Technical Paper 23

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Thermal assessment of internal shutters and window film applied to traditional single glazed sash and case windows

John Currie, Julio Bros Williamson, Jon Stinson & Marie Jonnard

Edinburgh Napier UNIVERSITY

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About the research team

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, performance evaluation of newly built low and zero carbon homes and social engagement strategies for pro-energy efficient attitudes in domestic and non-domestic built environment.

Marie Jonnard joined SEC in spring 2014, whilst completing her Master of Science studies in thermal engineering at the National Institute of Applied Sciences, Strasbourg, France. Marie's studies have specialised in heating, ventilation and air conditions, and thermal modelling. Marie has gained experience in predictive modelling of domestic heat loss, annual carbon calculations and heating installation with air treatment. During her studies, Marie has worked on architecture and engineering projects in Lyon, Vienne and Wales. Marie has previously been lead of a study for an EDF Group, investigating various ways of photovoltaic integrations on roof and impact on building regulations and evaluation of annual production costs.

Foreword

by Historic Scotland

Historic Scotland commissioned this technical paper to assess the effectiveness of two inexpensive and minimally invasive methods for improving the thermal performance of single glazed windows. This study supports current on-going research into energy efficiency improvements in traditional buildings. The improvement methods were trialled at Wee Causeway, a detached property in Culross, Fife, owned by The National Trust for Scotland. Previous works to this property are described in Historic Scotland Refurbishment Case Study 3, and included internal wall insulation and thermal improvements to the roof space.

In this follow up trial, The Scottish Energy Centre at Napier University investigated the thermal performance of a window film applied to the existing single glazed window panes, and the performance of the newly installed insulated window shutters. The performance of the upgraded elements were compared to an unimproved 'baseline' single glazed window in the property. The analysis was conducted using both measurements taken in-situ and calculated measurements using proprietary software programmes.

The in-situ analysis of these two interventions gave useful results. As would be expected the shutters performed well, reducing the U-value of the window considerably when in use; bearing in mind that the shutters are not normally closed during the day. The window film gave a more modest, but measurable, result. Both methods have a place in the overall suite of improvements that can be combined to improve energy efficiency and thermal comfort in traditional buildings.

Moving beyond the recent interventions, the building was then analysed in a more comprehensive manner, taking into account the upgrade works from the previous phase. Using proprietary software an optimal solution was modelled in order to establish how much the building could be improved with additional upgrade techniques. Some improvement was noted and this is reflected in an improved SAP rating for the property.

This technical paper demonstrates that a range of options, including minimally invasive and inexpensive methods, can play a worthwhile role in the overall thermal improvement of buildings. Historic Scotland will continue to test a variety of upgrade options for traditional buildings, supporting the growing body of evidence that the traditional built environment can be successfully adapted to comply with improved energy and sustainability requirements, using both traditional and new methods and materials where appropriate.

Contents

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1 Introduction

This report describes the work conducted by the Scottish Energy Centre (SEC) at Edinburgh Napier University for the National Trust of Scotland, measuring the thermal transmittance (U-value), for two types of glazing insulation: shutters and film. The objective was to determine the thermal insulation benefit of these measures when applied to an existing single glazed sash and case window.

The building selected for the study is a detached 18th century cottage, Wee Causeway, located in Culross. It is a dwelling of traditional construction (solid stone wall) where some energy efficiency refurbishment works were completed in 2012 (wall and ceiling insulation). In the summer of 2013, glazing film, designed to improve thermal performance, was installed on all rear windows of the building, except the bathroom window. The textured translucent glass of the bathroom window proved unsuitable for the application of the glazing film. Thermally insulated timber shutters were applied to the interior side of the front facing window openings. The heat transfer through the bathroom glass and a front window pane was subsequently measured to provide a reference benchmark, to compare with the improved windows.

This report also analyses the effectiveness of improvements for upgrading traditional buildings, combining 2012 wall monitoring (Currie *et al.*, 2013) and 2014 window testing. Using SAP software, the report presents several modelled thermal scenarios, which demonstrate the effectiveness of each intervention if applied in isolation. Each modelled scenario is presented in terms of energy efficiency rating (SAP), environmental impact score, and space heating requirements. The report concludes by combining the most thermally efficient materials for each element into one 'best case' model.

In Section 2, the methodology which was used for the testing of U-values in-situ is explained. The two methods of improving U-values for the windows are detailed in Section 3. Section 4 develops the results monitored in Wee Causeway and presents the findings of IR thermography and air-tightness tests. Section 5 provides a review of the wall and ceiling thermal measurements completed in 2013. Finally Sections 6 and 7 present comparative tables detailing retrofitting techniques, and thermal performance indicators for the solutions trialled at Wee Causeway.

2 Testing

To assess the application of thermal upgrades made to the windows at Wee Causeway, Edinburgh Napier University researchers conducted a programme of in-situ and desktop measurements. The package of in-situ testing included measuring the window and shutter thermal transmittance (U-value), whole building air-permeability assessment, and infra-red thermographic survey. The in-situ measured results were used to calibrate desktop models of the property, which were then used to run thermal heat exchange simulations.

2.1 In-situ U-values

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). The methodology for measuring the in-situ U-value was undertaken in the well-established format described in Baker (2010), Baker (2011) and Rye (2011) and conducted extensively by Edinburgh Napier researchers (Currie *et al.*, 2013). The equations for which are presented in ISO 9869-1:1994 'In-situ measurement of thermal transmittance', Part 1 heat flow meter method.

The in-situ U-value measurements were taken using Hukseflux HFP01 thermopile-based heat flux transducers (Fig. 1a and 1b) of 80 mm diameter and 5 mm thickness. These were attached to windows throughout the monitoring period (2 week duration). Four thermally improved windows were measured. Two windows were selected from the rear of the building and two on the front. An untreated single glass pane in a rear bathroom window, and a single glass pane with low-emissivity film from a rear bedroom window were selected. An untreated single glass pane in the landing window, and a window with a closed thermally improved shutter in a bedroom were selected from the front of the building. Single glass panes where measured on both orientations to provide a benchmark by which to measure any thermal improvements.

Fig. 1a *Rear window baseline*

Fig. 1b *Rear window with glazing film*

The U-values were determined by recording the heat-flow through the element together with internal surface and external surface temperatures of the glass. This was done by logging differential voltage from the heat flux transducers and temperature from calibrated K-type thermocouples.

Grant Squirrel data loggers with 24 bit A-D conversion resolution were used to log data from the heat flux transducers and the thermocouples.

Impact of heat flow mat fixation on monitoring

Particular precautions were taken to ensure that the low-emissivity window film was not damaged by the application of the heat flow mats. Several different methods of mechanically, rather than chemically fixing the heat flow mat to the window were trialled at Edinburgh Napier University. Prior to the installation of the sensors and loggers, an experiment was undertaken to identify any potential impact that the mechanical fixation methods would have on the final results. Details of this experiment are displayed in Appendix 1. The results showed that the measured U-value was not influenced by the addition of mechanical supports to the internal facing side of the heat flow mat. This allowed for the fixing type shown in Fig. 1a and 1b to be selected.

2.2 Error analysis of in-situ measured U-values

Sensor and logger related errors can occur, affecting the accuracy of the measured in-situ U-values. The sensitivity of the sensor or probe will impact on each recorded value during the period of monitoring. An error range can be established by calculating the uncertainty associated with each component in the calculation chain; temperature probes, heat-flow mats and data loggers. This calculation provides a value indicating the level of uncertainty derived from the individual temperature and a heat flow measurement. An error analysis for the results was calculated by using the established error analysis methodology described by Baker (2011). As part of the data analysis of U-value measurements, the results are presented with each measured value in Section 6.

2.3 Infra-red (IR) thermography

An infra-red thermography survey was conducted at the Wee Causeway to visually identify the benefits of shutters and glazing film compared to a single glazed window. Thermograms were captured on the internal and external elements in the property, and done so in accordance with BS EN 13187:1999 ‘Thermal performance of buildings – Qualitative detection of thermal irregularities in building envelopes - Infrared method’. Surface temperatures are used to compare these window improvement materials. Table 1 shows equipment and calibration details of the IR camera.

Equipment	Serial no.	Date of calibration expiration	Calibration certification no.
FLIR thermal imaging camera B335 with 320 x 240 pixel resolution and 25° lens	48803639	11/03/2014	n/a
Anemo Rotating Cup Anemometer	n/a	n/a	n/a
Testo 110 Thermometer with Probe	33922213/805	20/03/2014	UK07671

Table 1: *Equipment and calibration information for IR camera*

Assessing an infra-red image

The IR images (thermograms) are presented in Section 4.2. Each surveyed element is presented as a thermogram, in an iron colour pallet, and a photograph. White represents the hottest surface and black/purple represents the coldest surface. Above or below the gradient are the temperatures represented by these colours. This is called the range. Consequently an image can easily be misinterpreted because the same colour may represent different temperatures on different thermograms. To compensate for this, the report applies the same range to all thermograms to allow for easier comparison.

The interpretation of a thermal image should be carefully undertaken. Glass and other transparent or reflective materials are opaque to long wave radiation, therefore the IR camera cannot see through the glass. Glass will still conduct heat; as such the IR camera will still detect heat transferring through the glass (measured as the surface temperature). However, the IR camera will also detect the effect of heat emitting sources or heat absorbing sinks on the side of the thermographer, i.e. street lighting, external clear night sky. The thermograms in this report are thus more representative for examples including the thermal shutters only. However, the thermograms show a different thermal signature between glass with and without the film, although some anomalies are to be expected, these are identified.

2.4 Air-tightness testing

The equipment conformed to the requirements of BS EN 13829:2001 'Thermal performance of buildings – determination of air permeability of buildings – fan pressurization method'. The equipment was calibrated by a UKAS (United Kingdom Accreditation Service). Table 2 provides equipment and calibration details for those items of equipment used during the tests. The tests were carried out in accordance with the requirements of The Air Tightness Testing and Measurement Association Technical Standard L1 (ATTMA TS L1) 'Measuring Air Permeability of Building Envelopes' (2010).

Equipment	Serial no.	Date of calibration expiration	Calibration certification no.
Energy Conservancy Minneapolis Blower Door - Model 3 Fan 110V and Fan Speed Controller	15292	19/03/2014	UK07666
Energy Conservancy Micromanometer - 'DG-700 Pressure and Flow Gauge'	12681.6.700	20/03/2014	UK07670
Druck DPI 705 Barometer	70547644	20/03/2014	UK07669
Anemo Rotating Cup Anemometer	n/a	n/a	n/a
Testo 110 Thermometer with Probe	33922213/805	20/03/2014	UK07671
Energy Conservancy Software 'TECTITE' Version 3.6.7.0	n/a	n/a	n/a

Table 2: *Equipment and calibration information*

Measurement procedure

The air-permeability of a building was determined by positively and negatively pressurising the building envelope using a fan inserted to the front door of the property (Fig. 2a). Measurements of the air flow rate and corresponding indoor and outdoor pressure difference were used to create a building leakage curve over a range of fan flows. Before and after the measurements, recordings are made of the static pressure, the barometric pressure and the internal and external air temperatures. Air flow rates are adjusted accordingly and the air leakage rate can then be calculated at a given reference pressure relative to the internal envelope area. The reference building pressure used is 50 Pa. Temporary seals were applied to the active part of ventilation openings that could not be manually closed, this included the:

- Oven hood vent
- Bathroom extractor
- Chimney

All external doors, windows and trickle vents were closed with the exception of the opening where the blower door was fitted.

Fig. 2a *Blower door fitted on front entrance*

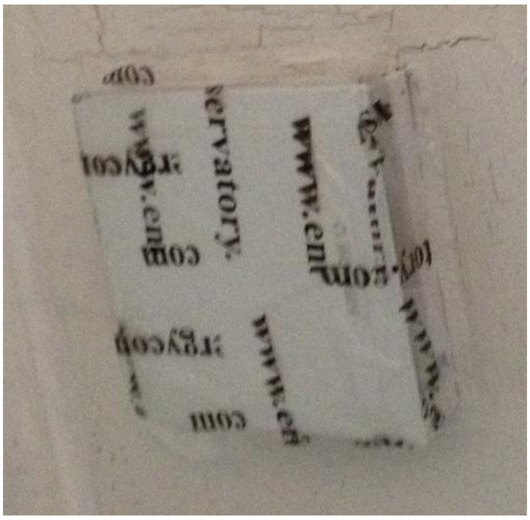
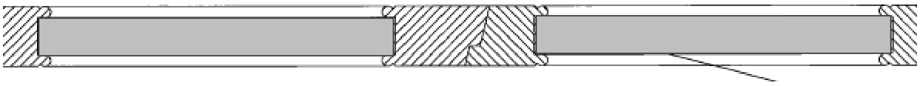


Fig. 2b *Bathroom extractor covered by plastic seal*

3 Methods of improving U-values for the windows

3.1 Using of shutters

Shutters were used in all front windows to improve U-values. The thermal shutter is constructed from a timber softwood frame and a centre panel of 22mm Gutex Multiplex insulation. Fig. 3 shows how insulation is incorporated into the shutter. The test was carried out in the top floor north bedroom.



Source: National Trust for Scotland. Insulation marked as solid, softwood timber frame marked as diagonal hatching

Fig. 3 *Top, Shutter plan view section drawing. Bottom, picture of Culross shutter measured for U-value*

3.2 Window film

The EnerLogic™ 70 window film was adopted by National Trust for Scotland (NTS) to be tested in this property. The film claims to reduce heat gain in summer and heat loss in winter. It has been applied to all rear window glass except the bathroom. To measure the U-value of glass with the film applied, the heat flow sensors and temperature probes were installed on the north room of the first floor.

4 Monitoring results

4.1 Windows improvement by U-value

Measured U-values

The in-situ U-value measurement was conducted during February 2014; side-by-side U-value measurements were conducted, over a monitoring period lasting 15 days. During this time the average internal and external temperature differed by more than 10°C, which is the accepted criteria that allows for a reduced uncertainty value. Table 4 presents the measured U-values for the untreated glazing, the film and a shutter. The original single glazing was measured to be 5.2 W/m²K; the addition of the thermal insulated shutters to the same type of window reduced the U-value to 1.1 W/m²K. The addition of the glazing film to the single glazing improved the U-value to 4.3 W/m²K. These values are centre of pane U-values, and do not include frame U-value.

Window orientation	Measure undertaken	Measured U-value (W/m²K)	Uncertainty (W/m²K)	Percentage improvement over original (%)
Front window	Single glazing (original)	5.2	±0.3	-
Front window	Single glazing with addition of Shutter	1.1	±0.1	79
Rear window	Single glazing with applied low-e film	4.3	±0.3	17

***Table 3:** Window improvement results*

The reference for rear windows was in the bathroom. Because condensation appeared on the heat flow mat, the result was incorrect. Consequently the rear window reference has been omitted from the final results.

Assuming that all the glazing in the building has a U-value of 5.2 W/m²K, the closed shutter has reduced the U-value by 79%. The glazing film has reduced the U-value by 17%. The calculated uncertainty of the U-value for the glazing with and without film is ±0.3 W/m²K (6%), and±0.1 W/m²K (8%) for the shutter. These are largely due to the temperature gradient across and along each element, however, the overall uncertainty for all three measurements are below the accepted ±10% uncertainty for measurements of this nature (Baker, 2011). If the temperature difference achieved across each element were to decrease, the uncertainty value would increase.

Calculated U-values

The single glazing and the film were modelled using Lawrence Berkeley National Labs (LBNL) 'Window' Program to calculate the aspirational or predicted U-value. The calculation method defined in ISO 10077-1:2006 'Thermal performance of windows, doors and shutters - Calculation of thermal transmittance' was used to calculate the U-value through the insulated shutters.

The properties of the film were adopted from the technical characteristics identified through Enerlogic publications (Solutia, 2012; DuBusk, no date). The base glass used in the 'Window' software was in the generic single glazing library. To calculate the shutter U-value, the entire window system was included in the equation as defined in ISO 10077-1. The calculation for the shutter U-value assumes average air permeability around the frame, and a complete window U-value of 3.9 W/m²K has been calculated for use in this equation. Table 4 presents the results of modelled and measured in-situ U-values, along with U-values identified from past published research specific to this area of investigation.

Type of window	Model U-value (W/m^2K)	Literature U-value (W/m^2K)	Measured in-situ U-value at Wee Causeway (W/m^2K)
Single glazing centre-of-pane	5.9 [1]	5.2- 5.5 [3]	5.2 [±0.3]
Single glazing with shutters insulated	1.3 [2]	1.6 [5]	1.1 [±0.1]
Single glazing with film centre-of-pane	3.3 [1]	2.9 [4]	4.3 [±0.3]

Table 4: *Comparative table for glass and window improvement*

List of Sources for each marked value in Table 4:
[1] LBNL Window program
[2] Used calculation method defined in ISO 10077-1
[3] Historic Scotland Refurbishment Case Study 1 and Historic Scotland Technical Paper 1
[4] A Review and Examination of EnerLogicTM Window Film Performance Claims by Steve DeBusk
[5] Historic Scotland Technical Paper 1. The exact type of insulation used in this model cannot be verified

All glazing values, except [4] relate to the U-values of a single pane only; they do not include the U-value of the frame. For the value [4], the Enerlogic document did not elaborate if the published U-value was inclusive of the frame U-value. To explore this further, an additional model was constructed with the LBNL Window software, the glazing characteristics remained the same and a standard timber frame was added to the model. This resulted in a calculated U-value result of 2.9 W/m²K. Consequently, the value [4] seems to include a timber frame which may explain the gap between the modelled and literature U-value for single glazing with film.

The in-situ U-values measured using the heat flow method, for single glazing and windows with a shutter are similar to those modelled and previously published values. However, the in-situ U-value for glazing with the film is higher than that modelled.

Draught proofed window

The resistance for each window system to ventilation heat loss was not evaluated using in-situ methods. The effects of ventilation heat loss around the shutters and individual window frames are presented as thermograms in Section 4.2. The whole house air-permeability value is presented in Section 4.3.

To accurately evaluate the draught proofing of each window system would require a laboratory based test following the BS EN 12412-2:2003 'Thermal performance of windows, doors and shutters - Determination of thermal transmittance by hot box'. One such test was conducted by Glasgow Caledonia University using the National Physics Laboratory guarded hot box method for a sash and case window. This is the subject of Historic Scotland Technical Paper 1 (Baker, 2010). The results presented in Historic Scotland Technical Paper 1 showed no statistically significant difference in the U-value of the single glazed window after retrofitting with draught proofing. The overall measurement uncertainty for the hot box test was ± 5.5%. The average U-value was presented as 4.4 W/m²K. The frame factor for this window was calculated to be 55%, meaning 55% of the overall window was glazing; therefore 72% of the heat is lost through the glazing assuming an indicative centre of pane glazing U-value of 5.7 W/m²K

- U = 4.5 W/m^{2}K before draught proofing
- U = 4.2 W/m^{2}K after draught proofing

4.2 Infra-red (IR) thermography

This section is divided into 4 parts. The first two parts present thermograms of the external, rear and front elevations respectively. Then, part three focuses on internal rear windows covered by the window film. Finally, part four presents the thermograms of internal front windows, where shutters have been installed.

Results are displayed as follow:
- Comments on the IR image
- IR image and photograph of the window
- Table summarizing the characteristics of the window

The average surface temperature has been calculated with FLIR software (FLIR, 2014). The area of glazing for the calculation was selected in order to give the most representative temperature. It includes the timber frame. Table 5 shows the recorded climatic conditions during the time of the IR survey.

Internal temperature (°C)	18.1
External temperature (°C)	7.2
External wind speed (m/s)	1
External Relative humidity (%)	60
Internal Relative humidity (%)	65

Table 5: *Average climatic recorded values over period of survey*

External conditions during the survey were dry with clear skies. A temperature drop of 1°C was recorded for the external temperature between the start and end of the survey.

External – application of window film

Rear windows - bathroom and bedroom

This IR image (Fig. 4a), shows different temperature profiles for window glazing with low-e film applied, and an untreated single glazed window. The window to the left in Fig. 4a and 4b are on the south room of the first floor which was treated with low-e film. The smaller window to the right (Fig. 4a and 4b) is the bathroom window which is the benchmark window with no film treatment or shutters. The darker colours of the window panes on the left in Fig. 4a indicate lower heat loss through the glazing when compared to the reference window on the right. The bright colours on the external thermograms represent larger amounts of heat transferring from the warmer internal environment to the colder external environment. Both windows are reflective of the same clear night sky and the internal temperature for both rooms was recorded to be the same (19°C).

Fig. 4a *Thermogram of first floor south room and bathroom window*

Fig. 4b *Photograph of first floor south room and bathroom window*

Characteristics	Bathroom window	First floor window
Orientation	Rear (south)	Rear (south)
Window improvement	None	Low-e film
Average surface temperature (°C)	2.2	0.8

Table 6: *Characteristics of bathroom and south first floor window*

Thermograms of the ground floor windows proved inconclusive, excessive build ups of condensation had manifested on the inside pane, meaning each window appeared much darker on the thermogram than perhaps would otherwise have been the case. Dense foliage restricted the view of the first floor north room window; therefore those images have been omitted from the report.

External – application of shutters

Front windows

A front window was thermographed to demonstrate the impact of the thermally improved shutter. The first set of images (Fig. 5a and 5b) is of the ground floor south room. In Fig. 5a the window has the shutter closed. In Fig. 6a and 6b, the same window has the shutter open. The shutter is an effective barrier to thermal transmittance through the glass. Therefore, the surface temperature in Fig. 5a is lower than in Fig. 6a. The higher temperature zone on the top panes of the window in Fig. 5a is due to heat movements within the airspace between the shutter and the glazing. Fig. 6a shows temperature stratification vertically within the whole room.

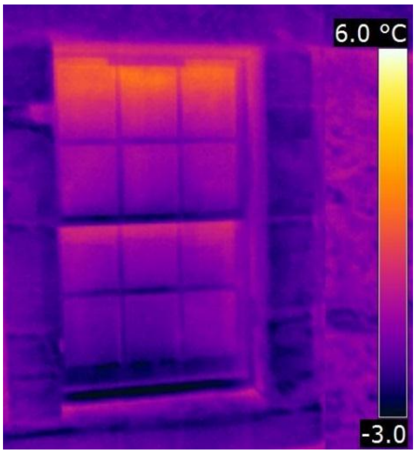


***Fig. 5a** Thermogram of a front window with shutter closed*

***Fig. 5b** Photograph of a front window with shutter closed*

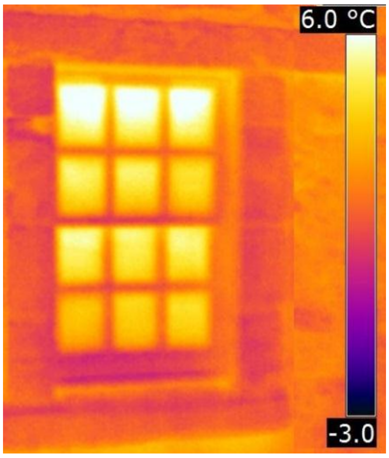


***Fig. 6a** Thermogram of a front window with shutter open*

***Fig. 6b** Photograph of a front window with shutter open*

Characteristics	Fig. 5a and 5b	Fig. 6a and 6b
Orientation	Front	Front
Window improvement	Shutter closed	None
Minimum surface temperature (°C)	-0.8	3.3

***Table 7:** Characteristics of windows 1 and 2*

The images in Fig. 7a, 7b, 8a and 8b provide an overview of thermal heat loss via the front windows of the house with shutters closed and opened. The top three windows are not representative of the impact of the shutter, as the thermogram displays darker colours on the top panes. This is due in part to the reflection of the clear night sky (-296^{o}K). Consequently, this is obscuring the temperature profile across those glass panes for comparison to the rest of the windows. However, the thermal signature of the windows with the shutter open is so large that it masks any reflection of the night sky. For the purpose of Table 8, the surface temperature comparison has been calculated for the bottom right window with the shutter closed and the same window with the shutter opened.

Fig. 7a *Thermogram of the house front with shutter closed*

Fig. 7b *Photograph of the house front with shutter closed*

Fig. 8a *Thermogram of the house front with shutter opened*

Fig. 8b *Photograph of the house front with shutter opened*

Characteristics	Fig. 7a & 7b – lower right window	Fig. 8a &8b – lower right window
Orientation	Front	Front
Window improvement	Shutter closed	None
Average surface temperature (°C)	-1.3	1.3

Table 8: *Characteristics of windows*

Hallway and landing windows

The thermogram below provides a comparison between a front facing window with the shutters closed and the single glazed panel above the door on the ground floor, which has no shuttering. The bright thermal signature of the glazed panel above the door compared with the shuttered window above (Fig. 9a) demonstrates the thermal resistance of the shutters. The angle of this thermogram has been chosen to reduce the effect of sky reflection.

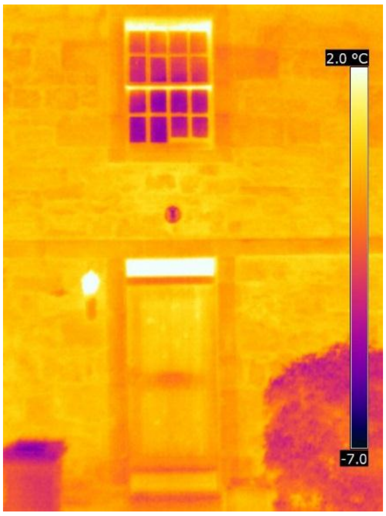


Fig. 9a *Thermogram of the house front with shutter closed*

Fig. 9b *Photograph of the house front with shutter closed*

Characteristics	Window above the door	First floor window
Orientation	Front	Front
Window improvement	None	Shutter closed
Average surface temperature (°C)	2.4	-1.8

Table 9: *Characteristics of windows*

Internal application of window film

Visual comparison between improved and original glass from the internal perspective is challenging. Thermograms taken from the interior sides of windows could not be taken side-by-side in the same image; therefore the same thermal range has been selected for all internal thermograms. Both rooms were heated to the same internal temperature (18°C). As mentioned previously, the bathroom window is the only rear facing window with no improvement and has been nominated as the benchmark image (Fig. 10a and 10b). The temperature profile for the internal images represent heat loss to the exterior; darker colours represent colder areas and therefore higher rates of heat transfer through the element. The thermogram in Fig. 11a shows the impact of the film on the surface temperature of the glass in the first floor north room. Compared to the benchmark temperature of the bathroom window (Fig. 10a and 10b), the window in the north first floor room appears to have a much higher temperature.

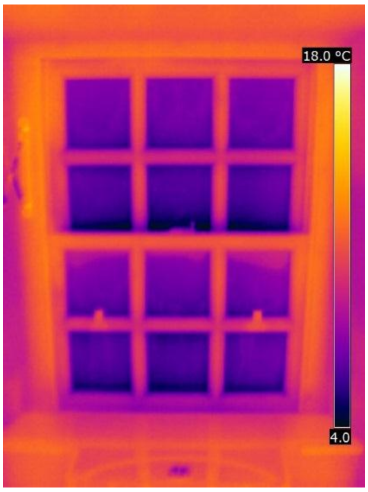


Fig. 10a Thermogram of bathroom window

Fig. 10b Photograph of the bathroom window

Fig. 11a Thermogram of rear facing window in north room first floor

Fig. 11b Photograph of rear facing window in north room first floor

Characteristics	Bathroom	North first floor room
Orientation	Rear	Rear
Window improvement	None	Film

Table 10: Characteristics of internal bathroom and first floor north window

When internal lights were left on during the survey, a considerable amount of reflection was observed on the glass in the internal thermograms. This was to be expected, however, it was much more apparent on the windows with the low-e film applied. As a result the temperature values for the internal thermograms of window film have been omitted from the study. The glass pane, and therefore window temperature as observed by the IR camera is very dependent on the surface temperature of the images reflecting in each pane. The thermogram in Fig. 11a and 11b is representative of the other thermograms captured in the first floor south room and ground floor south room.

Window film on each pane

Fig. 12a and 12b shows a thermogram of the film as applied to a single glass pane in the window of the north first floor room. The camera has been focused on the window film and especially on the boundary between the film and the glazing.

As way of a comparison, the thermogram presents two points, A and B. Point A is located on the window film, point B is on the uncovered single glazing. There is a visual temperature difference between the points in the thermogram. The thermogram shows a lot of reflection from other parts of room (Fig. 12a).

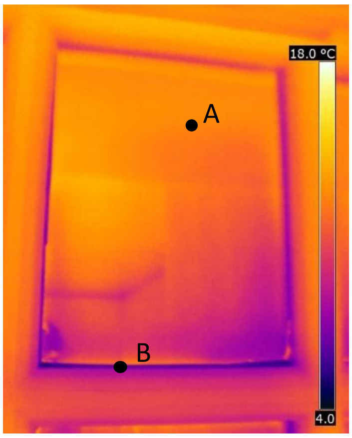


Fig. 12a *Thermogram of pane with film*

Fig. 12b *Photograph of pane with film*

Characteristics	Point A	Point B
Orientation	Rear	Rear
Window improvement	Film	None

Table 11: *Characteristics of point A and B*

Kitchen: Influence of condensation on IR image

During the thermographic survey, excessive condensation had manifested on the glass of many of the windows. In order to demonstrate the impact this has on the thermographic survey, researchers removed the condensation from 7 panes of one window. The thermogram in Fig. 13a shows the difference between wet and dry windows. When there is condensation on the pane, the water distorts the thermogram and presents lower temperatures (purple colour). However, the dry middle panes in yellow are comparable to the previous windows with film.

Fig. 13a *Thermogram of the kitchen window*

Fig. 13b *Photograph of the kitchen window*

Characteristics	Kitchen
Orientation	Rear
Window improvement	Film

Table 12: *Characteristics of internal kitchen window*

Internal – application of shutters

Front windows

The thermographs in Fig. 14a and 15a demonstrate the impact of the shutter on front windows compared to an untreated single glazed window. The first image, Fig. 14a and 14b, shows the window on the first floor landing with the shutter open. Fig. 15a and 15b shows the same window with the shutter closed. The dark coloured areas below the shutter on Fig. 15a are due to gaps around the frame of the shutter, allowing for the transmission of heat and ventilation heat loss under the shutter. The average surface temperatures shown in Table 13 were calculated omitting the area of heat loss below the shutter.

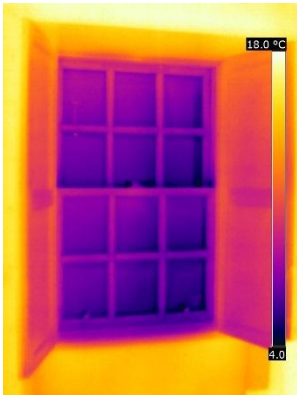


***Fig. 14a**. Thermogram of window in first floor landing with shutter opened*

***Fig. 14b** Photograph of window in first floor landing with shutter opened*

***Fig. 15a** Thermogram of window in first floor landing with shutter closed*

***Fig. 15b** Photograph of window in first floor landing with shutter closed*

Characteristics	Fig. 14a and 14b	Fig. 15a and 15b
Orientation	Front	Front
Window improvement	None	Shutter
Average surface temperature (°C)	7	15

***Table13:** Characteristics of front facing first floor south window*

Shutters ground floor north room

The following images, Fig. 16a and 16b, show the window in the ground floor north room. The thermogram shows the window with one half of the shutter in the closed position. Two points, A and B, were analysed. Point A is located on the single glazing; point B is on the shutter. The surface temperature calculation on these points shows a difference of 9°C.

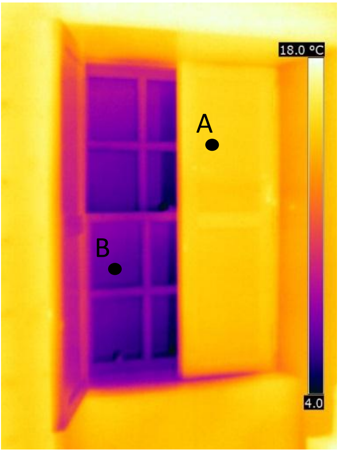


Fig. 16a *Thermogram of ground floor north room with shutter half opened*

Fig. 16b *Photograph of ground floor north room with shutter half opened*

Characteristics	Point A	Point B
Orientation	Front	Front
Window protection	Shutter	None
Surface temperature (°C)	15	6

Table 14: *Characteristics of half opened shutter*

Shutters ground floor south room

This thermogram, Fig. 17a, shows thermal irregularities along the horizontal and vertical joints of the shutters in the ground floor south room. This is attributed to adventitious ventilation heat loss. The average surface temperature on this zone is 13.2 °C, whereas the average surface temperature of the whole window is 16.2 °C, indicating that heat loss is occurring at the joints. Consequently the thermal bypass around the shutter is not one of great significance, but it does break the continuity of the thermal envelope.

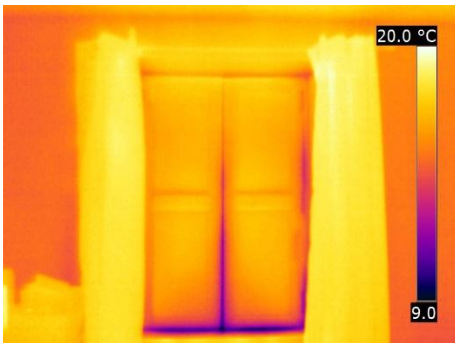


Fig. 17a *Thermogram of the ground floor south window shutter closed*

Fig. 17b *Photograph ground floor south window shutter closed*

Characteristics	Fig. 17a and 17b - Ground floor south window
Orientation	Front
Window protection	Shutter
Average surface temperature (°C)	16

Table 15: *Characteristics of ground floor south window*

Shutter first floor north room

These thermograms, Fig. 18a and 19a, show the thermal signature of the window in the first floor north room, with the shutter open (Fig. 18a) and the same window with the shutter closed (Fig. 19a). The shutter allows an improvement of 7°C in the surface temperature. The thermal continuity across and around the shutter is good with little obvious temperature difference around its perimeter.

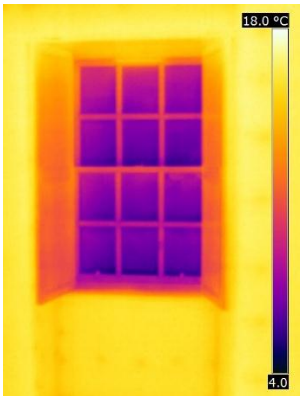


Fig. 18a *Thermogram of the first floor north room with shutter opened*

Fig. 18b *Photograph first floor north room with shutter opened*

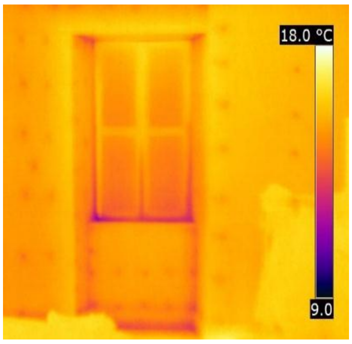


Fig. 19a *Thermogram of first floor north room with shutter closed*

Fig. 19b *Photograph first floor north room with shutter closed*

Characteristics	Window 1	Window 2
Orientation	Front	Front
Window protection	None	Shutter
Average surface temperature (°C)	7	14

Table 16: *Characteristics of first floor north room window*

Shutter first floor south room

This thermogram, Fig. 20a, shows a similar heat profile to that in the ground floor south room (Fig. 17a). The shutter improves the thermal resistance of the window, however, areas of irregularity and thermal bypass are observed in the bottom portion of the shutter joints and are likely due to adventitious ventilation.

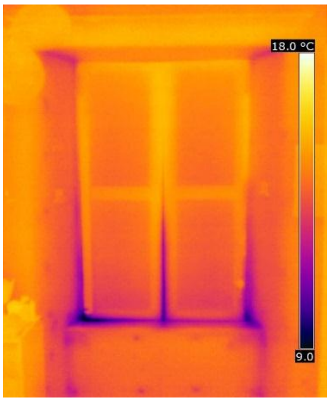


Fig. 20a *Thermogram of first floor south room shutter closed*

Fig. 20b *Photograph first floor south room shutter closed*

Characteristics	First floor south room
Orientation	Front
Window protection	Shutter
Average surface temperature (°C)	14

Table 17: *Characteristics of first floor south room window*

4.3 Air-tightness test

A pressurisation and depressurisation air –tightness test was undertaken on the dwelling to calculate its overall air-permeability value. The test was conducted during February and in ideal weather conditions, with low external wind speeds and little variation in zero fan flow rates before, after, and during the tests. High fluctuations in the zero fan flow rate would result in large fluctuations in the building flow rate, thereby affecting the accuracy of the air-permeability value. Internal and external temperatures are displayed in Table 18 with barometric pressure and wind speed; these values were used during the computation of building air flow rate. Table 19 shows the calculated dimensions of the dwelling used in the conversion from air flow rate to air permeability value.

Internal temperature (°C)	13.85
External temperature (°C)	9.8
Barometric pressure (Pa)	100425
Wind speed (m/s)	0

Table 18: *Test conditions*

Envelope area (m^2)	206.5
Volume (m^3)	188.8

Table 19: *Calculated building dimensions*

Results

Final values presented in Table 20 are the average results derived from the final pressurisation and depressurisation results @50pa.

V50 Air flow (m^3/h)	2680
n50 Air changes per hour (1/h)	14.20
q50 Air permeability $m^3/(h*m^2)$	12.98
n Flow exponent	0.617

Table 20: *Air-tightness test results*

The flow exponent [n] is obtained from the fan pressurisation and depressurisation measurements on each test. It describes the shape of fully developed air flows in the building fabric. For a valid test, under Guidance from Unwin and Jones (2010) and ATTMA (2007), the value of n must fall within 0.5 and 1.0. The value of n can be used to interpret the type of air flow through the structure. Where n approaches 1.0, this generally represents laminar air flow through a myriad of tiny apertures. When n is closer to 0.5, the air infiltration is more likely to be turbulent through the building elements, and represents airflow through larger apertures. (ATTMA 2007).

The calculated flow exponent value demonstrates a type of air flow which was expected. The air infiltration in the property is facilitated by larger apertures that arise from air flow through apertures around openings and service penetrations. It is likely that this has become the more predominate path for air infiltration as insulation and refurbishment has sealed off smaller pathways through the ceiling and wall cavities.

Comparison with current requirements for air permeability in the Scottish Building Regulations

The final averaged air-tightness value for Wee Causeway is 12.98 $m^3/m^2.h$ @ 50 Pa. By way of comparison, the Domestic Scottish Building Standards Section 6 Energy 2013, state the following for new build construction:

> *"The infiltration rate used '*as the baseline for SAP'* calculation is **7 $m^3/m^2.h$ @ 50 Pa**. Whilst no backstop value is set for uncontrolled infiltration, it is recommended that buildings are designed to achieve a value of 10 $m^3/m^2.h$ @ 50 Pa or better to allow a balanced approach to managing building heat loss.*
>
> *Lower air infiltration rates, of less than **5 $m^3/m^2.h$ @ 50 Pa**, may give rise to problems with internal air quality and condensation. Accordingly, where design infiltration rates are proposed below this rate, reference should be made to additional measures needed to ensure air quality under Standard 3.14, on provision of ventilation within dwellings.*
>
> *Alternatively, for any single dwelling, or any number of dwellings where a default design value of **15 $m^3/m^2.h$ @ 50 Pa** is stated in demonstrating compliance under Standard 6.1, testing need not be carried out."*

Additionally, past air-tightness results conducted on dwellings of a similar age have been investigated and included in Fig. 21. An air-tightness test conducted at Scotstarvit Tower Cottage, a late 19th century detached cottage in Cupar returned a value of 10.8 $m^3/m^2.h$ @ 50 Pa, post refurbishment. This value was obtained from Historic Scotland Refurbishment case study 7. The property had insulated walls, ceilings and secondary glazing on the majority of the windows.

Scottish Energy Centre conducted an air-tightness test on a red bricked late 19th century mining cottage in Mid-Lothian. The air-tightness test returned a value of 18.5 $m^3/m^2.h$ @ 50 Pa, which was the average of the pressurisation and depressurisation tests. The ceiling and coom of this property were insulated along with secondary glazing added to all but one window. Fig. 21 represents the different values of infiltration rate based on the values discussed above. The lower the air permeability or air infiltration rate, translates into less ventilation heat loss.

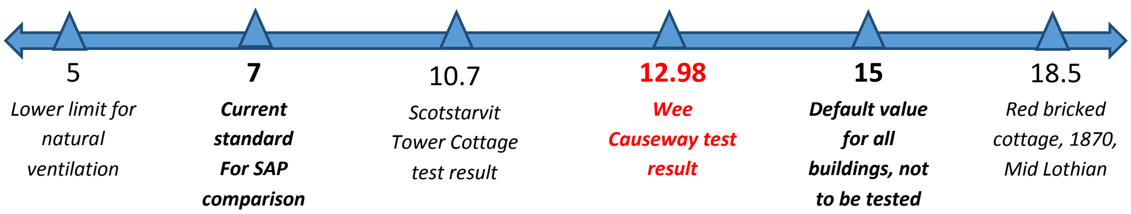


Fig. 21 *Infiltration rate scale all values in $m^3/m^2.h$ @ 50 Pa*

5 Summary of 2012 monitoring

Pre- and post-intervention in-situ U-value measurements were taken from five buildings elements across two rooms in Wee Causeway. 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 north and rear walls and the ceiling.

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 (Currie *et al.*, 2013). The ceiling measurements also returned a U-value typical of its lath and plaster finish with 100mm slumped mineral wool insulation. The pre-intervention results are presented in Table 21.

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 21. 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.

Element	**Construction and intervention**	**U-value measured W/(m^{2}K)**	
		Pre-intervention	Post-intervention
Ground floor North room	500 mm sandstone wall with lath and plaster. Retrofitted with blown polystyrene bead	1.4	0.5
Ground floor South room	500 mm sandstone wall with lime plaster on the hard. Retrofitted with Calcium silicate board	1.5	0.7 (calculated)
First floor North room	500 mm sandstone wall with lime plaster on the hard. Retrofitted with 10 mm aerogel blanket fixed to existing surface and plastered over	1.4	0.9
Ceiling	Traditional timber roof construction. Retrofitted with 275mm hemp wool insulation	1.5	0.2

Table 21: *Measured in-situ U-values for Wee Causeway cottage, Culross*

6 Comparative results – computer modelling

To compare the already installed and trialled thermal improvements, several models have been created using Standard Assessment Procedure (SAP) software. The reference model, Model 1, is based on Wee Causeway before any refurbishment work. This model is compared to the "As installed" model, Model 2, post refurbishment incorporating new insulation and upgraded windows. Four 'opaque' models represent the improvement made by the different wall and ceiling insulation types (Models 3 to 6). 'Openings' models show shutters and film improvement on the building composition (Models 7 and 8). Finally, the best case model, Model 9, was built from the best opaque and opening models.

Opaque and openings models are based on the reference model (Model 1). The only alteration to this model in each case was the addition of a specific insulation or a specific type of window protection. The list of all model characteristics is displayed in Table 23.

Assumptions:

- The air tightness value for the reference model (Model 1) is 15 m^3/hm^3 as presented in Fig. 21. For all other models, the in-situ measured value of 12.98 m^3/hm^3 was chosen.

- All windows U-values include the frame U-value. SAP requires that the total U-value is representative of the whole window system. Total U-values were calculated based on the centre-of-pane in-situ measurements and timber software frame characteristics as defined by ISO 10077-1. For instance, the in-situ centre of pane U-value of a single glazing is 5.2 W/m^2K. By adding the frame as measured in the property, the window U-value is improving to 3.9 W/m^2K. This approach is detailed in Appendix 3. Table 22 provides the U-values used for SAP modelling.

- As this was a study on the thermal improvements to the building fabric, all models assume the same heating system as is currently installed (2014).

Type	Centre of pane U-value (W/m^2K)	Total window U-value (W/m^2K)
Single glazing	5.2	3.9
Film on single glazing	4.3	3.4
Shutter	1.1	1.1

Table 22: *U-values used in SAP calculation for windows*

6.1 Shutter modelling

Because opening and closing shutters cannot be accurately or simply modelled in SAP software, the shutters were modelled using a method of splitting performance between 2 models.
Two sub models were generated to get energy needed for space heating:

- All shutters OPENED 100% of the time, simulated as a single glazing with a U-value of 3.9 W/m2K

- All shutters CLOSED 100% of the time, simulated as an opaque element with a U-value of 1.1 W/m2K

To formulate a more realistic representation of space heating requirement after the installation of thermally improved shutters, an opening and closing percentage was applied to space heating result. This was based on predicted behavioural use of shutters, accounting for time of day and period of year (see Appendix 2). SAP result (energy efficiency) and EI value (environmental impact – CO_2) were defined for this mixed model as an average of the SAP and EI values for the opened and closed models. The shutter modelling was used for Model 2 "As installed" and Model 8 "Shutters". Detailed tables are displayed in Appendix 2.

6.2 Results for modelled refurbishment scenarios

Table 24 presents the final results of Wee Causeway study. Each model is denoted by a number which defines the differences in each material. U-values are presenting in three categories: Wall, windows and ceiling. Table 25 provides more information about U-values depending on what type of insulation or window improvement was installed. Energy needs for space heating are given in kWh/year and in kWh/year.m^2 (for a dwelling area of 76.84m^2). The last two columns represents SAP result value (Energy Efficiency Rating) and EI value (Environmental Impact Rating, CO_2 emissions) generated by the SAP software. Examples of these values are presented in the Energy Performance Certificate format in Fig. 22. Best results are on the top of the pyramid, dark green for Energy Efficiency Rating and pale blue for Environmental Impact Rating. These are a European wide recognised indicator of cost to power and heat the dwelling, along with carbon dioxide emission, and are comparable between dwellings.

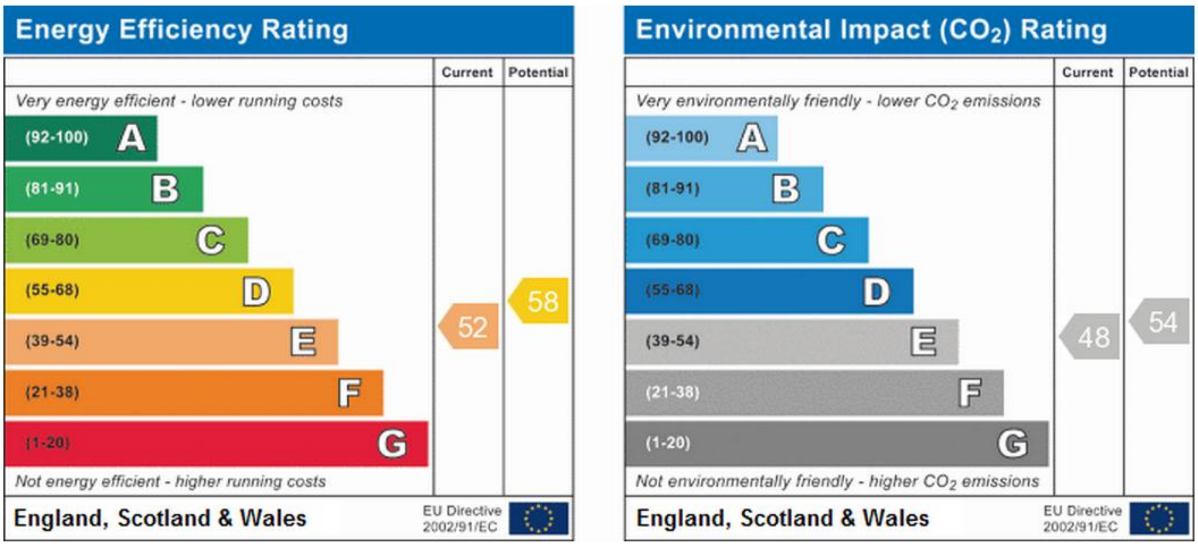


Fig. 22 *Example of Energy Performance Certificate*

After consolidating all the previous measured and calculated performance data, a best case model was constructed from the most effective individual improvements for each building element. This model is presented in Section 7 of this report.

Model number	Description	Wall improvement	Window improvement	Ceiling improvement
1	Wee Causeway Reference	No insulation	Single glazing	No insulation
2	As installed	Aerogel, Calcium silicate board and blown polystyrene bead	**Rear**: Film **Front**: Shutter in use	Ceiling insulation
OPAQUE MODELS				
3	Aerogel	Aerogel	Single glazing	No insulation
4	Calcium Silicate board	Calcium silicate board	Single glazing	No insulation
5	Blown polystyrene bead	Blown polystyrene bead	Single glazing	No insulation
6	Insulated Ceiling (hemp)	No insulation	Single glazing	Ceiling insulation
OPENINGS MODELS				
7	Glazing film	No insulation	All windows with film	No insulation
8	Simulated shutters	No insulation	All windows with shutters in use	No insulation
SOLUTION				
9	Best case model	Blown polystyrene bead	All windows with film	Ceiling insulation

Table 23: *Model characteristics for each modelled scenarios, evaluating the individual improvements on the whole dwelling*

Model number	Description	U- Value (W/m^2K)			Space Heating (kWh/year)	Space Heating ($kWh/m^2.year$)	SAP Result	EI Value
		Wall	Window	Ceiling				
1	Wee Causeway Reference	1.4	3.9	1.4	20,036	261	E 52	E 48
2	As installed	[1]	3.4 / 1.1 [2]	0.2	15,326	199	D 58 [3]	D 54 [3]
OPAQUE MODELS								
3	Aerogel	0.9	3.9	1.4	17,746	231	D 56	E52
4	Calcium Silicate board	0.7	3.9	1.4	16,868	220	D 57	E 53
5	Blown polystyrene bead	0.5	3.9	1.4	15,954	208	D 59	D 55
6	Insulated Ceiling (hemp)	1.4	3.9	0.2	18,060	235	D 55	E 51
OPENINGS MODELS								
7	Glazing film	1.4	3.4	1.4	19,558	255	E53	E 48
8	Simulated shutters	1.4	3.9 /1.1 [2]	1.4	19,784	257	E 51 [3]	E47 [3]
SOLUTION								
9	Best case model	0.5	3.4	0.2	13,575	177	D 63	D60

Table 24: *Final results table for each simulated model*

[1] Wall U-values for "As installed" model are detailed in following Table 25.

[2] U-value for film on rear windows is 3.4 (W/m^2K). U-value for insulated shutters on front windows is 1.1 (W/m^2K).

[3] See Appendix 2 for details. SAP result and EI value are defined regarding the new calculated energy for space heating. In most cases, it is an average of opened and closed models.

Wall	Insulation type	U-value (W/m^2K)
1 - Kitchen	Non insulated	1.4
2- Living room	Calcium silicate board	0.7
3- Hallway	Non insulated	1.4
4- Bedroom1	Blown polystyrene bead	0.5
5- Bathroom	Non insulated	1.4
6- Bedroom2 + 3	Aerogel	0.9

Table 25: *Wall U-values for "As installed" model*

7 'Best case' scenario

The 'best case' model was bringing together the best improvements made to each element trialled at Wee Causeway. Analysis of Table 24 gave the following results:

- Wall insulation: Based on the 2012 in-situ U-value measurements, the blown polystyrene bead insulation delivered a reduction in U-value from 1.4 to 0.5 W/m^2K. This insulation delivered the largest reduction in wall heat loss compared to the two other insulation materials measured in the property. The selection of this material for the 'best case' model is based solely on the U-value result. It should be noted that this insulation is applied to walls with a cavity, i.e. air gap between the internal lining and solid stone wall, and may not be suitable to all walls of traditional solid stone construction.
- Ceiling insulation: The insulation of the ceiling reduces the energy consumption from 261 kWh/m^2.year to 235 kWh/m^2.year which is a significant improvement. Only one material was trialled at Wee Causeway, hemp wool, therefore it is added to the 'best case' model.
- Window openings solution: Two solutions were trialled and their U-values measured. The in-situ U-value for the insulated shutter system returned a significantly lower U-value than the glazing with the film. Applying the U-value of the closed shutter directly to a SAP model would unrealistically represent that the shutters are closed 100% of the time. Therefore, assumptions were applied to the percentage of time that the shutter is opened and closed. Thereby the U-value of each window element fluctuates between 3.9 and 1.1 W/m^2K over the course of the day. Once applied to the SAP model, the shutter reduces the amount of heat loss from the window element; however, it also prevents all the benefits of solar heat gain. Therefore, the glazing film presents marginally better results for the whole building in comparison to the shutter alone. Consequently, all windows are covered by the film in the 'best case' model. No model was created to combine the properties of the insulated shutter and glazing film. It is not known how these materials will behave together.

The selection of the above materials is combined to construct the 'best case' model as they provided the best individual results in Table 24. Each solution, listed above, has been selected for the 'best case' model based on their contribution/improvement to the dwellings annual space heating demand, SAP rating and Environmental Impact rating, compared to Reference Model 1. Cost and complexity of installation for each material does not factor into the selection of the 'best case' model. Table 26 shows energy costs and CO_2 emissions of this most effective solution compared to the "Original" Reference Model 1. The most effective solution shows a 30 % decrease of fuel costs and a considerably decreased CO_2 emissions.

Model	Fuel costs for primary space heating system (£/year)	CO_2 emissions from primary heating system ($kgCO_2$/year)
Reference Model 1	621	3970
Best case model	421	2690

Table 26: *Fuel costs and CO_2 emissions*

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Appendix 1: Influence of heat flow plate fixation on monitoring

To verify the effect of mechanically supporting the heat flow plate to the window using a balsa wood rig, U-value measurement trials were conducted on a single glazed window at Edinburgh Napier University offices. Four different methods of securing the sensors to the window were trialled over a 5 week period. Table 27 shows the measured U-values obtained from this test. Fig. 23 shows the configuration of the sensors secured to the window. Results show no statistically significant difference between the U-value measurements when using the balsa wood compared to other common forms of adhesive tape. 4.5 W/m²K was the expected U-value for this type of modern plate glass.

Type of fixation	Measured U-value (W/m^{2}K)
Double tape	4.5
Supporting rig in balsa wood *[method elected for use in Wee Causeway]*	4.5
Masking tape	4.5
Low tack transparent tape *[typical method of securing sensor to element]*	4.5

Table 27: *Measured U-values depending on fixation type*

Fig. 23 *Fixation types used for testing.*
From left to right: double tape, masking tape, low tack tape and wood support

Appendix 2: Shutter modelling

In the 'As Installed' and "Simulated shutters" models (Models 2 and 8), shutters have to be simulated to account for portion of time when shutters are open. The limitation of the SAP software, as a simple numerical program, does not accurately model shutters. SAP does not provide an input field for the thermal transmittance of the shutter or to modify the percentage of time for opening or closing the shutter. Therefore, the more realistic impact of shutters on internal temperature, and so on energy consumption, needed to be verified by combining the output of two SAP models.

To account for this factor, two SAP models were built:

- **Model A**: All shutters OPENED 100% time, simulated as a single glazing with a U-value of 3.9 W/m^2K.
- **Model B:** All shutters CLOSED 100% time, simulated as an opaque element with a U-value of 1.1 W/m^2K

The opaque element used for the shutters as a timber framed wall. The U-value of 1.1 W/m^2K is the in-situ value measured at Wee Causeway. A list of the other materials applied to the 'As Installed' model is displayed in Table 31.

The above information was used to create a new model, labelled **Model C**, which should provide a more realistic account of heat transfer through the window element with the shutter 'in use'. A short analyse of shutter use was conducted to define an opening percentage. Outcomes are displayed in Table 28.

	Winter	**Summer**
Opening time period	8 a.m. – 5 p.m.	8 a.m. – 10 p.m.
Number of hour	9 hours	14 hours
Day-opening percentage	37 %	59 %
Deduced closing percentage	63 %	41 %

Table 28: *Shutters opening period*

The times corresponding to the period by which the shutter is open, relates to the average day time working hours. This assumes that the shutters are not closed because the house is likely vacant. During the summer period, it is assumed that the shutters are closed later in the day because of the longer daylight hours.

These closing and opening percentages were then applied to the space heating result of Models A and B defined above. In SAP software, energy needs are given by month, so the percentage can be applied each month. Table 29 presents space heating values from SAP software for Model A and B, and calculated values for Model C.

MODEL A: AS INSTALLED OPENED 100 %													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Space heating kWh/year	2506	2087	1897	1394	821	0	0	0	0	1142	1904	2431	14182
MODEL B: AS INSTALLED CLOSED 100 %													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Space heating kWh/year	2764	2362	2206	1682	1065	0	0	0	0	1375	21367	2672	16263
MODEL C: AS INSTALLED													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Space heating kWh/year	2669	2261	2092	1513	921	0	0	0	0	1237	2051	2583	15326

Winter period Summer period

Table 29: Simulation of Model C

As SAP conventions considers that space heating from June to September is equal to zero, the summer period was defined from April to October. The winter period was elected to run from November to March in line with the coldest months in Scotland.

Example:

In March, this is winter period.

$$Model\ C = Model\ A * 0.37 + Model\ B * 0.63$$
$$Model\ C = 1897 * 0.37 + 2206 * 0.63$$
$$\boldsymbol{Model\ C = 2092\ kWh/year}$$

SAP result and EI value was defined depending on the space heating result; for the purpose of this model, these results were taken as the average of SAP and EI from the opened and closed models.

Example:

Results for the model with all shutters, called Model 8 "simulated shutter", are displayed in Table 30.

Model	Space heating kWh/year	SAP result	E I value
Model A	20,036	E 52	E 48
Model B	19,763	E 51	E 47
Model C	19,784	E 51	E 47

Table 30: Results for Model 8 "simulated shutter"

SAP result and EI value for model C were defined as the same as Model B because both space heating result are relatively similar.

Model number	Description	Wall improvement	Window improvement	Ceiling improvement
2-A	As Installed Shutter opened	Aerogel, Calcium silicate board and blown polystyrene bead	**Rear** : Film **Front**: Shutters opened	Ceiling insulated
2-B	As Installed Shutter closed	Aerogel, Calcium silicate board and blown polystyrene bead	**Rear**: Film **Front**: Shutters closed	Ceiling insulated
2-C	As installed	Aerogel, Calcium silicate board and blown polystyrene bead	**Rear**: Film **Front**: Shutter in use	Ceiling insulated
OPENINGS MODELS				
8-A	Shutters opened 100 % time	No insulation	Single glazing	No insulation
8-B	Shutters closed 100 % time	No insulation	All windows with shutters closed	No insulation
8-C	Simulated shutter	No insulation	All windows with shutters in use	No insulation

Table 31: *Characteristics for Model 2 and 8*

Appendix 3: Total window U-value calculation

This appendix details the method which was used to determine the total window U-value, from the centre of pane U-value.

The dimensions of the windows were measured at Wee Causeway, and an average window size was generated and drawn using computer drafting software (Fig. 24). The percentage of frame to glass was calculated to define the frame-factor. The calculations provided a result of 40 % to 60%, frame to glazing percentage. Fig. 25 shows the main screen of the software used to calculate total window U-value. The glass thermal conductivity value was manually manipulated to generate the same U-value for centre-of-pane as that measured at Wee Causeway.

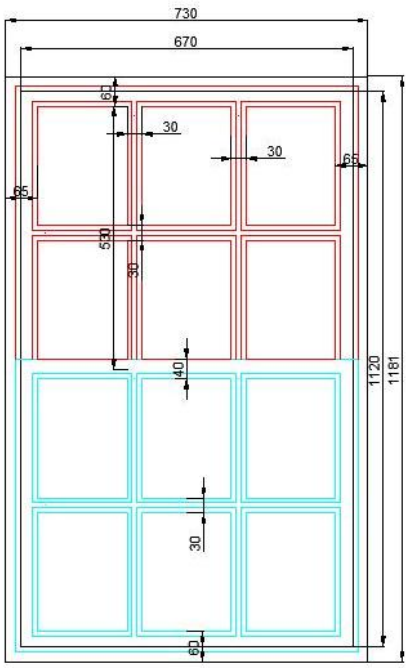

Fig. 24 Drawing of a typical window in Wee Causeway

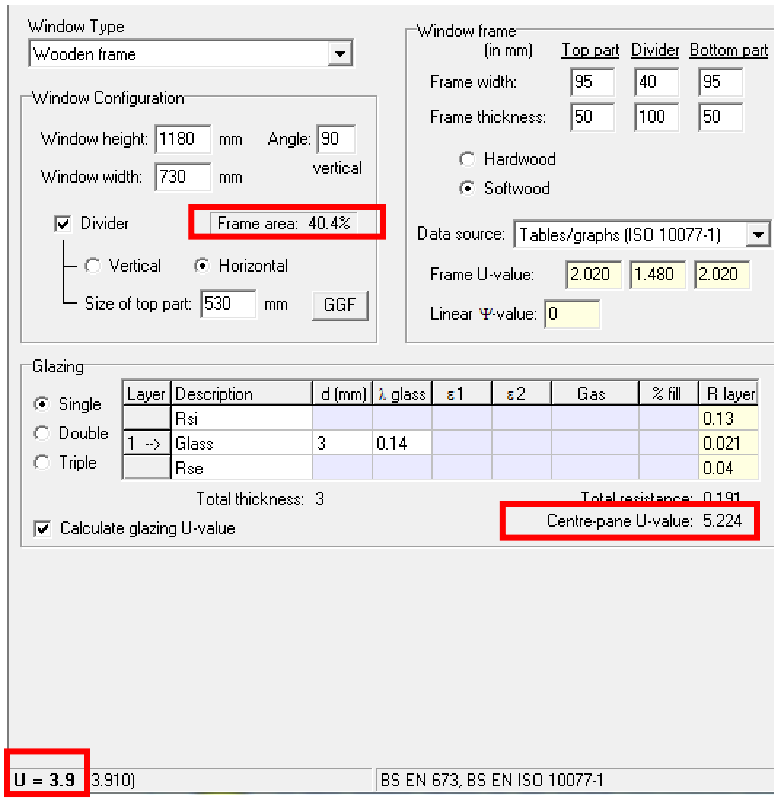

Fig. 25 U-value calculator's main screen for single glazed window

The BRU U-value calculator has a "Window" section which allows for the calculation of the total window U-value. By filling in the frame dimensions, the calculator deduces the frame area (first red rectangle in Fig. 25).

Then the thermal conductivity of the glass, or lambda value, is modified to obtain the in-situ centre pane U-value. The expected centre pane U-value is 5.2 W/m^{2}K, for a single glazed window (second rectangle in Fig. 25).

Finally, the total U-value of 3.9 W/m^{2}K is calculated (third rectangle in Fig. 25).

Appendix 4: Graphical display of materials and performance of models

This appendix graphically represents each of the models as described in Section 6. Each page displays each model with a highlighted graphic of the material applied to that model. The values displayed by each model as those generated from the SAP computer software.

Model 1

Wee Causeway Reference

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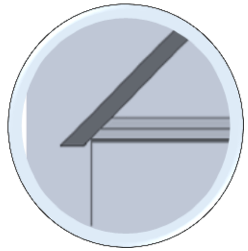
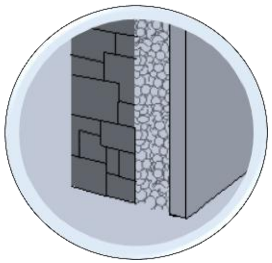
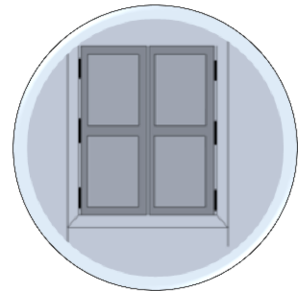
Scottish Energy Centre



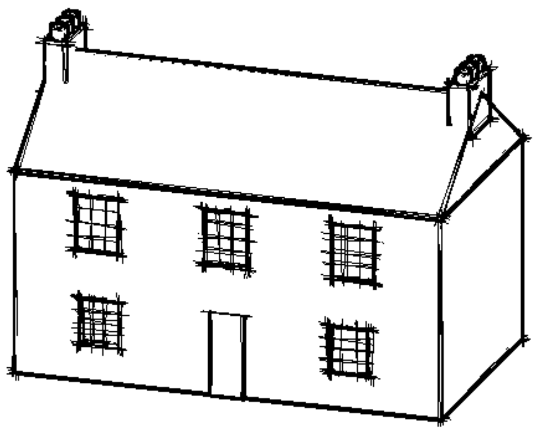
Ceiling insulation



Blown polystyrene beads



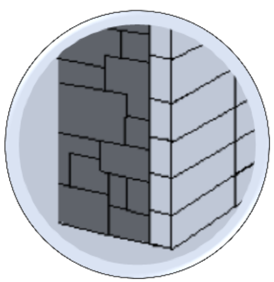
Shutters



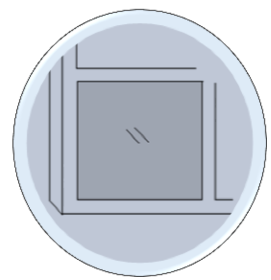
***261** kWh/m².year*

*SAP : **E 52***

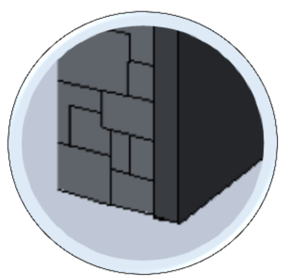
*EI : **D 48***



Calcium silicate board



Enerlogic film



Aerogel

Model 2

Wee Causeway As installed

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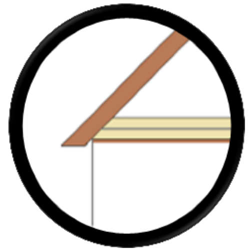
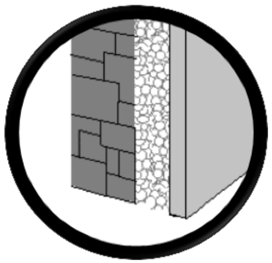
Scottish Energy Centre

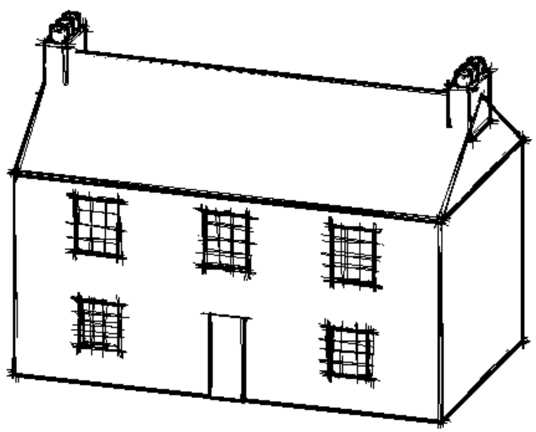


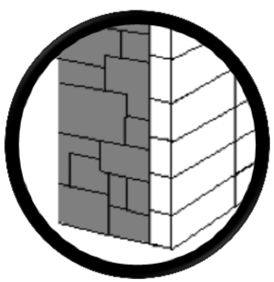
Ceiling insulation



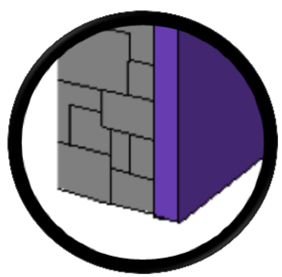
Blown polystyrene beads

Shutters

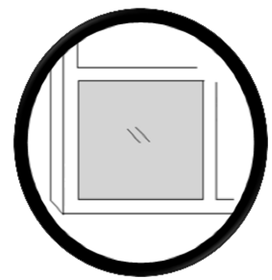




Calcium silicate board



Aerogel



Enerlogic film

***199** kWh/m^2.year*

*SAP : **D 58***

*EI : **D 54***

Model 3
Aerogel

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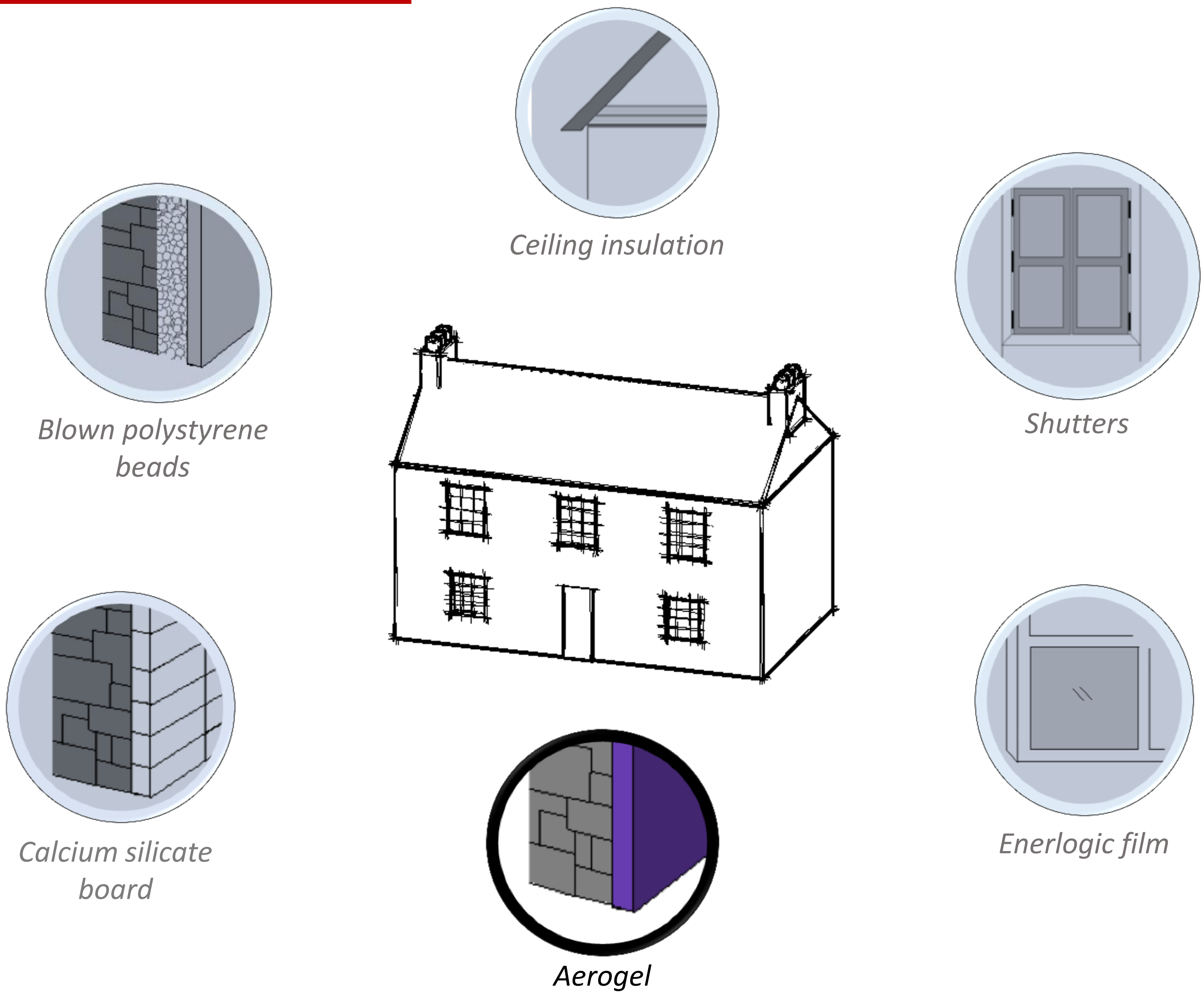
Scottish Energy Centre



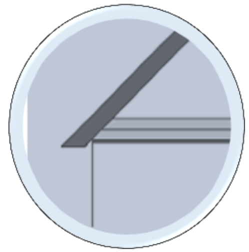
***231** kWh/m².year*

SAP : ***D 56***

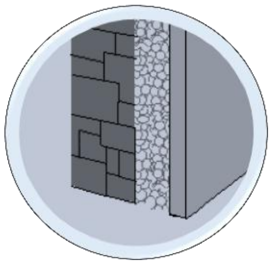
EI : ***E 52***

Model 4
Calcium silicate board

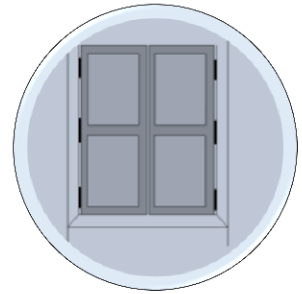
Edinburgh Napier UNIVERSITY
Scottish Energy Centre



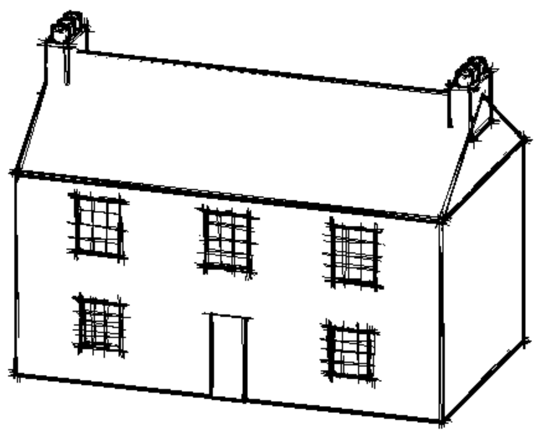
Ceiling insulation



Blown polystyrene beads



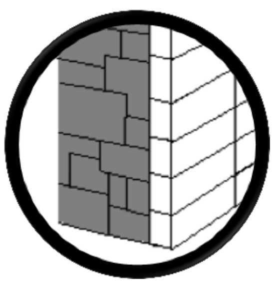
Shutters



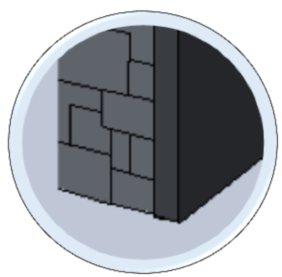
***220** kWh/m².year*

*SAP : **D 57***

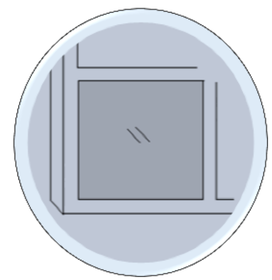
*EI : **E 53***



Calcium silicate board



Aerogel

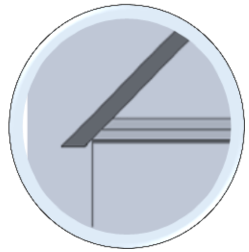


Enerlogic film

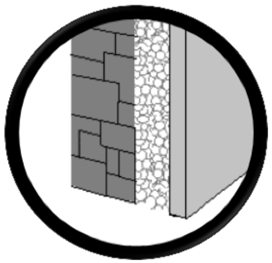
Model 5

Blown polystyrene beads

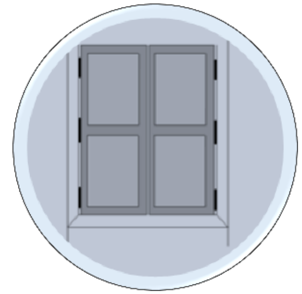
Edinburgh Napier UNIVERSITY
Scottish Energy Centre



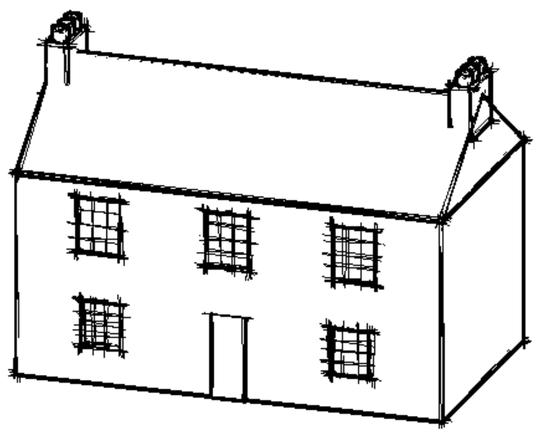
Ceiling insulation



Blown polystyrene beads



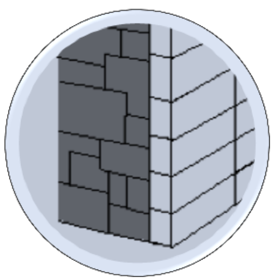
Shutters



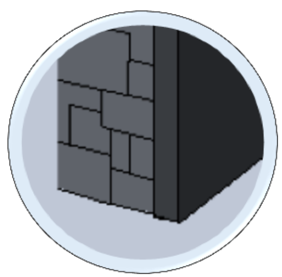
***208** kWh/m^2.year*

*SAP : **D 59***

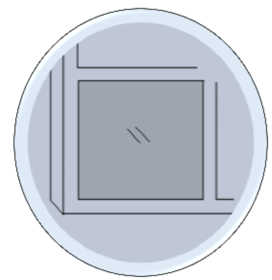
*EI : **D 55***



Calcium silicate board



Aerogel



Enerlogic film

Model 6
Ceiling insulation

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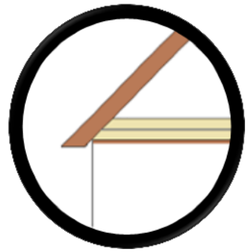
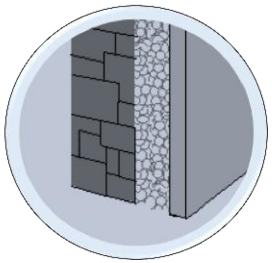
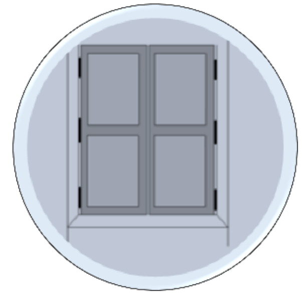
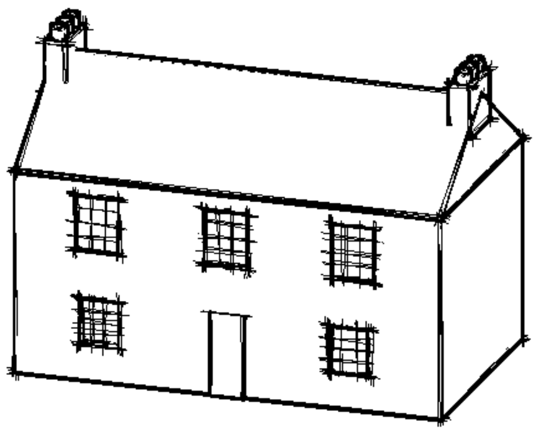

Ceiling insulation


Blown polystyrene beads

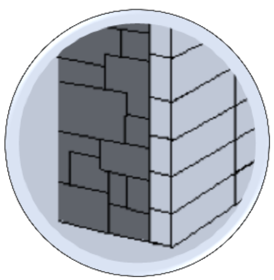

Shutters

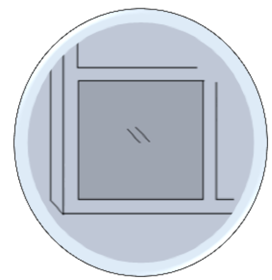


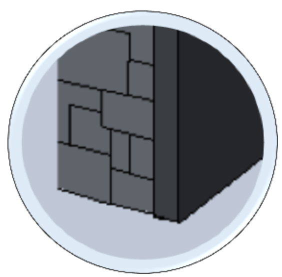
***235** kWh/m².year*

*SAP : **D 55***

*EI : **E 51***


Calcium silicate board


Enerlogic film


Aerogel

Model 7
Glazing film

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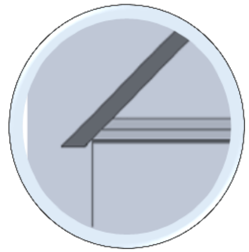
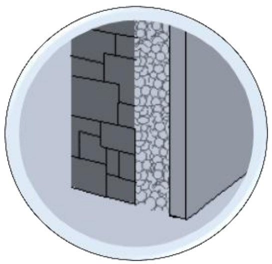
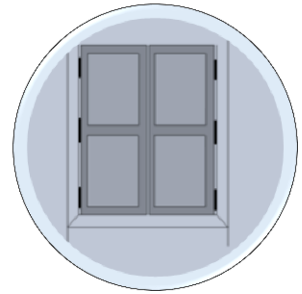


Ceiling insulation



Blown polystyrene beads

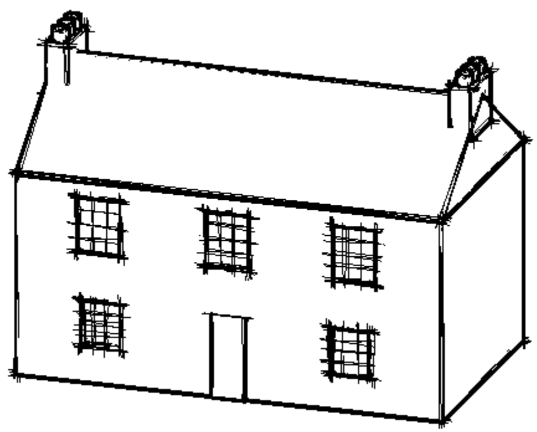


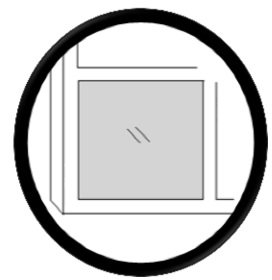
Shutters

255 *kWh/m².year*

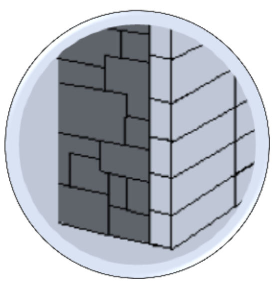
SAP : ***E 53***

EI : ***E 48***

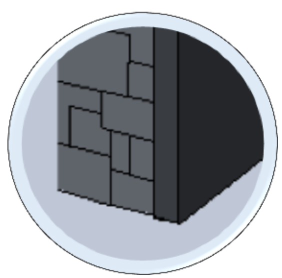




Enerlogic film



Calcium silicate board



Aerogel

Model 8

Simulated shutters

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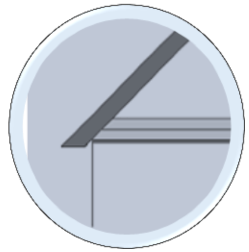
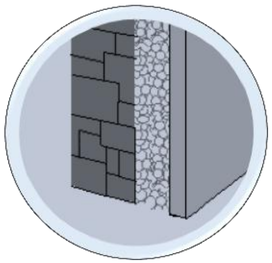
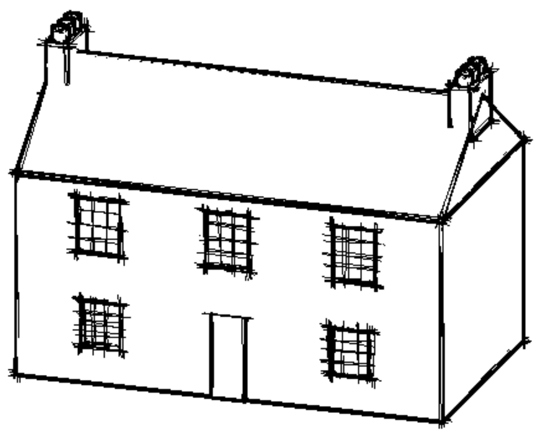


Ceiling insulation



Blown polystyrene beads

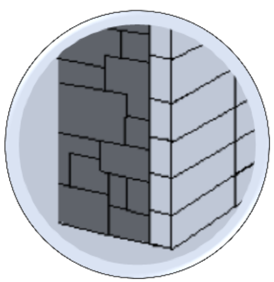


Shutters

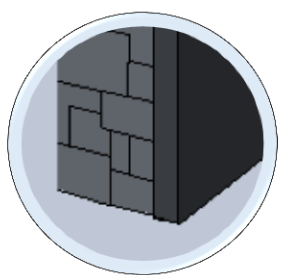
257 *kWh/m².year*

SAP : ***E 51***

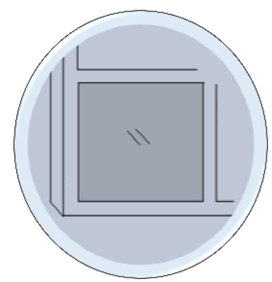
EI : ***E 47***



Calcium silicate board



Aerogel



Enerlogic film

Model 9

Best case model

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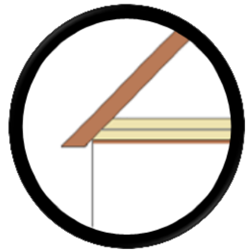
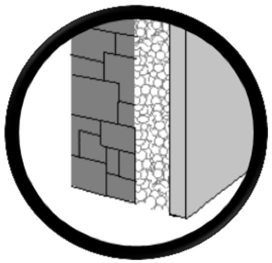
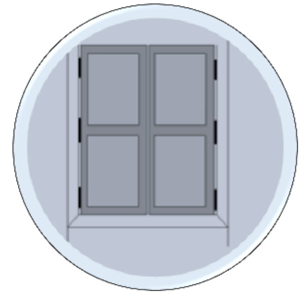
Scottish Energy Centre



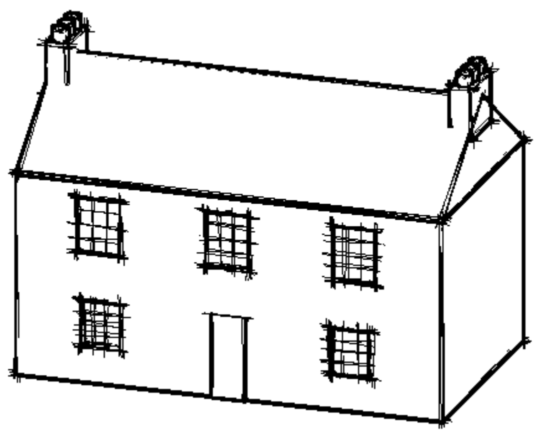
Ceiling insulation



Blown polystyrene beads



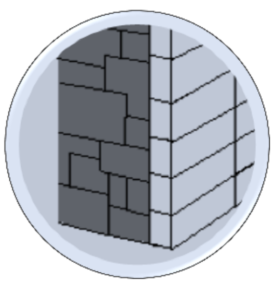
Shutters



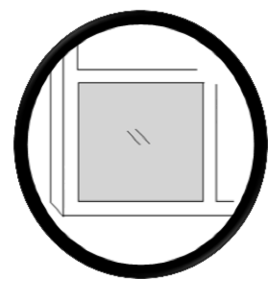
***177** kWh/m^2.year*

*SAP : **D 63***

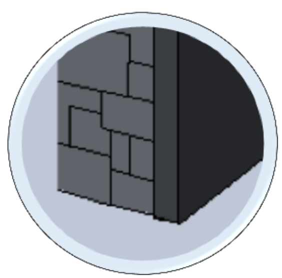
*EI : **D 60***



Calcium silicate board



Enerlogic film



Aerogel

September 2014

Historic Scotland Technical Papers

Available at www.historic-scotland.gov.uk/technicalpapers

1 Thermal performance of traditional windows

2 In situ U-value measurements in traditional buildings – *Preliminary results*

3 Energy modelling analysis of a traditionally built Scottish tenement flat

4 Energy modelling in traditional Scottish Houses (EMITSH)

5 Energy modelling of a mid 19th century villa

6 Indoor air quality and energy efficiency in traditional buildings

7 Embodied energy in natural building stone in Scotland

8 Energy modelling of the Garden Bothy, Dumfries House

9 Slim-profile double glazing – *Thermal performance and embodied energy*

10 U-values and traditional buildings – *In situ measurements and their comparison to calculated values*

11 Scottish Renaissance interiors – *Facings and adhesives for size-tempera painted wood*

12 Indoor environmental quality in refurbishment

13 Embodied energy considerations for existing buildings

14 Keeping warm in a cooler house – *Creating thermal comfort with background heating and locally used supplementary warmth*

15 Assessing insulation retrofits with hygrothermal simulations – *Heat and moisture transfer in insulated solid stone walls*

16 Green Deal financial modelling of a traditional cottage and tenement flat

17 Green Deal, Energy Company Obligations and traditional buildings

18 Evaluating energy modelling for traditionally constructed dwellings

19 Monitoring of thermal upgrades of ten traditional properties

20 Slim-profile double-glazing in listed buildings – *Re-measuring the thermal performance*

21 Data sources for energy performance assessments of historic buildings in the United Kingdom – *Identifying online data sources for the EFFESUS project*

22 Scotstarvit Tower Cottage - *A study of infrared electric heating installed in a refurbished 19th Century dwelling*

23 Thermal assessment of internal shutters and window film applied to traditional single glazed sash and case windows