# Solid sandstone thermal performance retrofit trials - superbead EPS bonded bead in cavities

Thermal Intervention testing:

- *In-situ* thermal transmission (U-value)
- Air leakage (Air permeability)
- Condensation risk analysis

## March 2020


**Prepared by:**

**Edinburgh Napier University**

**The Scottish Energy Centre**

**Dr Julio Bros-Williamson**


Image credits: Julio Bros-Williamson, 2019, Edinburgh Napier University

# i. Executive summary

This report aims to create a robust body of evidence of the effectiveness of the thermal improvements capable within a reduced cavity behind dry linings of solid walls. The trials involved the use of the *superbead* EPS bonded bead product by energystore Ltd.

## The stakeholders:

**energystore Ltd**; Material providers & main client.

**Everwarm Ltd**; Installers & main contact with HA's

**Williamsburgh HA**; Provided 3 dwellings in the study based in Paisley, Renfrewshire.

**CastleRock Edinvar HA.** Provided 1 dwelling in Edinburgh.

**Hillcrest HA**; Provided 6 dwellings in Forfar, Angus.

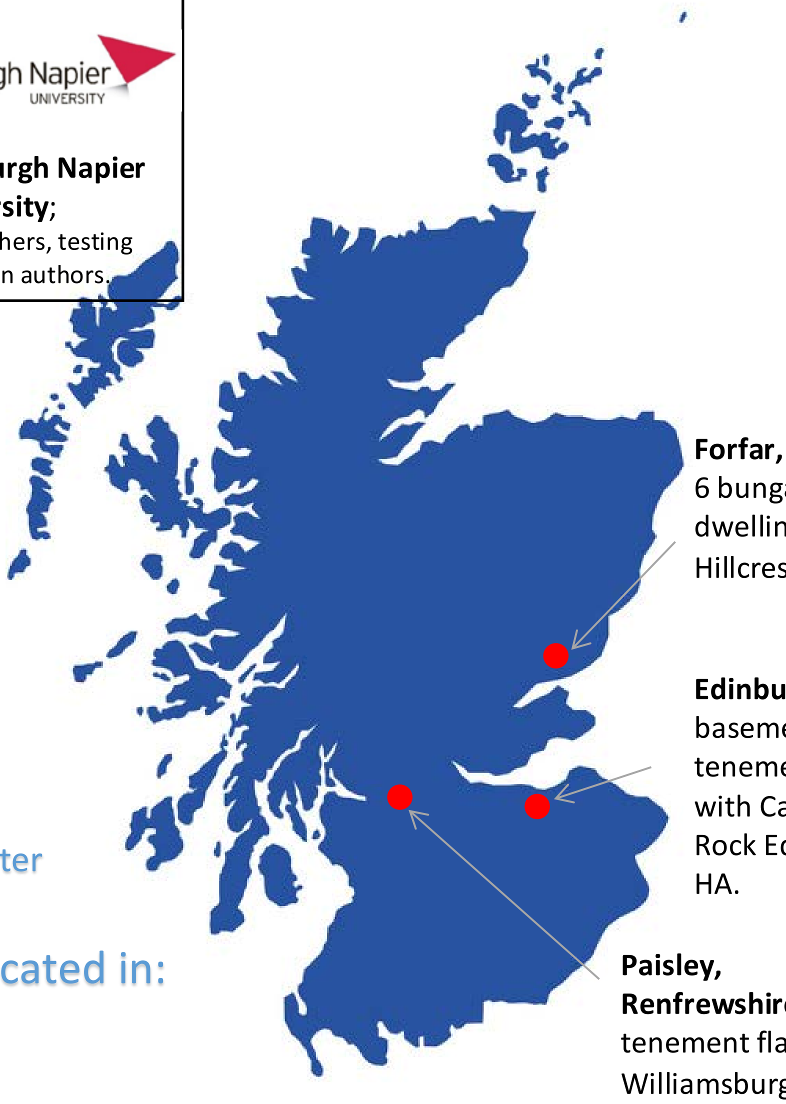
**Edinburgh Napier University**; Researchers, testing and main authors.

## Scope of the study:

10

Solid stone dwellings with plasterboard or lath-&-plaster drylining

Located in:

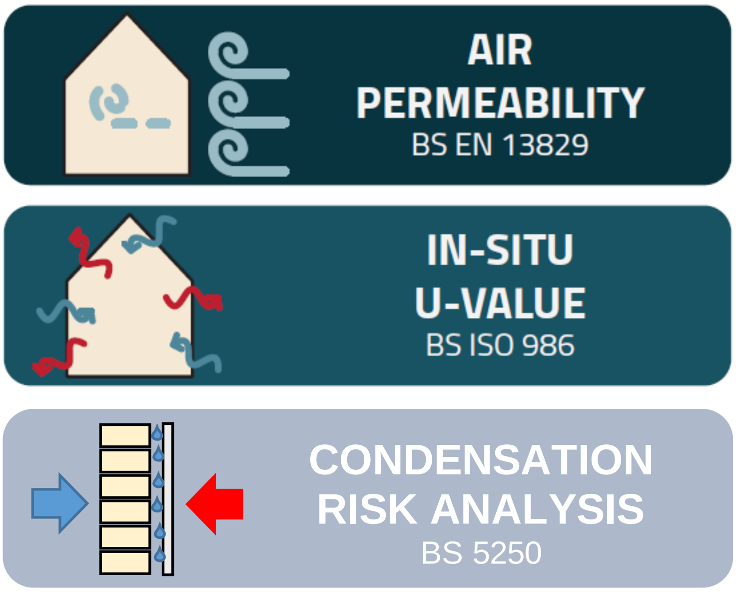


**Forfar, Angus.** 6 bungalow dwellings with Hillcrest HA.

**Edinburgh**, 1 basement tenement flat with Castle Rock Edinvar HA.

**Paisley, Renfrewshire**. 3 tenement flats with Williamsburgh HA.

## 3 Main tests performed:

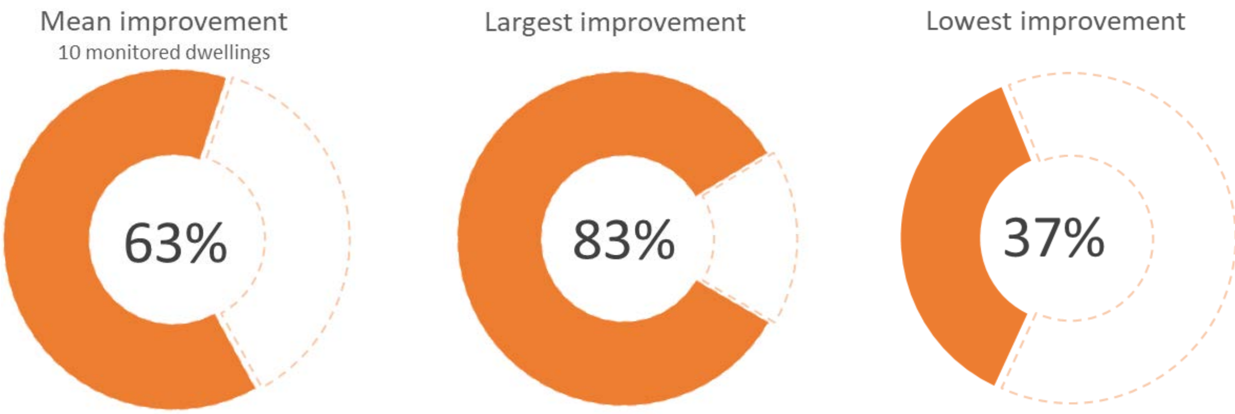



In-situ tests were performed at the pre-intervention stage (baseline) and then post-intervention stage with EPS beads in cavity.

# Results:

## In-situ U-value comparison

Mean, largest and lowest difference between pre and post-intervention testing

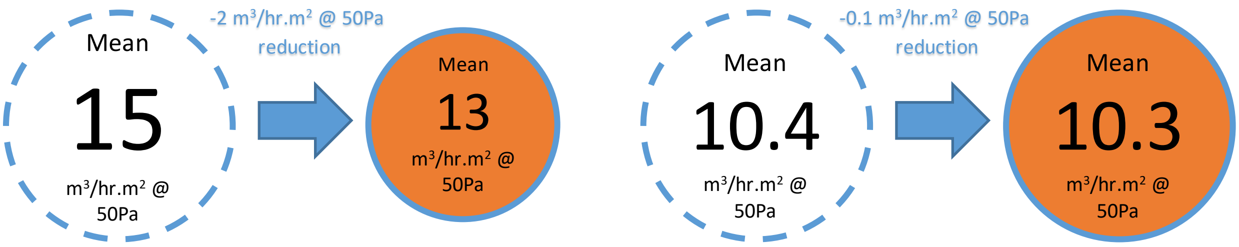



The dwellings presented varying cavity depths between 80mm and 130mm. This impacted on the results where the volume of *superbead* insulation determined the thermal resistance improvement.

## Air permeability (Air leakage) comparison

Dwellings with the EPS *superbead* in all wall's achieved (3 dwellings, all tenement flats):

Dwellings with the EPS *superbead* in only one wall achieved (6 dwellings, all bungalow homes):



### Condensation risk analysis

- During monitoring (15 days) no risk of condensation built-up was observed. However, this was a snapshot of the baseline and post-intervention periods.

- The separation between cavity temperature and dew point temperature (margin) was calculated which presented a mean of 8˚C at pre-intervention and 10.5˚C at post-intervention.

## Key outcomes and discussion

Although the mean U-value improvement is a high 63%, this corresponds to 10 dwellings monitored. Robust data from the 6 dwellings in Forfar showed a reduction of 56%.

Varying wall cavity depths impacted the thermal resistance. Different depths were also found in single walls due to the rough sandstone finish.

The importance of wall surveys in all retrofit projects highlights the varying conditions found in existing buildings, which often directs the most adequate intervention.

Air permeability reduction between baselines and post-intervention was higher when all walls were insulated, and other retrofit interventions were in place.

Less exposed tenement dwellings at ground floor had a higher reduction of air permeability compared with those in a top floor.

Using *superbead* EPS bonded bead behind dry linings of solid walls is an efficient non-invasive solution that can save: 3,450kWh energy, £136 on bills and 750 $kgCO_2e$/yr.*

More testing is required to assess the risk of condensation using dewpoint margin; monitoring a larger sample over a 12-month period is recommended.

*These yearly estimates are based on projections using current EPC calculations for space heating only, using natural gas as the heating fuel and all walls insulated using the energystore Ltd *superbead* EPS bonded beads.

# ii. Foreword

This document presents findings from surveys, in-situ thermal transmission and air permeability monitoring and analysis of ten traditional dwellings in Paisley, Edinburgh and Forfar in Scotland. The Scottish Energy Centre (SEC) and Robin McKenzie Partnership (RMP), both affiliated to Edinburgh Napier University, performed this work during two phases: 1) January to March 2019 and 2) November to December 2019.

Acknowledgements go to Ralph McMaster the Operations Supervisor at Everwarm Ltd (Sureserve Group) who had direct contact with the HA’s and provided survey information of all dwellings. Credit also goes to team members of the three housing associations: Williamsburgh HA in Paisley, Castle Rock Edinvar in Edinburgh and Hillcrest HA in Forfar for providing access and tenant engagement. Equally important are the residents of some of the dwellings who without their approval and patience, these tests would not be possible.

Likewise, the research team is thankful to CS-IC for providing the funding for this industry and academic engagement. Credit also goes to Amy Dickson, a 4th year student of the BSc Architectural Technology degree at Edinburgh Napier University who supported the equipment installs and performed data analysis retrieved from the monitoring.

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| Author: | Dr Julio Bros-Williamson, Scottish Energy Centre |
| Collaborators: | Amy Dickson, Dr Jon Stinson, Gareth Henderson & Dale Porteous |
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# iii. Contents

# 1. Introduction

This document describes the results and analysis obtained from monitoring of ten thermal upgrades to traditional dwellings with solid sandstone walls. The thermal interventions included the use of an EPS bonded bead system, specifically the “*superbead*” product injected behind the lath-and-plaster linings of the dwellings monitored. The product manufactured by *energystore Ltd* was installed in this project by *Everwarm Ltd* part of the *Sureserve Group.* This project has greatly benefited from the Construction Scotland Innovation Centre (CS-IC) Collaborative project grant funding for the academic engagement between Edinburgh Napier University and industry partners energystore Ltd, to test and analyse an innovative method of reducing envelope heat loss in existing buildings.

This report aims to create a robust body of evidence of the effectiveness of the thermal improvements capable within a reduced cavity behind the lath-and-plaster linings of solid walls. Within the objectives of the report are to describe the installation process and survey requirements experienced in the trial projects. Another of the project's objectives is to thermally measure and report on a larger sample size of cases adopting this method of insulating solid wall dwellings. Early use and testing of such thermal interventions were performed by Historic Environment Scotland where results showed clear thermal benefits but within a small number of cases.

The *superbead* product by energystore Ltd is an expanded polystyrene (EPS) bead that by itself is a closed-cell material likely to repel and have a small reaction to moisture absorption (low hygroscopicity). When bonded with special adhesives in a constrained space (cavity), it provides high resistance to heat loss but equally offers the free passage of air and water between the bonded beads and any adjacent surfaces. Typically, the bonded beads are blown into cavities as small as 40mm between masonry walls while still allowing air from vents to circulate the cavity. Other closed-cell insulants that fill cavities such as foams, tend to also have low absorption to moisture (low hygroscopicity) but often block the free movement of air in cavities, enhancing capillary action between other surfaces (brick, block, etc). The *superbead* product has a low thermal conductivity value of 0.033 W/mK with high resistance to heat passing by particularly in deep cavities or spaces.

The *superbead* product is typically placed into partially filled or fully uninsulated masonry cavities by drilling holes in the external leaf (brick or block) and injecting beads mixed with adhesive at a predetermined pressure. This bead system is also applied into uninsulated timber walls with masonry or timber clad outer exposed leaf. Such beads are injected from the inside of the wall (plasterboard side) directly into the timber kit. This is particularly effective as such cavities can reach depths of up to 140mm providing a higher thermal resistance (4.24 $m^2K/W$) in comparison with the masonry fill with cavity depths of 50 to 75mm (mean 1.90 $m^2K/W$). For more information on the third-party certifications and technical guidance, refer to [http://energystoreltd.com/certification/](http://energystoreltd.com/certification/).

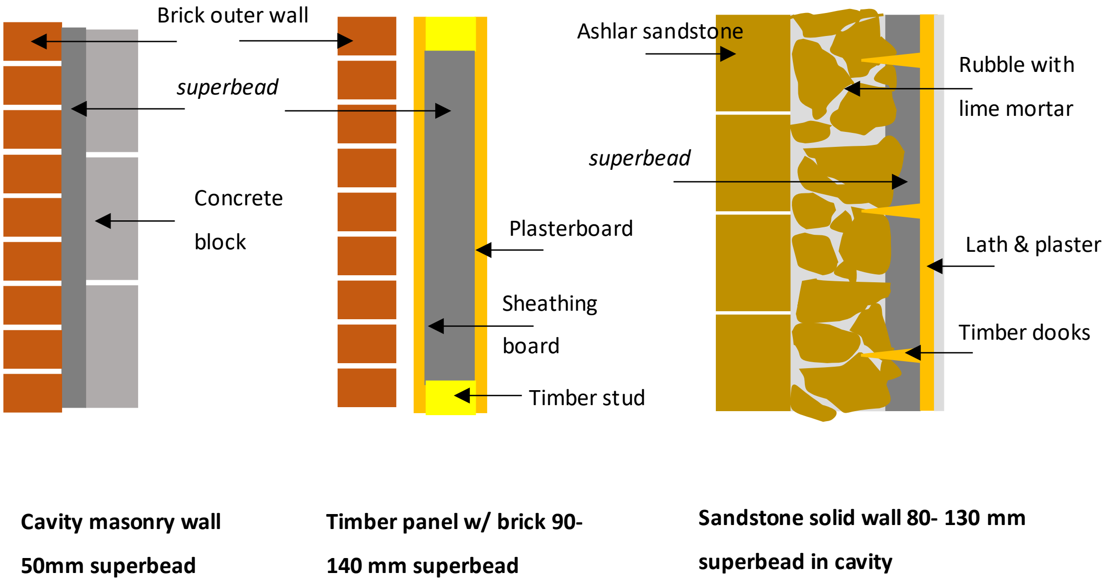



*Figure 1: Location of the superbead EPS bonded bead in different wall types, Source: JBW 2020*

Similar to the timber kit installation, the trials performed for this project injected the beads from the inside of the walls into a cavity behind the traditional existing lath-and-plaster lining, or otherwise a plasterboard lining from a previous retrofit. The cavity depth varied from 80 to 130 mm and often-uneven surfaces were observed, typical of a rubble wall with a rough finish, as seen in Figure 1 above.

The document is split into five sections that begin with a literature review of similar studies and testing methodologies. It is followed by the description of the applied methodology for testing and data analysis based on the complexities of the buildings and occupiers as well as the time constraints and equipment availability. Subsequently, the report shows the results obtained after monitoring. Case study information of the analysed dwellings can be found in Appendix A. Finally, the data obtained are discussed and concluded highlighting trends and important outcomes from the project.

### 1.1. Example installation of beads – omitted as per company request

## 2. Literature Review

The literature review of this report covers decisive topics relevant to pre-1919 buildings and methods of evaluation relevant to this study.

### 2.1. History, building materials and methods of construction

The improvement and preservation of existing buildings with historical and social importance is a pressing concern in the UK and Scotland. The impact buildings have on the environment, mainly through its operational energy and $CO_2$ emissions accounts to 20% of the total emission in Scotland (1). Domestic dwellings emit a large share of that total 13%, where at least 64% being from space heating keeping occupants thermally comfortable (2). Solid stonewall buildings play an important role in Scotland’s built environment covering many centuries, archetypes, styles and uses reflecting on the country’s rich heritage. This construction method, typical starting in the Stuart era (also known as Jacobean style) around the 17th Century spanning towards its peak during the Victorian between the early 19th Century and early 20th Century (3). Advances in construction materials, their availability and new techniques as well as the need to build faster to fulfil housing shortage after WWI brought in the use of cavity masonry walls that revolutionised the construction industry playing a big part of house building in the 21st Century. In Scotland, there are approximately 2,278,000 dwellings with 60% of all dwellings built pre-1945 and 23% pre-1919 tenement flats (4). Key findings from the 2017 Scottish House Condition Survey (5), including updated fuel poverty rates, energy efficiency ratings and carbon emissions show that the primary heating fuel affects the household fuel poverty status. Increasing demand due to poor building conditions is a determining factor to the affordability of the dwellings.

Many Scottish cities have representative buildings using such sandstone types and methods; from refined ashlar sandstone features, cornices and wall facings to more rustic and rough-surfaced facades of rubble walls using lower quality locally available stone. A distinctive sandstone wall is composed of a 200-300 mm thick ashlar external layer followed by a 300 to 400mm thick rubble stonewall of a varied composition of stone and lime mortar, typically 60/40 (6). Subsequently, a vented cavity of 50 to 80mm is kept between a timber frame fixed to the wall with dooks to hold timber laths and lime plaster finish. Section 26 of the Tenement (Scotland) Act 2004 best defines a tenement as: ‘’Two or more related but separate flats divided from each other horizontally” (7). The definition is framed broadly to include not only traditional tenement dwellings but also four-in-a-block houses and larger houses, which have been subdivided and often include shop units on the ground floor part of the whole tenement block. Examples of pre-1919 tenements are typically found in Edinburgh and Glasgow, widely occupied by many households considered difficult and expensive to heat due to their low thermal resistance and high air leakage (8). However, advantageous qualities such as their high thermal inertia (mass) and low moisture permeability of materials still merits its original composition and performance.

The use of sandstone solid walls in housing, for example in tenements and other archetypes, accounts for 19% of the total number of dwellings in Scotland (5). Before the 1930s in the UK, and particularly looking at pre-1919 solid sandstone wall dwellings, house building consisted of frameless structures, with the external façade acting as the loadbearing wall. In the case of masonry examples such as sandstone, approximately 75 quarries were present in the Glasgow district alone (9). More typical of East coast quarries supplying Edinburgh and the Lothians, was the blonde sandstones, laid down in vast river systems, evidence of which comes from finding pebbly layers or even bits of plant debris within this rock. It is a quartz-rich stone with <10% other components providing the pale beige colour (9). The red sandstone more typical of

Western towns and cities of Scotland originates from Dumfries and Ayrshire and is from the Permian period (circa 270 million years ago). During this period, a vast and expansive desert stretched across Scotland, resulting in massive dunes and arid conditions. Today the evidence of this desert can be found in the red sandstones used in Glasgow, in the form of cross-bedding (evidence of where desert sand formed dunes) and by the red colour itself, representing an iron-rich coating of the sand grains, a phenomenon which can still be seen today in the Sahara.

Also typical of pre-1919 buildings is the use of lath and plaster technique which evolved to reduce the direct contact of plaster finished directly onto the stone or to create ceilings supported by a timber frame above. The process of lath and plaster consists of narrow strips of wood or laths that are nailed horizontally across the wall studs or ceiling joists and then coated in plaster (10).

The Energy Saving Trust (11) estimates that an un-insulated dwelling loses a third of all its heat through the walls and a further quarter through the roof. As a result, insulation and airtightness can play a significant role in reducing energy consumption and in lowering heating bills effectively, making it cheaper and thermally comfortable. It’s estimated that currently 66% of pre-1919 external wall construction using sandstone walls remains un-insulated. Such lack of thermal resistance poses large constrains among occupants who find it difficult to heat such dwellings, forcing them to be leading towards unhealthy conditions and socially inadequate dwellings. With 80% of our built environment expected to still be in use by 2050, mostly built under poor building codes and standards, tackling existing buildings remains a priority particularly leading towards a low and net-zero carbon and recent climate emergency (2).

At the forefront are studies and trials by Historic Environment Scotland that seek to preserve the built heritage but equally improve thermal conditions for occupiers. Some of these case studies include the use of insulation materials/techniques such as blown insulation involving an expanded polystyrene (EPS) bead, rigid insulation with the use of wood fibreboard, timber and aluminium frame secondary glazing, amongst others as part of HES Technical Documents as indicated by (12).

Few reported cases exist of the thermal effectiveness of EPS beads in cavities. However, some case studies have provided information on the technical approaches, consistency of the materials and some thermal improvements (12). Raps *et al.*(2015) (13) analysed how polymer beads and foams have evolved focusing on technology and the effectiveness of techniques. The article found that EPS beads are the most widely used bead foam material with a consumption of 4.7 Mt per year due to its low price and high availability. The CIBSE Guide A (14), Table 3.36; in its description of non-hygroscopic materials, explains that loose-fill or moulded EPS beads during laboratory testing at 10°C has a thermal conductivity value (ʌ) of 0.036 W/mK, density of 16 kg/m$^3$ and specific heat capacity 1210 J/kgK. Also analysing the hygrothermal performance of EPS beads is information the Building Standard 12524 (15) that describes the density to be between 10 and 30 kg/m$^3$ and the specific heat capacity to be 1400 J/kgK. Additionally, the water vapour resistance factor is quoted to be 2$\mu$ which is important for understanding its water permeability during condensations risk analysis. The energystore Ltd *superbead* product states a thermal conductivity value of 0.033 W/mK and a lower density of 12 kg/m$^3$ however; the product uses an additional coating that improves its thermal performance. In an earlier study by Anderson *et al.* (1985) performing in-situ U-value testing of walls in dwellings built before and after 1976 found that those that had their cavity fully filled with EPS beads improved by 63% from 1.5 W/m$^2$K down to 0.55W/m$^2$K (pre 1976 dwellings). For more recently built dwellings (post 1976) the improvement was 55% from 1 W/m$^2$K to 0.45 W/m$^2$K. An investigation over the water ingress and hydrothermal performance of retrofitted walls with cavity EPS beads were developed by Van Goethem, Van Den Bossche and Janssens (17). It found that after comparing non-insulated cavities with bead-insulated cavities, that the water ingress into insulated cavities does not necessarily stop water filtrating into the cavity, despite this if the cavity remains well ventilated the risk of infiltration into the interior leaf is minimal.

Other insulation products trialled in technical guidance provided by Historic Environment Scotland expands on retrofit options, particularly in solid wall buildings (6). Focusing on internal wall insulation in tenement solid wall buildings in Glasgow, explored the performance of materials such as: blown cellulose fibre sprayed directly to internal sandstone masonry walls, as well as hemp and wood fibreboard applied between timber strapping. Additionally, new products were used, such as 40mm of aerogel backed against a rigid board. All interventions provided an outlook over the best technique to apply as an intervention and also show thermal improvements between baseline measurement and post-intervention stages. The U-value results were significant as they showed mean reductions of 30 to 80% (12).

## 2.2. Methods of Evaluation

### 2.2.1. Thermal transmission testing (Heat flux)

The U-value of a building element or component is defined 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.” (18). Its calculation using steady-state methods was developed by Anderson (19), and most industry-related calculations for the thermal performance of building components adopt this methodology. On-site, physical measurements are possible over a set period of time to calculate in-situ U-values (thermal transmission) of components (6). In-situ measurements as defined by (6), (20), (21), and (22) all coincide that if the methods proposed by the latest British and ISO standard 9869 (23) are implemented, a more realistic and dynamic set of U-value results can be obtained considering actual conditions. Studies of particular solid wall examples are used in work by Francis et al (21) who argue that many of the assumptions used for calculating the impact and savings of retrofits of solid walls have been incorrect as most used steady-state calculations which appear to be higher than the actual in-situ test.

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 (24). Reliable results are obtained with a temperature differential ($\Delta t$) of >10°C across the building element. Calculating the uncertainty related to temperature probes and heat flux transducers (HFT’s) 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 been calculated by using the established error analysis methodology described in (6).

### 2.2.2. Airtightness

Airtightness or air permeability test measures uncontrolled ventilation (infiltration) and heat loss through the envelope of a building. Sherman and Chan (21) define it as a “fundamental building property” that impacts building performance and dependent on the quality of the envelope as it measures the movement of air through gaps, cracks and “adventitious openings in the building envelope”. Gillott et al. (25) claim that air infiltration contributes to one-third of heat losses through the building envelope. In the UK, standards set by BS EN 13829 (26) and best practice set by CIBSE TM23 (27) form much of the framework for conducting air permeability testing. The Airtightness Testing and Measurement Association (ATTMA) produced an industry best practice guide for the measurement procedure (28) and Liddament (29) explains that air permeability testing indicates an airflow rate in $m^3/h$ for each $m^2$ of envelope area at a pressure rate of 50 Pascals (50 Pa). The Energy Saving Trust (30) through its case studies of air permeability testing explains that a fundamental part of a new airtight building is the dwellings air barrier. It concludes that careful attention should be taken in ensuring that the air barrier is not perforated and should wrap around the dwelling envelope.

Measurements are obtained by doing a blower-door test where all openable ventilation outlets are closed and sealed, this includes window trickle vents, ventilation flues and other extractor fans (31). A fan is fitted where the blower-door canvas is placed, usually the main door to the property (28). The conditions in which tests are performed depending on the outside wind speed influencing pressure readings. Tests should be performed during calm, light air and light breeze conditions according to the Beaufort scale for wind force indication (BS EN, 2001, p 23). Before testing, building exposed areas (floor, roof and wall) are calculated and used in air permeability results at 50 Pascals building pressure. If air exchanges (ACH) are required, the building volume is used instead (32).

### 2.2.3. Moisture risk analysis

To adequately assess the performance of a retrofit intervention it is important to consider moisture accumulation based on the interfaces between the layers in a component. Dew point temperature is used as a measure that indicates at what point water vapour saturates and condensation appears on a surface. It can be measured by the ambient conditions in a room reaching its water vapour saturation point in which water droplets are formed. Repeated instances of the risk of dew point for long periods can have a detrimental effect on the components structural and thermal performance (33). Assessment of dew point in building components as explained by the Glaser Method (34), provides a steady-state approach to understanding where condensation may appear in between layers of the component. The method is useful as an assessment tool but it does not consider air movement, actual moisture content of materials, the impact of driving rain and other climatic conditions. Work by Browne (35) explains how certain in-situ tests can be made considering ambient temperature (°C), humidity (RH%) and water content that provide a good indication of a component's performance over time.

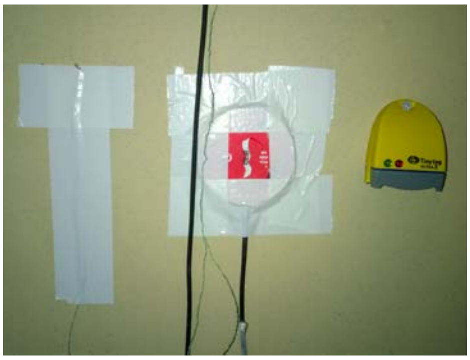
# 3. Monitoring methodology

Tackling a project of this nature requires an adequate methodology both in acquiring baseline data, reference to benchmarks and performing in-situ monitoring over set periods. Some testing is weather dependant and can only be performed on set periods and conditions. Other testing, such as the condensation risk analysis requires long periods of continuous data gathering but given the constraints of time and access to the dwellings, meaningful monitoring is not possible. Before any testing and with the support of Everwarm Ltd, a survey of the cavity depth, wall thickness and consistency of stonework took place that allowed for the appropriate allocation and placement of monitoring equipment.

The following testing was performed before any insulation was applied to the building and after the thermal upgrades were conducted.

## 3.1. Thermal transmission testing (Heat flux)

The in-situ U-value measurements were taken using Hukseflux HFP01 thermopile-based heat flux transducers (HFT’s) of 80 mm diameter and 5 mm thickness. They were attached to external walls where future interventions were to be applied building element being tested throughout monitoring (typically > 14 days). Two such HFT’s were located at different heights, typically at 100mm and 2000mm distances from the finished floor level to verify the accuracy and protection against equipment failure. The elemental U-values were determined by recording the heat flow through the walls together with internal surface/ ambient and external air temperature (23). This was performed by logging differential voltage from the HFT's and temperature from calibrated K type thermocouples, with backup additional Tinytag temperature / humidity loggers installed internally and externally. Grant Squirrel data loggers with 24bit conversion resolution were used to log data from the HFT's and the thermocouples. Calculation of the resultant U-values was conducted using the guidelines and calculation methodology set by BS ISO 9869 (23). Such tests were done at the pre-intervention stages to obtain a baseline figure of the monitored wall followed by the post-intervention stage measuring improved U-value of the same wall. The same location of HFT's was used to keep consistency in measurements.



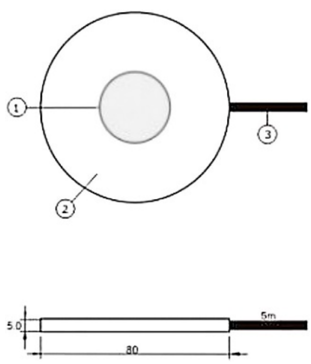




*Figure 2: (left) Wall heat flux installation with a Tiny Tag sensor and an ambient room thermocouple*

*Figure 3: (Centre): (1) Sensor diagram; (2) guard of ceramics-plastic composite; (3) cable connected to a data logger.*

*Figure 4: (right) Typical HFP sensor by Hukseflux*

All measured values underwent an error analysis which suggests small errors may exist during the period of testing. Two reasons result in increased uncertainties of some of the *in-situ* measurements: too small a differential between the inside and outdoor temperatures; and unknown factors in the build-up of a building element. Previous testing and much of the literature available reports an overall uncertainty value of ±0.10 W/m$^2$K which represents an 8 to 10% displacement. Typical uncertainties of tests vary between 8% and 15%, predicated on the periods of testing with increased indoor and outdoor temperature differences (6) & (22)

## 3.2. Airtightness testing

The airtightness testing or Blower-door test consisted of imposing a pressure difference between the inside and the outside to evaluate the air leakage rate. Heating, ventilation air conditioning was turned off and 50 Pa pressure difference was reached with increments between two values of no more than 10 Pa (26). Airtightness testing was performed to obtain a baseline result before insulation was installed. The same procedure and testing regime was performed once the EPS *superbead* insulation was installed giving a performance figure and reduction benefit.

Testing in this project extended to include both pressurisation and depressurisation which examined the dwellings air leakage including window and door seals in both directions of flow allowing for a more extensive evaluation of the building envelope. Testing of this nature is typical in new buildings where a reduced air leakage signifies less infiltration heat loss through the building envelope. In this project to identify the effectiveness of the intervention, the only independent variable changed between pre and post-intervention stages was the installed insulation layer within the dwellings external walls. All other air leakage pathways remained during both testing phases which would assure the singular effectiveness of the intervention. Air leakage in older dwellings can be difficult to remediate unless a deeper retrofit programme is undergone. This is due to the intricacy of identifying the origin of an air leakage pathway as it is not always directly located near an identified hole, crack or penetration. More information can be found in the final report (Appendix B) by RMP Consultants who conducted the air permeability tests.

## 3.3. Condensation Risk

Conducting a hygrothermal assessment of the building element provided critical information of any condensation risk within the monitored walls. Monitoring took place at two points inside the cavity with additional ambient temperature and relative humidity conditions. The period of monitoring was short; 14 days at a pre-intervention phase followed by 14 days post-intervention.

Pre-and post-intervention analysis included the monitoring of in-situ cavity condensation converting temperature and humidity readings into dew point and dew point margin showing how close the reading was to saturation and condensation at a material interval. Longer periods of this can provide seasonal condensation patters that can identify risk periods of condensation build-up. A high risk of moisture accumulation over prolonged periods can be detrimental to the building component.

Apparatus to retrieve hygrothermal data included the use of hygro-pins connected to a Grant Squirrel data logger. The hygro-pins were inserted into the cavity at different depths; Hygro-pin HC01 was inserted fully into the cavity at a depth of 80mm until reaching the sandstone interface and the other, HC06 into the lath and plaster at a depth of 20mm, see Figure 5 and Figure 6.

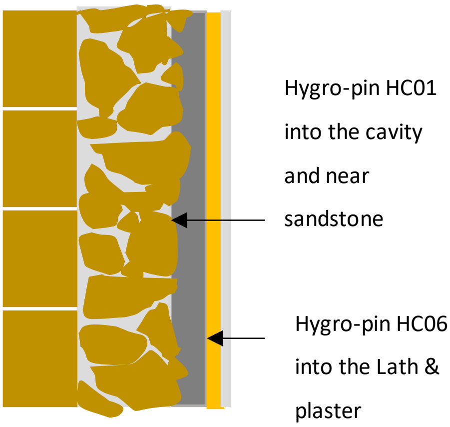



*Figure 5: (left)Diagram of pin location in the monitored wall*

*Figure 6: (right) Example hygro-pin as inserted into walls*

## 3.4. Periods of testing

The testing took place during two heating periods in 2019. The first, intermittently from January to March 2019 monitored the performance of four dwellings in Paisley and Edinburgh. The second period from November to December 2019 monitored six dwellings in Forfar.

Pre-intervention testing took place to define a baseline result of a representative wall in each property. It also allowed the research team to perform a whole-dwelling survey to extract measurements and dimensions to support the air permeability testing and inform the testing conducted. The deployment of the loggers took place while residents were in the home, but in some instances some dwellings were unoccupied.

Following the retrieval of data after post-intervention testing, results analysis took place considering all data points from night and day periods of monitoring. This provided a full spectrum of the results, however, as results are more accurate with a wider temperature difference across the surface of the components ($\Delta t$), the impact of solar radiation and increased day time temperatures became less reliable with a larger uncertainty. As a result, night-time data was analysed separately to obtain a more reliable set of results with a smaller margin of error.

# 4. Monitoring results and analysis

This section presents and describes the results of all the monitoring performed in each of the dwellings. Appendix A - Case study analysis shows specific information of the monitored dwellings highlighting individual results against the baseline pre-intervention stages. Results are presented according to the monitoring technique as follows:

## 4.1. *In-situ* U-value test results and analysis

The following results have been obtained after retrieving and analysing each data set following each testing period. Results are first presented as pre-intervention values of the actual wall without any insulation being placed in the cavity. They act as a benchmark and baseline figure to indicate the rate of change against any subsequent tests. Post-intervention results show the change after the *superbead* EPS insulation was injected in the cavity. These results show the effect of such intervention at the location of the monitoring apparatus, typically presented as the mean between HFT's at 1000mm and 2000mm heights above floor level.

| | | Pre-intervention | | Post-intervention | | |
|---|---|---|---|---|---|---|
| Code | Dwellings | U-value (W/m$^2$K) | Uncertainty | U-value (W/m$^2$K) | Uncertainty | % difference improvement |
| T15-S | 15 Seedhill Rd | 2.11 | ±0.2 | 0.42 | ±0.04 | 80% |
| T26-M | 26 McKerrell Rd | 1.46 | ±0.74 | 0.35 | ±0.04 | 76% |
| T10-M | 10 McKerrell Rd | 1.39 | ±0.35 | 0.43 | ±0.07 | 69% |
| T17-D | 17 Drummond St | 1.5 | ±0.38 | 0.45 | ±0.13 | 70% |
| B7-LC | 7 Lowson Cottages | 0.85 | ±0.07 | 0.40 | ±0.05 | 53% |
| B9-LC | 9 Lowson Cottages | 0.96 | ±0.09 | 0.38 | ±0.04 | 60% |
| B10-LC | 10 Lowson Cottages | 0.79 | ±0.07 | 0.38 | ±0.06 | 52% |
| B11-LC | 11 Lowson Cottages | 1.45 | ±0.135 | 0.25 | ±0.06 | 83% |
| B14-LC | 14 Lowson Cottages | 0.83 | ±0.1 | 0.52 | ±0.06 | 37% |
| B17-LC | 17 Lowson Cottages | 1.39 | ±0.11 | 0.67 | ±0.11 | 52% |

*Table 1: Pre and post-intervention In-situ U-value results*

Table 1 above shows the results for the ten dwellings at the baseline pre-intervention and post-intervention stages of the project. Analysing the pre-intervention results further, and focusing on the first four dwellings (T15-S, T26-M, T10-M and T17-D) the results are similar to previous baseline tests obtained (1,2,8), however, the uncertainty of the results are high and not reliable enough to use as a benchmark. Validation against steady-state calculations indicates that a typical U-value for these first four dwellings at a pre-intervention stage is approximately 1.40 W/m$^2$k. Dwellings T26-M, T10-M and T17-D show some alignment to this calculation, however, T15-S does not. The high uncertainty is due to the inconsistency of the heating system at the time of the tests where indoor/ outdoor temperature difference seldom reached above 10°C. The remaining six dwellings analysed, B7-LC, B9-LC, B10-LC, B11-LC, B14-LC and B17-LC show more reliable results at pre-intervention with conventional uncertainty values. A steady-state calculation for these uninsulated walls shows that the typical U-value is 1.20 W/m$^2$K. From the test results, the higher U-values at this baseline stage in dwellings B11-LC and B17-LC (1.45 W/m$^2$K) may indicate a deeper cavity depth which is consistent with the surveys performed where cavities reached 130mm. Smaller cavities surveyed at 80mm, in the remaining dwellings show a consistent set of results where the U-value’s has a mean of 0.86 W/m$^2$K.

At the post-intervention phase results for dwellings T15-S, T26-M, T10-M and T17-D became more consistent and reliable due to the adequate operation of the heating systems during the tests. Despite this, the heating controls and installed thermostats were pre-set to a cyclic heating pattern which produced cold patches during testing, lowering the temperature difference at periods throughout the monitored days. The low uncertainty reflects a more reliable set of results with a lower overall error. Results show an average U-value of 0.38 W/m2K with the lowest result appearing in dwelling T26-M at 0.35W/m2K and the highest in dwelling T17-D at 0.45W/m2K. The mean improvement percentage between the pre and post-intervention tests reached 74%, however, this is considering the unreliable pre-intervention results. The remaining six dwellings at the post-intervention stage showed worthwhile reductions in U-values. As a means of comparison, the steady-state insulated wall calculation obtained a U-value of 0.42 – 0.44 W/m2K. The lowest value achieved from the tests was 0.25 W/m2K in dwelling B11-LC which corresponds to a deep cavity of approximately 130mm. Subsequently, dwellings B7-LC, B9-LC and B10-LC achieved a value of 0.40 - 0.38 W/m2K, corresponding to a percentage reduction of 0.53%, 60% and 52% respectively. Lower percentage reductions are shown in dwellings B14-LC and B17-LC of 37% and 52% with U-value results of 0.52 W/m2K and 0.67 W/m2K respectively. Considering all ten dwellings, the mean percentage reduction was 63% which demonstrates a substantial improvement against uninsulated solid wall U-values, see Figure 7. However, taking only the six Forfar dwellings with more reliable results and less uncertainty bring the mean reduction to 56%.

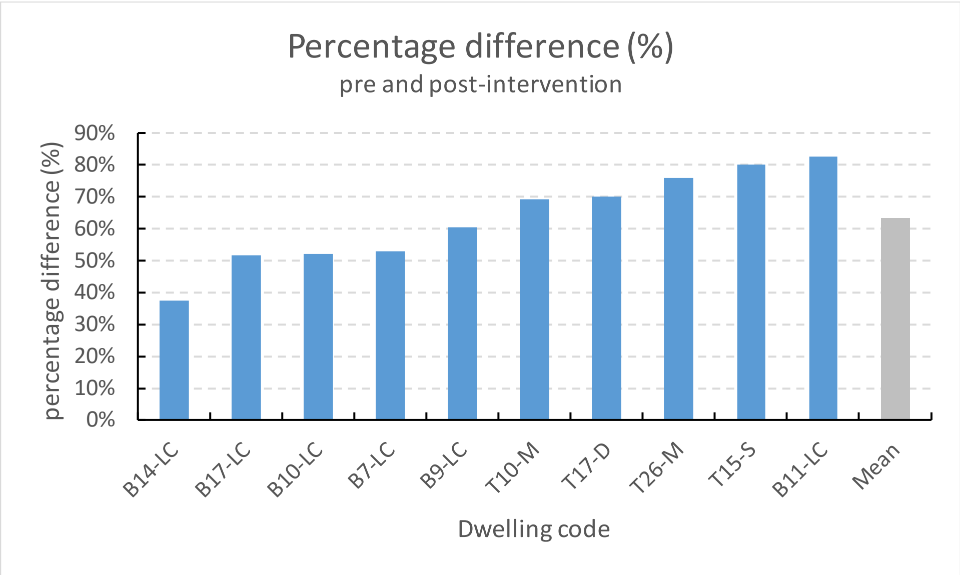



*Figure 7: Percentage difference between pre and post-intervention studies – dwelling code*

After a detailed survey of the walls, particularly the cavities in each of them at different locations within the wall, different depths of the cavity were measured. To analyse and compare easily, results were presented against three different depths of the cavity; 80mm, 100mm and 130mm. As a result of the scope and availability of apparatus, up to two heat flow measurements per tests were possible at different heights above the floor level. This allowed two points of contact and results, however, many more could appear which were not surveyed and tested. These were modelled and calculated and set against the two measurements taken at the pre and post-intervention monitoring periods, as seen in Figure 8 and Figure 9.

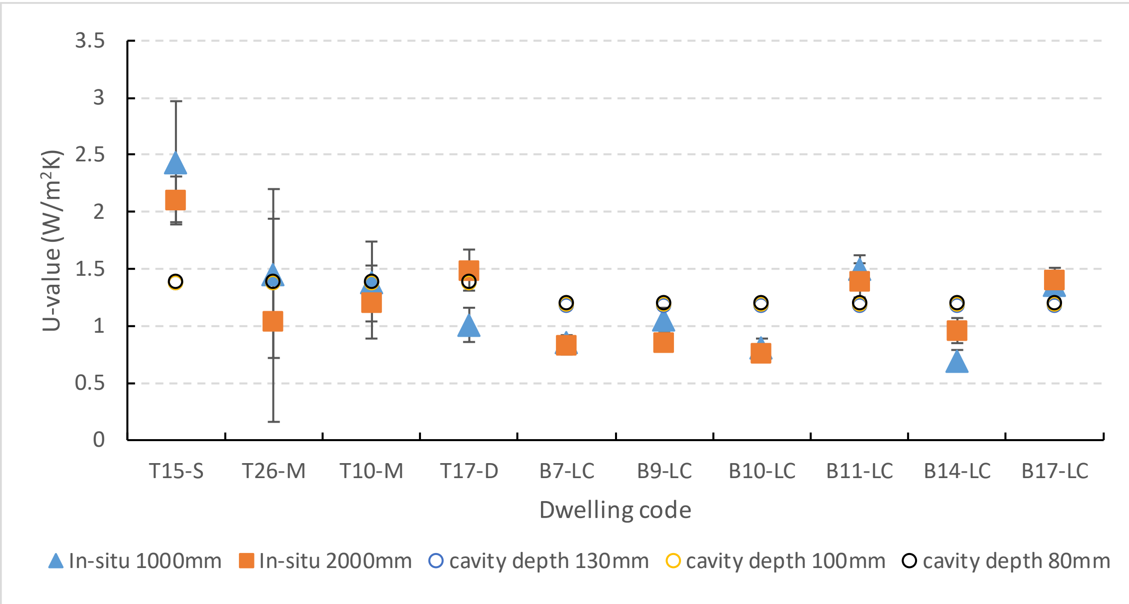



*Figure 8: Pre-intervention In-situ measurements against steady-state calculation at different depths of cavity*

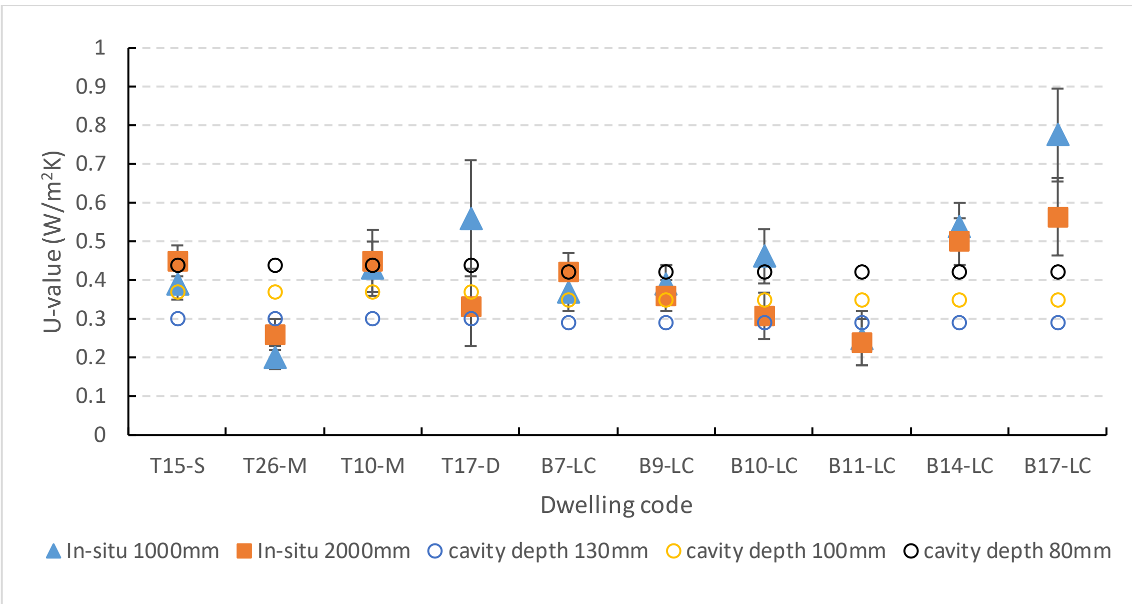



*Figure 9: Post-intervention In-situ measurements against steady-state calculation at different depths of cavity*

Figure 7 shows a clear improvement of the thermal transmissions (U-value) between the baselines and the insulated cavities, however, also important is the alignment of results to the depths of the cavities. This highlights the importance of a good survey in future projects that will not necessarily undergo testing. Although there is a clear difference between steady-state calculations and in-situ testing, the depth of cavities would signify the impact of the insulation material and its capacity to resist envelope heat loss.

## 4.2. Air permeability results

Air permeability testing was conducted in parallel with the dwelling U-value testing. The results depended on building survey data obtained during the pre-intervention stages. This included the dwelling's volume, treated floor area and envelope area. A mean result between the pressurisation and depressurisation tests is used to identify the final air permeability value of the dwellings at pre and post-intervention phases, as shown in Table 2 below.

| | | Air permeability (q50, $m^3/hr.m^2$ @ 50Pa) | | |
|---|---|---|---|---|
| Code | Dwellings | Pre-intervention | Post-intervention | % difference improvement |
| T15-S | 15 Seedhill Rd | 17.05 | 13.82 | 19% |
| T26-M | 26 McKerrell Rd | 16.23 | 15.35 | 5% |
| T10-M | 10 McKerrell Rd | 12.16 | 10.4 | 14% |
| T17-D | 17 Drummond St | - | - | - |
| B7-LC | 7 Lowson Cottages | 13.9 | 13.7 | 1% |
| B9-LC | 9 Lowson Cottages | 7.6 | 7.3 | 5% |
| B10-LC | 10 Lowson Cottages | 11.5 | 11.6 | -1% |
| B11-LC | 11 Lowson Cottages | 10.5 | 10.2 | 3% |
| B14-LC | 14 Lowson Cottages | 10.6 | 10.9 | -2% |
| B17-LC | 17 Lowson Cottages | 8.2 | 8.7 | -7% |

*Table 2: Pre and Post-intervention results for air permeability in dwellings*

To achieve low ventilation heat loss, air permeability values in Scotland for new dwelling design should achieve values between 5 and 10 $m^3/hr.m^2$ @ 50Pa, however, lower values are needed to pass compliance energy performance calculations such as SAP. More stringent measures such as the *Passivhaus* recommend approximately 1 $m^3/hr.m^2$ @ 50Pa and the retrofit equivalent *EnerPHit* standard can be adjusted to reach lower airtightness levels of above 1.5 $m^3/hr.m^2$ @

50Pa. Values obtained between the pre and post-intervention testing show that dwellings that endured a full refurbishment (T15-S, T26-M and T10-M) experienced a larger percentage difference between the pre and post-intervention phases, ranging from 19%, 5% and 14% respectively. These dwellings were unoccupied and therefore had most of their walls insulated as part of the enhancements conducted. The remaining tests in dwellings B7-LC, B9-LC, B10-LC, B11-LC, B14-LC and B17-LC only endured enhancements on one face of the external wall. As a result, the impact of the interventions was smaller ranging from 1% to 5% percentage improvement. Three dwellings experienced a negative value due to the uncertainty of reference values and accuracy of the tests which typically ranges between 5% and 10%, estimated using error propagation calculation. Figure 10 charts the results and difference between recommended and best practice values. A clear distinction between the dwellings that underwent other retrofit interventions with a larger wall coverage of insulation and the ones that only one wall was insulated is shown.

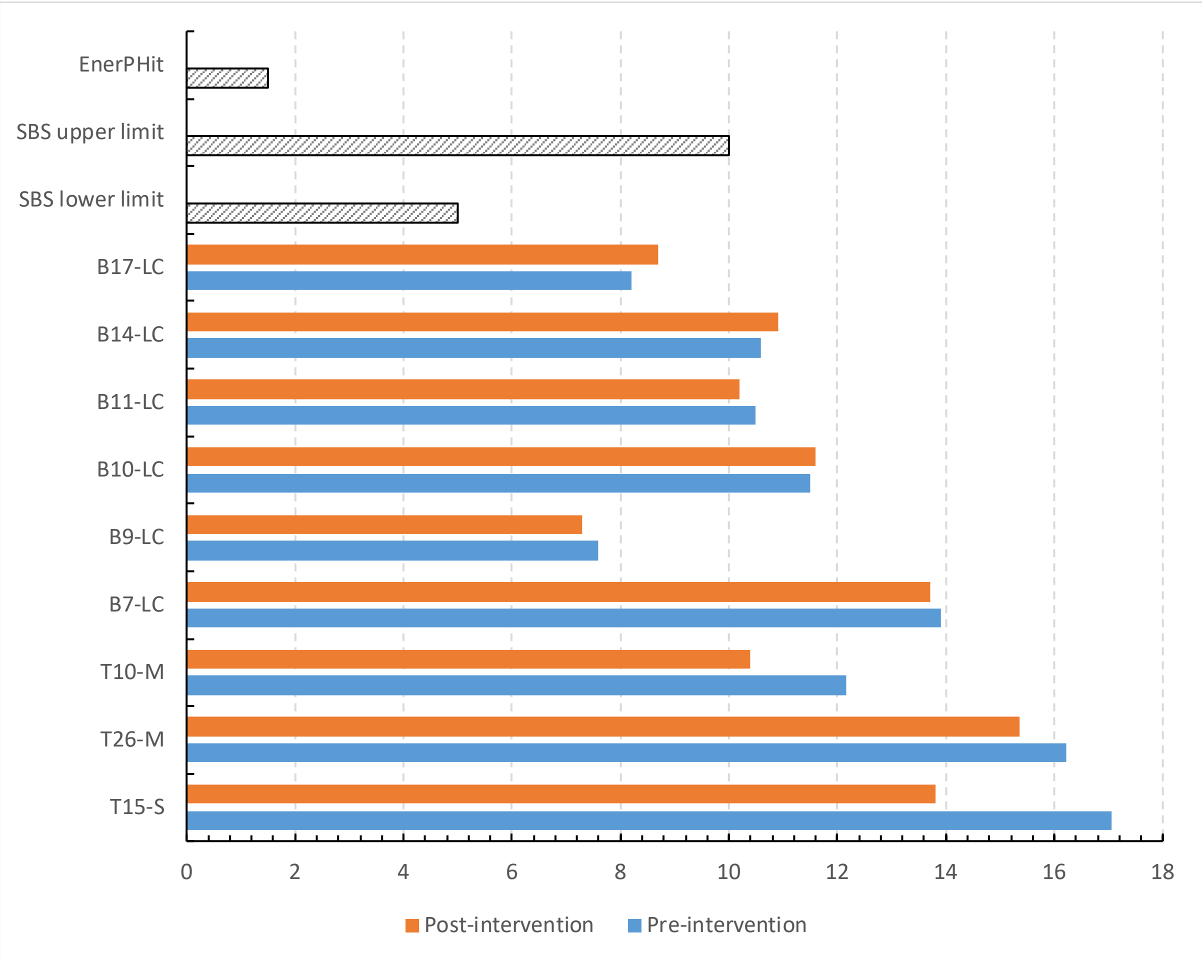



*Figure 10: Comparison between best practice new & retrofit air permeability values and results*

## 4.3. Condensation Risk, results and analysis

The condensation risk tests in this project were performed in dwelling B17-LC, whilst other monitoring took place. The results and its analysis focused on the dew point temperature reached inside the cavity. Two hydro-pins were located at different depths inside the cavity and results compared the temperature inside the cavity against the dew point temperature. If these two temperatures are equal; there would be a greater risk of condensation occurring at that location during a given timeline. Longer periods of this occurring can be detrimental to the building envelope.

Figure 11 shows the pre-intervention hygrothermal analysis with data results for hygro-pin HC01 and HC06. Shown with these temperatures are internal and external ambient conditions that are important when comparing and analysing the data. During the time of monitoring, neither the temperature nor the dew point temperature crossed each other, meaning there was no risk of condensation occurring and the cavity remained dry. The dewpoint margin – the difference between the two temperatures (cavity temperature and the dewpoint) maintained an 8°C mean difference throughout the monitoring. The largest margin between these temperatures was 11°C and the lowest 6.3°C which under these circumstances and this timeline maintains the cavity dry.

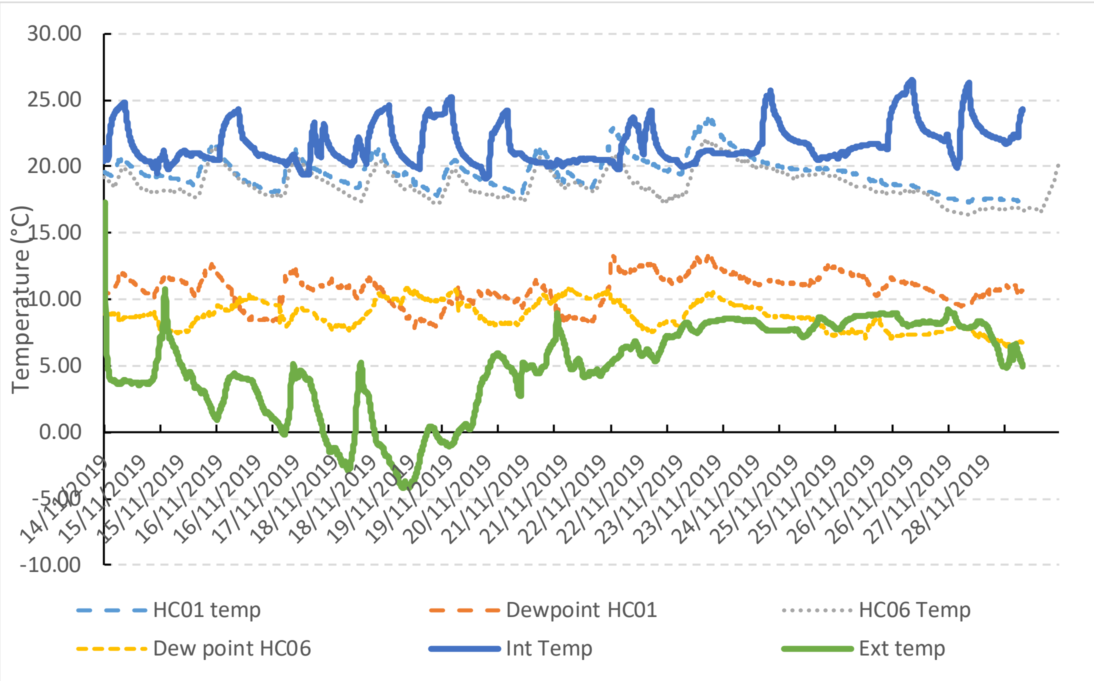



*Figure 11: Pre-intervention hygrothermal analysis inside the uninsulated cavity – two hygro-pins HC01 & HC06*

At post-intervention, as shown in Figure 12, the two hygro-pins remained in the cavity whilst insulation was injected. Results show that the dew point temperature and cavity temperatures did not cross each other meaning the cavity remained dry. Despite external temperatures reaching a mean of 4.3°C and a minimum of -4.5°C, dew point temperatures maintained a mean margin of 10.3°C with maximum and minimum margins of 14.5°C and 9.3°C respectively, indicating very little risk of condensation appearing.

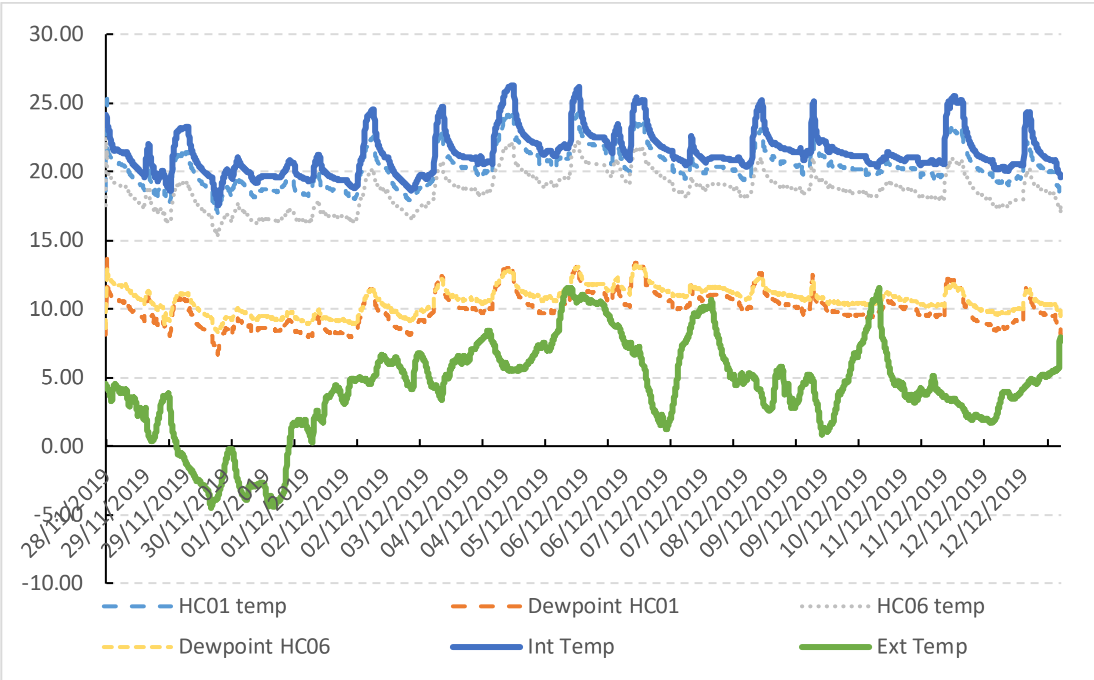



*Figure 12: Post-intervention hygrothermal analysis inside the uninsulated cavity – two hygro-pins HC01 & HC06*

A comparison of the pre-and post-intervention results shows that there is a difference in the temperature and dew-point behaviour of the cavities. Dew point temperatures and temperatures inside the cavity in the post-intervention show a similar outline to the ambient room temperatures which allow the assumption that conditions are stable and not influenced by the cold stone wall, thus the EPS *superbead* insulation is stabilising the cavity and controlling temperatures, in this case keeping them similar to room temperatures. A close analysis of the pre-intervention cavity temperatures compared with the ambient conditions inside the room shows a large disparity and misalignment with a slight time-lag between them. Also noticeable is the difference between the dewpoint temperatures, despite being at different depths inside the cavity, show different results. Such behaviour can be explained given its proximity to the dry-lining and the stone and the overall conditions in the uninsulated cavity which can be cold and uncontrolled. The dewpoint temperatures in the post-intervention filled cavity show similar results despite its location inside the cavity, showing the influence of the beads to control the conditions.

Such tests have been performed during small periods (<15 days) and provide a limited understanding of the hygrothermal conditions inside the cavity. A longitudinal test covering all seasons of the year at a post-intervention stage would provide a more assertive analysis of the impact of such insulation in the cavity.

## 4.4. Impact on energy, cost and carbon emissions

To calculate the impact of interventions, the dwellings in Forfar were modelled with the *superbead* EPC bonded bead placed <u>in all of the walls</u>. Considering compliance models cost deflator constants and formulas typically used for compliance calculations in energy performance certificates (EPC’s) of dwellings, the improvement of space heating energy, cost reduction to the bill payer and carbon emissions as an environmental impact were calculated. Table 3 indicates the results based on constants and models shared by Hillcrest HA and energystore Ltd using the dwellings floor area and original space and water heating estimates. The results show an energy efficiency rating improvement of a minimum of 5 points and a maximum of 8 points. On average the energy savings for heating only, accounted for 3,450kWh which represent a yearly saving of £136 using natural gas, saving 750 kg$CO_2$/yr. Dwelling B9-LC obtained a saving of 4,450 kWh, the highest saving in energy; which equates to £175 saving on energy bills and 960 kg$CO_2$/yr in carbon emissions. A total of 4,500 kg$CO_2$/yr, more than £800 in energy bills and a total of 20,700 kWh of energy would be saved if this intervention was applied to all the walls in the analysed dwellings in Forfar. This equates to, on average, the consumption savings of 1.5 dwellings of similar composition and size.

| Code | Dwellings | Energy Efficiency rating | | | Approximate savings | | |
|---|---|---|---|---|---|---|---|
| | | Pre EPC | Post EPC | SAP improvement | Energy for heating (kWh) | Cost of heating (£/kWh) | Impact ($kgCO_2e/yr$) |
| B7-LC | 7 Lowson Cottages | D-64 | C-70 | 6 | 3,335.00 | 131.40 | 720.36 |
| B9-LC | 9 Lowson Cottages | D-62 | C-70 | 8 | 4,445.00 | 175.13 | 960.12 |
| B10-LC | 10 Lowson Cottages | D-62 | C-69 | 7 | 3,226.00 | 127.10 | 696.82 |
| B11-LC | 11 Lowson Cottages | D-62 | C-70 | 8 | 4,441.00 | 174.98 | 959.26 |
| B14-LC | 14 Lowson Cottages | D-64 | C-69 | 5 | 2,440.00 | 96.14 | 527.04 |
| B17-LC | 17 Lowson Cottages | D-63 | C-69 | 6 | 2,828.00 | 111.42 | 610.85 |

*Table 3: EPC and SAP scores of original evaluations against an improved envelope – approximate figures*

## 5. Conclusions & discussion

This document has summarised the results and presented an analysis of pre and post-intervention measurements of ten dwellings undergoing EPS injected bonded bead referred to as *superbead* by energystore Ltd. The aim and primary objectives of this project have been fulfilled after conducting short term non-destructive surveys of each of the dwellings and their walls as well as measurements of thermal transmission (In-situ U-values), air permeability and condensations risk analysis. The results provided a baseline to understand the actual levels of performance followed by similar tests at a stage where insulation was injected in cavities to provide thermal resistance and lower envelope heat loss.

The measurements obtained for thermal transmission (U-value) indicate significant savings in energy, cost (bills) and carbon emissions for space heating. The average U-value difference between the pre and post-intervention in the Forfar dwellings reached a 56% improvement and considering all dwellings (10) can reach up to 63%, however, this is considering the unreliable pre-intervention results of the Paisley and Edinburgh tenement dwellings. Given the low uncertainty of the results in Forfar, the energy performance certificate re-calculations provide some assurance of the impact of the results. Although considering all walls were filled with *superbead* EPS beads, the savings amount to at least 1.5 dwellings of a similar composition and size which is significant both in energy and cost to the occupier and the environment as carbon savings.

Air permeability results provided some assurance that by injecting *superbead* into all walls there can be a reduction of air leakage, thus reduce ventilation heat loss. However, the better results in air permeability were evident with other changes, improvements and interventions of the building fabric. This was particularly evident in the Paisley dwellings during pre-intervention surveys that identified many holes, cracks and crevices around all building components. Once repaired the air permeability reduced by 19% and 14% in two of the dwellings, which although the superbead EPC bead played a big part on this, it was also due to the repairs and filled gaps by decorative interventions. This was not evident in the Forfar dwellings as only one wall of each dwelling was filled with superbead EPS. The improvement of air permeability will be more significant if other interventions to the fabric are made which collectively improve and lower ventilation heat loss.

Tests were undertaken to measure the risk of condensation build-up inside the cavity of walls. Only one dwelling at pre and post-intervention phases were tested which measured the difference between an unfilled slightly ventilated compared cavity with the equivalent filled the cavity with the *superbead* EPS beads. At the two phases, there was no risk of condensation build-up measured with the risk of dew point temperatures against ambient cavity temperatures. The results showed that these two temperatures did not cross each other which signified that the airborne water vapour did not condensate or become saturated to form liquid water on surfaces and materials. The dew point margin is a measure that was used throughout the tests, it did not reach cero which is the boundary point at which condensation occurs. What was observed through the results was the pattern of results between the cavity temperatures and dew point against the indoor ambient temperatures. It was found that in the pre-intervention phase, although there was no risk of condensation, the temperatures did not show any alignment and similar pattern, often a time lag and disparity at certain times of the day. This was not observed in the post-occupancy monitoring results, instead, the cavity temperatures and dew point temperatures aligned themselves with the same pattern and line path which signifies that the conditions inside the cavity were similar to the ambient temperatures given the insulations capacity to control any fluctuations and be influenced directly by colder elements, such as the sandstone walls.

A key outcome of the trials and tests was the comparison of U-value results to the depth of the cavity as calculated using steady-state models. Given the nature of the dwelling occupancy and accessibility, only two HFT locations were possible which did not necessarily account for the variety of cavity depths in a given wall. It was found through the surveys that the depths of cavities differed from 80mm to 130mm which was difficult to directly account for an even U-value across the wall. The deeper the cavity, the more *superbead* EPS beads are placed and better thermal improvement.  This highlights the importance of conducting adequate surveys and investigation on the dwellings and walls to intervene which will not only account for the accurate requirement of beads at installation stage but also understand the impact the beads will have to the walls thermal performance. This project highlights the importance of conducting these surveys and to possibly use the results obtained to future gage the impact and improvement in U-value.

# Appendices

## Appendix A - Case study analysis

**Dwelling: T15-S** **Location:** 15 Seedhill Rd, flat 01, Paisley, PA1 1RT **Date:** 1880’s

| | | |
|---|---|---|
|  | **Testing conditions:** | Vacant dwelling undergoing many improvements. Heating pattern uncontrolled and faulty during tests. Small day time temperature difference between wall surfaces. Multiple air infiltration gaps, holes and cracks in the envelope. |
| | **Type of construction:** | Blonde Giffnock sandstone wall, ashlar and rubble front wall and all rubble at the back wall. Approximately 600mm thick wall with a mean 80mm cavity behind a plasterboard lining. |
| | **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| | **Location of tests:** | Ground floor, back wall on the north orientation (bedroom). Close to window at 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, $W/m^2K$) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** ($m^3/hr.m^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.40 | 2.11 | 11.3 | ≤7-10 | 17.05 |
| **Post** | 0.44 | 0.42 | 17.7 | ≤7-10 | 13.82 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

| **Dwelling: T26-M** **Location:** 10 McKerrell St, flat 01, Paisley, PA1 1HT **Date:** 1880’s | | |
|---|---|---|
|  | **Testing conditions:** | Vacant dwelling undergoing many improvements. Heating pattern uncontrolled and faulty during tests. Small day time temperature difference between wall surfaces. |
| | **Type of construction:** | Blonde Giffnock sandstone wall, ashlar and rubble front wall. Approximately 600mm thick wall with a mean 80mm cavity behind a plasterboard lining. |
| | **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| | **Location of tests:** | Ground floor, front wall on the northeast orientation (living room). Close to window at 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, W/m$^2$K) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.40 | 1.39 | 8.4 | ≤7-10 | 12.16 |
| **Post** | 0.44 | 0.43 | 5.7 | ≤7-10 | 10.40 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: T10-M** **Location:** 26 McKerrell St, flat 3/2, Paisley, PA1 1HX **Date:** 1880’s

| | |
|---|---|
| **Testing conditions:** | Vacant dwelling undergoing many improvements. Heating pattern uncontrolled and faulty during tests. Small day time temperature difference between wall surfaces. |
| **Type of construction:** | Red Dumfries or Ayrshire sandstone wall, ashlar front wall. Approximately 600mm thick wall with a mean 80mm cavity behind a plasterboard lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| **Location of tests:** | Top floor, front wall on the northeast orientation (kitchen). Close to window at 1000 & 2000mm height. |

**Results *:**

| | Thermal transmission (U-value, W/m$^2$K) | | Mean temperature* ($\Delta t$ °C) | Air permeability (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.40 | 1.46 | 14.3 | ≤7-10 | 16.23 |
| **Post** | 0.44 | 0.35 | 8.14 | ≤7-10 | 15.35 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

| **Dwelling: T17-D** **Location:** 17 Drummond Street, flat A2, Edinburgh, EH8 9XP **Date:** 1880’s | | |
|---|---|---|
|  | **Testing conditions:** | Occupied dwelling undergoing many improvements. Heating pattern uncontrolled and faulty during tests. Small day time temperature difference between wall surfaces. |
| | **Type of construction:** | Blonde Craigleith sandstone wall, ashlar and rubble front wall. Approximately 600mm thick wall with a mean 130mm cavity behind a plasterboard lining. |
| | **Type of tests performed:** | In-situ U-value tests at a post and pre-intervention stages. Air permeability was not possible due to access to the dwelling. |
| | **Location of tests:** | Basement flat, back wall on the south orientation (bedroom). Close to window at 1000 & 2000mm height. Wall sheltered from solar radiation. |

**Results *:**

| | **Thermal transmission** (U-value, W/m$^2$K) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.38 | 1.5 | 7.6 | ≤7-10 | - |
| **Post** | 0.30 | 0.45 | 6.85 | ≤7-10 | - |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: B7-LC** **Location:** 7 Lilybank Rd, Lowson Cottages, Forfar, DD8 2JD **Date:** 1880’s

| | |
|---|---|
| **Testing conditions:** | Occupied semi-detached bungalow dwelling undergoing only front wall interventions. Heating pattern controlled by the occupant. Acceptable temperature difference between surfaces. |
| **Type of construction:** | Red Balmashanner Hill (Forfar) sandstone wall, rough dressed rubble walls. Approximately 600mm thick wall with a mean 80mm cavity behind a lath & plaster lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| **Location of tests:** | Ground floor front wall on the southwest orientation (living room). Close to window at 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, W/m$^2$K) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.21 | 0.85 | 16.40 | ≤7-10 | 13.9 |
| **Post** | 0.42 | 0.40 | 16.75 | ≤7-10 | 13.75 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: B9-LC** **Location:** 9 Lilybank Rd, Lowson Cottages, Forfar, DD8 2JD **Date:** 1880's

| | |
|---|---|
| **Testing conditions:** | Occupied semi-detached bungalow dwelling undergoing only front wall interventions. Heating pattern controlled by the occupant. Acceptable temperature difference between surfaces. |
| **Type of construction:** | Red Balmashanner Hill (Forfar) sandstone wall, rough dressed rubble walls. Approximately 600mm thick wall with a mean 80mm cavity behind a lath & plaster lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| **Location of tests:** | Ground floor front wall on the southwest orientation (living room). Close to window at 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, W/m$^2$K) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.21 | 0.96 | 15.70 | ≤7-10 | 7.64 |
| **Post** | 0.42 | 0.38 | 16.01 | ≤7-10 | 7.26 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: B10-LC** **Location:** 10 Lilybank Rd, Lowson Cottages, Forfar, DD8 2JD **Date:** 1880's

| | |
|---|---|
| **Testing conditions:** | Occupied semi-detached bungalow dwelling undergoing only front wall interventions. Heating pattern controlled by the occupant. Acceptable temperature difference between surfaces. |
| **Type of construction:** | Red Balmashanner Hill (Forfar) sandstone wall, rough dressed rubble walls. Approximately 600mm thick wall with a mean 80mm cavity behind a lath & plaster lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| **Location of tests:** | Ground floor front wall on the southeast orientation (living room). At 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, W/m²K) | | **Mean temperature*** (Δ*t* °C) | **Air permeability** (m³/hr.m² @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.21 | 0.79 | 14.58 | ≤7-10 | 11.58 |
| **Post** | 0.42 | 0.38 | 13.69 | ≤7-10 | 11.57 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: B11-LC** **Location:** 11 Lilybank Rd, Lowson Cottages, Forfar, DD8 2JD **Date:** 1880’s

| | |
|---|---|
| **Testing conditions:** | Occupied semi-detached bungalow dwelling undergoing only front wall interventions. Heating pattern controlled by the occupant. Acceptable temperature difference between surfaces. |
| **Type of construction:** | Red Balmashanner Hill (Forfar) sandstone wall, rough dressed rubble walls. Approximately 600mm thick wall with a mean 100mm cavity behind a lath & plaster lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| **Location of tests:** | Ground floor front wall on the southeast orientation (living room). At 1000 & 2000mm height. |

**Results *:**

| | Thermal transmission (U-value, W/m$^2$K) | | Mean temperature* ($\Delta t$ °C) | Air permeability (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.20 | 1.45 | 15.23 | ≤7-10 | 10.52 |
| **Post** | 0.35 | 0.25 | 13.92 | ≤7-10 | 10.21 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: B14-LC** **Location:** 14 Lilybank Rd, Lowson Cottages, Forfar, DD8 2JD **Date:** 1880’s

| | |
|---|---|
| **Testing conditions:** | Occupied semi-detached bungalow dwelling undergoing only front wall interventions. Heating pattern controlled by the occupant. Acceptable temperature difference between surfaces. |
| **Type of construction:** | Red Balmashanner Hill (Forfar) sandstone wall, rough dressed rubble walls. Approximately 600mm thick wall with a mean 80mm cavity behind a lath & plaster lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. |
| **Location of tests:** | Ground floor front wall on the southeast orientation (living room). At 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, W/m$^2$K) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.21 | 0.83 | 12.52 | ≤7-10 | 10.61 |
| **Post** | 0.42 | 0.52 | 12.54 | ≤7-10 | 10.86 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

**Dwelling: B17-LC Location:** 17 Lilybank Rd, Lowson Cottages, Forfar, DD8 2JD **Date:** 1880’s

| | |
|---|---|
| **Testing conditions:** | Occupied semi-detached bungalow dwelling undergoing only front wall interventions. Heating pattern controlled by the occupant. Acceptable temperature difference between surfaces. |
| **Type of construction:** | Red Balmashanner Hill (Forfar) sandstone wall, rough dressed rubble walls. Approximately 600mm thick wall with a mean 80mm cavity behind a lath & plaster lining. |
| **Type of tests performed:** | In-situ U-value and air permeability tests at a post and pre-intervention stages. Dew point hygrothermal analysis in the side cavity. |
| **Location of tests:** | Ground floor front wall on the southeast orientation (living room). At 1000 & 2000mm height. |

**Results *:**

| | **Thermal transmission** (U-value, W/m$^2$K) | | **Mean temperature*** ($\Delta t$ °C) | **Air permeability** (m$^3$/hr.m$^2$ @50Pa) | |
|---|---|---|---|---|---|
| **Intervention** | **Calculation** | **Measured** | **Measured** | **Best practice** | **Measured** |
| **Pre** | 1.21 | 1.39 | 12.52 | ≤7-10 | 8.16 |
| **Post** | 0.42 | 0.67 | 17.56 | ≤7-10 | 8.72 |

* Based on night-time data and mean between tests

* Mean ambient temperature difference across the internal and external face

## Appendix B – Air permeability report – RMP Consultants

Please refer to a separate document which should complement this report.

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