied the response function of a large number of buildings in relation to predictions of future climate. Over 1000 combinations of future weather, architecture, ventilation strategy, ventilation type, thermal mass, glazing, U-value and building use were

[16] Improving the Flood Performance of New Buildings
http://www.planningportal.gov.uk/uploads/br/flood_performance.pdf

[17] http://www.ciria.org.uk/flooding/flood_performance.htm

[18] Cryptocrystallisation refers to the process of forming cryptocrystalline structures through crystallisation. These structures are microscopic in scale and can only be observed with the use of a polarizing microscope.

[19] Salt efflorescence (also known as bloom) refers to the deposit of salt crystals, most commonly following evaporation of water containing a hydrated or solvated salt. This typically results in a white powdery accretion on the surface of a building material, (a cosmetic problem and referred to as primary efflorescence), or in more severe cases may indicate structural weakness (secondary efflorescence).

studied. Results show that with more aggressive climate change scenarios, increasing numbers of buildings experience hours above >28°C. For instance, a modelled school does not overheat in the design summer year (e.g. baseline 1980s time slice); however, from the 2020s onwards, the school fails during summertime for all UKCIP02 emission scenarios studied and peaks at more than 40% of occupied hours >28°C in the 2080s. Other building variants show as much as >90% of occupied summer hours above 28°C by 2080.

The authors argue that the complexity of factors involved makes it difficult to discuss in any simple way the relative benefits of any particular building attribute or draw general conclusions about adaptation strategies. This opinion is echoed by Gupta and Gregg (2012). For instance one design might demonstrate little change in internal temperature related to small changes in external climate but it might show a much more significant response to greater changes, while a second design might demonstrate the opposite response. Kershaw and Coley (2009) argue that a single set of coefficients can describe the expected response of “any design to any reasonable amount of climate change. Further, these coefficients can be used to establish a definition of climate change resilience. Their argument suggests that these coefficients might provide a metric for use in building regulations and codes which would facilitate promotion of measures aimed at climate change adaptation.

De Wilde *et al* (2008) utilise a transient model of terraced houses using the EnergyPlus simulation to compare uncertainties in climate change prediction with a very large number of variations in thickness of construction materials, HVAC control settings and building occupancy patterns. The authors conclude that there are significant uncertainties in long-term thermal performance predictions (even of a simple house), with standard deviations of over 100%. They point to the need for deeper investigation of topics related to the variables used in the research; this point was later repeated in De Wilde and Coley (2012).

While most predictive study of the effect of climate change on the UK built environment has focused on archetypal cities such as London and Edinburgh, Gupta and Gregg (2012) examine housing in ‘typical’ suburban areas of England. They argue that these areas represent the majority of the English population. The risk of overheating and patterns of energy use are modelled using four house archetypes and a variety of retrofits, against weather predictions for future years using dynamic simulation software (IES). Suburban areas do not exhibit the urban heat island effect that compounds the problem of summertime overheating. Many of their outcomes are similar to those from other research. External insulation (i.e. exposed thermal mass) is found to outperform internal and cavity wall insulated homes. An example of the results produced in this research is shown in the figure below.

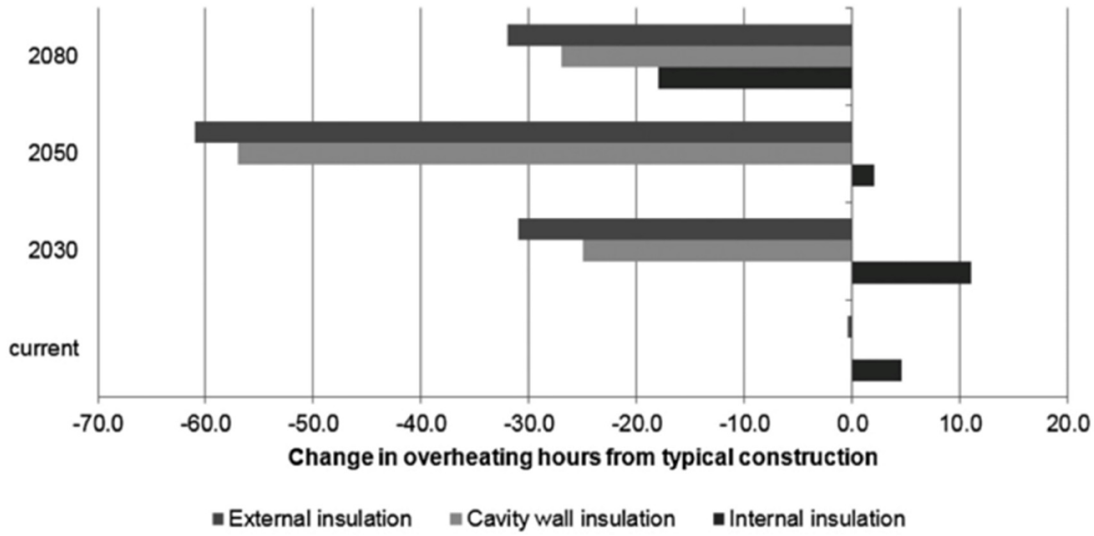

Figure 14: Differences in the effectiveness of insulation measures in reducing overheating hours for a detached house modelled by Gupta and Gregg (2012, p. 32)

In a subsequent publication (Gupta and Gregg 2013), the authors report on the use of a GPS-based model (DECoRuM-Adapt: Domestic Energy, Carbon Counting and Carbon Reduction Model). Looking at six house archetypes and using Bristol, Oxford, and Stockport data, the authors assessed the change in overheating in relation to adaptation packages through dynamic thermal simulation. Fabric alterations used in the model included wall insulation, shading, and high albedo surfaces. Insulation was found to decrease thermal transmittance of the envelope as well as (where applied externally) contributing to attenuating thermal swings and controlling heat loss through thermal mass.

Orme *et al* (2003) present results drawn from an APACHE(2) thermal analysis and regression analysis which demonstrate the sensitivity of various insulation measures to alternative climate scenarios. Although the study does not investigate SWI, it is of interest in its exploration of cavity insulation and overheating in homes. This work determined that, although the relative performance of different measures (e.g. shading, glazing or insulation) changes in response to different climate scenarios, the ranking of each insulation measure remains consistent. Their research also demonstrates that it is possible to achieve low annual heating demand while maintaining a high summer performance.

Peacock *et al* (2010) argue that high bedroom temperatures will be a significant problem under future climate change. Finding ways to alleviate these higher bedroom temperatures is an important part of a climate change adaptation strategy. The authors note that, in the Southern UK and for lightweight constructions, average internal temperatures were simulated at over 28°C for almost 12% of the year, even when a window-opening schedule was used. Applying a metric they define as ‘cooling nights’, they assert that there could be a cooling demand in bedroom areas for approximately one-third of the year. This problem diminishes significantly for (uninsulated) solid wall dwellings and at more northerly latitudes. In line with other research on this topic, the problem of overheating is largely relevant to more southerly latitudes of the UK and to lightweight constructions. Although the research does not examine SWI directly, the results suggest that positioning insulation to the inside of thermal mass was a contributing factor to overheating.

Porritt *et al* (2011) used dynamic thermal simulation (coupled to a nodal airflow model) to investigate the ability of late 19th century terraced houses in the UK to cope with future heat waves by adopting a range of mitigations including solar shading, insulation and ventilation strategies. Using a predicted weather year in the 2080s, the research found that overheating could be addressed by purely passive means. It determined that insulation was the most effective intervention for reducing overheating during occupied hours. EWI accounted for the greatest reductions and reduced the dry resultant temperature by as much as 1.4°C (Porritt *et al*, 2011) (see Table 9). This contrasts with the findings in many other similar works which show shading and albedo to be more effective strategies in relative terms.

Table 9: Ranking of reduction of degree hours by various single interventions. Results of research presented by Porritt et al (2011, p. 88)

Single intervention ranking.

Degree hours over CIBSE threshold temperatures (percentage reduction in brackets)							
Bedrooms summer		Bedrooms heat wave		Living rooms summer		Living rooms heat wave	
Ext wall insulation	244 (31%)	Ext wall insulation	53 (32%)	Ext shutters	73 (51%)	Ext wall insulation	28 (43%)
Ext shutters	245 (30%)	Ext shutters	61 (22%)	Ext wall insulation	83 (45%)	Ext shutters	33 (33%)
High albedo walls	259 (26%)	Int wall insulation	63 (19%)	High albedo walls	94 (37%)	Window rules	39 (20%)
Int wall insulation	282 (20%)	High albedo walls	65 (17%)	Night ventilation	113 (25%)	High albedo walls	40 (18%)
High albedo roof	305 (13%)	Int blinds	71 (9%)	Window rules	117 (22%)	Night ventilation	41 (16%)
Int blinds	310 (12%)	High albedo roof	71 (9%)	Int blinds	118 (21%)	Int wall insulation	42 (14%)
Window rules	311 (12%)	Window rules	72 (8%)	Int wall insulation	130 (13%)	Int blinds	43 (12%)
Ext shading	318 (10%)	Ext shading	73 (6%)	Low-e glazing	137 (9%)	Low-e glazing	46 (6%)
Night ventilation	335 (5%)	Night ventilation	75 (4%)	Ext shading	140 (7%)	Ext shading	47 (4%)
Loft insulation	344 (2%)	Low-e glazing	76 (3%)	High albedo roof	142 (5%)	High albedo roof	48 (2%)
Low-e glazing	346 (2%)	Loft insulation	77(1%)	Loft insulation	146 (3%)	Loft insulation	48 (2%)
Base case	352 (0%)	Base case	78 (0%)	Base case	150 (0%)	Base case	49 (0%)

Oikonomou *et al* (2012) assess variations in indoor temperatures in London dwellings during periods of high external temperature, and seek to explain variations in indoor temperature between dwellings by identifying thermal characteristics of buildings and exposure to the urban heat island effect (UHI). EnergyPlus simulation was used with input data of 15 notional dwelling types typical of London. Weather data was taken from the UKCIP 2002-2050 Medium-High Emissions Scenario. The authors found noteworthy variations in indoor temperatures across all dwelling types. A strong correlation was observed between daytime living-room and night-time bedroom temperatures. They also noted that the thermal 'quality' of dwellings had a greater effect on indoor temperature than the urban heat island effect. This study appears to be the first to discuss the relative importance of structural characteristics and UHI in overheating of London domestic stock. The authors suggest that more research is required to understand more fully the interaction of UHI and fabric retrofits, as well as UHI and climate change variations.

Similar work was carried out by Mavrogianni *et al* (2012), who used EnergyPlus to create dynamic thermal simulations of 3,456 combinations of dwelling types and characteristics representative of London domestic stock (the authors caution that the study should not be viewed as representative of the entire London stock). The research utilised two Design Summer Year weather files in order to represent present and future climate conditions. Weather files were taken from CIBSE 1984-2004 and UKCP09 50th percentile of external temperature 2050s medium emissions scenario. The research found a significant variation in overheating between dwelling types but noted a generally more pronounced influence of factors such as orientation, surrounding buildings, and insulation level. While, in general, insulation measures were shown to decrease internal temperature, IWI tended to increase overheating during warm periods when no night-time ventilation was provided. For instance, IWI was associated with an increase in daytime living-room temperatures (combined effect of 0.46°C increase in mean temperature and 0.71°C increase in maximum temperature).

The issues raised in this section need further detailed research to fully understand the effects of future climate change. Close investigation of the assumptions and predictions of the UKCP09 weather data is also needed, but the findings on placement of insulation do support the principle that external insulation is more beneficial when dealing with the risk of overheating and maximising the benefits of useful thermal mass. The influence of solar gain on u -values should also be examined as part of this project.

4.4.3 Climate change and health

Broad evidence indicates a positive effect on levels of mortality and (for certain population groups) hospital admissions during periods of abnormally high summer temperatures in the UK (Johnson *et al*, 2005). The importance of controlling indoor temperatures during heatwaves should be seen as significant. Modelling by the Hadley Centre predicts that by the 2040s a 2003-type summer is likely to be about average (Stott 2004, as cited by Kershaw and Coley 2009).

Hajat *et al* (2002) studied the relationship between heat and mortality in London between 1976 and 1996. Their research suggests that a rise in heat-related deaths during this period began at about 19°C. Average temperatures above the 97th centile value of 21.5°C (excluding those days from a 15 day "heatwave" period in 1976) resulted in an increase in deaths of 3.34% (95% CI 2.47% to 4.23%) per one degree increase in average temperature above 21.5°C.

These results suggest that heat-related deaths in London may begin at relatively low temperatures. Hot days occurring in the early part of any year may have a larger effect than those occurring later on; and analysis of separate heatwave periods suggests that episodes of long duration and of highest temperature have the greatest effect on mortality.

4.5 Damp and moisture

In instances of poor design or SWI system failure, water or vapour ingress can cause significant damage to the building fabric. The characterization of moisture 'behaviour' in buildings and materials is generally a well-understood topic and an expansive body of research has contributed to this understanding. It is, however, a highly complex topic and clearly the literature is continually evolving. This section presents a broad range of relevant aspects of knowledge and research. Moisture affects buildings in a variety of ways, including surface condensation, interstitial condensation, wind-driven rain, bulk moisture ingress, rising damp and risk of freeze-thaw damage and corrosion.

Detailing and design to control the ingress of moisture into buildings has been researched and written about for many years. Many of the principles can be found in technical publications produced for building professionals. One example is Thomas *et al* (1992). This pamphlet identifies the pathways of rising damp, rain penetration, condensation, and vapour build-up and describes the potential damage to buildings and occupant health. It also points out a number of practical considerations to bear in mind during refurbishments, such as the risks posed by inflexible sealants (e.g. cement mortar instead of lead flashing), leaking water supply pipes, or cracked modern renders. Sources of general information on how to manage condensation and moisture flows in buildings are abundant and include information pamphlets by organisations such as BRE, RICS and the Property Care Association.

Trotman *et al* (2004) produced a very substantial resource aimed at a wide range of professionals in the building design and construction industry. The book is primarily focused on protection against the effects of damp in existing buildings. It outlines the causes and effects of dampness, its identification and measurement, and includes wide-ranging strategies for dealing with rain penetration, surface and interstitial condensation, and rising damp. It gives a good description of various damp problems, many of which could be created or worsened by the installation of SWI, and suggests that, while the extent of problems such as 'reverse condensation' is unknown, they are likely to be common. Importantly, the authors highlight a variety of traditional design features which protect buildings from rain (e.g. large overhangs, external rendering, string courses), as well as a number of routes for penetration (e.g. cracked or detached rendering, pointing in poor condition, cracks or defects in sills, blocked throatings or rainwater goods, unprotected joints and openings around windows, doors, air bricks, etc.). They further suggest that inadequately designed or maintained watertightness features are commonly found in UK housing.

The issues identified in this section are key when quantifying the risks surrounding the introduction of external wall insulation. Problems with moisture paths, and increases in damp related solid wall insulation should form one of the main parts of any future categorisation of unintended consequences. There is a need for guidance on detailing and strategies for resisting rain and moisture ingress when installing external insulation systems.

De Freitas *et al* (1996) describe moisture transfer mechanisms in buildings as well as theoretical models for vapour and liquid movement. They also comprehensively review experimental and theoretical techniques which can be used to investigate moisture behaviour in buildings and materials. Although this research dates from the mid-1990s, it contributed several useful concepts including an enhanced understanding of the behaviour of moisture at the interface between layers of building fabric. The authors demonstrated that “gravity has no influence on the profiles of water content” in the materials they studied (p. 107), as well as verifying significant wetting of walls due solely to interstitial condensation (De Freitas *et al*, p.107).

4.5.1 Condensation

While condensation can cause immense damage in buildings, it is not necessarily problematic; for instance it can be managed successfully on the inner surface of the outer leaf of a cavity wall by the provision of detailing which will allow for its control. It can also be controlled by heating, ventilation, building layout and materials (BS 5250; Trotman 2004; BRE Digest 369). For instance, because IWI creates a ‘fast response’ structure, surface condensation is unlikely with adequate heating and ventilation. Conversely, because the thermal response of EWI walls is slow, a constant low-output heating is preferable (BS 5250).

BS 5250 (2011) states that interstitial condensation is unlikely if a system has low vapour resistance. In systems with high vapour resistance materials (e.g. cladding), a vapour control layer should be installed at the interior of the wall and/or a vented airspace should be installed on the immediate interior surface of the cladding. The standard outlines procedures for the calculation and prediction of condensation and high humidity, as well as information about their effects. It also presents a wide variety of design principles to enable successful control of condensation. Included in the standard are sections on IWI and EWI. Both EWI and IWI pose condensation risks, although IWI clearly poses higher risks. To help reduce the risk, thermal bridges should be minimised and temperature gradients maximised by taking steps such as returning insulation into reveals of openings and along abutting internal walls. Advice on reducing thermal bridges in this way (with CFD modelling to show its effectiveness) is due to be published later this year (Weeks, King, Ward et al, ' Reducing thermal bridging at junctions when designing and installing solid wall insulation' in press). Where their use is deemed appropriate, vapour controls should be returned into reveals and kept intact and unbridged. Vapour control barriers, however, can create a risk of ‘reverse condensation’ (outside to inside), and where this is deemed to be likely, a vented airspace should be provided to the cold side of the insulation; alternatively, low vapour resistance external surfaces can be applied. Good workmanship is important to controlling condensation; this requires on-site supervision and a concurrence between the designer’s intentions and the builder’s understanding of the work.

The use of Vapour Control Layers (VCL) has, however, been questioned and current research indicates that the introduction of a VCL can cause the build-up of toxic mould growth at the interface of the VPC and existing wall. This has the potential for backfill of moisture in the wall structure leading to an inflated risk of freeze thaw frost damage. Further detailed research on this area may offer a definitive view on the use of such VPC layers, as some industry views and those of the materials manufacturing industry are diametrically opposed.

Understanding of the fundamentals of condensation has existed for many years, and reasonably comprehensive guides having been available to the industry throughout this time. BRE *Digest 369* (Building Research Establishment 1992), for instance, provides readers with guides to principles, a calculation procedure and recommendations for design and material considerations. This work demonstrates that significant knowledge about hygrothermal behaviour of buildings (i.e. winter air temperature and vapour pressure in occupied buildings is generally higher than outside and so drives heat and water vapour outward) has been understood and widely available for more than a generation.

In CIC Start Online (2011) results from a CFD model developed in ANSYS Fluent 13.0 are compared to those from monitoring when investigating interstitial condensation in a sandstone wall before and after the installation of low-density, open-cell, water blown, polyurethane insulation (Icynene). The author found that, in those cases where interstitial condensation was present, it was present in both the insulated and the uninsulated models. A conclusion is made that "reasonable agreement" exists between the results of monitoring and modelling.

Wooden structure members are at particular risk from the installation of IWI due to their potential exposure to prolonged damp or wet conditions. Research by Morelli *et al* (2010) describes a solution developed with the use of 2D and 3D thermal simulation programs and coupled heat, air, and moisture transport models. Focussed on the problem of beam ends and driving rain, this paper proposes a solution that the authors claim would nearly halve the heat loss through a typical section compared with the original configuration. The authors note that increased condensation risk linked to IWI is compounded by its lowering of wall temperatures which reduces the drying potential. As in BS 5250 (2011), the authors note that vapour barriers can have the unintended consequence of reducing drying potential. The critical moisture content for fungi growth in wood is reported as 20% and for mould growth the critical relative humidity >80% - 90% (depending on temperature and duration). Using HEAT2 and HEAT3 software, as well as DELPHIN, the authors found that 3D calculations gave higher temperatures near the beam end compared to 2D calculations. They interpret this to mean that the drying potential is higher than what was calculated by 2D methods. Therefore, if 2D analysis provides results which are on the cusp of being problematic, then in reality construction should perform acceptably well. Finally, the authors call attention to the 'great importance' of including wind-driven rain loads in any analysis of moisture flows in constructions.

Stud and mineral wool IWI systems applied to solid brick walls were found to present a high risk of wintertime condensation and mould growth by Brandt *et al* (2012). These systems are generally highly vapour diffusive. As a consequence, they present exacerbated risks of condensation when coincident with highly absorbent bricks or leaking joints in the exterior wall, the presence of organic materials on the interior surface of the wall, or an incomplete vapour barrier at the inside face of the system.

Straube *et al* (2012) , on behalf of the US Department of Energy, ran simulations which highlighted uncertainty about the suitability of hygrothermal conditions within walls for embedded timber members. In light of this, they suggest in-situ measurements are made to verify temperature and moisture conditions before undertaking IWI. They suggest, however, that further research in this area is warranted (including the use of two-dimensional hygrothermal simulations).

The on-going discussion over the relevance and shortcomings of using BS5250, when compared to assumptions of standards that use an acceptance of the presence of moisture, and local weather data, should be explored through this project, as part of the analysis of unintended consequences.

4.5.2 Bulk moisture ingress and wind driven rain

The ingress of bulk moisture from external weather is a concern in any building and this becomes increasingly relevant when SWI is applied. Both internal and external insulation systems reduce the drying potential of walls and limit 'accidental' air flow which, in older constructions, is typically relied on for management of indoor humidity. Effective IWI design relies on exclusion of moisture ingress by the existing building envelope and in some instances the provision of mechanisms within the IWI system to 'control' ingress which occurs through walls or around vulnerable areas such as windows, doors or services penetrations. EWI typically relies on an uninterrupted barrier at the external surface of the system and effective detail design at all penetrations and vulnerable areas.

Wind-driven rain (WDR) refers to rain which has a degree of horizontal velocity as a result of the force of wind. Quantification of wind-driven rain is an area of research which began with R.E. Lacy in 1951. Precipitation wets horizontal and sloped surfaces, but WDR also humidifies vertical surfaces, which adds to the complexity of measuring and predicting its behaviour (Hens, 2010). Global evidence indicates that it can potentially be a damaging source of moisture in buildings. BS 8104 (2008) is a British Standard for assessing the exposure of walls to wind-driven rain.

A key review of WDR research was written by Blocken and Carmeliet (2004) in which experimental, semi-empirical and numerical methods of WDR quantification are discussed. This work presents a comprehensive summary of WDR research relevant to building science. Like other authors, Blocken and Carmeliet highlight that the interaction of WDR and buildings is difficult to analyse and for this reason numerical modelling is a logical method to employ. Field measurement research is reported as prone to very high levels of error (up to 100%). Semi-empirical methods – which combine weather station data for wind speed, wind direction and horizontal rain fall with theoretical assumptions that are approximately proportional to WDR – are capable of providing only rough estimates of the fall of WDR on building facades. Numerical modelling is clearly an attractive method to employ given the high rates of inaccuracy inherent in field measurement and semi-empirical methods. At the time of Blocken and Carmeliet's writing, computing power was considered to make this modelling an arduous and slow process. Nevertheless, validation studies which the authors reviewed suggested encouraging rates of success in this modelling.

Hens (2010) argues that computational fluid dynamics (CFD), which is the primary method of WDR prediction for designers, is still not yet capable of being fully useful; this follows from his comparison of three real-world cases with model results. This paper includes an overview of CFD calculations, which utilise windfield calculations and droplet trajectory tracing to calculate 'catch-ratio distributions' and include data on bouncing, splashing, evaporation and buffering of surfaces. Hens argues that several aspects of WDR behaviour are well understood: events that occur when a drop of rain hits a surface, how walls should be constructed in order to be rain-tight, and the effects of rain absorption on wall's thermal properties. He argues, however, that run-off is highly complex and cannot yet be addressed by models, and he draws several important conclusions which are useful in the design of buildings to resist WDR:

- the use of capillary active veneers is beneficial (provided that the inside leaf has a high moisture buffer capacity);
- it is important that trays are mounted and sealed in line with best practice;
- mortar debris should be kept out;
- the airtightness of the inside leaf should be designed and maintained with care;
- care should be given to ensuring that coping is airtight;
- oblique cavity walls with rain screens that are not watertight are problematic; and
- if veneers lack capillarity, run-off management is particularly important.

The importance of excluding rain is also highlighted by Künzel and Zirkelbach (2006), who studied temperature and moisture distributions in EWI assemblies on lightweight structures using the hygrothermal simulation model WUFI. The authors report that the modelling shows the assemblies pose no moisture related problems in the cold and moderate climates which were studied. They point out that the results were dependent on rainwater being completely excluded; the assemblies fail where the North American Standard (ASHRAE 160) assumption of 1% penetration of driving rain is adopted. Künzel and Kießl (1996) conducted research on sealing bricks by siloxane impregnation by comparing their moisture behaviour with untreated bricks (with and without cracks) on exposed as well as sheltered facades. The authors found that, in all cases, impregnation of exposed bricks with elevated moisture led to more thorough drying, although the drying of a 24 cm thick wall element took about one year. The authors note that the drying time of a wet wall impregnated with siloxane treatment ranges from two to seven years.

4.5.3 Vapour and 'breathability'

Kingspan Insulation (2009) argues for the importance of providing adequate ventilation in buildings. The Kingspan paper rejects claims made about the importance of 'breathable' construction and breathable insulation, based on evidence from research it commissioned from Cambridge Architectural Research, Ltd*.* Kingspan acknowledges that if air-borne moisture in a building is allowed to remain, it may lead to surface condensation, mould growth and exacerbated house dust mite populations*.* It argues, however, that moisture is transported by vapour diffusion through the building elements ('breathability') and by bulk air exchange (intentional ventilation plus air leakage)*.* It asserts that 95-96.7% of vapour transfer from a house with 'breathable walls' occurs through ventilation; bulk air exchange, it claims, is at least 19 times more important in controlling moisture problems than 'breathability'*.* It states that vapour diffusion does not contribute significantly to the rate of vapour transfer from a house and calls breathability a "red herring" in the avoidance of surface condensation, mould growth, and dust mite populations.

May (2009) argues against many of these points put forward by Kingspan Insulation (2009) and notes that 'breathability' was established by the historic building sector to describe not just vapour permeability but also 'hygroscopicity' (how a material absorbs and desorbs water vapour in relation to relative humidity) and 'capillarity' (how a material absorbs liquid water)*.* He reports modelling of EWI on masonry that generally shows few problems with moisture until higher levels or rainfall are simulated (+5% in London or +3% in Swansea). He reports that porous wood fibre insulation systems do not accumulate moisture in this modelling while PU (polyurethane foam) and EPS (expanded polystyrene) systems do*.* Highlighting the potential for damage caused by residual moisture, May argues for the importance of the qualities of natural insulation materials*.* He asserts that most 'standard non-breathable' systems are modelled based on a homogenous section, without the inclusion of wall or floor junctions*.* In reality, he argues these junctions are highly vulnerable to vapour entry*.* In light of this, he argues for the use of 'breathable' constructions*.* He also asserts that breathability also allows 'hygroscopic buffering' (the capacity of a material to absorb and desorb moisture as ambient relative humidity changes), which can reduce levels of relative humidity in buildings (citing Svennberg, K. *et al*, 2007).

Research on the control of vapour in walls has been on-going for many years. Karagiozis and Kumaran (1997) present relatively early modelling predictions using the LATENITE model developed at IRCINRCC, a transient 2-D and 3-D model*.* This model was employed to numerically solve heat, air and moisture transport through various EWI systems*.* This study investigated three vapour control strategies in one climatic location, but newer research has drawn on more powerful models to investigate more complex scenarios of materials, construction, and weather conditions.

Karamanos *et al* (2008) investigate the performance of stone wool insulation under varying temperature and humidity conditions through modelling as well as long-term laboratory experiments*.* Their data show a significant increase in thermal conductivity due to vapour condensation in the insulation, nearly to values expected of masonry materials (practically of no insulation value)*.* The authors point out, however, that although humidity will inevitably penetrate most installations of stone wool, this does not pose a significant problem as long as the construction enables sufficient aspiration to allow the material to dry*.* The authors suggest that the 'real point of danger' is using highly vapour-resistant outer layers in constructions, such as those paints and plasters that might trap moisture*.* This issue should be examined as part of this project. The use of acrylic finishes is widespread in current industry practice, and an area where clearer guidance and information is required to enable better informed decisions to be made.

Toman *et al* (2009) present research that assessed the in-situ hygroscopic and thermal performance of a mineral wool IWI system sited in a late 19th century brick building in the Czech Republic*.* IWI was applied without a vapour barrier, but with a lime-cement vapour retarder[20] between insulation and brick wall*.* Hygrothermal testing and study was conducted over a four year period*.* The authors note a 'very good' level of hygrothermal performance with no condensation observed during this time*.* In comparing their

[20] A vapour retarder differs from a vapour barrier in that it allows some moisture movement rather than attempting to block it all.

work to a prior experiment, the authors suggest that their work benefited from application of the insulation during the summer months when the wall was drier than it would have been in winter.

Moisture transmittance of wall elements is affected by the hydraulic properties of all component materials. For instance, gypsum plaster is a material which possesses varying moisture transport and thermal characteristics (Wang, 2011).

Work presented by Künzel and Zirkelbach (2006), which investigated external insulation systems on light-weight structures in North American using WUFI software, found that well-detailed systems presented no moisture problem to buildings in cold and moderate climates. Conversely, poor detailing may lead to problems; this research is also relevant to the use of EWI in solid stone or masonry walls. The research found that EPS slabs cannot provide significant drying toward the exterior and the authors note that their use may pose a risk of moisture damage to the building fabric. They recommend the installation of a humidity controlled vapour retarder at the inside of the building, instead of the conventionally employed polyethylene film, in order to allow some vapour diffusion toward the interior of the wall. They note, however, that a significant temperature differential between inside and outside is required for this mechanism to compensate for moisture loads such as small rain ingress, suggesting that this solution is best used in warmer locations. Other suggestions include using high density mineral wool slabs instead of EPS or the provision of drainage between insulation and wall.

Pavlík and Černý (2008) present a laboratory technique to simulate on-site conditions that can be used for the assessment of hygrothermal performance of building envelopes. An IWI mineral wool system is applied to two common structural types and exposed to a range of climate conditions. Monitoring and experimental results demonstrate satisfactory hygrothermal behaviours, with both envelopes remaining dry during the most critical climate variations. The research points to the critical role played by the vapour retarder and the authors note that retarders used in similar systems must have a sufficiently high vapour diffusion resistance factor in order to protect the systems from condensation risk.

The issues raised here surrounding the condition of the building fabric prior to insulation is particularly relevant for this project, as there is little evidence that the condition of the existing structure is examined in any great depth when considering external wall insulation. This research indicates that the presence of damp or wet sub strata can compromise the performance of the insulation, and this moisture may never evaporate if isolated from the effect of the sun, subsequently the moisture may then track towards the internal face of the building resulting in damp forming.

4.5.4 Rising damp

There are several routes by which moisture can enter a SWI system, and one of these is rising damp. Ingress of moisture into building walls (through rising damp or any other route) is of particular concern where SWI is being installed due to the reduction of drying potential effected by installation. Both EWI and IWI reduce vapour diffusivity of wall assemblies, and IWI further reduces drying potential since it leads to lower wall temperatures in winter (due to decoupling the wall from the heated indoor space). The risk of rising damp and control measures should therefore be assessed when considering the suitability of SWI in properties. Many authors have written on its diagnosis and treatment in both peer-reviewed and grey literature. A useful review is BRE Digest 245 (Trotman 2007). This guide notes that walls built with stone, bricks, blocks and mortar are porous and that the diameter and distribution of pores is highly variable. The porous structure enables rising damp where a source of moisture is present in the ground and no membrane (or damp-proof course) exists to impede its flow via capillary action. Smaller diameters of pores in wall support greater heights of rising damp. Trotman states that, in old walls with pores as small as 0.001 mm in diameter, a column of water “far higher” than one metre can be supported. Other factors in play include the rate of evaporation from the wall (influenced by indoor and outdoor climate), salts (both in the soil and in the building materials), the degree of saturation in the soil, and the use of heating in the property. One suggested measure is improving the soil drainage around a building. This area is one that requires further research to fully understand the effects of rising damp in older buildings, especially the phenomena of water being able to rise to heights of greater than 1m, which is the accepted norm of capillary actions.

4.5.5 Freeze-thaw and corrosion risk

Straube (2009) investigates the risks of freeze-thaw damage (as well as corrosion of embedded steel components, mould growth and deterioration risks) associated with IWI in cold climates. He instrumented a large-scale mock-up of a school building in Ontario with measurement and monitoring devices in order to allow comparisons between insulated and non-insulated walls. During the study period, climate conditions were less severe than average so Straube used computer models (WUFI) to simulate wall performance under more severe conditions. The study found a low risk of freeze-thaw damage correlated to IWI, but an increased risk of steel corrosion. The author notes the relatively limited scope of the study. Recommendations of the study include avoidance of excessive wetting of walls (maintenance of pointing, effective detailing, etc.), and the inspection of embedded steel prior to IWI installation (to determine the function, extent and condition, and protection of components).

In 'Assessing the freeze-thaw resistance of clay brick for interior insulation retrofit projects', Mensinga *et al* (2010) outline the use of a frost dilatometry[21] method. They argue that 2D and 1D hygrothermal models are not well suited to assessing freeze thaw problems, and that typical physical tests do not adequately represent real exposures. The authors summarise limitations of the various approaches which have been used to test freeze thaw resistance and present an alternative method to determining the critical degree of saturation of bricks. Their conclusions indicate that if the moisture contents predicted before and after retrofit are both below the critical degree of saturation of the brick during freezing events, the design can be considered safe, even if the brick does not meet the modern American and Canadian authorities pass/fail standards. . The authors report that this method is relatively simple and quick (6-12 days to complete) and highly accurate. The full findings were presented in 2010[22] at the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference, in Clearwater, Florida.

BRE Report 466 (Trotman *et al* 2004) suggests that IWI may be advantageous because the insulation is isolated from driving rain. This point, however, is contrasted by global evidence which shows that IWI cools the temperature of walls, hence making walls less able to dry out between wetting periods and more prone to freeze-thaw damage.

Hygrothermal modelling

The Glaser method (see BS EN ISO 13788-2012) – commonly referred to as the 'dew-point method'— has been used since the late 1950s as a means of calculating vapour pressure difference in building envelopes. It was originally developed to evaluate interstitial condensation on freezer walls (Glaser 1959). The method states that condensation occurs on or within layers where vapour pressure exceeds saturation pressure at a given temperature (i.e. 'dew point temperature'). It is based on three equations: a balance equation of heat, a balance equation of liquid water, and a steady-state diffusion equation.

In this method, transport of heat is independent of moisture. Several basic assumptions are made in the method, which include the following (Vydra, 2007, p.344):

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[21] The measurement of changes in the volume of a liquid or dimensions of a solid which occur in phenomena such as allotropic transformations, thermal expansion, compression, creep, or magnetostriction.

[22] Assessing the Freeze-Thaw Resistance of Clay Brick for Interior Insulation Retrofit Projects

Conference Paper- 1013

- thermal and moist transports are independent, one-dimensional and steady state;
- moisture is transported purely by vapour diffusion according to Fick's law;
- heat is transported exclusively by heat conduction according to Fourier's law;
- there is no sorption and no migration of liquid water in the wall; and
- liquid moisture in the wall is due to condensation of water vapour, which takes place on interstitial surfaces where water vapour pressure is equal to saturated vapour pressure or higher.

Sanders (2005) argues that the assumptions in Glaser models can be simplistic and include the following:

- water vapour generated inside a building in winter raises the internal vapour pressure above external conditions (in warm humid climates, air-conditioned buildings will have a vapour gradient from inside to out);
- all materials are dry until relative humidity reaches 100% (predicted by the relationship between vapour pressure and temperature) and condensation deposits liquid water;
- diffusion processes are slow;
- vapour transport is one-dimensional;
- most building materials contain significant quantities of water;
- pores in a material absorb water at an increasing rate as humidity rises and desorb water as it falls (condensation is not instantaneous);
- driving forces of moisture movement vary on short timescales; and
- ventilation can remove water vapour quickly from a structural cavity.

The author reviews modelling programs including BRECON, MATCH, WUFI, and ICOND, and argues that Glaser calculations will typically overestimate the risk of problems in heavy-weight structures where the materials are initially dry and do not account for water stored in materials in massive structures. Further critiques can be found in Hens (2002), studies by Historic Scotland, STBA and SPAB (Baker 2011; Rye 2010; Rye and May 2012; Rye and Hubbard 2012; Rye and Scott 2012; May 2012b). May and Rye (2012) argue that the Glaser method is limited because it does not cover groundwater, precipitation, built-in moisture and moisture conventions. They conclude that even BS EN 15026, as a standard for hygrothermal analysis could be limited because the complexities of hygrothermal behaviour are not fully understood (May and Rye 2012; Browne 2012).

BS EN ISO 13788 (2012) responds to the knowledge that moisture transfer is complex and that in practice, understanding of material properties, boundary conditions, and moisture transfer mechanisms can be limited. This standard provides simplified calculation methods based on assumptions that moisture transport occurs solely by vapour diffusion alone and the use of monthly climate data. The standard is not intended to supplant the use of more advanced methods, rather it takes a simplified though cautious approach to prediction. The standard addresses critical surface humidity, interstitial condensation, drying times and drying 'behaviours' of building components. The author echoes many critiques of the Glaser method and acknowledges a variety of limitations including that it is likely to be less reliable for application to structures with large thermal mass or moisture capacity.

Nevertheless, the method is by far the most common tool used to assess moisture balance in buildings. It is widely agreed that this method has limitations, yet it remains a principal method by which moisture response is predicted. It is used today in several common models and u-value calculators, including Build Desk Energy, IES-ve, Hevacomp, and JPA Designer (McLeod and Hopfe, 2013). Recent additions to the method include incorporating capillary action and a wider range of indoor and outdoor boundary conditions (Hens 2012, cited by McLeod and Hopfe 2013).

McLeod and Hopfe (2013) argue that over-simplification of modelling of physical phenomena commonly leads to substantial errors in building design and assessment. Their research is concerned with steady-state versus dynamic modelling of hygrothermal behaviour. They argue that the simplified steady-state assumptions of the Glaser method cannot be relied on. Instead, dynamic simulation tools that can account for thermal and hygroscopic inertia (i.e. sorption and desorption), movement of moisture through capillaries, and non-homogenous material properties – as well as considerations such as wind driven rain effects and building moisture sources – are more likely to produce reliable predictions. The authors assert that the Glaser method does not allow for the transient nature of boundary conditions to be accounted for and hence is only useful for structures where this transience is negligible. Energy Solutions (no date.) agrees with this point of view and recommends that SWI installation never be assessed with the Glaser method but rather through hygrothermal simulation in line with the BS EN 15026 standard.

In support of their argument, the authors review several pieces of recent research including that by May (2009) already mentioned, in which three different wall constructions with similar u-values were modelled in two different climate zones. In the more moderate climate of London, conventional insulation materials such as PU foam are shown to have a rising moisture content and failure point of two years. Meanwhile, the same constructions modelled in Swansea with severe driving rain were predicted to fail within the first 9 months. McLeod and Hopfe (2013) also examine Hens' work (2012) and agree with his argument that limitations of dynamic modelling still exist, particularly with regard to data and input sources. For instance, non-homogeneity in building materials makes it difficult to avoid uncertainty in modelling parameters. They cite for instance that a 1x1000mm crack in a parge coat on masonry or a similar tear of a membrane in a timber construction poses the risk of introducing approximately 360g of water vapour per day.

Moreover, the authors note that the UK experiences high localised climate conditions and has a high proportion of historic buildings. They argue that dynamic tools that couple heat and moisture processes (such as WUFI Passive) offer a potential avenue to adopting a precautionary approach, but assert that "unless accompanied by widespread building physics training schemes, for UK building professionals, it seems likely that achieving deep refurbishment targets will engender serious risks for the moisture response and structural integrity of many UK buildings." (McLeod and Hopfe, 2013, p.14). Finally, they urge caution with the use of any modelling tool.

Various researchers have produced models which expand on the Glaser method. One example is Vydra (Vydra, 2007), who proposes a method with which moisture in the building envelope can be evaluated, taking into account sorption properties of timber and other materials. The author implements a 3D numerical code in order to account for risks at thermal bridges. Conclusions drawn in the paper are that the method successfully accounts for sorption properties of timber and can incorporate risks of thermal bridges.

Künzel and Holm (2009) explain the fundamentals (including required data and obtainable results) of hygrothermal models and present examples of guidelines which were developed using hygrothermal analyses. The authors argue that simulations assist in finding a balance between, "two opposing tasks: to prevent or at least limit the moisture entry into a building component and to let moisture, that has entered, dry out as fast as possible." (p.101). They argue that such optimisation is increasingly relevant as moisture tolerance in buildings is increasingly being encouraged (such as by EN 15026, ASHRAE Standard 160, and ASTM guidance). The authors point to the importance of hygroscopic 'buffering' and suggest that 'whole building models' which can simulate complex heat and moisture transfer have been developed within the IEA-Annex 41 project, "MoistEng" (ECBCS).

Straube and Schumacher (2006) present ways in which hygrothermal models (primarily WUFI™) can be used to assess the implications of fabric energy efficiency improvements on durability of historical buildings. The discussion includes the selection of input data as well as methods for generating corrosion indices and freeze-thaw counts for materials. The authors examine modelling of retrofits in five different Canadian climates. While their work endorses the development of more robust models of hygrothermal behaviour for retrofit design, the authors also suggest that detailing of enclosures (e.g. to address exfiltration, thermal bridging) generally requires detailed inspection and should be considered individually.

Experimental investigations of moisture behaviour in buildings tend to be expensive and time-consuming. Although calculation models are vulnerable to inaccuracy, they are potentially a very valuable tool for designers and specifiers (Wyrwa and Marynowicz, 2002). Sanders summarises available models for analysis on interstitial condensation risk in 2005 (Sanders, 2005) and discusses the availability of data on material properties and appropriate boundary conditions for modelling.

ASHRAE Standard 160 (2009) notes that, although the use of computer simulation to predict thermal and moisture conditions in buildings is becoming widely used, results obtained from the models are 'extremely sensitive' to boundary conditions used in the models. It argues that a consistent framework of design assumptions (i.e. assumed 'loads') should be adopted for use in modelling and, "the question [of] whether design features such as vapour retarders or ventilation systems are necessary cannot be answered objectively unless there is a consensus definition of the interior and exterior moisture boundary conditions that the building is expected to be able to sustain without negative consequences to itself or its inhabitants" (p.3.) In response to this requirement, the author presents a standardised set of design assumptions for use in modelling.

BS EN ISO 10456 (2007) provides data for heat and moisture transfer calculations for thermally homogenous materials used in construction. Data is also provided to enable calculation of thermal values for various climatic conditions.

Should this project, and other financially supported areas of work by DECC, result in a shift from EN13788 to EN15026, the issues raised in this area of research would need to be fully researched including the creation of:

- accurate and reliable weather files for numerous locations across the UK
- a materials database of UK materials, with material properties to allow the modelling of performance in such tools as Wufi, and TRYNSYS, which currently do not exist;
- a clear set of parameters, outlining when this dynamic modelling should be used;
- a competent persons scheme or qualification;
- guidance in how to detail at two dimensional junctions (which all of the currently available dynamic software does not accurately assess).

4.5.6 Measurement and monitoring

Determination of the moisture content of a wall can be made in several ways. Non-destructive indirect measurement can be made using infrared thermography imaging, *in situ* measurement of the electrical properties of materials (AC and DC systems), radar and microwave-based methods. Direct methods, which generally require removal of material from a building and so are considered 'destructive' include neutron scattering techniques, nuclear magnetic resonance (NMR), calcium carbide and gravimetric methods (Binder, et al, 2010, Sandrolini & Franzoni, 2006). Sandrolini and Franzoni (2006) argue that measurement techniques often provide non-repeatable or qualitative results or present safety and practical concerns and difficulties (i.e. neutron scattering and NMR). The authors propose an alternative technique based on a gravimetric method which they argue is reliable, quantitative and accurate. BS 82101 and BS 53252 recommend measuring Relative Humidity[23] in a sealed pocket or glass container containing a fragment of material. Drawbacks of this approach include the results being temperature dependent and each test needing to be studied for relationships between RH and moisture (including investigation of the nature and microstructure of materials).BS EN ISO 12572 (2001) specifies a method for testing thermal and moisture-related properties of building materials and products. The method uses

[23] The amount of water vapour in the air at any given time is usually less than that required to saturate the air. The relative humidity is the percent of saturation humidity, generally calculated in relation to saturated vapour density.

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cup tests to determine the vapour permeability of materials under isothermal conditions, and is applicable to all hygroscopic and non-hygroscopic materials*.* Direct methods of measurement such as the calcium carbide and gravimetric methods are recognised as being the most reliable quantitative measurements. These methods, however, do display a small systematic underestimation of moisture content (2-3wt%), and are sensitive to operator error, wind, slope and vibrations (Sandrolini and Franzoni, 2006). The area of understanding referred to here is a very much an emerging area of knowledge and considerable research is still needed to understand the ways in which moisture can be accurately measured and monitored in a building structure.

4.6 Mould growth

There is robust literature on the prediction of mould growth in buildings, which includes calculation methods and modelling*.* This work has been published over many years and indicates that a capability exists to produce reliable assessment of conditions necessary for the growth of moulds (Sedlbauer, 2002)*.* Mould risk was once predicted based solely on temperature ratios in buildings*.* More sophisticated methods which account for surface temperature and relative humidity are now used (e.g. isopleth systems, biohygrothermal model, ESP-r mould prediction model, empirical VTT model) (Vereecken and Roels, 2012). Sedlbauer and Vereecken and Roels argue, however, that these tools wrongly neglect exposure time*.* The authors present an overview of prediction models and discuss the impact of simplifications made within the models*.* Sedlbauer (n.d.) developed a 'biohygrothermal' model which he asserts far exceeds previous predictive methods.

Hyvarinen *et al* (2002) present research that associates a range of fungal genera and actinobacteria with specific types of moisture-damaged building materials. They studied 1140 samples of a range of building materials and found that generally concentrations of fungi and bacterial numbers were highest on materials such as wood and paper products, and lowest on ceramic products and products which included mineral insulation. Clarke *et al* (1999) performed an extensive literature review in order to define growth limits for six generic mould categories (minimum combination of temperature and relative humidity for growth on building materials). Using ESP-r computer simulation, the authors incorporated data about growth limits to produce a prototype predictive tool with which environmental conditions favourable to mould growth could be predicted. The authors suggest that future work might include mycological studies of growth limits under transient conditions.

Prediction of conditions which present a risk of mould growth in building materials is difficult and the complexity of factors related to biological processes of aging and damage means that in situ observation often reveals erroneous simulation results (Viitanen *et al*, 2010)*.* Viitanen and Ojanen (2007) present a study which creates new results and an improved mathematical model of mould growth on the surface of building materials, as well as new evaluations to predict the dynamic effects of humidity on growth of mould*.*

Brandt *et al* (2012) analysed a range of IWI cases over roughly two decades for mould growth risk*.* The authors state that IWI may cause low temperatures and high relative humidity on the interior face of a wall, which is likely to lead to mould growth*.* The authors argue that the risk of mould (on the interior surface of a brick wall) can be minimised if the following precautions are taken:

- the wall is not made of highly absorbent bricks or leaking mortar joints
- the interior surface of the wall is free from organic materials (e.g. wallpaper or glue)
- the vapour barrier is airtight (the authors assert that if room air penetrates, then surface condensation and mould growth is unavoidable under winter conditions).

The authors recommend the use of an inorganic insulation with high capillary action (as this will attain a level of equilibrium and reduce transport of water) but acknowledge that the effectiveness of insulation may not always be optimal due to periodic critical moisture content.

The information covered in this section does raise concerns for this project as the findings indicate that the risk of mould growth, exacerbated by the use of IWI, can be minimised but only if certain conditions exist. In particular the need for the wall to not be of highly absorbent bricks or mortar, the internal surface to be free from organic materials and the introduction of a VCL. In the UK the most prevalent building type with solid walls are of clay brick and lime mortar based construction. In addition other research indicates the potential risk of introducing a VCL in these types of structure. Further examination of unintended consequences will need to consider the conflicting views and lead towards the creation of guidance that clarifies the situation for industry.

4.6.1 Impacts on health

The impact of damp, excess cold and heat, and indoor air quality on occupant health and well-being has been shown to be significant (Roys *et al*, 2010; Davidson *et al*, 2011; Davidson *et al*, 2012). This association is not new; public health and housing professionals in the early 20th century were well aware of the associations between housing conditions and poor health, increased infant mortality, and infectious disease. A multitude of studies since then have found correlations in these associations (Hynes *et al*, 2003), including the adverse effects of indoor mould growth on adult asthma (Zock *et al*, 2002) and asthma, allergic rhinitis, atopic dermatitis, incidence of common colds and other respiratory infections (but not between dampness in homes and allergic conjunctivitis) (Kilpeläinen *et al*, 2001). Emenius *et al* (2004) showed an association between living in homes with high humidity and increased instances of wheezing. Koskinen *et al* (1999) found a significant association between exposure to mould and sinusitis, acute bronchitis, nocturnal cough, nocturnal dyspnoea and sore throat. They also observed significantly more episodes of common cold and tonsillitis, cough without phlegm, nocturnal cough, sore throat, rhinitis, fatigue and difficulties in concentration.

Bone *et al* (2010) summarise the impact of energy efficiency interventions on occupant health and assert that many health hazards which are associated with energy saving in homes derive from insufficient ventilation. They add that this happens in spite of much evidence linking ventilation to indoor air pollutants and indoor air pollutants to health impacts. The authors call for more research to establish direct links between energy efficiency measures and occupant health. Elements of this call for research will be partially addressed in this project. In particular the field trials, where changes to infiltration rates, internal humidity and temperatures, influenced by the application of external wall insulation, will be monitored over a minimum of a full heating pre and post improvement. However, further evidence will be required in the future with regard to the effect of insulation on indoor air quality.

4.6.2 Early cavity walls

Guidance on risks, materials, methods, and principles for improving energy performance of early (pre-WWII) cavity walls is provided by Ogley (2010). Early cavity construction first appeared in exposed areas such as coastal zones and was intended to provide protection against driving rain and climate elements. They are generally considered unsuitable for cavity insulation and therefore will need to be treated with SWI. Many early cavity buildings were built with lime-based mortars and renders (which readily exchange moisture with the indoor and outdoor environments); the authors argue that any insulation installed should maintain this 'breathability'. Advantages of EWI for these buildings include protection of external faces and wall ties from continuous wetting of the external leaf. However, there are also many potential disadvantages including reduced drying of the wall induced by solar heating and difficulties with the eventual cavity wall ties. Applying EWI to cavity walls can reduce its effectiveness as this can lead to a thermal bypass via air movement in the existing cavity. This will reduce the insulation provided by the EWI to a considerable degree. In such walls it raises the question of filling the cavity before applying EWI and this may have unintended consequences of its own (Miles-Shenton *et al* 2011)

Since many early cavity buildings were built with an assumption that the outer leaf would be able to dry by evaporating toward the outside face, insulating the wall externally may pose risks. IWI, which reduces the heat passing into walls, can cause the cavity temperature to fall considerably and the author cites research which suggests that such cavities (particularly on northern walls) can be permanently damp.

This can lead to wall tie corrosion, mould, or frost damage (particularly, it is added, where repointing with inappropriately hard mortars may have contributed to unduly wet walls).

Although this project is not directly researching the performance of cavity walls, it is important in the context of ECO funding and the Green Deal that the original purpose of the introduction of a cavity to buildings is understood. The focus of attention has shifted towards Hard to Treat (HTT) cavities, and measures that are suitable for improving their performance. Current guidance requires a Chartered Surveyor with appropriate qualifications to make the decision on the most appropriate form of insulation. However, there is no clarification of what those appropriate qualifications may be and no clear guidance for those surveyors on the hygrothermal principles that they should take into consideration during their survey.

4.7 Best practice guidance for installation – avoiding unintended consequences

Guidance and case studies on SWI are abundant and can be found both in professional and industry publications dating from the 1970's onwards and in academic sources. An overview of significant sources is presented in this section.

Many of the challenges in minimising the risk of causing unintended consequences when installing SWI that we recognise today have been understood for many years (Building Research Establishment Defects Prevention Unit 1989; Mason 1992; Building Research Establishment 1996; BRECSU 2000a and 2000b). More recently, a wealth of general guidance has been made available by authors on accepted best practices for installation, selection, cost, detailing, and maintenance (Energy Saving Trust 2006a; Straube *et al* 2012; Honour 2010; King and Weeks 2010; Stirling 2002; Building Research Establishment, 2006a and 2006b). Given the availability of such guidance, there is good reason to believe that with investment in training for installers and designer/specifiers and in quality control and construction management of SWI projects best practices can be achieved. Perhaps more research is required, however, to examine how often best practices are actually followed, the obstacles to achieving these practices, and effects caused by not adhering to them. Changes and updates to many of these guidance documents may be required if there is change to the principles of calculating condensation risk. This project should highlight, in particular, the areas where clearer guidance is required in the context of older breathable buildings and the most appropriate manner in which they should be thermally improved.

4.7.1 Thermal bridges

Stirling (2002) provides considerable discussion of strategies for reducing thermal bridges, noting for instance that the junction of uninsulated roofs and solid walls can require insulation between ceiling joists and over wall plates (as well as EWI), while ensuring that roof ventilation is not impeded. One of the most common thermal bridges in SWI is the reveal around a window or door. During installation of SWI, insulation should be returned into window and door reveals (to eliminate condensation on otherwise cold surfaces). Discussion of thermal bridging appears in BRECSU Good Practice Guide 183 (BRECSU 1996); this can be usefully applied to SWI installation and design. The Energy Saving Trust (2006b) suggest that insulation with an R-value of 0.50m^{2}K/W should be specified (frame depths may prohibit this).

Windows and door reveals may be difficult to treat with insulation as accommodation is needed for the added thickness of insulation against existing windows and doors. Treatment of these areas may be enabled by high performance materials such as aerogel or vacuum insulation panels, however these materials are much more expensive than more commonly-used insulants. The impact of not insulating at these two dimensional junctions should be examined in detail as part of the current project, particularly when classifying the risk of unintended consequences through not adopting good practice principles. We are aware the Government is in the process of producing guidance on minimising cold bridges for internally applied external wall and insulation and the soon to be published document "Reducing thermal bridging at junctions when designing and installing solid wall insulation" (Weeks, Ward, King). The document sets out good practice principles for externally applied solid wall insulation.

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4.7.2 System boundaries

EWI may necessitate extending roofs at eaves and gable-ends in order to protect insulation systems from weather. Although verge caps provide one solution to this problem, roof extensions will provide a more durable and reliable solution.

Where SWI is installed in a multi-unit dwelling against a neighbouring property which is not being insulated, second difficulties will be encountered. The most significant of these is the creation of a sharp temperature gradient between insulated and non-insulated properties. This introduces a thermal bypass and also presents a condensation risk both at the inner wall surface and interstitially. The second difficulty presented is in detailing the transition in a weather-proof and aesthetically acceptable manner (Energy Saving Trust 2006a; Honour 2010). The identification of the typical details that introduce cold bridges and points of weakness into a cladding system, and guidance in how to minimise these risks are key to improving the durability and efficiency of external wall insulation.

4.7.3 Protection from weather and moisture management

Special treatment must be given to areas such as window sills, rainwater downpipes, and areas where walls meet roofs and projections such as porches or conservatories and care should be taken to avoid inadvertently blocking important functions such as window trickle vents, or eave ventilation (Energy Saving Trust, 2006a and 2006b); (Honour 2010; Stirling 2002). Careful attention to detailing (e.g. holes made by fixings in EWI) is important to ensuring durability of systems (King and Weeks 2010).

Stirling (2002) cautions that rendered SWI should not be specified for Exposure Zones above 4. In areas with a high rain exposure or history of rain penetration, the author recommends that closed cell or encapsulated insulation is considered in order to reduce the risk of moisture retention. Where a wall is in Zone 3 or 4, he recommends that IWI only be installed where the walls are at least 328 mm thick of brick, 250 mm of aggregate block, or 215 mm of autoclaved concrete block with a notional cavity between masonry and insulation (or where impervious cladding with nominal cladding has been installed externally). Where liquid-applied sealants are used to treat external walls, the author stresses that the manufacturer's coverage rates and re-application guidance should be followed carefully.

Where exposure to driving rain or damp is high, a small cavity behind the dry lining may be advantageous in order to reduce the risk of moisture migrating through the wall assembly (mortar joints can become porous; unrendered and unclad walls can allow rain penetration) (Energy Saving Trust, 2006b). Honour (2010) and Stirling (2002) argue that cladding must include a ventilated cavity, insulation must fit tightly in order to prevent moisture problems and plasterboard should be sealed fully along all edges and penetrations. Stirling (2002) recommends applying 'breathable' external finishes.

There is, at times, conflicting guidance on the most appropriate manner in which to detail for weather tightness and reduced risk of moisture ingress when applying external wall insulation. This project will need to carefully consider the existing guidance and try to outline a clear and consistent process for practitioners and installers alike.

4.7.4 Existing substrate

External insulation should not be installed if the existing substrate is structurally unsound or cannot be repaired. Fixings should only be made following verification of the nature and condition of the substrate, as well as assessment of the dead and imposed loads. Consider also potential corrosion and movement of the building fabric or system (appropriate renders should be selected and where necessary movement joints provided and movement of metal components within render considered). The Energy Saving Trust (2006a and 2006b) suggests that manufacturers are consulted to ensure that the correct adhesive is used. BS 5628: Part 3: 2001 (Code of Practice for use of masonry materials and components, design and workmanship for guidance on resistance to weather) or its replacement is recommended as a useful guide in determining whether a wall is suitable for IWI.

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4.7.5 Specification, installation and on-site practice

Advice on specification and site practice can be found in guidance documents provided to industry, such as BRE Good Building Guide 68 (Building Research Establishment, 2006a and 2006b). These documents present advice on minimising air leakage and thermal bridging; and highlight correlations of these issues to condensation, mould growth and energy loss. They also provide a basic overview of options, techniques, and principles such as airtightness that are relevant to SWI. Stirling (1999) provides a general overview of EWI systems, and highlights areas of concern such as ageing joint sealants, insufficient overhangs at the roof/wall interfaces, and higher thermal movement resulting from darker finishing colours. Harrison and De Vekey (1998) provide a comprehensive guidance document (BRE Report 352) on avoiding and correcting defects in walls, windows and doors. It does not discuss SWI at a substantive level, but presents many principles of practice which are relevant to insulation installation and detailing. Doran *et al* (2009) describe earlier forms of construction and problems likely to be encountered with walls, while providing solutions and discussion. Although specific discussion of SWI is not a feature of this publication, it is a comprehensive guide to issues such as condensation control, damp, and maintenance.

The Energy Saving Trust (2006a) provides useful advice specific to SWI such as avoiding bi-metallic corrosion, ensuring that the Damp Proof Course (DPC) is not bridged by the system and that structural movement joints are not covered. It also suggests that specifiers consider the embodied energy of materials. Site hazards such as particles spread from working with polystyrene insulation are also identified in this document. It also calls attention to the importance of ensuring that weather conditions are suitable at time of wet render application. In line with research on limiting overheating (Gupta and Gregg 2012; Oikonomou *et al* 2012; Energy Saving Trust 2010), Honour (2010) suggests that render should be light-coloured to limit solar gain (which might also lead to thermal stresses to the fabric).

Site precautions recommended by the Energy Saving Trust include the avoidance of fire risks and hot surfaces or points of ignition and ensuring that electrical cables are not covered by insulation without guarding (PVC sheathing may degrade, particularly if in contact with polystyrene). A specification for the installation of SWI exists in the PAS 2030 (Publically Available Standard): 2012 (BSI, 2012). The PAS focuses on management of processes and control of quality throughout the phases of installation. By shaping more consistent installation practices, the standard is likely to encourage better control of workmanship. Naturally, poor workmanship during the installation process can contribute to a wide variety of risks such as those described elsewhere in this document (and in BS 5250). The importance of strict quality control in the installation process is emphasised by many authors, particularly in relation to IWI (Honour, 2010).

Work undertaken as an early part of this project has highlighted that there is an apparent lack of quality control on site during the installation process. Although standards, such as PAS 2030, requires checks to be made, the knowledge and experience of the person making such checks are not defined, and there is little evidence that the required standard is being achieved in any methodical way.

Social and economic impacts

'Soft factors' that may be affected by the installation of SWI are discussed by Haines, Mitchell, & Mallaband (2010). The authors present work from a four-year project called CALEBRE (funded by the EPSRC and E.ON) in which various aspects of value perceptions held by householders were examined in the context of energy refurbishment. The document reflects on the potential relevance of SWI to "motivations for improving… homes and the complex interplay of factors relating to aesthetics, lifestyle, life events, energy efficiency and finance." Relevant to this research is a paper by Energy Solutions (no date), which argues that the installation of IWI may be disruptive to occupants and that relocating existing fixtures, architectural details, and fittings such as radiators and electrical installations can be problematic. This is also noted by many other authors (e.g. Honour 2010; Energy Saving Trust 2006a; Iwaszkiewicz *et al* ,2010). The paper also highlights the visual obtrusiveness of EWI when abutting uninsulated properties (including complications with planning permission). Further consideration may need to be given to the reduction in floor area which IWI leads to and the potential impact on accessibility or living standards this may cause or the need it may trigger for replacing furniture or interior fittings.

Rasmussen (2010) aims to demonstrate that economic savings of refurbishments can be predicted easily. He presents results from simulations of a solid brick and timber beam building typical of Danish construction between 1850 and 1920. The simulated building was insulated with 95 mm mineral fibre IWI. Energy demand was calculated with the Be06 computer programme. Moisture conditions at the junction of solid brick and timber beams were considered and the authors state that they deemed an airtight shell as well as vapour barrier be installed to protect the beam from elevated moisture levels. Cost calculations showed that measures were narrowly profitable, based on an estimated payback period of 30 years. The author notes that profitability varied greatly with energy prices and interest rates.

Guidance on the assessment of the social, economic, and environmental performance of refurbishments of Victorian housing is provided in Yates (2006). This accounts for standards of acoustics, energy, whole building performance, as well durability, maintainability and reliability of building fabric.

4.8 SUSREF: risks in insulated properties

Sustainable Refurbishment of Building Facades and External Walls (SUSREF)[24], was a research project conducted by a European consortium which included BRE and Cardiff University. The consortium carried out a major review of refurbishment options for a range of different façade constructions. The main aim of SUSREF was to evaluate and describe the concepts for sustainable refurbishment of external walls; and to create results for those assessments undertaken.

The concepts were assessed from the viewpoint of:

- Thermal bridges and Airtightness
- Condensation/Damp
- Impact on daylight
- Structural Stability
- Buildability
- Vulnerability to damage
- Acoustics
- Disturbance
- Aesthetic quality

The study focused on additional thermal insulation of external walls; all other fabric elements of components and systems were excluded. The goal of the study was to give a comprehensive view of the different technologies available for the refurbishment of external walls, and highlight any weaknesses or considerations that should be factored in. Each of the technologies has some advantages and disadvantages, which are listed in the table below.

[24] See project website at http://cic.vtt.fi/susref/.

Table 10: Advantages and disadvantages of options

Insulation mode	Advantages	Desadvantages
Insulation by outside	Eliminating risks of local thermal bridges Protecting the wall from freezing and fissuring Protecting the wall from penetration by driving rain Improving the external appearance in the case of a degraded external surfacing Conserving thermal inertia Conserving inside volumes and finishing	Changing the outside appearance (town planning permit application – difficulties with listed buildings and heritage sites) Costly solution, because it involves a new facing Possible encroachment on public ground
Insulation by inside	The external appearance is conserved (no town planning permit application) The cost is generally lower than for insulating on the outside	Thermal bridges sometimes not eliminated Possible degradation of the outer wall due to its cooling and increased dampness Risk of fissuring due to the temperature variations in the outer wall New interior finishes and smaller interior volumes (according to the insulation's thickness) Loss of thermal inertia Continuity of the vapour barrier difficult to achieve Modification of water network – placing the pipes so that they are protected from freezing

The findings of the SUSREF report provides insight into many of the challenges that are currently faced by the insulation industry in the UK, and refers to many of the unintended consequences that will need to be quantified as part of this project. Several of the unintended consequences identified have already been discussed earlier in the chapter. Specifically, risks associated with thermal bridges, altered air tightness, condensation and mould. However, the report highlighted a few other potential consequences not discussed thus far. These are described below.

Impact on daylight

Illumination, and more specifically daylight, plays an important role in the delivery of comfort and quality of life in buildings for the occupiers. Correct daylight design can also deliver significant potential for reduction of energy consumption in buildings.

Building façade refurbishment can significantly alter daylight quality in the interior spaces of the refurbished buildings, even when windows are not replaced, by changing the geometry of the aperture in which the window is inserted and reducing the width of the aperture by insulating the reveals and heads.

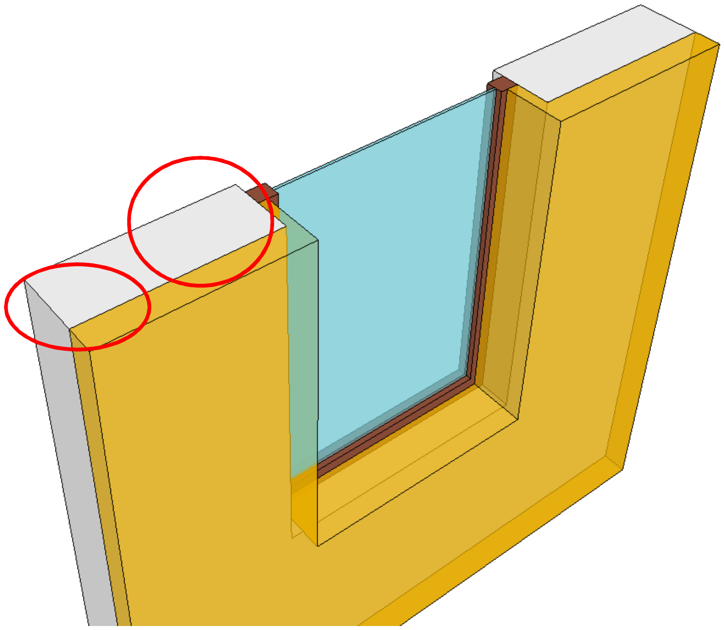

Figure 15: Example of the change in aperture after facade refurbishment

Geometry variations (more evident in the case of external insulation) can include an increase in wall thickness as well as occasional slight variations in aperture dimensions as a result of the insulation of window reveals. Energy refurbishment solutions involving an increase in façade thickness can substantially affect daylight availability in interior spaces, with associated additional energy consumption for lighting.

Large increases in façade thickness substantially affect the amount of daylight availability, with reductions of up to 15% of daylit time for 30 cm. of added insulation, and 8%-9% for 20 cm.

Reductions in Useful Daylight Illuminance indicate lower increases in values for time with no useful daylight, (4% to 6% for 30 cm.) However the insulation can also result in a reduction in potential glare situations (especially in west and south orientations).

The condition of the existing wall

The quality of the existing wall must be assessed. An assessment of the current condition of an existing wall will highlight the need for any repairs and suitability for improvement prior to refurbishment. If the surface of the existing wall is very rough or uneven, air gaps might occur between the insulation and the wall, this may affect the performance of the external insulation, and in these cases this gap must be closed (e.g. by weathers trip, dubbed out or rendered etc.).

Necessary repairs that could be encountered might include the removal of existing cladding or render, improving joints or drainage. Furthermore it is imperative to assess the load-bearing capacity on the existing wall. Rot damage to a load-bearing wood structure or ripped/torn concrete might be impossible to improve to the extent where it can support an additional refurbishment system, and it is therefore important that this is assessed correctly from the outset. A visible assessment of a cladded wall will not necessarily reveal moisture damage beneath, and therefore some destructive investigation may be required.

Vulnerability to damage

Refurbishment of external walls can affect the future need for care and maintenance in several ways. First the refurbishment process may involve replacing existing materials with new materials with a longer or shorter expected service life. Also, temperature and moisture conditions in the wall may change, affecting the maintenance need and expected service life of the existing structure, as well as any new materials. Where new external surfaces are introduced, surface treatment methods may change completely. Finally, a refurbished wall may be more or less susceptible to mechanical damage or vandalism than the existing structure.

External insulation risks:

- Vandalism (graffiti): High
- Pollution Risk: Low/medium (Painted surface (organic paint)

Sulfur dioxide (SO_2) is oxidized to sulfuric acid (H_2SO_4). The main component in acid rain is sulfuric acid. In recent times the levels of sulfur dioxide as atmospheric pollutant have decreased. Soot and nitrogen compounds now form the main part of pollutants depositing on building surfaces (Grossi, et al., 2007). The photo initiated reaction of atmospheric hydrocarbons with nitric oxide (NO) leads to the formation of ozone. Ozone reacts with nitric oxide and leads, in the end, to the formation of nitrogen dioxide (NO_2) and nitric acid (HNO_3) (Charola, et al., 2002). The effect of nitrogen compounds on building materials has been much less studied than the effect of sulfur dioxide/sulfuric acid.

- Microbial growth Risk: Medium (Render: algae and cyanobacteria) - Low-medium (Painted surface: algae, fungi and cyanobacteria)

The roughness and porosity of paint and render greatly influences algae and bacterial growth. The use of low porosity, smooth surface materials reduces growth.

- Mechanical damage: Low

Mechanical damage involves minor cracks that do not lead to increased moisture ingress and major cracks and delamination. Cracks are frequently found along insulation board joints. Damage to the render due to movements in the structural wall occur more seldom on EWI facades than on conventional masonry due to the decoupling effect of the insulation layer.

- Moisture risk: Medium

Moisture ingress due to contact with the ground or improper finishing of the EWI towards windows, balconies etc. Moisture and temperature strains (built in moisture or moisture from driving rain combined with high temperatures) may cause damage to the mineral wool insulation in EWI.

The water vapour permeability of the render and coating layer should have a value not exceeding sd = 0.6 m (equivalent air layer thickness) (Šadauskiene, et al., 2009). Otherwise moisture may build up in the insulation. When a facade is repainted several times with an acrylic coating the water vapour resistance of the render-coating layer may become too high. This will not be a problem when inorganic coatings are used as these coatings have a much lower water vapour resistance than an acrylic coating.

The report confirms the difficulties of minimising cold bridging when using both internal and external wall insulation, the risk of a change in humidity levels, air infiltration rates, and indoor air quality. It makes reference to disturbance to the residents of the properties being refurbished and that there can be a reduction in daylight factors and internal space, depending on the choice of insulation method. All of these areas and many more will need to be investigated further as part of this project.

4.9 Conclusions and recommendations

This section has focused on two main unintended consequences of the installation of SWI: the risk of overheating in buildings; and changes to the distribution of moisture in a building and the damage this may cause to the building and its occupants. As in previous sections of the review, there is a call for more research to address gaps in existing knowledge. This call is qualified by a request for greater rigour in the conduct of the research. Many of the existing studies are based on modelling using computer software rather than careful studies of actual buildings in sufficient numbers.

The influence of thermal mass on post-insulated buildings is not well understood and needs to be studied in greater detail. It also needs to be considered alongside orientation and fenestration to assess the risk of overheating. There is conflicting evidence on the role of thermal mass and particularly on the best place to put insulation to avoid overheating, though there is a clear preference for external insulation so that the existing mass of the external walls can remain in play and thereby moderate the excesses of internal temperature swings.

The limitations of the Glaser method in assessing condensation risk have been mentioned previously, as well as those of current hygrothermal simulation tools. There is a lack of field studies on real, occupied buildings that confront the complexity of heat and moisture balances under a range of conditions. The main argument is over the need for ventilation versus breathable constructions, as a means to reduce condensation on surfaces and within constructions. In one sense the debate hinges on a conflict between the traditional and the modern, and is mainly centred on interventions in heritage buildings, though the principles apply to all retrofitted buildings.

A thorough and extensive review of buildings that have been insulated with EWI should be undertaken, to endeavour to clearly identify the causes of unintended consequences; the current arguments are affected by the limitations in different numerical models (Glaser / Wufi). Although Wufi encompasses more parameters (wind-driven rain, water ingress, and local climate data) than Glaser, it is still a numerical model, with serious limitations on the materials and climate data bases within the tool. Much research uses this type of modelling, but it is both costly and impractical for a mass roll-out of supported / funded insulation schemes.

A comprehensive review could throw important light on the areas of key weakness that are thought to exist in the current external wall insulation marketplace. Although at an early stage in this project, there are already indications that the areas of weakness in the EWI process could be categorised into three main causes of unintended consequences: the initial assessment of buildings, systematic problems, and factors relating to occupancy. There is already a growing list of these that need to be considered, and ranking these by risk and effect will help focus the minds of the people involved in making the decision whether to insulate or not.

5 Heritage and conservation[25]

5.1 Introduction

The challenge facing the UK is significant when considering thermal improvements to the existing building stock, especially when endeavouring to preserve the appearance and heritage of buildings. To fully understand this challenge it is necessary to quantify the meaning of heritage. The notion of "heritage buildings" applies to structures of architectural, social or historical significance. In this literature review, *heritage buildings are those that have a special architectural feature or character desirable to preserve and likely to be of traditional construction*. Buildings of traditional construction are those with permeable fabric that absorbs and enables the evaporation of moisture (English Heritage 2012a and 2012b). In other words, buildings built pre-1919 made of solid walls and with materials that are permeable to moisture are traditionally constructed buildings[26]. Heritage buildings represent approximately 35% of the existing dwellings in the UK as a whole and a large proportion of solid wall buildings. This section covers the aspects relevant to energy efficiency interventions on listed buildings, buildings in conservation areas and traditionally constructed buildings, with a focus on solid wall insulation. Many of the issues have been introduced earlier but a review focussing on solid wall insulation must give due consideration to this important group, especially when a relatively large amount of research work has been undertaken on properties of this type. The purpose here is to highlight those aspects that are particularly important to heritage buildings and ones that this project will need to consider when making recommendations and issuing any guidance advice.

In the UK, the main institutions charged with the protection of built heritage are English Heritage, Historic Scotland, Cadw (Wales), and the Northern Ireland Environment Agency. In addition, there are organisations that specialise in studies of built heritage, notably SPAB (Society for the Protection of Ancient Buildings) and the recently formed STBA (Sustainable Traditional Buildings Alliance.) In general terms, it is recommended that interventions to improve the energy efficiency of heritage buildings should be based on informed approaches that prevent any risks of "unacceptable damage to the character and appearance." Energy efficient retrofits of heritage buildings should not cause "any technical conflicts between the existing traditional construction and the energy efficiency measures" (English Heritage 2012a). There are two main aspects to consider for heritage buildings:

- preservation of the original internal and external features due to their historical significance; and,
- the way that heritage buildings are constructed and the way they function.

The way heritage buildings are constructed and operated (envelope properties, floor plan arrangements, ventilation characteristics, heating regime) enables them to cope with the presence of damp differently to modern buildings. (English Heritage 2012a; Roger Curtis, Historic Scotland 2007; Northern Ireland Environmental Agency 2006). However, heritage buildings can suffer from a build-up of damp leading to deterioration, requiring refurbishment works and interventions to address existing damage, to prevent further deterioration and to improve the performance of the wall. They can also be problematic to heat. Thus, any work that produces alterations, extensions (external and internal) or changes in the building's character and/or behaviour should be based on a full understanding of the existing conditions and the

[25] Principal authors: Gabriela Zapata and Christopher Tweed (Cardiff University).

[26] It should be noted that this review uses the term 'heritage buildings' to refer to buildings made of traditional materials as defined by English Heritage (2012a).

potential consequences to avoid any risk of damage and decay. The following section considers the specific problems posed by the refurbishment of heritage buildings.

5.2 Thermal behaviour and building physics of heritage buildings

The thermal behaviour and building physics of buildings have been discussed earlier, but it is worth considering the particular characteristics and problems associated with heritage buildings to understand why they may need special treatment in a programme of solid wall insulation, especially with the need to minimise the risk of unintended consequences. Traditional constructions and materials are often cited as being superior to modern equivalents because they allow buildings to ‘breathe’ and so avoid extreme damp either because of rain penetration or condensation. The use of lime plasters is seen as crucial to this behaviour and their replacement with gypsum plasters is seen as a retrograde step by many traditionalists because they are much more impervious to the moisture movement.

Heritage buildings are complex environmental systems in which the internal environment is created by interactions between the properties of the building envelope and internal features such as chimney stacks, floor plan arrangement (cellular rooms) and draught lobbies (English Heritage 2012a). In heritage buildings, thermal mass, air infiltration rates and properties of the fabric work together to regulate heat loss. Unlike modern buildings, heritage buildings do not have moisture barriers or impermeable membranes to avoid water penetration. Heritage buildings are likely to be made of materials that enable the transport of water through the fabric. In most cases, the small amount of water in the fabric of heritage buildings is not detrimental. However, the ventilation and heating regimes of heritage buildings must contribute to the evaporation of this water. Therefore, the underlying principles that govern the performance and the indoor environment of heritage buildings are likely to differ from those of modern buildings, and this has implications for expectations of thermal comfort. The figure below illustrates some differences between modern and heritage buildings:

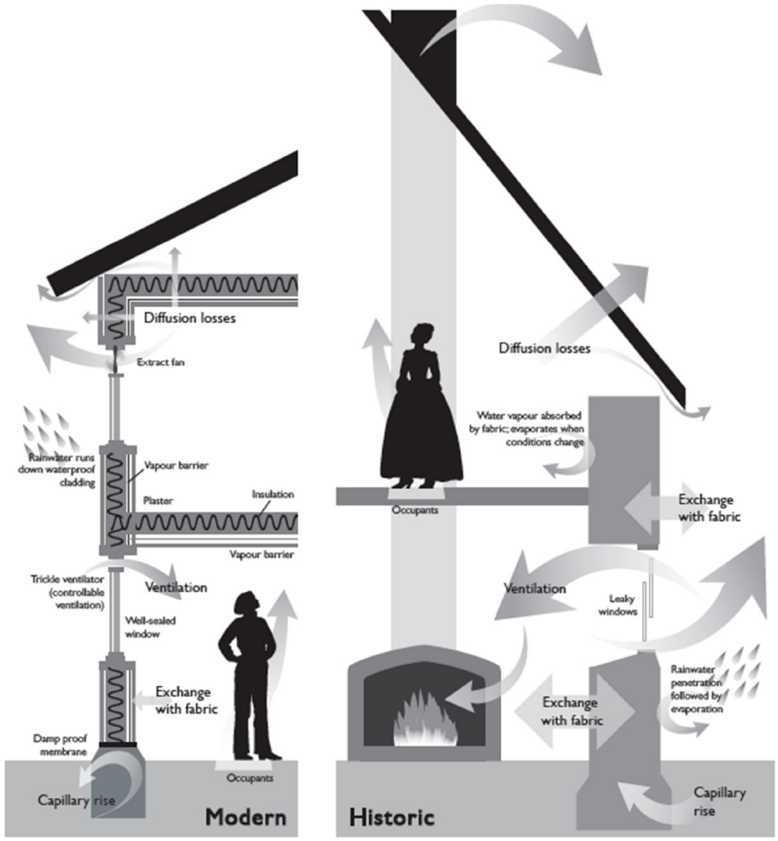

Figure 16: Comparison of the behaviour of modern buildings (left) and historic buildings (right). Extracted from English Heritage (2012a, p.28), image by Robyn Pender.

One of the key differences between modern and heritage buildings is the properties of the fabric. A heritage building's fabric tends to be 'breathable'—it allows moisture within the fabric to evaporate. Breathability refers to "the behaviour of liquid water and water vapour and their effects on the building envelope and its internal environment" (English Heritage 2012). The solid masonry walls of pre-1919 buildings tend to be breathable, consisting of stone or brick with mortar joints, or earth. Solid ground floors, lime-based plasters and renders also have good hygroscopic properties. Breathability refers to the materials' ability to absorb and release water as vapour following humidity changes (hygroscopicity) and as a liquid through contact (capillarity).

Materials with good hygroscopic capacity stabilise the indoor air humidity, reduce surface condensation and may be able to absorb interstitial moisture without lasting detriment. The ability of walls to absorb moisture depends on the depth of the material exposed to the humidity. This is related to thickness, density, equilibrium of the mositure content and the position of the material in the construction. Vapour permeability is related to the ventilation and air leakage of the building and to the hygroscopic capacity of the fabric. It is measured as the resistance of the material to moisture movement (resistivity). Capillarity defines the absorption and release of water as a liquid.

The main sources of moisture that affect heritage buildings are precipitation, rising damp (heritage buildings do not have damp-proof membranes, though some do have physical damp-proof courses, such as slate), internal moisture vapour (created by occupants and processes) and damaged, leaking services. High moisture levels can lead to the damage of structures, growth of mould and bacteria and a reduced thermal performance of the fabric. Changing the rainwater run-off properties is a good example of a problem created by inadequate consideration of the permeability of the construction. While new buildings tend to have a heavy run-off (impermeable fabric), heritage buildings have a reduced rainwater run-off because they absorb some rainwater into the outer layers of their permeable fabric and release it as water vapour when weather conditions change, sometimes months later. The balance between capillarity water ingress and evaporation is achieved due to the breathability of the fabric and air infiltration in the buildings. In this way, the building is capable of maintaining tolerable levels of moisture within the fabric. If a heritage building is painted on the outside with a closed capillarity material (a non-breathable layer), it creates an impermeable layer, so altering the breathability properties of the fabric and leading to potential decay of the material within the body of the wall. The introduction of an insulated cladding system also has the same effect on the porous nature of the building and needs to be considered carefully when choosing to thermally upgrade or not. The resulting effect of this change will need to be considered during this project.

5.3 Hygrothermal performance of buildings

Hygrothermal performance refers to the combined effects of heat and moisture. Hygrothermal behaviour of walls has been discussed previously, but it is worth summarising the main points again. The thermal and hygroscopic behaviour of a building element are interdependent. Increased moisture content increases heat losses, which in turn affect moisture transport. For heritage buildings, where the building materials are likely to have high hygroscopic characteristics, understanding the mechanisms of moisture transport and the hygroscopic behaviour is fundamental to understanding its thermal performance (Changeworks 2008; English Heritage 2012a and 2012b; Browne 2012).

5.3.1 Calculation of the hygrothermal performance of building elements

As noted in Section 2, current legislation stipulates the Glaser method for assessing condensation risks in walls. However, this has been shown to be lacking, particularly (but not only) in heritage buildings, with their complex hygrothermal behaviour (Baker 2011; Rye 2010; and Rye and Scott 2012). It is a steady-state method that uses simplified boundary conditions. It is generally applicable for modern building materials, but may not be applicable to the analysis of heritage buildings if the materials have hygroscopic properties that differ from those of modern impermeable construction. Modern buildings use gypsum plasters and plastic membranes to restrict the flow of moisture across layers of a construction. Cavity construction poses fewer problems with interstitial condensation because the inner leaf is at a higher temperature than the outer.

The Glaser method is not capable of representing short term variations, nor the effect of rain and solar radiation. The method does not consider capillary moisture transport nor the absorption capacity of the building element. As a consequence, the method is not able to represent the complex mechanisms of heat and moisture that occur in the building components exposed to variable weather and internal conditions. It is recommended, therefore, that for heritage buildings and for those that have complex hygrothermal behaviour, analysis should be carried out using tools that consider the principles of EN15026 such as the more sophisticated dynamic modelling software WUFI™. This still does not offer a definitive answer or solution but does give a more accurate prediction of moisture build up and transfer. This study also warns that materials whose hygroscopic properties are subject to change over time should be further investigated so as to determine the moisture behaviour accurately and this is a particular area of research that will need to be investigated in more depth should there be a change in standards for calculating condensation and moisture risk as discussed earlier.

Field measurements, when possible and feasible, are even better than relying on models. It is worth noting that although research suggests that calculated and laboratory based results are generally in agreement (Künzel 1998), there is very little long term research on the behaviour of traditional constructions in practice. The SUSREF project, described in chapter 4, is one of the first to carry out this type of study in the field.

5.3.2 Problems resulting from the hygrothermal behaviour of traditional constructions

Problems occurring in traditional constructions as a result of solid wall insulation are usually because of changes in the moisture flow and distribution exacerbated by changes in the flow of heat throughout the construction. Künzel & Holm (2009) highlight the practical consequences of this moisture behaviour for porous materials exposed to wind-driven rain; for example, the "material degraded caused by dilatation processes in the micro-structure due to the expansion of freezing water or crystallising salts." The same paper describes a case study of a half-timbered structure and the consequences of applying a vapour retarder. They find that "the wall's drying potential to the interior will be severely reduced." He suggests improvement of the drying potential of the wall towards the interior by using a vapour retarder with variable diffusion resistance or with capillary active insulation materials, for example Calcium Silicate boards. Another study, by Browne (2012), concludes that the use of a vapour control layer on the warm side of the insulation (the normal industry solution) has a negative effect[27]. According to the WUFI™ simulation, it could cause the failure of the insulation. The research suggests that current British standards on condensation risk should be improved. Poor design for moisture control can produce degradation of the building fabric and the deterioration of the indoor environment with health risks to the building occupants.

The study recommends that new *in situ* measured information should inform the models to increase their accuracy and improve the energy saving designs. It also recommends:

- the incorporation of a database of brick and stone materials in WUFI™ that includes the physical characteristics, geological derivation and common regions of usage for the appropriate selection of materials;
- the employment of standardised approaches to simulating traditional buildings;
- the liability of manufacturers with legal obligations if there is a failure after the implementation of retrofitting strategies and this failure is attributable to errors in the manufacturer's calculations; and
- the use of in situ monitoring of relative humidity in the interface between internal insulation and masonry. In the event of disquieting results, further investigations could be developed.

This area of work will need to be researched more significantly as to move to the use of dynamic software without correct material and weather databases could lead to an unjustified feeling of security over any solutions proposed, the software is complex and dependent on the application of accurate boundary conditions and accurate material and weather databases to be at it most reliable.

5.4 *In situ* U-value measurements

In situ studies have identified that the performance of traditional building materials tends to be better than anticipated and that the standard performance of the material might fail to represent the performance measured *in situ*. Chapter 2 of this review presents the relevant studies in this area. The studies show that U-values can vary significantly from building to building and even within the same building. This area of work is in line with the work undertaken under WP 4 of this project which indicates that the performance of solid walls has been underestimated when using the mathematical calculation method set out in the British Standard.

[27] A detailed discussion is outlined in Chapter 4, unanticipated consequences of the application of insulation

Contrary to what steady-state calculations suggest, no simple generalisation can be stated about the relationship between U-value and type of material or thickness of elements. The actual construction of the element, defective areas, irregularities, ventilated cavities and the specific characteristics of the local materials could all lead to localised thermal performance variations and discrepancies between calculated and *in situ* thermal performance (Rye and Scott 2012).

5.5 Case studies of interventions on heritage buildings

This section presents a summarised discussion of case studies on the energy efficiency retrofit of heritage buildings. The case studies presented outline the existing condition before the investigation, describe the scope of the retrofit work and present the pre- and post-retrofit performance. Relevant case studies of energy efficiency retrofit in heritage buildings and buildings made of traditional materials have been summarised in **Table 11** below. These case studies have been developed by Historic Scotland (cases 1-11), STBA (cases 12-14), SECHURBA Sustainable Energy Communities in Historic Urban Areas, a partnership between Shropshire Council, Marches Energy and Intelligent Energy Europe (cases 15-18), Changeworks (case 19) and the Technology Strategy Board's Retrofit for the Future programme (case 20).

The following table presents a short description of the pre-existing condition of the case studies, the scope of the retrofit works and the measures used to evaluate the improvement after the retrofit. Note that case studies 8, 15, 18 and 19 do not apply insulation to the walls.

Table 11: Summaries of retrofit case studies.

Case study		Description	Wall ins	Description of the retrofit works	Measure of improved performance	Reference
Historic Scotland						
1	16 Roxburgh St	Ground floor flat, within a three-storey and basement terrace circa 1840. Existing: Walls in living room and entrance hall: polished ashlar with chamfered rustication, masonry thickness 600mm; external wall (bedroom and kitchen): random rubble stone with broached ashlar window surrounds, masonry thickness 650mm	Yes	Rigid insulation: Pavaflex wood fibreboard. Wood fibreboard was specified; however, due to procurement issues, rigid phenolic insulation board was installed in some locations (Kooltherm K12); blown insulation; Warmfill insulation: an expanded polystyrene bead insulation with bonding agent	U-values (in situ measurement) Wall U-value from 1.4 to 0.8 W/m2K in living room	(Jack and Dudley 2012)
2	22 Drummond St, Flat 8	Rear second floor flat, accessed from common stair, within five-storey, tenement block c 1790. Existing fabric: random rubble stone with broached ashlar window surrounds. Masonry thickness approx. 750mm	Yes	Open cavities packed with mineral wool and bonded polystyrene bead blown in behind the plasterboard to fully fill the cavity (approx. 100mm deep)	U-values (in situ measurement) Wall U-value from 0.5 to 0.4 W/m2K in bedroom	(Jack and Dudley 2012)
3	33 Marshall St, flat 1F2	End of terrace first floor apartment, within four-storey plus attic, mid-19th century tenement. Upgrading works to a single room (bedroom) with two external walls and two windows. Existing fabric: stugged ashlar with fair-faced window surrounds. Overall masonry thickness approx. 750mm and 60mm respectively	Yes	Open cavities around window openings packed with mineral wool insulation. Expanded polystyrene bead insulation was blown into cavities through the mineral wool packing to fully fill the cavity (35-45mm deep)	U-values (in situ measurement) Wall U-value from 1.3 to 0.3 W/m2K in bedroom	(Jack and Dudley 2012)
4	2 Roxburgh St, flat 2F1	North corner, second floor apartment accessed off common stair, with four-storeys plus basement, tenement c 1800. Upgrading works carried out to the two external walls and five windows. Existing fabric: Broached ashlar, with droved margins to window surrounds. Overall masonry thickness approx. 650mm	Yes	Open cavities below cil level packed with mineral wool insulation and any gaps around the perimeter of the window opening were also filled to form a continuous seal. Expanded polystyrene bonded bead insulation (warmfill white) blown into the wall cavity (40-50mm deep to NW wall and 20-30mm deep to the NE wall) through the holes in the plaster and timber grounds.	U-values (in situ measurement) Wall U-value from 1.4 to 0.7 W/m2K in living room	(Jack and Dudley 2012)

Case study		Description	Wall ins	Description of the retrofit works	Measure of improved performance	Reference
5	2 Roxburgh St, flat 2F2	NE facing first floor apartment within a four-storey plus basement tenement c 1800. Upgraded works were carried out to the front wall and two windows to a single room (living room). Existing fabric: broached ashlar with droved margins to window surrounds. Overall masonry thickness 650mm	No	Works on windows and shutters (100mm spacetherm blanket insulation to shutters)	U-values Sash window 5.2 to 1.5 W/m2K and shutter 2.2 to 0.40 W/m2K	(Jack and Dudley 2012)
6	Wells O'Wearie, Edinburgh	Single storey detached cottage from early 19th century with an addition to the east dating from c 1880, category B listed. Sandstone rubble, bound with lime and finished with ashlar quoins and margins	Yes	Blown cellulose; blown aerogel (bead type high performance silica product) trialled on the second wall; surface applied insulation (wind driven water penetration walls). 10mm layer of aerogel blanket used, secured to the wall behind an expanded mesh sheet and fastened with thermally decoupled fixings.	U-values from 1.3-1.4 to 0.6-1.0W/m2K after the insulation (U-values vary on walls)	(Curtis 2012)
7	Wee Causeway, Culross	Detached cottage house mid-18th century. Sandstone rubble masonry bound with lime, although repointed with cement in several areas	Yes	Aerogel blanket - 10mm thick aerogel blanket; calcium silicate board sand and lime treated; blown polystyrene bead	U-values walls: Ground floor from 1.5- 0.5 W/m2K and first floor 1.6- 0.9 W/m2K (U-values vary on walls)	(Jenkins 2012a)
8	Sword St, Glasgow *	Four-storey tenement property with a ground floor retail accommodation and upper three floor containing two flats each. Sandstone rubble masonry with brick internal partitions dated 1890. External walls U-v 1.1W/m2K	Yes	Six internal insulation measures trialled: Blown polystyrene bead; blown cellulose; hemp fibreboard; wood fibreboard; 40mm and 50mm thick aerogel board and synthetic porous material finished with skim plaster coat.	U-values from 1.1 to 0.19-0.37W/m2K (varies per insulation type); average humidity over 18-month monitoring period on probes at 50mm depth of the wall thickness (RH=14.3-66.6%) and at the interface between insulation and wall (RH=14.8-65.2%) (RH varies per insulation type)	(Jenkins 2012b)
9	Kildonan, South Uist	Mass masonry building c 1935 of cement mortar whinstone rubble	Yes	Wood fibreboard insulation (wall linings had decayed- so retention was impractical); calcium silicate board insulation.	U-values from 1.1 to 1.0 W/m2K (ground floor, wood fibreboard) and 0.4 W/m2K (first floor, calcium silicate board)	(Jenkins 2012c)

Case study		Description	Wall ins	Description of the retrofit works	Measure of improved performance	Reference
10	Scotstarvit cottage, Cupar	Cottage late 19th century detached cottage. Built of roughly squared sandstone rubble bonded with lime mortar. Internally it is lined with lath and lime plaster on timber battens with a timber suspended floor. In some areas the plasterboard had replaced the lath and plaster	Yes	Walls: perlite poured in between all the uprights ; ceilings: Lath and traditional haired lime plaster finished with clay paint; floor: hemp-fibre batts and solum isolated using a geotextile breathable membrane	No U-values after the retrofit (before the retrofit 1.6W/m2K). Airtightness pre retrofit 16.9 and after 10.7m3hm2 at 50Pa	(Snow 2012)
11	Garden Bothy, Cumnock	Two-storey building. Sandstone rubble masonry except for rear elevation lined on the outside with brick, forming part of the walled garden. Originally all internal walls were lined with lath and plaster. Not totally derelict but in need of repair (enabling works)	Yes	Hemp insulation and clay board; 50mm hemp board between the timbers; 80mm wood fibre insulation finished with clay board, plaster and paint; blown cellulose (26mm diameter holes every 20mm blown dry behind the wall lining on 30-40mm depth of cavity	No results comparing pre and post-performance of walls. Moisture monitoring to be published.	(Jenkins 2012d)
SPAB Building Performance Survey						
12	116 Abbey Foregate, Shrewsbury **	End terrace two storey house with attic, c 1820. Brick with plain tiled roof with elements of timber framing and modern single storey extension	Yes	Internal insulation of all external walls on the ground and first floor with woodfibre board (except for the rear single storey extension) and fitting of secondary double-glazing to ground and first floor sash windows on the front elevation.	U-value improvement from 1.48-0.48 W/m2K (in situ)	(Rye and Hubbard 2012; Rye and Scott 2012)
13	Firs, Riddlecombe **	Two storey semi-detached 19th century cob cottage with an early 20th century single storey addition in cob, new timber double-glazed units	Yes	External cement render, repair and re-render of walls with insulating lime render. Internal gypsum plasters were replaced with lime and limewash finishes.	U-value improvement from 0.76-0.72 W/m2K (in situ)	(Rye and Hubbard 2012; Rye and Scott 2012)
14	Mill House, Drewsteignton **	Barn built in granite from the 19th century or earlier, converted to a dwelling in 1970s with a modern extension added on the south east. UPVC double glazed windows.	Yes	No major refurbishment works have been applied in this building but in 2011 it was internally insulated with PIR insulation	U-value improvement from 1.2-0.16 W/m2K (in situ)	(Rye and Hubbard 2012; Rye and Scott 2012)
Shropshire Council, Marches Energy and Intelligent Energy Europe (see SECHURBA Guide)						
15	Albert St	Victorian terraced house situated in conservation area	Yes	60mm of Diffutherm insulating board	U-values from 2.1 - 0.55 W/m2K	http://www.sechurba.eu/files/34%20Albert%20St_Shrewsbury_UK.pdf

Case study		Description	Wall ins	Description of the retrofit works	Measure of improved performance	Reference
16	St Alkmund's Church	Grade II listed building. Heat loss modelling identified 21 % loss through the roof	No	250mm insulation added on the roof	Heat loss from 21 to 1% through the roof	http://www.sechurba.eu/files/WP4%20D10_audits%20st%20alkmunds%20church.pdf
17	Cottage in Greyfriars, Shrewsbury	Listed cottage from the 14th century	Yes	The exposed stone work inside was originally rendered, it could be plastered again with an insulating plaster material such as Hemp or Lime or EcoRender Plus	Estimate reduction 1.89-1.56 W/m2K on wall if 20mm coat of Eco-render plus is applied.	http://www.sechurba.eu/files/St%20Julia's%20Greyfriars_Shrewsbury_UK.pdf
18	Shrewsbury Library	Listed building from the 15h century	No	Silicon-based gel draught proofing system Quattroseal installed around 90% of windows	Monitoring of fuel bills over the winter of 10/11, no results included in the publication. Air leakage improvement of 14-30% (varies on different rooms)	www.shropshire.gov.uk/.../sustainable-energy-communities-in-historic-urban -areas/
				Changeworks		
19	Lauriston Place, Edinburgh	B listed Georgian tenement (1820s)in a conservation area, world heritage site, social housing	No	Energy efficiency measures: secondary glazing, draughtproofing, shutter reinstatement, floor insulation, A rated boilers, loft insulation, low energy lighting, smart monitors, domestic energy advice. Solid wall insulation was not applied due to cost, risk (breathability) and conservation issues.	CO_2 reduction from 6.5 - 5.4 tonnes/y (estimated on NHER)	
				TSB Retrofit for the future		
20	Lena Gardens	1870s Victorian terrace house in a conservation area in West London, 195m2	Yes	n/a	Metered energy use (89% savings) after implementing several strategies including wall insulation	(Borgstein et al 2011)
*****	Compares the performance of different insulation measures resulting in different post-retrofit U-values (case 8)					
******	Includes the estimation of U-value by simulation before and after the intervention and the monitoring of indoor environment parameters (case studies by SPAB Building Performance Survey)					

Some key conclusions can be drawn from the case studies:

- The retrofit strategies in the case studies were informed by an understanding of the existing condition of the fabric. Wall insulation is likely to be carried out in combination with other measures to improve the performance of the windows and the airtightness. In some cases, the insulation of walls is incompatible with overall conservation and reversibility[28] principles; thus, insulation is deemed unviable (cases 8, 15, 18 and 19).
- The materials used to insulate the walls were compatible with the existing materials in terms of breathability properties, such as wood fibreboard, calcium silicate board, sand and lime, polystyrene beads, and cellulose insulation.
- Retrofit works require detailed care in the construction work (e.g. monitoring of onsite work, and the use of thermographic surveys when insulation is blown into cavities).
- The indicators monitored before and after the intervention were the U-values, moisture content in the wall and factors of the indoor air environment (relative humidity, temperature, CO_2 levels), air leakage, and the heat loss reduction.

The case studies by Historic Scotland compare the performance of different insulation materials. The investigation monitors the U-value improvement and the moisture content of the walls that received the intervention. Table 12 below shows the performance of the insulation strategies:

Table 12: Pre- and post-retrofit U-values for different insulation types.

Insulation Type	Method of Installation	Unimproved U-value	Improved U-value
80mm Wood fibre	*Applied between timber framing*	*1.1*	*0.19*
100mm Hemp board	*Applied between timber framing*	*1.1*	*0.21*
40mm Aerogel board onto metal straps	*Applied onto metal straps*	*1.1*	*0.22*
100mm Cellulose fibre	*Sprayed damp onto masonry*	*1.1*	*0.28*
50mm (approximately) Bonded polystyrene bead	*Blown behind existing wall lining*	*1.1*	*0.31*
30mm Aerogel board	*Applied onto metal straps*	*1.1*	*0.36*
100mm Wood fibre	*Applied between timber framing*	*2.1*	*0.4*
50mm (approximately) Cellulose bead	*Blown behind existing wall lining*	*1.3*	*0.6*
10mm Aerogel blanket	*Applied directly to masonry*	*1.6*	*0.9*
50mm Calcium silicate board	*Applied directly to masonry*	*2.1*	*1*

[28] That the construction can be restored to its original condition.

5.6 Balancing energy efficiency and conservation concerns

A number of guidance documents for the retrofit of heritage buildings have been published by English Heritage, Historic Scotland (case studies and guidelines), STBA and SPAB. Local councils have also published their own documents, usually referring to the work by these organisations.

In general terms, the publications offer guidance and recommendations for the energy efficiency retrofit of heritage buildings in relation to:

- concepts and principles of conservation (compatibility, reversibility, maintenance);
- motivation, concepts and principles of energy efficiency (reduction of energy use, improvement of indoor environment);
- relationship between energy efficiency and conservation;
- preservation of the character of the buildings;
- need to understand how the fabric, ventilation and heating regime of heritage buildings work in order to propose retrofit measures that are compatible with the pre-existing conditions; and
- risk of uninformed or incompatible interventions that could produce the accelerated decay of the structures, affect the moisture balance and create moisture and damp problems.

These findings will need to be considered and incorporated into any suggested improvements to the assessment process for solid wall insulation, that are formulated as part of this project, with particular attention on the knowledge required by ECO and Green Deal Assessors.

Apart from the general focus on delivering energy efficiency measures, it is important to consider general conservation principles when proposing retrofit intervention on heritage buildings. English Heritage (2012a) proposes energy conservation strategies for heritage buildings that will minimise the disturbance to the existing fabric and take into account the intrinsic quality and behaviour of the building and its parts. People undertaking energy efficiency works should consider compatibility between the existing conditions and the proposed measures, the reversibility of the intervention and the maintenance needs to preserve the building after the intervention. English Heritage (2012a) recommends that energy efficiency interventions can be considered at the following three levels:

1. Large scale: the whole building performance should be evaluated in relation to heating, ventilation, insulation and energy efficiency.

2. Medium scale: the localised performance variation around the building, for example from room to room and in terms of orientation.

3. Small scale: the junctions between existing elements and the different types of insulation that could be used.

As mentioned earlier, the walls of heritage buildings tend to have high hygroscopic properties which need to be taken into account to avoid compromising the existing fabric. The literature emphasises that the application of any non-breathing material to an older porous wall compromises the ability of the existing material to breathe and regulate moisture and air levels (Changeworks 2008). If moisture is trapped inside the wall, damp and structural damage occur. “The insulating material and installation method are critical for improving the thermal efficiency of walls” (Changeworks 2008). It is recommended that insulating materials are breathable and compatible with the other wall materials. Correct installation methods are crucial to achieve the required results and to diminish the risks associated with the insulation application, for example, to avoid cold bridges at junctions, such as between the walls and floor or ceiling (English Heritage 2012a).

The guidance by English Heritage emphasises that materials used in repair and maintenance must be selected with care: “Modern impermeable materials, not just vapour control layers, but cement renders, plasters and pointing and many modern paints will impair the breathable performance and will tend to trap moisture." An evaluation of the existing conditions should assess aspects such as:

- thermal mass;
- environmental influences (micro-climates of different orientations);
- existing damp problems (decay in timbers in contact with wet masonry, deterioration of the external fabric of the wall due to freezing and thawing, movement of salts, movement of tars and other chemicals through the walls that stain the surface); and
- growth of mould on the inside surfaces of walls.

English Heritage (2012a) suggests that in principle, the interventions should opt for an increased breathability progressively from interior to exterior, especially for materials such as stone, brick, timber and earth-based materials. It highlights the importance of permeability, warning that modern impervious materials are detrimental to the traditional fabric because they get glued to the original materials and cause localised areas of dampness. However, there are grounds for some caution in applying insulation internally even when the materials used are claimed to allow the wall to breathe, as has been discovered in recent *in situ* studies such as those described below.

The guidelines by English Heritage (2012a) suggest that, in general for a traditional building, the retrofit strategies are likely to be prioritised as follows (greatest energy savings at lowest risk of damage and decay when compared to the investment costs):

- draughtproofing of windows and doors;
- roof insulation;
- replacement of outdated services with high efficiency units and updated controls;
- repair of shutters and fitting of curtains, with the possible installation of secondary glazing;
- floor insulation;
- wall insulation.

Due to the uncertainties and dispersed knowledge about the effects of insulation of walls, solid wall insulation appears to be one of the least preferable retrofit measures for heritage buildings. The literature and empirical research in the field suggest the need for detailed studies supported by appropriate expertise, adequate care during construction and careful monitoring of post-retrofit performance. In summary, the guidance by Historic Scotland, English Heritage and the research by STBA and SPAB recommend the careful surveying of the pre-existing conditions of the buildings. The retrofit of the building should be informed by criteria of compatibility and minimum intervention to reduce the risk of unintended consequences[29].

[29] Chapter 4 of this literature review; unintended consequences, covers in detail potential problems caused by energy efficiency interventions. Some publications have covered in detail the topics of mould growth, such as Sedlbauer (2011); the deterioration of the indoor air quality and the indoor environment in relation to retrofit work on existing buildings (Halliday 2009; Hobday 2011). Altamirano-Medina et al (2009) suggest legislative safeguards to avoid the risk of mould formation. The project CALEBRE (Consumer Appealing Low Energy Technologies for Building Retrofitting) draws attention to the risk of summer overheating after the application of internal insulation due to the reduction of the thermal mass benefits of temperature and humidity buffering (Loveday et al 2011).

5.7 Conclusions and recommendations

Heritage buildings are complex systems that exhibit a delicate equilibrium between thermal mass, air leakage, building envelope properties and heating regime. The literature review reveals many unknowns and uncertainties about the interconnections between these aspects and their individual and combined effect on the performance of the buildings. Some of the knowledge gaps include:

- limited validity of many current standards and models—specifically, BS 5250, BS EN 13788, and the Glaser method—to assess hygrothermal performance; the need to fully consider changing the standard for assessing condensation risk to EN15026, and the interventions that would need to be set in place for that to happen i.e. UK weather data availability, and accurate material databases on typical UK materials.
- uncertain and varying values of thermal conductivity for traditional materials (the discrepancies between the U-values measured in situ and values embedded in the databases of traditional materials used by models to determine the building performance);
- air permeability and ventilation rates in heritage buildings and how the pre-existing ventilation conditions are related to the specific hygrothermal characteristics of the envelope (U-values, breathability, moisture transport within and throughout wall build-ups);
- uncertainties about the medium and long-term consequences of applying insulation to solid walls made of traditional materials—the change in the performance of the envelope could lead to changes in the whole building performance (balance of moisture, hygrothermal performance), in the indoor environment conditions (mould formation, deterioration of indoor environment quality, overheating risk) and in the overall building condition (decay and damage).

The guidance and the research presented here highlight the need to understand the pre-existing conditions and characteristics of heritage buildings when proposing energy efficiency retrofits to ensure compatibility between the existing and the new and to prevent damage and deterioration. This is particularly relevant for the implementation of insulation on solid walls due to the complexity of moisture transport within and across the wall build-up, the hygrothermal performance of traditional materials, the breathability of the envelope and the relationship of those aspects to the overall performance and physics of heritage buildings.

There is an urgent need to consider how the knowledge gained about the *in situ* performance and post-retrofit monitoring studies could inform and improve the standards, performance models, methods and guidelines used by the building industry for determining the performance of the building and building elements; and, enhance the data about traditional materials embedded in databases. From the few detailed *in situ* studies that exist, there are enough warning signs to suggest that insulating external walls either externally or internally can lead to undesirable consequences when not done with proper consideration of the factors presented here. Further studies are needed before a large scale roll-out of wall insulation for heritage buildings can be recommended.

Finally, retrofit work should balance the different aspects concerning heritage buildings: conservation principles, an improvement in energy performance and the indoor environment, the role of occupants in energy consumption reduction and a reduction of existing decay and damage. Therefore, research on the performance of heritage buildings should be disseminated to the building industry, planning and building control authorities to increase their knowledge about the considerations and risks associated with retrofit works. The current premise of setting minimum acceptable performance levels when retrofitting as part of the Building Regulation requirements may need to be re-assessed, if the likelihood of a mandatory standard results in the creation of unintended consequences, by requiring buildings to improve above their technical capabilities.

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Chapter 5 - Heritage and conservation

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Appendix A UK housing stock statistics

Each member country of the UK reports individually on its dwelling stock. This has historically been done using a sample stock condition survey which is run annually in the case of England and Scotland and periodically in the case of Wales and Northern Ireland. The data collected can be used to describe the characteristics of the UK stock.

Table 13 - Stock age by UK member country

Stock Age	England (2007)	Scotland (2008)	Wales (2008)	N Ireland (2006)	Total	% of UK
Pre 1919	4,766,000	433,000	440,000	114,000	**5,753,000**	22%
1919 - 1944	3,864,000	331,000	155,000	71,000	**4,421,000**	17%
1945 - 1964	4,345,000	531,000	349,000	141,000	**5,366,000**	20%
1965 - 1980	4,806,000	543,000	97,000	169,000	**5,615,000**	21%
Post 1980	4,409,000	492,000	290,000	210,000	**5,401,000**	20%
Total	**22,190,000**	**2,330,000**	**1,331,000**	**705,000**	**26,556,000**	100%
% of UK	84%	9%	5%	3%	100%	

Further investigation of the relevant countries' stock condition surveys gives a greater insight into the range of solid wall types within the UK. Table 14 to Table 17 below provide more detail for each country of the UK. The number of dwellings with each predominant type of wall structure is shown for a range of age bands. It can be seen that the majority of solid walled dwellings were constructed before World War II and the majority of those before World War I. It should be noted that the stock condition surveys in England, Wales and Northern Ireland all share a common methodology and so the outputs are comparable. Scotland uses a different methodology and so although similar, the age bands and wall type categories do not match precisely. Where the underlying sample for a particular cell is so small that the figures are not meaningful the information has been replaced with an asterisk.

Table 14 - Wall structure by dwelling age; England

Predominant type of wall structure	Dwelling age					
	Pre 1919	1919 - 1944	1945 - 1964	1965 - 1980	Post 1980	Total
Masonry cavity	687,000	2,228,000	3,773,000	4,437,000	4,233,000	**15,358,000**
Masonry single leaf	30,000	12,000	10,000	15,000	22,000	**89,000**
9 inch solid	2,569,000	1,386,000	218,000	26,000	10,000	**4,209,000**
Greater than 9 inch solid	1,187,000	125,000	41,000	11,000	13,000	**1,377,000**
In situ concrete	*	13,000	112,000	73,000	5,000	**203,000**
Concrete panels	*	7,000	127,000	88,000	*	**222,000**
Timber panels	27,000	10,000	17,000	105,000	75,000	**234,000**
Metal sheet	*	*	15,000	9,000	19,000	**44,000**
Mixed types	262,000	88,000	42,000	48,000	11,000	**451,000**
Total	**4,762,000**	**3,870,000**	**4,355,000**	**4,812,000**	**4,388,000**	**22,187,000**

Table 15 - Wall structure by dwelling age; Scotland

Predominant wall structure	Dwelling age					
	Pre 1919	1919-1944	1945-1964	1965-1982	Post-1982	Total
Masonry cavity	*	255,000	449,000	438,000	254,000	**1,397,000**
Up to 18 inch solid	48,000	30,000	12,000	*	*	**91,000**
More than 18 inch solid	390,000	24,000	5,000	*	*	**419,000**
All concrete	*	*	41,000	64,000	*	**110,000**
Timber	*	*	13,000	41,000	226,000	**283,000**
Metal	*	*	13,000	*	*	**20,000**
Mixed types	*	*	*	*	*	**7,000**
Total	**439,000**	**317,000**	**535,000**	**546,000**	**490,000**	**2,327,000**

Table 16 - Wall structure by dwelling age; Wales

Predominant type of wall structure	**Dwelling Age**					
	Pre 1919	**1919 - 1944**	**1945 - 1964**	**1964 - 1980**	**Post 1980**	**Total**
Masonry cavity	29,000	110,000	202,000	220,000	207,000	**768,000**
Masonry single leaf	*	*	*	*	*	**5,000**
9 inch solid	100,000	14,000	5,000	*	*	**119,000**
>9 inch solid	199,000	10,000	*	*	*	**214,000**
In situ concrete	*	*	18,000	8,000	*	**28,000**
Concrete panels	*	*	14,000	5,000	*	**21,000**
Timber panels	*	*	*	6,000	5,000	**14,000**
Metal sheet	*	*	*	1,000	*	**5,000**
Mixed types	29,000	*	*	*	*	**38,000**
Total	**361,000**	**138,000**	**249,000**	**245,000**	**219,000**	**1,212,000**

Table 17 - Wall structure by dwelling age; Northern Ireland

Predominant type of wall structure	Dwelling Age					
	Pre 1919	**1919 - 1944**	**1945 - 1964**	**1965 - 1980**	**Post 1980**	**Total**
Masonry cavity	13,000	43,000	134,000	163,000	208,000	**561,000**
Masonry single leaf	*	*	*	*	*	*****
9 inch solid	40,000	25,000	*	*	*	**66,000**
>9 inch solid	49,000	*	*	*	*	**54,000**
In situ concrete	*	*	*	*	*	**9,000**
Concrete panels	*	*	*	*	*	*****
Timber panels	*	*	*	*	*	*****
Metal sheet	*	*	*	*	*	*****
Mixed types	*	*	*	*	*	**9,000**
Total	**109,000**	**74,000**	**143,000**	**168,000**	**209,000**	**703,000**

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