Technical Paper 19

HISTORIC SCOTLAND
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MONITORING THERMAL UPGRADES TO TEN TRADITIONAL PROPERTIES

John Currie, Julio Bros Williamson & Jon Stinson

Edinburgh Napier
UNIVERSITY

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Historic Scotland Technical Paper 19

MONITORING THERMAL UPGRADES TO TEN TRADITIONAL PROPERTIES

John Currie, Julio Bros Williamson & Jon Stinson

Introduction

by Historic Scotland

This Technical Paper sets out the pre- and post-intervention monitoring work carried out by The Scottish Energy Centre (SEC) at Edinburgh Napier University for Historic Scotland as part of the energy efficiency refurbishment pilot programme on traditional and historic buildings.

The measurements were concerned with quantifying the thermal improvements achieved by the upgrade measures, and as such follow a before and after sequence. While hygrothermal monitoring is ongoing in several of the Historic Scotland pilots (Wells O Wearie, Cumnock and Newtongrange) that aspect of the monitoring work is a longer-term process (over a 12 to 24 month timeframe) and will be a part of a separate study.

Details of the site work at the locations discussed are discussed further in the Refurbishment Case Studies published by Historic Scotland. The results in this paper contribute to the increasing evidence available on the thermal performance of traditional building elements. This will be a useful contribution to a knowledge base, which can be used towards the development of suitable energy performance modelling tools for older buildings in the future.

About the authors

John Currie is Director of the SEC at Edinburgh Napier University and Fellow and Chairman of the Energy Institute in Scotland. A chartered engineer with over 30 years' experience in teaching, research and practice, John was formerly Chief Engineer at a brewery. Widely published, his research interests currently include improving building energy and environmental performance, monitoring and modelling pollution in the urban environment, and the development of novel renewable energy technologies. He presently co-chairs the Scotland 2020 Climate Group, recently launching 'Retrofit Scotland', and sits on the Engineering Accreditation Board of the Engineering Council.

Julio Bros Williamson is an energy and building consultant with the SEC. He has been educated as an architect at the Marista University in Mexico City and an MSc in Energy Efficient Building at Oxford Brookes University. He has been a chartered Mexican architect since 2003. At SEC he has been a firm contributor to the renewable, energy efficiency and the sustainability sector, involved in post-occupancy evaluation of domestic buildings. Julio is a Director at the Scottish Ecological Design Association and the Scotland 2020 Climate Group as an advisor to the Scottish Government.

Jon Stinson graduated from Edinburgh Napier University in 2007 with an honours degree in Architectural Technology. He joined the SEC as a research assistant after completing a research degree in low carbon strategies and SMART technology. During this time, he was involved with monitoring the impact of energy awareness technology on the social and behavioural aspects of domestic energy use, addressing fuel poverty and the carbon reduction agenda. Jon currently works in the field of thermal performance of historic buildings and performance evaluation of newly built low and zero carbon homes.

Contents

1. Introduction

This report describes the work conducted by the SEC at Edinburgh Napier University for Historic Scotland, measuring the U-value, or thermal transmittance, through elements of traditionally constructed buildings. These measurements are a recognised indication of the thermal performance of a building element.

The U-value is an indicator of the heat transfer through each square metre of a building element, for a given temperature gradient, measured in watts per metre squared, per Kelvin [W/(m^2 K)].

The properties featured in this report are typical examples of pre-1919 construction types in Scotland. All of the properties are of traditional construction (solid walls), and some properties are listed. Most are constructed from lime-bonded rubble or ashlar stonework, typically 400 to 600 mm thick, with natural slate or tile roofs, timber windows and doors. The properties in the report were part of the Historic Scotland Refurbishment Case Studies and represent a range of building types from across Scotland.

This Technical Paper describes a study assessing in situ measured U-values from a range of traditional building elements and components, namely walls, floors, ceilings, coombs and timber doors and windows. After measuring the U-value of the original building envelope, each property underwent thermal upgrading in the form of insulating materials being added to various elements. After thermal upgrading, the U-value was measured again, the object being to compare the pre- and post-intervention U-values and quantify the thermal improvements.

In the following sections, the methodology that was used for the testing of U-values in situ is explained (Section 2) and the fabric interventions used to improve the thermal performance of the buildings are outlined (Section 3). The ten case studies are then described, including the interventions carried out and the pre- and post-intervention U-value results (Section 4). The report finishes with an analysis of the U-value measurement data (Section 5), before drawing conclusions (Section 6).

Other work conducted by the SEC relating to the thermal transmittance values of Scottish properties are published in Historic Scotland Refurbishment Case Study 1 (Historic Scotland, 2012).

2. Methodology

The methodology for measuring the in situ U-value was undertaken in the well established format described in Baker (2008), Baker (2011) and Rye (2011). The U-value, or thermal transmittance, of a building element or component is defined in BS EN ISO 7345:1996 as the "*heat-flow rate in the steady state divided by the area and the temperature difference between the surroundings on each side of a system*." (BSI, 1996, p.5).

2.1. In situ U-values

The in situ U-value measurements were taken using a Hukseflux HFP01 thermopile-based heat flux transducers (Fig. 1) of 80 mm diameter and 5 mm thickness. These were attached to each building element throughout the monitoring period (typically less than 2 weeks duration). When possible and where equipment availability allowed, two such devices were co-located in order to verify the accuracy of the measurements and to provide protection against potential equipment failure.

The elemental U-values were determined by recording the heat-flow through the element together with internal surface and external air or surface temperature. This was done by logging differential voltage from the heat flux transducers and temperature from calibrated K-type thermocouples (Fig. 2).

Fig. 1 Heat flux transducer (heat-flow mat) mounted to the wall face

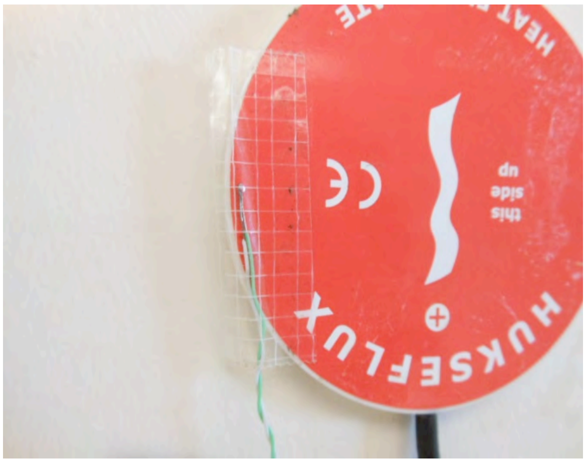


Fig. 2 K-type thermocouple mounted to face of heat flux transducer

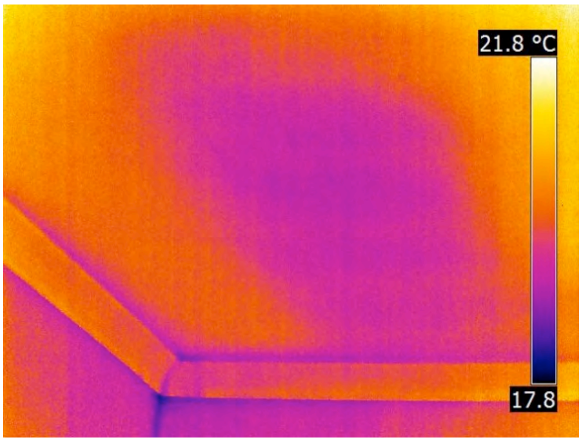
Grant Squirrel data loggers with 24 bit A-D conversion resolution (Fig. 3) were used to log data from the heat flux transducers and the thermocouples. Where required, Tinytag temperature / humidity loggers (Fig. 4) were used for locations where it was not possible to run cabling back to the main data logger.

Fig. 3 Grant Squirrel data logger to log data from heat flux transducers and thermocouples

Fig. 4 Stand-alone Tinytag View2 data logger measuring air temperature and relative humidity

2.2. Thermography

Infra-red thermography was used in several sites to locate areas of significant temperature differences and inhomogeneous construction elements. The thermographic infra-red camera also assisted with ensuring that the sensors were not placed on cold bridges, by identifying the location of timber studs. Fig. 5 and Fig. 6 show examples of a thermographic image using different colour palettes. Fig. 5 shows an internal corner junction of a room ceiling, identifying the thermal gradient across the elements. A stud detector was also used to assist with the optimal placement of the heat-flow mats.



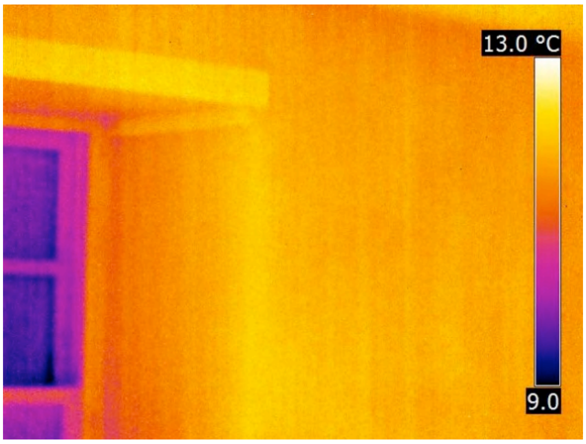


Fig. 5 Example of a infra-red image, showing temperature differential across a ceiling before intervention

Fig. 6 Infra-red image showing a homogeneous temperature gradient across a wall after intervention

2.3. Error analysis of in situ measured U-values

The certainty of the measured in situ U-values is influenced by sensor related errors. The sensitivity of the sensor or probe will impact on each recorded value during the period of monitoring. Calculating the uncertainty related to temperature probes and heat-flow mat allows for an error range to be found, which provides a ± value indicating the level of uncertainty derived from the individual temperature and heat flux measurements. An error analysis for the results from each case study has been calculated by using the established error analysis methodology described in Baker (2011). The results are presented in sections as part of the data analysis of U-value measurements (Section 5).

3. Fabric Interventions

Throughout this report, reference is made to the post-intervention monitoring which took place after insulation was added to the existing structure or element, with the aim of improving the thermal performance (and thereby reducing the u-value) of the respective element in order to improve the occupant's thermal comfort and reduce energy usage.

When applying insulation materials to traditional buildings, a number of options are available. Selecting the appropriate materials, location and application of insulation for older buildings will depend on several factors, including the condition and historic significance of internal linings and finishes, the available budget and the level of disruption that the occupant is willing to tolerate during the works.

3.1. Walls

Traditionally constructed walls in Scotland are usually 400 to 600 mm thick, and built with either rubble or dressed stones bedded in lime mortar with a rubble-mortar core. The wall is often finished internally with lath and plaster lining with a 30 to 50 mm air gap between the lining and stone wall (Fig. 7). In some areas walls are plastered directly onto the stone, 'on the hard', although this is less common in most domestic buildings. For the case studies in this report, a number of different approaches to improving the U-value of the walls were taken. These trial intervention methods broadly fell into three categories and depended upon the presence and condition of the internal lining:

1. An insulation blanket or board fixed to the face of the internal lining (Fig. 8)
2. Loose fill or blown insulation inserted into the gap between the lining and wall. This is an option where internal timber finishes, cornicing and window details must be retained or where it would be difficult to apply materials to the face of the linings (Fig. 9)
3. Original lining removed and rigid insulation added around the framework, then new or original lining re-attached. Fig. 10 shows the placement of insulation on the hard, where no internal lining exists or the internal lining was in a state of disrepair.

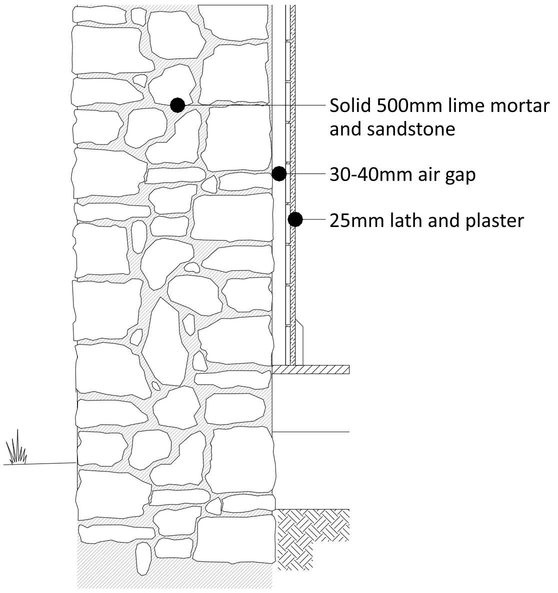


Fig. 7 Wall detail before adding insulation; this wall type was typical of the properties assessed in this report

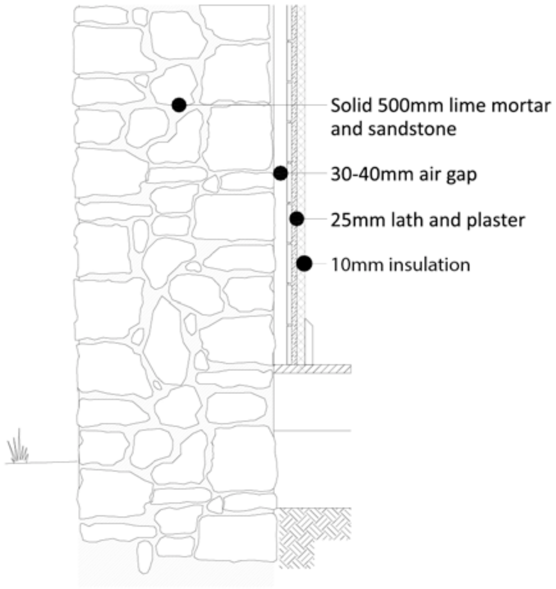


Fig. 8 Wall detail with insulation added to the face of the internal lining, thereby maintaining the air gap between the lining and stone face

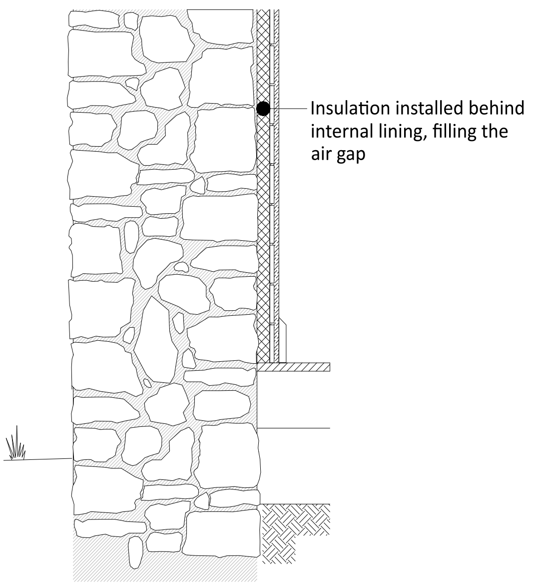


Fig. 9 Wall detail with insulation added between internal lining and stone face

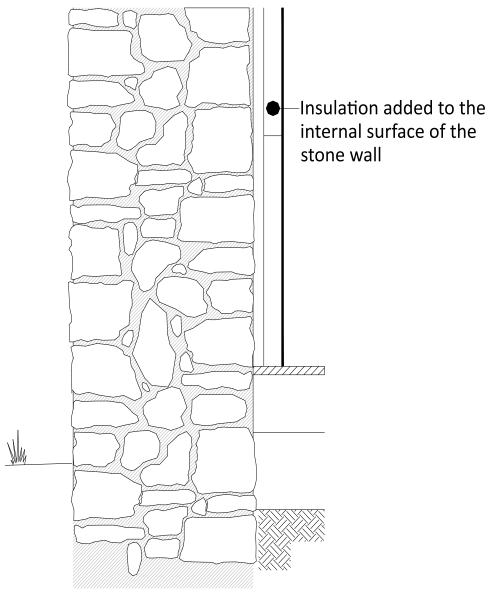


Fig. 10 Wall detail with rigid insulation added directly to the face of the original plaster finish

3.2. Roofs and ceilings

Adding insulation to the roof or ceiling has been shown to be a cost effective solution that can reduce the passage of heat and enhance the thermal performance of the roof. Whether it is applied between the ceiling joists (cold roof) or applied directly under the roof between the rafters (warm roof), the solutions appear to be simple, effective and relatively low risk with respect to condensation. Care has to be taken to maintain ventilation in order to reduce the risk of moisture accumulation.

3.3. Floors

The placement of insulation to reduce heat loss through the floor depends on the construction type. With suspended timber floors, insulation can be inserted between the joists, fixed by netting or, if rigid insulation is used, with battens that hold the insulation boards in place. Both solutions are cost effective, straightforward and technically viable, but can be disruptive for occupants. For solid stone or concrete floors, the available options are more limited. In one of the Refurbishment Case Studies (Kildonan, Uist) a thin, high performing insulation product was tested, laid directly on top of the existing concrete surface.

3.4. Windows

Traditional sash and case windows typically make up a substantial proportion of the external wall area, particularly in Victorian tenement buildings. Single glazed units have, on average, a U-value of about 5.8 W/(m^2 K). Improvements include applying secondary glazing, replacing single glazed panes with slim-profile double glazing units (retaining the original timber frames), and upgrading frames and draught proofing them. Trials of this nature have previously been carried out by Historic Scotland (Baker; 2008 and 2011).

Throughout the report reference is made to the elemental build-up of each structure in an attempt to provide some context and relationship between the structure and its measured U-value. However, traditional methods of construction associated with older buildings present specific challenges when attempting to define exact materials, thickness and their conditions.

It is difficult to make accurate comments on the materials within the multiple layered elements. A common example, as described by Rye (2011), is the proportions of materials within a solid stone wall (i.e. stone and mortar). The same can be said when describing the intervention methods. Although specified and instructed with reasonable levels of accuracy, issues with workmanship and application will still arise, especially when the insulation is applied blind, e.g. injecting or blowing insulation into cavities without removing the internal lining or when insulation materials are applied in a new manner.

4. Site reports

The site report presents, for each property, the U-values measured in situ pre- and post-intervention. Each site report covers the times and conditions experienced during the monitoring period, the building element or elements that were monitored, and the improvements that were undertaken. The pre- and post-intervention measurement results are presented in tables and the differences are discussed.

The results from the sites are collated in the data analysis Section 5, where they are categorised by building element and discussed based on the intervention method and material.

4.1. Wells o' Wearie, Edinburgh – A detached cottage

Heat-flow mats were positioned to monitor heat transfer through walls, floor, ceiling and window glass. Four heat-flow mats were attached to three walls during the pre- and post-intervention stages. The heat-flow mats were placed on the surface of the lath and plaster lining (Fig. 11): two heat-flow mats were added to the north wall on either side of the window, a single mat was added to the west wall and another to the east wall. A heat-flow mat was also added to the centre of the window (Fig. 12). The window glass, floor and ceiling were monitored in the locations marked in Fig. 13. Further details of the works undertaken are published in Refurbishment Case Study 2 (Historic Scotland, 2012).

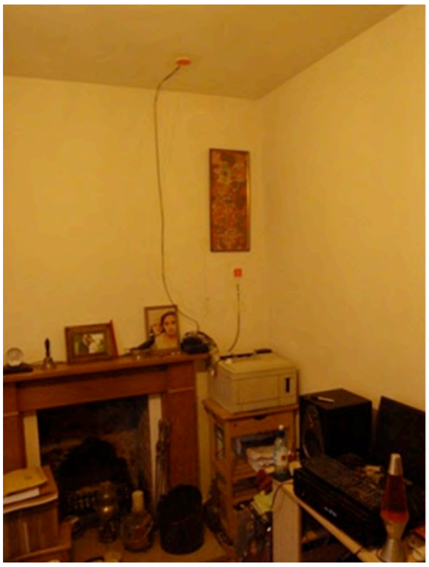


Fig. 11 Heat-flow mats on the wall and ceiling

Fig. 12 Heat-flow mats on the window glass and wall

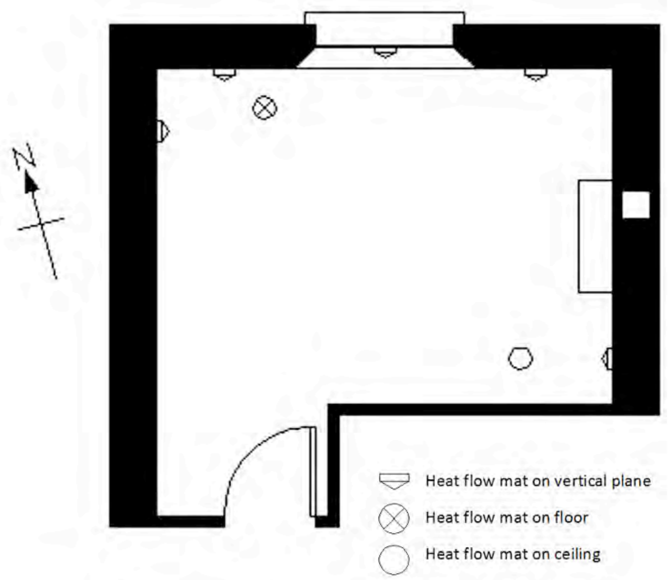


Fig. 13 Floor plan showing the location of heat-flow mats

The 19th Century cottage is located in Holyrood Park on a relatively sheltered site below the road level with mature deciduous foliage dressing the boundary of the site. Pre-intervention monitoring took place during October 2010 whilst the property was unoccupied. Data was logged at two minute intervals. External environmental conditions during the data collection period were monitored. The average outdoor air temperature was 8 °C and average relative humidity was 75 %.

The indoor climate was maintained through the use of space heaters and humidifiers. During this period the average internal air temperature was 18 °C at 49 % average relative humidity. The in situ measurements returned values, as expected for traditionally constructed elements, within the range of results from similar elements and those reported by other authors. Similar U-values were measured from all the walls in this property, ranging between 1.3 and 1.4 W/(m^2 K). The detailed U-value results are listed in Table 1.

During the pre-intervention monitoring phase, a thermographic survey was conducted to identify locations of anomalies in the internal fabric and to provide an indication of the thermal profile across the surface of various elements (Fig. 14 and Fig. 15). The latter figure shows the temperature gradient as captured by the infra-red camera. The bluer and darker areas indicate zones of lower surface temperature, representing a higher rate of heat loss through the building element, whereas the yellow through to red areas depict higher surface temperatures. The qualitative analysis of the thermograms captured during the pre-intervention testing shows a varying temperature gradient across the internal surface of the walls, ceiling and floor, with heat loss across the elements and at junctions.

Fig. 14 Photograph of the east wall pre-intervention, showing the junction between the east wall and ceiling

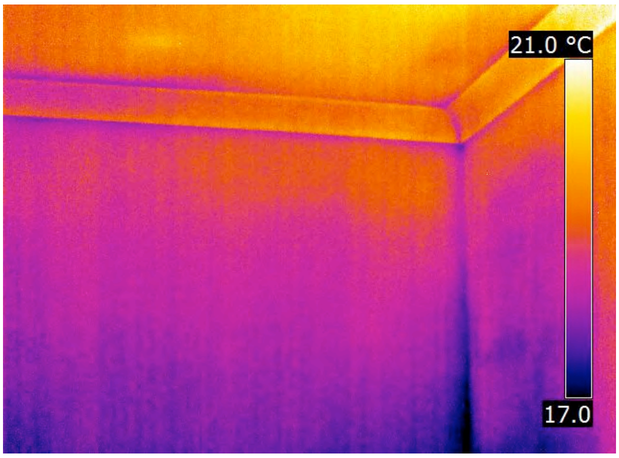


Fig. 15 Thermogram of the junction between the corner of the east wall and ceiling

Post-intervention monitoring was conducted during February and March 2012, during which time the property was furnished and temporarily unoccupied. The average internal air temperature was 15 °C at 60 % average relative humidity, and the average external air temperature during the monitoring period was 9 °C at 80 % average relative humidity. The monitoring probes were reinstated at the same locations as during the pre-intervention period. The measured pre- and post-intervention U-value results are listed in Table 1.

Table 1 Measured U-values for Wells o' Wearie cottage, Edinburgh

Ground floor: east room	Construction and intervention	U-value measured W/(m^2 K)	
		pre-intervention	post-intervention
Ceiling	Slate roof, timber rafters and ceiling joists, finished internally with lath and plaster Retrofitted with 200 mm sheep wool above original linings, laid between joists	1.4	0.2
Floor	Suspended timber floor joists with timber floor boards Retrofitted with 80 mm wood-fibre insulation batts	2.4	0.7
Wall, north (left of window)	600 mm sandstone wall, finished internally with lath and plaster, framed out on timber battens with a 40 mm cavity Retrofitted with shredded cellulose insulation, blown into 40 mm cavity	1.3	0.8
Wall, north (right of window)		1.3	0.6
Wall, west		1.3	1.0
Wall, east	As for north wall Retrofitted with 10 mm aerogel blanket added to surface of internal lining	1.4	0.7
Window	Single pane of window glass. Retrofitted with secondary glazing (magnetized acrylic sheet)	5.4	2.4

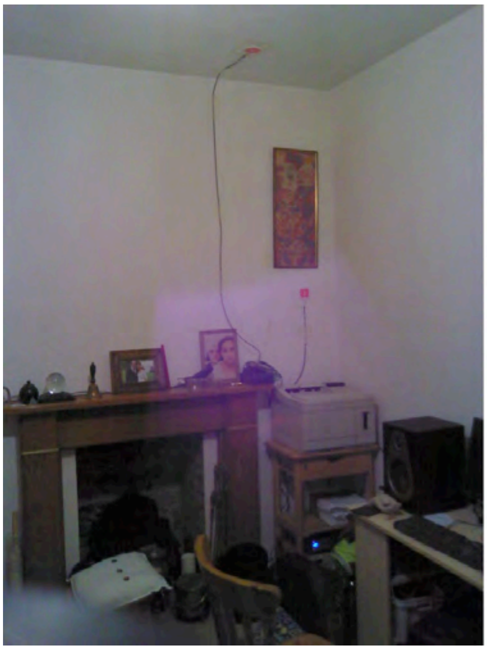
Two approaches were taken to improve the thermal performance of the walls: shredded cellulose material was blown in behind the wall lining on the north and east facing walls, and an aerogel blanket was applied to the internal surface of the west wall. The cellulose filled the 40 mm cavity between the lath and plaster finish and the masonry face, creating an insulated layer. The 10 mm aerogel blanket was attached to the surface of the lath and plaster and finished with a mesh liner and a skim coat of plaster. The post-intervention results presented in Table 1 show a reduced U-value for all the walls treated in this property.

The addition of 200 mm sheep wool insulation placed above the lath and plaster ceiling, laid between and above the ceiling joists, improved the U-value from a nominal 1.4 to 0.2 W/m^2 K. The suspended timber floor also showed an improvement; an original U-value of 2.4 W/m^2 K, which, after the wood-fibre insulation batts were fitted underneath the floorboards, dropped to 0.7 $W/(m^2 K)$.

Secondary glazing with magnetic tape securing a proprietary polycarbonate sheet to the inset of the window frame reduced the thermal transmittance from 5.4 $W/(m^2 K)$ to a value of 2.4 $W/(m^2 K)$, which is comparable to the U-value of a double glazed window unit.

The thermal performance investigation formed part of a wider investigation which includes assessing the hygrothermal conditions in the filled space behind the lath and plaster layer. Monitoring is on-going in the property to track the humidity variations. The data needed to obtain results for this investigation requires monitoring equipment to be in place for some time - years not months. The ongoing monitoring will provide more clarity on the heating and cooling pattern of the building element and the associated hygrothermal conditions within the building envelope resulting from its occupancy profile.

A thermographic survey was repeated during the post-intervention testing and focused on the same areas of the internal fabric as surveyed during the pre-intervention monitoring. Fig. 17 shows a infra-red image of the view in Fig. 16.



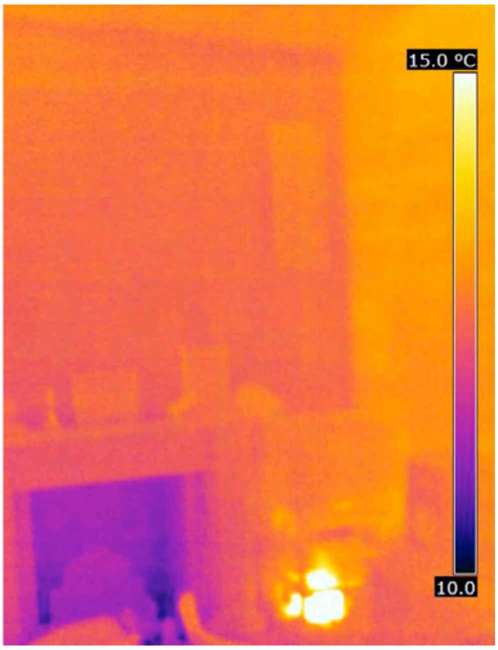


Fig. 16 Photograph of the east wall post-intervention, showing the junction between the south east wall and the ceiling

Fig. 17 Thermographic image of the junction between the corner of the east wall and ceiling

In comparison to Fig. 14, the pre-intervention image in Fig. 17 shows a more homogeneous colour profile across the surface of the walls and ceiling, which indicates the continuity of insulation across the building elements that were treated with additional insulation. Fig. 17 is representative of the images of the other walls and floor in the study. The thermographic results revealed no obvious cold spots or areas of contrasting temperature difference on the surfaces treated as part of the thermal upgrade project.

4.2. Wee Causeway, Culross – A detached cottage

Pre- and post-intervention in situ U-value measurements were taken from five building elements across two rooms in Wee Causeway, a two-storey 18th Century cottage in Culross, Fife and details of this can be found in Refurbishment Case Study 3 (Historic Scotland, 2012). On the ground floor, heat-flow mats were fixed to the surfaces of the west and south facing walls. On the first floor, the heat-flow mats were fixed to the west and north walls and the ceiling. Photographs of the mat placement are shown in Fig. 18 and Fig. 19, and the locations of the heat-flow mats are marked in Fig. 20.

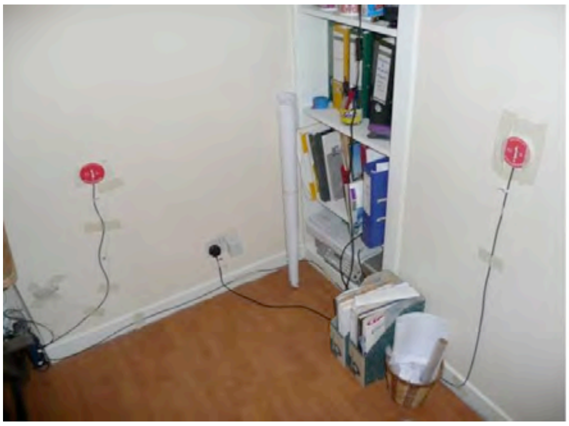


Fig. 18 Heat-flow mats in position on the ground floor

Fig. 19 Heat-flow mats in position on the first floor

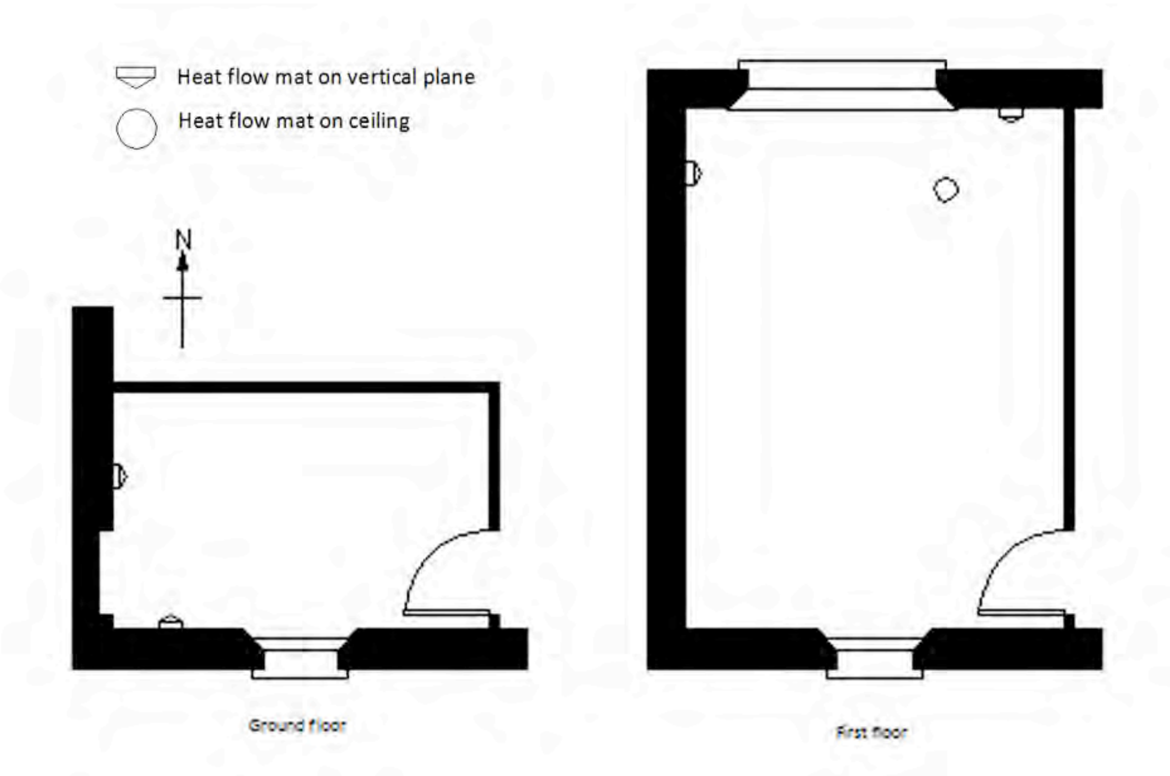


Fig. 20 Floor plan showing the location of heat-flow mats

The property overlooks the Firth of Forth and is in an elevated position with relatively high levels of exposure to the prevailing weather. The pre-intervention monitoring took place at the end of November 2010 whilst the property was occupied. The pre-intervention monitoring lasted 15 days, during which, the internal temperature averaged 13 °C and the relative humidity 53 %. The outdoor temperature averaged 5 °C, with temperatures dropping to 0 °C during the late evenings and overnight. The external average relative humidity was 76 %.

All the monitored walls in the property showed similar U-value results, ranging between 1.2 W/(m^2 K) and 1.6 W/(m^2 K). This range is typical for a solid stone wall with lath and plaster finish. The ceiling measurements also returned a U-value typical of its lath and plaster finish with 100 mm slumped mineral wool insulation. The pre-intervention results are presented in Table 2.

Data logging equipment was installed after the intervention measures had been completed; the probes were set up on the same elements as tested during the pre-intervention monitoring. The equipment was left in situ for 15 days during February 2012. The results are also displayed in Table 2. The property was furnished and often occupied. The recorded internal air temperature averaged 15 °C, with temperatures peaking at 23 °C. The average external temperature was 10 °C (which is higher than the seasonal average for February), and the external temperature dropped to 3 °C during the night.

Table 2 Measured in situ U-values for Wee Causeway cottage, Culross

Ground floor: west room	Construction and intervention	U-value measured W/(m^2 K)	
		pre-intervention	post-intervention
Wall, west	500 mm sandstone wall with lime plaster 'on the hard' Retrofitted with 30 mm calcium-silicate board	1.5	0.5
Wall, south		1.3	0.5
First floor: west room	**Construction and intervention**	**U-value measured W/(m^2 K)**	
		pre-intervention	post-intervention
Ceiling	Timber ceiling joists, finished internally with lath and plaster Retrofitted with 200 mm sheep wool above original linings, laid between joists	1.5	0.2
Wall, west	500 mm sandstone wall with lime plaster 'on the hard' Retrofitted with 10 mm aerogel blanket fixed to existing surface and plastered finish	1.2	0.9
Wall, north		1.6	0.9

The walls on the ground and first floor were insulated in different ways: the ground floor walls were insulated with calcium-silicate boards, while the first floor walls received 10 mm thick aerogel blankets, secured to the internal finish. Table 2 shows the U-value improvements for each wall. For the walls treated with calcium-silicate boards, the U-value improvement is between 0.8 and 1 W/(m^2 K). Less of an improvement was observed in the U-value for the walls on the first floor, insulated with aerogel. Sheep's wool was added above the ceiling laid between and on top of the timber ceiling joists, as a result the U-value improved from 1.2 to 0.2 W/(m^2 K).

4.3. Newtongrange, Midlothian – A terraced house

The property at Newtongrange is a brick built, 19th Century, mid-terrace former miner's cottage. The accommodation consists of a ground floor kitchen and living room, with bedrooms and a bathroom on the upper attic floor. The U-values of the coomb and the ceiling in the front bedroom were measured in this property as shown in Fig. 21 and Fig. 22. During the pre- and post-intervention testing, the building was occupied and the room was in use as a bedroom.

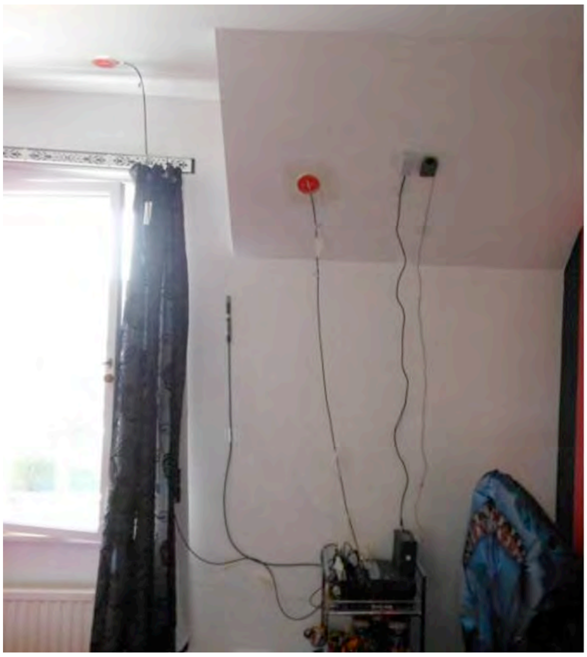


Fig. 21 Heat-flow mats on the coomb and ceiling

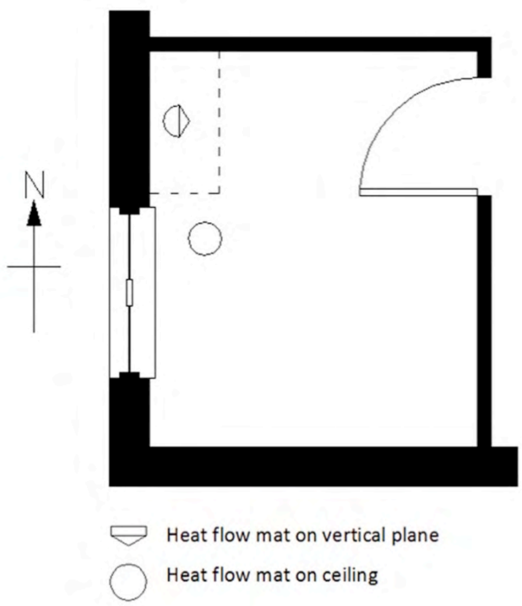


Fig. 22 Floor plan showing the location of heat-flow mats

U-value testing of the original building elements took place during December 2011. The same elements were retested in March 2012 after insulating material had been added. The measured U-value results are presented in Table 3.

Table 3 Measured in situ U-values for Newtongrange, Midlothian

First floor: West room	Construction and intervention	U-value measured $W/(m^2 K)$	
		pre-intervention	post-intervention
Coomb	Slates, timber sarking and timber rafters, finished internally with plasterboard Retrofitted with bonded polystyrene beads blown into the coomb cavity between the rafters	1.9	0.3
Ceiling	Unventilated attic with timber ceiling joists, finished internally with plasterboard Retrofitted with 240 mm sheep's wool above original linings laid between and above joists	1.6	0.4

During the pre-intervention monitoring, the average internal air temperature was 17 °C, fluctuating between 13 °C and 20 °C. The average relative humidity was 58 %, reaching 84% at various points during the 15 days. External temperatures averaged at 3 °C, dropping to 0 °C at times. The average external relative humidity was 88 %. Internal temperatures during the post-intervention stage averaged at 21 °C. The average external temperature was 11 °C dropping to 5 °C during the night.

4.4. Pleasance, Edinburgh – A top floor flat with mansard roof

Monitoring equipment was added to one room in an attic floor tenement flat in Edinburgh, with additional information available in Refurbishment Case Study 5 (Historic Scotland, 2012). During the pre- and post-intervention testing the property was occupied, and the room was being used as a living room. Heat-flow mats and temperature probes were attached to the coomb and the surrounding surfaces of a dormer window, as shown in Fig. 23 and Fig. 24.

Fig. 23 Heat-flow mats in position on the coomb and dormer

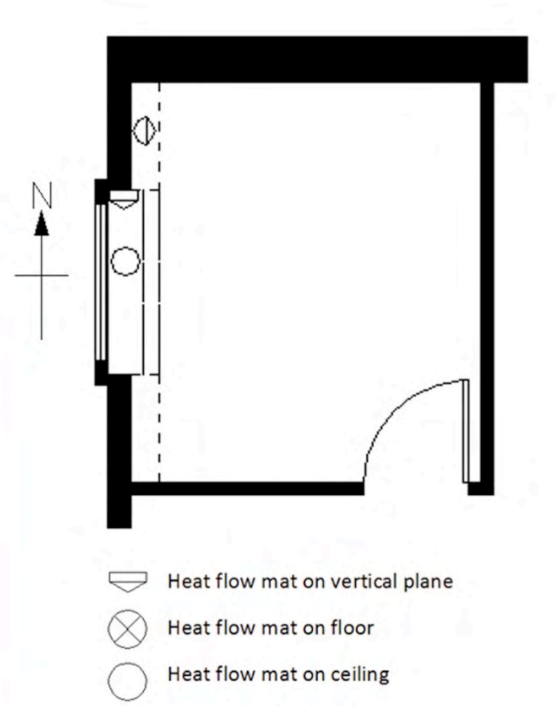


Fig. 24 Floor plan showing the location of heat-flow mats

The in situ U-value measurements of the original building elements were conducted in November 2011. The external temperature fluctuated between 2°C and 9 °C. Internally the temperature averaged at 19 °C, fluctuating +/-1 °C during the 15 day monitoring period. After insulating materials were added, the same testing regime was carried out during March 2012. The average internal air temperature was 18 °C, the external temperature varied from 3 °C to 10 °C. The measured pre- and post-intervention U-value results are displayed in Table 4.

Blown bead insulation was installed behind the internal lining of the coomb and into the dormer cheek and soffit. The attic was insulated with sheep's wool. The U-value of the dormer ceiling and coomb improved after the insulation was added. The performance of the dormer cheek was also monitored, and it returned a U-value of 0.9 W/(m^2 K) for the pre-intervention testing, indicating no change from the pre-intervention testing. Subsequent investigation revealed that the contractor had, in fact, not insulated the dormer cheek.

Table 4 Measured in situ U-values for the property at the Pleasance, Edinburgh

Second floor flat: west room	Construction and intervention	U-value measured $W/(m^2 K)$	
		pre-intervention	post-intervention
Coomb	Slates on timber sarking nailed to rafters, finished internally with lath and plaster Retrofitted with bonded polystyrene bead, blown into the coomb cavity between the rafters	1.5	0.4
Dormer ceiling	Lead on timber sarking and timber uprights, finished internally with lath and plaster Retrofitted with bonded polystyrene bead blown into the cavity between the uprights	1.5	0.5

4.5. Columshill Street, Rothesay – A tenement stair

This case study involved the monitoring of the thermal performance of an external wall in a communal staircase, in a turn of the 19th Century property in Rothesay on the Isle of Bute (Fig. 25). The heat-flow mat was installed as shown in Fig. 26. The pre-intervention testing was conducted during January 2011. The wall was tested again in September 2011, after 10 mm thick aerogel blankets (fixed to the wall with expanded steel mesh) had been added to the internal lining.

The measured pre- and post-intervention U-value results for the wall are shown in Table 5.

Fig. 25 Exterior view of common staircase

Fig. 26 Heat-flow mat placement in the stairwell post-intervention

Table 5 Measured in situ U-values for the property at Columshill St, Rothesay

Communal stairwell	Construction and intervention	U-value measured W/(m^2 K)	
		pre-intervention	post-intervention
Stairwell wall	500 mm rubble stone wall, lime plaster on the hard internally Retrofitted with 10 mm aerogel blankets added to face of internal lining	1.3	0.6

4.6. Colbeck Place, Rothesay – A ground floor flat

This trial involved testing the thermal performance of an external timber door before and after insulation retrofit works had been carried out (Fig. 27 and Fig. 28). The recessed panel door and frame were made of timber with high thermal transmittance, and air infiltration occurred around the edges and at meeting points between door and frames.

Pre-intervention testing took place over 14 days in January 2011, during which time the average recorded external temperature was 4 °C and the average external relative humidity was 95 %. The recorded internal environment averaged at 18 °C and 45 % relative humidity. The door was then insulated with 10 mm thick aerogel blankets over the internal side of the door and fitted with strips of seals and brushes around the frame to reduce air leakage.

U-value testing equipment was reinstated on 24th September 2011, and testing took place over 21 days. During this time, the average internal and external temperature and relative humidity levels were recorded. The internal environment was 21 °C at 67 % relative humidity; the external environment was 13 °C at 89 % relative humidity.

The pre- and post-intervention U-value testing results are shown in Table 6.

Fig. 27 External view of the door at Colbeck Place

Fig. 28 Placement of heat-flow mats on the inner door face

Table 6 Measured in situ U-values for the property at Colbeck Place, Rothesay

External door	Construction and intervention	U-value measured $W/(m^2 K)$	
		pre-intervention	post-intervention
Door	Hardwood timber door with four panels of 19 mm thickness Retrofitted with 10 mm thick aerogel blankets added to panels	3.9	0.8

4.7. Bluevale Street, Glasgow – An external pend

This project involved testing external insulation on a wall within a sheltered pend (Fig. 29). The wall was insulated with wood-fibre boards and finished with a proprietary render system.

Pre-intervention testing was carried out in October 2011 (Fig. 30). The average external and internal temperatures and relative humidity recorded over the pre-intervention monitoring period was internally 16 °C at 65 % relative humidity and externally 10 °C at 72 % relative humidity.

Once the thermal retrofit work was complete, post-intervention testing was carried out during February 2012. The average internal environment was recorded as 17 °C at 60 % relative humidity. Externally the recorded average temperature was 8 °C at 75 % relative humidity.

The pre- and post-intervention U-value testing results are shown in Table 7.

Fig. 29 External view of the property at Bluevale Street (Image source: Google Streetview [Accessed: 09 Aug. 2013])

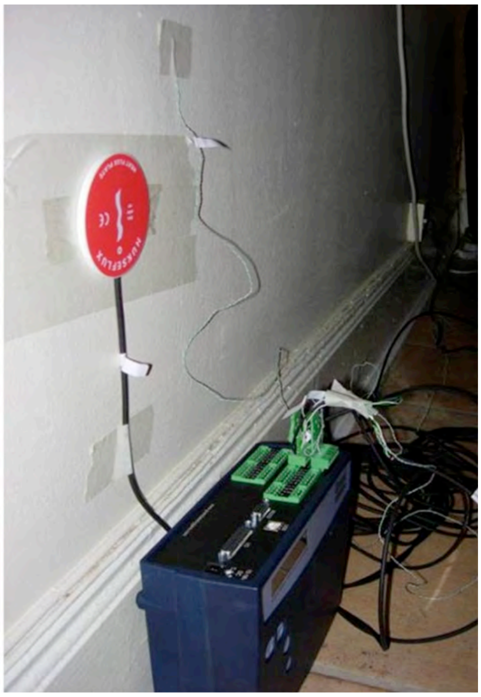


Fig. 30 Placement of heat-flow mats

Table 7 Measured in situ U-values for the property at Bluevale Street, Glasgow

Ground floor flat: living room	Construction and intervention	U-value measured $W/(m^2 K)$	
		pre-intervention	post-intervention
Wall	500 mm sandstone rubble wall, rough render external finish. Lath and lime plaster internal lining Retrofitted with 100 mm wood-fibre insulation and render to external wall	1.3	0.4

4.8. Whitevale Street, Glasgow – A tenement flat

In this project, the main objective was to look at ways of improving the thermal performance of the walls within stairwells and other communal areas in a tenement building. The selected flat was located on the ground floor of a tenement property in Glasgow (Fig. 31). Data loggers were set up in the bathroom, which faced the internal passageway leading to the back yard of the tenement (Fig. 32).

Temperatures in this stairwell (an average over a 14 day monitoring period 14 °C and 60 % relative humidity) were not as low as external temperatures (an average of 10 °C and 55 % relative humidity) but nonetheless were considerably lower than the internal flat temperatures (20 °C and 70 % relative humidity) and provided sufficient thermal gradient for testing. Pre-intervention testing was conducted in October 2011.

The wall was retrofitted with a 10 mm thick aerogel blankets, fixed to the internal lining of the wall. The wall was then retested during February 2012. The average internal temperature was measured at 20 °C at 67 % relative humidity; the average temperature and relative humidity within the stairwell was measured 9 °C at 84 % relative humidity.

The pre- and post-intervention U-value results are shown in Table 9.

Fig. 31 External view of the property at Whitevale Street, Glasgow

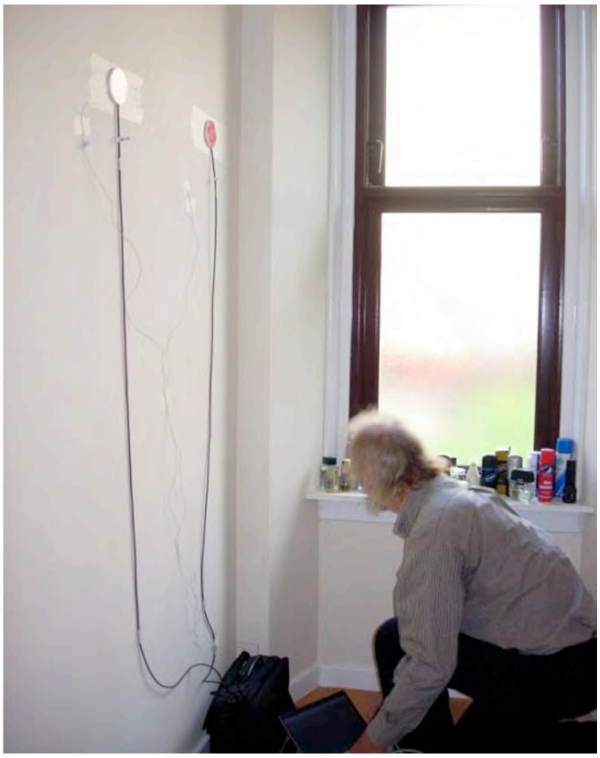


Fig. 32 Heat-flow mats in place and monitoring equipment setup

Table 8 Measured in situ U-values for the property at Whitevale Street, Glasgow

Bathroom facing communal passageway	**Construction and intervention**	**U-value measured W/(m^2 K)**	
		pre-intervention	post-intervention
Wall	250 mm brick wall, with lath and lime plaster internal lining Retrofitted with 10 mm thick aerogel blankets to internal wall	1.4	0.3

4.9. Leighton Library, Dunblane – A detached library

Leighton Library is a detached masonry building of domestic scale and proportions (Fig. 33). The aim of the project was to upgrade the ceiling and coomb (Fig. 34).

Fig. 33 External view of Leighton Library

Fig. 34 Heat-flow mats on the ceiling and coomb

The timber ceiling was not insulated and the thermal upgrade included the installation of 200 mm wood-fibre insulation directly above the timber board lining. Following a review of the ventilation requirements behind the bookcases, the coomb was not insulated to ensure full air movement was maintained. In other projects, coombs have been insulated, but this library building has an impermeable, cement based external render, which appreared to be inhibiting the dispersal of water vapour to the exterior.

This Refurbishment Case Study was not only concerned with measuring U-values pre- and post-intervention, but also with changes in the relative humidity within the roof space and library. Humidity probes were installed in the ceiling and the coomb to monitor any changes in relative humidity. The humidity monitoring is still ongoing.

The pre-intervention monitoring took place in January 2012 over a 21 day monitoring period. During this the internal and external temperatures and relative humidity were recorded. The averages for January 2012 were internally, 12 °C and 69 % relative humidity and externally 2 °C and 95 %.

The post-intervention monitoring took place in March 2012. The average recorded internal temperature was 15 °C at 57 % relative humidity. Externally the temperature was 1°C at 69% relative humidity.

The pre- and post-intervention U-value testing results are shown in Table 10.

Table 9 Measured in situ U-values for Leighton Library, Dunblane

Main library reserve	Construction and intervention	U-value measured W/(m^2 K)	
		pre-intervention	post-intervention
Ceiling	Ventilated attic with timber ceiling joists, finished internally with softwood v-groove lining Retrofitted with wood-fibre insulation	1.3	0.2
Coomb	Slates on hardwood sarking on timber rafters, finished internally with softwood v-groove lining	1.5	n/a

4.10. Kildonan, South Uist – A detached cottage

This case study involved the thermal upgrade of a two-storey cottage on the Isle of Uist in the Outer Hebrides, and published in Refurbishment Case Study 6 (Historic Scotland, 2012). This Case Study was part of a larger project conducted by Sustainable Uist, focusing on improving the thermal performance of 'hard to treat' properties on the island. The dwelling consists of three rooms on the ground floor, and three on the first floor. The front of the building is orientated to the east, with four out of the five windows in the property on the east elevation. The gable walls in the main rooms of the building are orientated north and south.

During July 2011, the U-values were measured in seven locations on building elements, namely ceilings, roof, floors, half walls and walls (Fig. 35 and Fig. 36). The locations of the heat-flow mats are marked in the floor plans in Fig. 37. The internal environment was heated to an average of 22 °C. This higher level of heating was required to compensate for the higher external summer temperatures, which averaged at 14 °C during the monitoring period.

Fig. 35 Heat-flow mats on the ground floor for post-intervention monitoring

Fig. 36 Heat-flow mats on the first floor for post-intervention monitoring

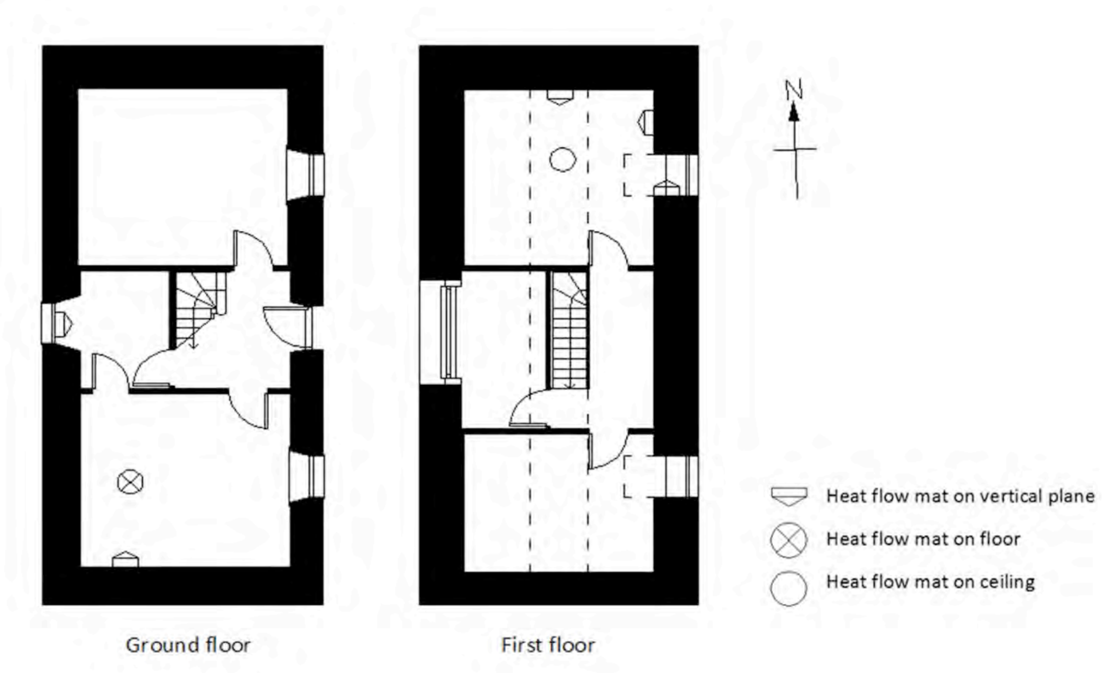


Fig. 37 Floor plan showing the location of heat-flow mats

The property was then upgraded, with insulation added to the solid stone walls, timber roof, solid concrete ground floor and secondary glazing added to a single glazed window.

The original floor construction is a 100 mm concrete slab over loose stone fill. To improve the thermal performance of the floor, a levelling screed and 10 mm composite aerogel boards were added, which improved the measured U-value from 3.9 to 0.8 W/(m^2 K).

Wood-fibre insulation batts were placed above the internal lining of the ceiling, reducing the U-value from 2.1 to 0.4 W/(m^2 K).

As the existing linings on the ground floor were decayed and no longer usable, they were removed from the south wall and calcium-silicate insulation boards were attached directly to the stone wall and finished with plaster. Polycarbonate secondary glazing was added to the window frame, improving the U-value from 5.4 to 2.4 W/(m^2 K).

On the first floor, the internal lining was carefully removed from the walls; then new framing and wood-fibre insulation batts were installed, and finally the original linings were reinstated. The coombs were also improved with wood-fibre boards.

The dormer cheek was improved by installing a 10 mm thick composite board with aerogel insulation that reduced the U-value from 1.7 to 1.2 W/(m^2 K). This was then taped and filled to finish.

Post-intervention U-value measurements were carried out in October 2011. The building remained unoccupied and unfurnished during the project.

The pre- and post-intervention U-value testing results are shown in Table 12.

Table 10 Measured in situ U-values at the property at Kildonan, South Uist

Ground floor and first floor	Construction and intervention	U-value measured W/(m^2 K)	
		pre-intervention	post-intervention
Ground floor, floor	Cement screed on 100 mm concrete floor slab over loose stone fill Retrofitted with 50 mm levelling screed, 10 mm aerogel and 8 mm MDF interlocking panels	3.9	0.8
Ground floor, south wall	800 mm cement-bedded whinstone, 25 mm cavity, 75 mm timber frame, 13 mm plasterboard Retrofitted with lining removed, re-plastered with 30 mm lime plaster, 50 mm calcium-silicate boards with plaster finish	2.1	1.0
Ground floor, window glass	Single glazed window Retrofitted with secondary glazing (magnetized acrylic sheet)	5.4	2.4
First floor, north gable wall	800 mm cement-pointed whinstone, 25 mm cavity, 75 mm timber frame, 13 mm plasterboard Retrofitted by removing internal finishes and replace them with framing at 600 mm centres, fitted 50 mm from external wall; 100 mm wood-fibre insulation fitted between, finished with 12.5 mm pine lining	2.1	0.4
First floor, east wall (half wall)	400 mm rendered stonework, 50 mm air space; 100 x 50 mm timber studs finished with 12.5 mm pine lining Retrofitted as above with wood-fibre board	1.6	0.8
First floor dormer cheeks facing south	Vertically hung slates, 22 mm sarking; 100 x 50 mm studs finished internally with 12.5 mm pine panelling Retrofitted with composite insulating board including aerogel blanket (9.5 mm plywood, 10 mm aerogel and 12.5 mm plasterboard)	1.7	1.2
First floor roof/ceiling (collar tie)	Asbestos slates, 15 mm sarking, 50 mm polystyrene, 9 mm plywood 13 mm plasterboard Retrofitted by replacing existing linings with 100 mm wood-fibre insulation, finished with plasterboard	1.9	0.4

5. Analysis of U-value measurement data

The study monitored the thermal performance of ten traditionally constructed properties across Scotland. The building element measured were; 13 walls, 6 ceilings, 3 coombs, 2 windows, 2 dormer cheeks and 2 floors. After the intervention work was complete, monitoring equipment was returned to the same locations in the properties to quantify the thermal improvement in terms of U-values. The results from each of the case studies are collated and presented in a range of charts and tables below.

5.1. Error analysis

An error analysis has been carried out on the pre- and post-intervention U-values measured in situ. The results broadly fall into two categories, which appear to derive from the temperature difference experienced at each monitored location. Instances where the temperature differential was >10 °C, the uncertainty of results ranged between ±4 and ±10 % for the pre- and post-intervention values. It is recognised that an uncertainty level of ±10 % is common for the testing method. For the cases where the difference in internal and external temperature was smaller, i.e. <10 °C (which can be due to unheated internal space) as seen in the stairwell at Columshill Street and Whitevale Street and where the external surface was sheltered, as was the case at Bluevale Street the level of uncertainty increased to ±15 and ±20 %. These results correlate with the findings made by Baker (2011), which demonstrated the relationship between the temperature differential and the level of uncertainty attributed to the results.

5.2. Summary of measured U-values in building elements

Due to the small number of samples for each building element, simple range bar charts have been used to visualise the distribution of the U-value results. The range bar charts display the mean values plotted for each type of building element and intervention method, the graph also includes the upper and lower U-values recorded for each building element / intervention type. The length of a range bar on either side of the mean value indicates the variability of the values recorded from each of the samples in the study. The narrower the range bar, the closer each of the values in the group are to the overall sample mean value.

Fig. 38 shows the average U-values measured in situ from the pre- and post intervention results for the walls monitored in this report. The chart presents the pre- and post-intervention results based on the intervention materials and methods used. There are no range bars available for results with one value, this is seen for the results where wood-fibre and external insulation was used.

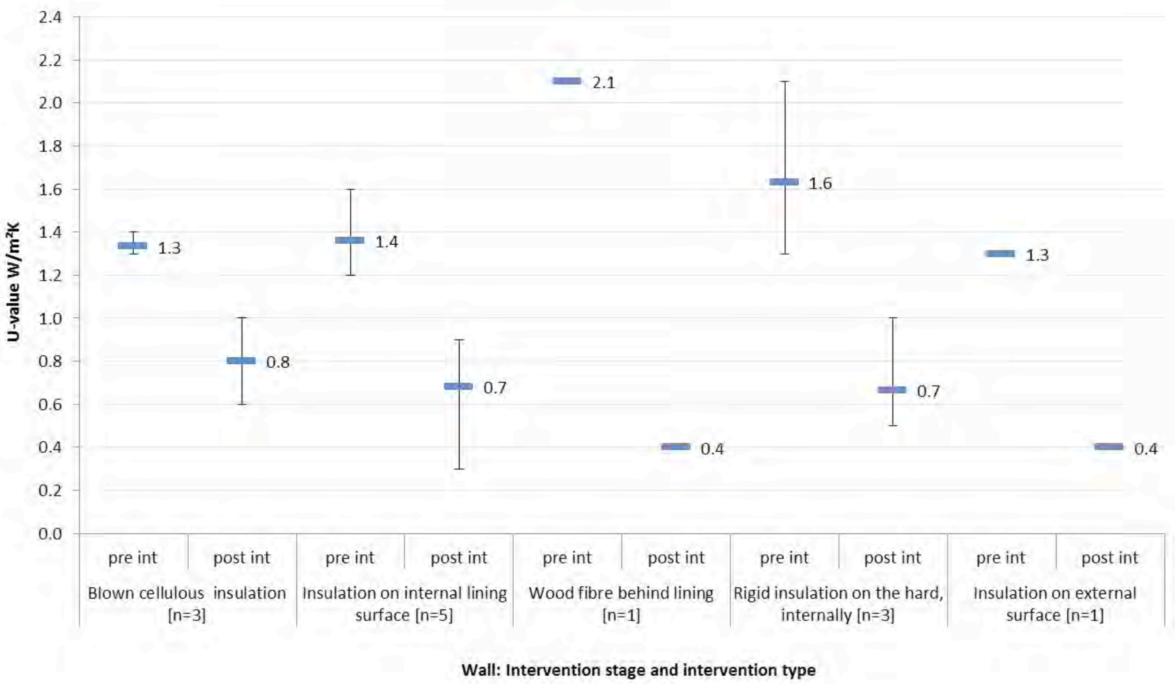


Fig. 38 Stone walls: Range bar chart of average, upper and lower U-value (recorded pre- and post-intervention) for all the walls monitored in the report (n= number of elements tested)

The intervention method of using blown cellulose insulation, aerogel insulation on internal lining surface, and rigid insulation 'on the hard', provided enough samples to produce range bars. The range bar results recorded from the walls where blown cellulose insulation was used is relatively small, indicating that the values from the sample are closely grouped. Usually this result would imply that, if blown cellulose insulation was used in a different location with the same wall type, the improved U-value would be circa 0.8 W/(m² K).

However, as these results came from the same property (Wells o' Wearie), a degree of caution must be exercised in making wider assumptions. The U-values measured from the walls with insulation on the internal lining, i.e. aerogel blanket, ranged between an upper limit of 0.9 W/(m² K) in the Wee Causeway cottage, down to a lower limit of 0.3 W/(m² K) in the property at Whitevale Street. This value range may be the result of workmanship, but more likely, it may be the result of the air cavity behind the lath and plaster and whether it was ventilated to the external environment.

Where rigid insulation was added to the internal surface 'on the hard' (in the form of calcium-silicate boards, as shown in Fig. 8), the U-value improvement ranged from 0.9 to 1.1 W/(m² K). The largest range bar shown in Fig. 38 is a consequence of including the results from the U-values measured at Kildonan. Excluding the Kildonan figures from the 'rigid insulation on the hard' section of Fig. 38 will reduce the pre-intervention range bar to between 1.3 and 1.5 W/(m² K), and the post-intervention U-value becomes 0.5 W/(m² K) with no range, in this instance, the values come from two measurements taken solely at Wee Causeway in Culross.

The pre-intervention U-values for the walls treated with rigid wood-fibre and rigid insulation were monitored in Kildonan, South Uist. A hard whinstone (gneiss) is often used in the Uists for construction and the average U-value for these walls averaged at 2.1 W/(m²K). Sandstone is common for the buildings monitored in Scotland's central belt and the average pre-intervention U-value for the walls monitored in Edinburgh, Glasgow, Fife and the surrounding areas was 1.3 to 1.4 W/(m²K). Table 11 takes the values from Fig. 38 and lists the average U-values for the intervention methods and the average U-value of the original wall based on stone type. A variety of wall interventions were monitored but with relatively small samples within each intervention method.

The measured pre- and post-intervention U-values for each of the building elements are shown in Fig. 39 for ceilings and Fig. 40 for coombs. The average U-values for the other elements are displayed in Fig. 41. All the measured U-values are listed in Table 15.

Table 11 Average U-values of the walls and associated number of monitored samples, listed by wall and insulation types

Original construction	Added materials	Average U-value measured W/(m² K)		Number of samples
		pre-intervention	post-intervention	
Sandstone wall	Blown cellulose insulation	1.3	0.8	3#
	Insulation on internal lining surface	1.4	0.7	5§
	Insulation on external surface	1.4	0.4	1
	Rigid insulation 'on the hard' internally	1.4	0.5	2‡
Whinstone wall (Gneiss)	Wood-fibre board insulation behind lining	2.1	0.4	1
	Rigid insulation 'on the hard' internally	2.1	1.0	1

two walls in same property
§ five walls in four different properties
‡ two walls in same property

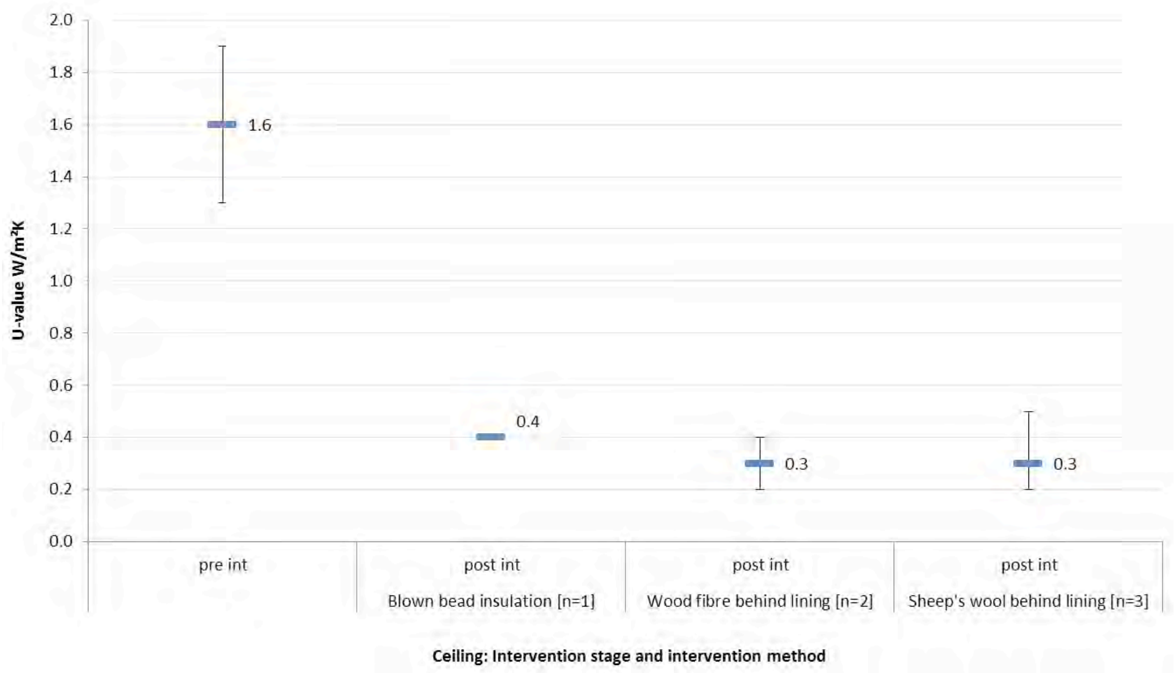


Fig. 39 Ceilings: Range bar chart of average pre- and post-intervention U-value results for all the ceilings monitored in the report

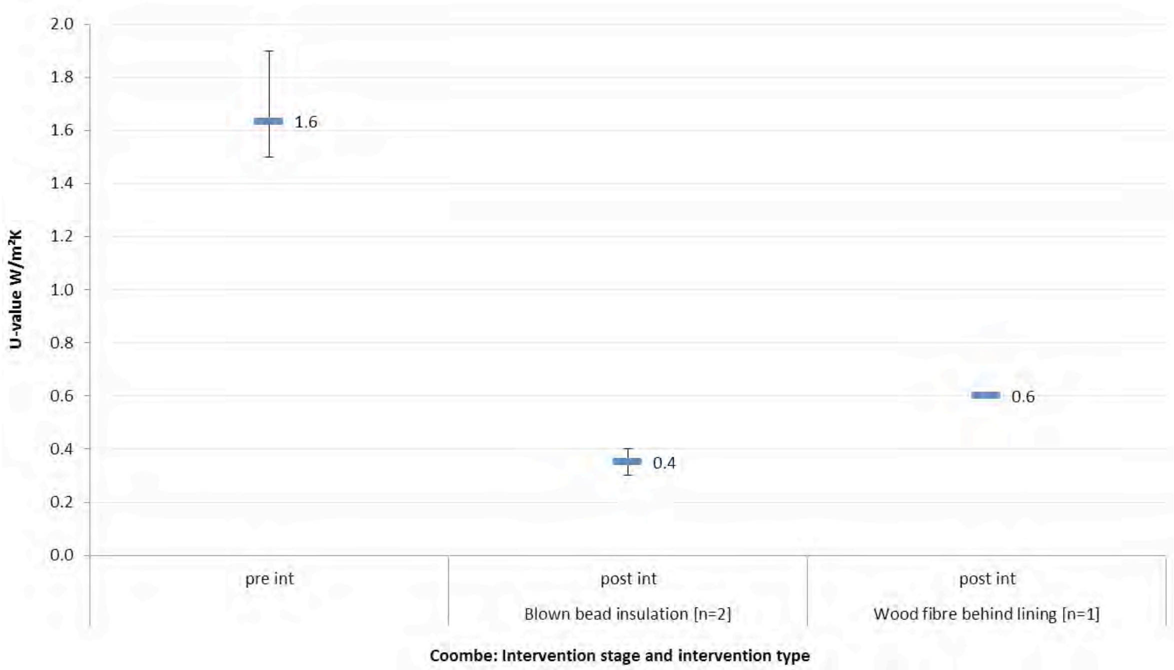


Fig. 40 Coomb ceilings: Range bar chart of average pre- and post-intervention U-value results for the coomb ceilings monitored in the report

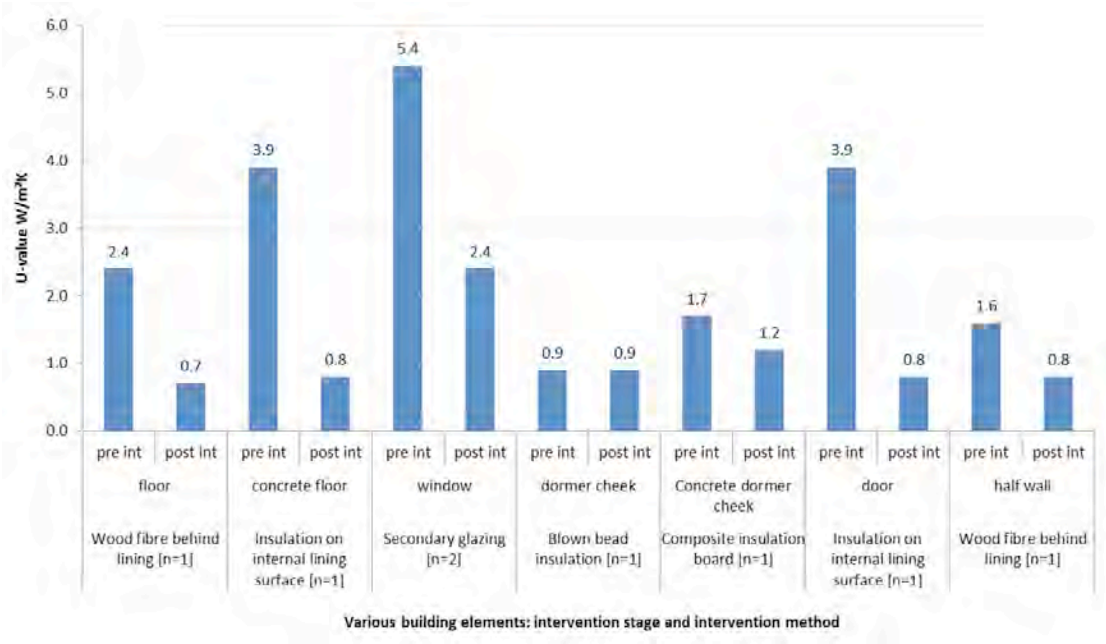


Fig. 41 Bar chart of average pre- and post-intervention U-values for various building elements

Table 12 Summary of pre- and post-intervention U-value measurements, categorised by element type

Building element	Location	Improvement measure / added material	U-value measured W/(m^2 K)	
			pre-intervention	post-intervention
Wall	Wells o' Wearie	Blown cellulose insulation	1.3	0.8
			1.3	0.6
			1.4	1.0
		Aerogel insulation on internal lining surface	1.3	0.7
	Wee Causeway	Aerogel insulation on internal lining surface	1.2	0.9
			1.6	0.9
	Columshill Street	Aerogel insulation on internal lining surface	1.3	0.6
	Whitevale Street	Aerogel insulation on internal lining surface	1.4	0.3
	Kildonan	Wood-fibre behind lining	2.1	0.4

		Calcium silicate insulation on the hard	2.1	1.0
	Wee Causeway	Calcium silicate insulation on the hard	1.5	0.5
			1.3	0.5
	Bluevale Street	Wood-fibre insulation on external surface	1.3	0.4
Window	Wells o' Wearie	Polycarbonate secondary glazing	5.4	2.4
	Kildonan	Polycarbonate secondary glazing	5.4	2.4
Ceiling	Newtongrange	Blown polystyrene bead insulation	1.6	0.4
	Leighton Library	Wood-fibre behind lining	1.3	0.2
	Kildonan	Wood-fibre behind lining	1.9	0.4
	Wells o' Wearie	Sheep's wool behind lining	1.3	0.2
	Wee Causeway	Sheep's wool behind lining	1.5	0.2
	Pleasance	Blown polystyrene bead insulation	1.5	0.5
Coomb	Newtongrange	Blown bead insulation	1.9	0.3
	Pleasance	Blown bead insulation	1.5	0.4
	Leighton Library	Wood-fibre behind lining	1.5	n/a
Timber Dormer cheek	Pleasance	Blown bead insulation	0.9	n/a
Door	Colbeck Place	Aerogel insulation on internal lining surface	3.9	0.8
Concrete floor	Kildonan	Aerogel composite on existing surface	3.9	0.8
Timber floor	Wells o' Wearie	Wood-fibre behind lining	2.4	0.7
Concrete dormer cheek	Kildonan	Aerogel composite insulation board	1.7	1.2
Wall	Kildonan	Wood-fibre behind lining	1.6	0.8

6. Conclusions

This report has quantified the thermal performance improvements made to a number of traditional building elements by the retrofit of insulation material. In each instance where insulation material was added, regardless of its location and method, an improved U-value was recorded post-intervention.

It is hard to draw detailed conclusions based upon a small number of properties and building elements; moreover, the number of building elements in each intervention type is relatively small. However, across the five stone walls treated with aerogel insulation to the internal lining surface, the average U-value improvement that can be seen in Fig. 38 was 0.7 $W/(m^2 K)$. This is similar to the value for the average of the three walls treated with blown cellulose insulation. Walls treated with rigid insulation ‘on the hard’ (calcium-silicate board) improved on average by 1 $W/(m^2 K)$ and the wall treated with wood-fibre insulation behind the lining improved on average, by 1.7 $W/(m^2 K)$. Likewise, this result came from only one sample, which was monitored in South Uist.

Where more than one element was monitored, range bars showing the upper and lower recorded values are displayed to represent the range of values around the average. The short range bars show that the values measured are similar to the samples mean value. This is the case for the pre- and post-intervention wall U-value where blown cellulose insulation was used and also observed from the post-intervention U-value results for the coombs and ceilings. A small sample is used to calculate the average U-value for all elements discussed above; with a small sample size it becomes difficult to identify which U-values are unusual in terms of the sample average.

This report summarises the measured in situ U-value results from ten properties, measuring ten elements and eight different intervention types and adds considerably to the portfolio of construction detail and measures tested by Historic Scotland. These results provide the basis for better understanding of the U-value improvements that would be expected when applying a certain range of innovative insulation measures to traditionally constructed buildings.

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