CeBE Centre for the Built Environment

LEEDS METROPOLITAN UNIVERSITY
Leeds Sustainability Institute

Final Report to Joseph Rowntree Housing Trust

Project Title: Temple Avenue Project Part 2

Energy efficient renovation of an existing dwelling: Evaluation of design & construction and measurement of fabric performance

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Introduction

1 This report is designed to complement part 1 of the Temple Avenue Project (Miles-Shenton et al., 2010) by tackling the issues involved in the upgrading of existing dwellings, with the overall aim of establishing the extent to which an existing 1930s masonry house can be renovated so as to achieve a level of performance commensurate with the advanced energy and carbon standard achieved in the prototype new dwellings constructed in part 1 of the project.

Background

2 As in the case of the new build prototype dwellings, the exploration of renovation works to an existing dwelling could act as a prototype for renovation schemes to traditional cavity walled masonry dwellings. This type of dwelling has been constructed in very large numbers from the late 1920s onwards with very little variation in technology or form. It is estimated (Utley and Shorrock, 2006) that out of a total housing stock of 24.8M dwellings some 18.1M (73%) are of cavity construction, with only around 6.6M (37%)[1] known to be insulated. Even in the case of dwellings with cavity wall insulation the wall U-values achieved (0.55 W/m^2K) do not address the demanding requirements imposed by an 80% reduction in carbon emissions.

3 The investigation of the prototype renovation of the existing dwelling sought to improve understanding, for all parties involved, in the following ways:

a) To establish and characterise the design and construction issues in meeting low carbon housing standards in existing dwellings.

b) To enable an evaluation to be undertaken of the ease with which the various measures can be applied and the way in which the constraints of an existing structure can be overcome.

c) To establish the level of energy and carbon performance achieved in practice and how this compares with theoretical estimates made at design stage. This involved the identification of those features that perform as expected and those that do not.

d) To enable guidance on design and/or construction practice to be provided so as to improve the processes involved and to aid effective replication. The knowledge obtained could be used to develop guidance that would be relevant to both private and social housing stocks.

e) To provide feedback on performance measurement methods and to enable recommendations to be made as to performance control approaches for housing modernisation schemes.

4 This report is designed to address items a, b, & c above and, based upon the understandings gained during the renovation design and construction process, makes recommendations as to the most appropriate way forward in areas d & e.

Evaluation

5 The broad aim of the evaluation is to establish the extent to which the energy performance of existing housing can be improved bearing in mind the government's policy targets, which seek an 80% reduction in carbon emissions by 2050.

6 In meeting this general aim the project has the following principal objectives:

a) To explore the impact of two standards of renovation, one reflecting the standard fabric measures that are currently considered to be cost effective (an intermediate standard) and one reflecting the more challenging requirements of an 80% reduction.

b) To evaluate, based on design documentation, the predicted performance of the renovation scheme and the information and models used by the design and construction teams.

c) To evaluate the construction process through site observations of construction and a review of detailed construction information and how it is applied by the site teams.

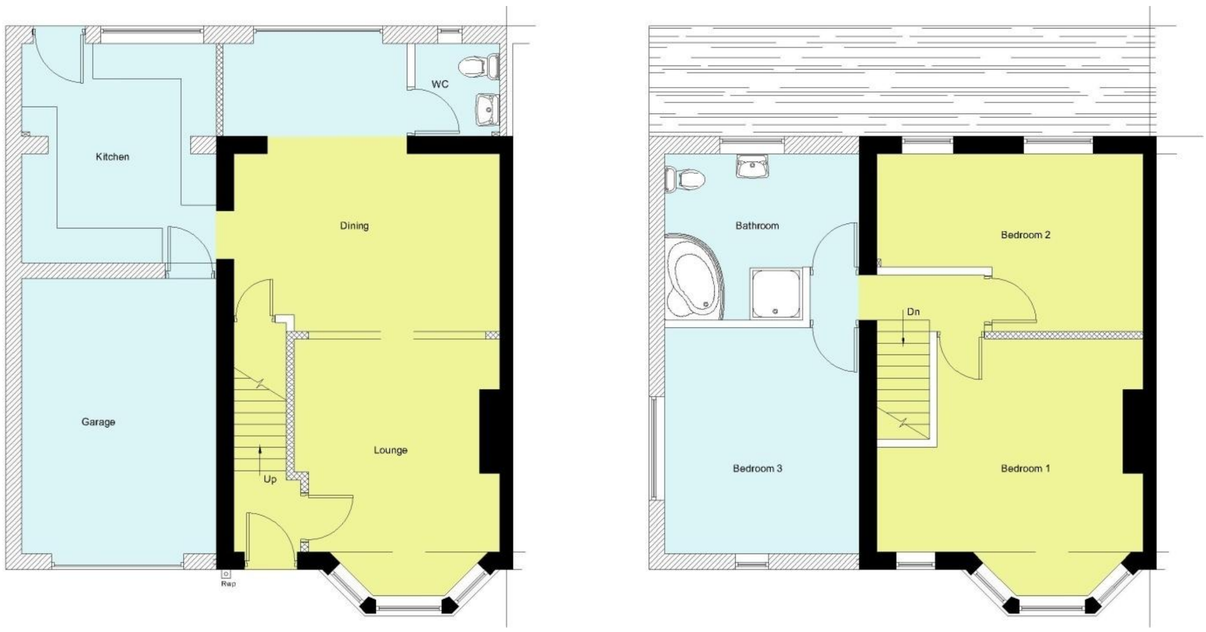
d) To measure the performance of the dwelling fabric and the expected performance of dwelling services based on observations of installation together with commissioning data and other documentation.

[1] This number is an estimate with the highest level of certainty. There are a further 1.7 million dwellings where the fill status is uncertain. If one assumes that about half of these dwellings were insulated the total would be around 7.5 million (41%).

Design assessment

Initial Dwelling Assessment

7 The existing dwelling used in this project is a 2 storey semi-detached property originally constructed in the 1930s which has been extended to the side and rear. The original 2 bedroom dwelling was transformed to a 3 bedroom house by a 2 storey side extension, which comprised of an integral garage and kitchen on the ground floor and a bedroom and bathroom on the first floor. The rear extension is single storey and extended the lounge/dining area and housed a downstairs closet. Figure 1 shows the floor plans of the property prior to the commencement of any renovation work and distinguishes between the original property and the extensions. An initial survey and visual inspection of the property was conducted on 1st July 2009 by the architects, with a further borescope investigation carried out on 18th August 2009 to establish the wall construction. The architects drew up general arrangement drawings for the property, which have been used in calculations of areas and volumes, but were not required to draft any large scale detailing for the purposes of this project. A set of full detail designs would have been impracticable for a project of this size and budget, particularly as it was set up as a learning project and designs were expected to undergo modifications as the project progressed. The U-values referred to in this section (and in Table 3) are those calculated by the architects using their NHER U-Value calculator v1.1.7 software.



GROUND FLOOR PLAN FIRST FLOOR PLAN

Figure 1 Floor plans of the existing dwelling, prior to renovation work commencing, adapted from the architect's drawings.

8 The property is constructed of masonry cavity walls with a solid brick separating wall. Whilst all the outer leaves of the external walls are of brick, the inner leaves vary from brick on the original walls to block on the extension walls. The original side wall had its brick outer leaf removed and replaced with blockwork. The original external wall on the front elevation between the bay and extension had its outer leaf brickwork replaced, presumably at the time of the extension.

9 The original brick-brick cavity walls were un-insulated apart from the re-skinned section of the front elevation, with an estimated U-value of 1.68 W/m^{2}K. The insulated section of original wall and the extension walls had 25 mm mineral fibre batts as partial-fill cavity wall insulation in a 70~75 mm cavity, and were assumed to have a U-value of around 0.65 W/m^{2}K. The original external wall at the side of the property, which now formed the wall between the hall and garage, contained no insulation in the cavity and was open to the loft-space at the top, and was assigned a U-value of 0.62 W/m^{2}K. The partially filled block-block wall between the kitchen and garage was assigned a U-value of 0.39 W/m^{2}K.

10 The ground floor of the original dwelling was of timber suspended construction, with chipboard deck in the dining area and t&g boards elsewhere, and a stated U-value of 0.39 W/m^{2}K. The extensions had solid concrete ground floors and were assigned a U-value of 0.88 W/m^{2}K. The intermediate flooring was all timber, with chipboard in the side extension and t&g in the original dwelling, and insulation between the joists in the area directly above the garage gave this an assumed U-value of 0.25 W/m^{2}K.

11 The main loft had insulation laid between the ceiling joists. This averaged somewhere around 75 mm deep but was noticeably more compressed above the original part of the dwelling and covered with dirt, dust and debris throughout. The loft hatch was un-insulated chipboard with no catches. The insulation and loft hatch fitted in the rear extension were of a similar description. Both were allocated a U-value of 0.52 W/m^{2}K. The bay roof in bedroom 1 was assumed un-insulated and assigned a U-value of 1.99 W/m^{2}K.

12 Windows were uPVC double glazed throughout the property. The windows showed signs of wear and tear with 2 of the windows, one in bedroom 2 and one in bedroom 3, not closing fully. The external doors were of a similar standard, but the door from the kitchen to the integral garage was a basic internal door without draught-stripping. A SAP default U-value of 2.7 W/m^{2}K was assumed for all windows and doors.

13 Ventilation for the property was provided by intermittent extract fans in the kitchen, downstairs WC and the bathroom, and via an open flue fireplace in the lounge. The initial airtightness test carried out on the property, whilst it was still occupied, on 1st July 2009 provided a mean air permeability of 15.76 m^3/(h.m^2) @ 50Pa; a second test was performed on 6th November once the dwelling had been vacated and all furniture and carpets removed and showed an increase in mean air permeability to 20.66 m^3/(h.m^2) @ 50Pa.

14 The U-values listed above classify the garage as an unheated space providing additional shelter, and as a result the architect's calculations[2] provided a SAP rating of 59 (Energy Band D), with estimated annual emissions of 5751 kg CO_2 and a DER of 62.22 kg CO_2/m^2/yr.[3]

Figure 2 Front and rear elevations prior to any renovation work.

Stage 1 Renovation

15 The stage 1 renovation was intended to carry out any necessary repairs on the property and to replicate energy saving measures that could easily be performed by occupants of dwellings similar to the existing dwelling in this project.

16 Blown mineral fibre insulation was to be installed into the original external cavity walls, including the original cavity walls which are no longer external walls, designed to reduce the external wall U-values to 0.45 W/m^{2}K and 0.20 W/m^{2}K for the semi-exposed elements with the garage also benefitting from an additional 75 mm phenolic foam backed plasterboard lining. To reduce the effects of thermal bypassing in the cavity walls the gaps at the top of the cavities were to be closed by packing with mineral wool quilt.

[2] The architects' SAP calculations were carried out using NHER Plan Assessor v4.2 (SAP2005 v9.81).

[3] The architects' SAP calculations list a TER of 22.73 kg CO_2/m^2/yr to achieve 2006 Building Regulations Part L compliance for this dwelling.

17 Reparatory work was necessary to level the intermediate floor of the side extension and provide new floor decking, the insulation in the floor being replaced with fresh mineral fibre and under drawn with 75 mm phenolic foam to reduce the U-value to 0.25 W/m^2K.

18 The partial boarding in the main loft was to be removed along with the old compressed loft insulation and debris, 400 mm of mineral wool quilt was to be laid (100 mm between joists and 300 mm perpendicular to joists) to bring the U-value down to 0.11 W/m^2K. The same U-value of 0.17 W/m^2K was to be achieved in both the rear extension, by the addition of rigid PU insulation at rafter level, and the bay roof in bedroom 1.

19 The windows and doors were to be left unaltered as part of the stage 1 renovation, as double glazing was already fitted throughout the property and it was prudent to replace all the external doors and windows only once and in one lot. As high performance triple glazed windows were to be installed in the stage 2 renovations there seemed little benefit in incurring extra cost by undergoing a 2 phase replacement programme.

20 Various additional measures were designed to improve the airtightness of the dwelling. The suspended timber ground floor was to be sealed using a temporary hardboard covering with compressible edge sealing and taped joints. The chimney breast in the lounge was to be blocked up. Service penetrations through the external wall removed and either temporarily sealed, patched up or filled with expanding foam; these included bathroom and kitchen waste pipes and the recessed lights in the bathroom ceiling. The aim of these measures was to reduce the air permeability of the dwelling to below the figure of 10 $m^3/(h.m^2)$ @ 50Pa outlined in the 2006 Building Regulations, with a target mean air permeability of 9 $m^3/(h.m^2)$ @ 50Pa.

21 The architects' calculations provided a SAP rating of 77 (Energy Band C) for the dwelling following these proposed stage 1 renovations, with estimated annual emissions of 3121 kg CO_2 (a 46.73% reduction on the initial dwelling assessment) and a DER of 30.69 kg $CO_2/m^2/yr$.

Stage 2 Renovation

22 The stage 2 renovation was intended to achieve an 80% reduction in CO_2 emissions from those prescribed to the dwelling in its original condition, and bring it roughly in line with the 2 prototype dwellings constructed as part 1 of this project. Some of the measures taken involved high capital costs; this, coupled with the huge disruption, would prevent most of these measures being replicated by occupiers but are of greater interest to social landlords looking to raise stock dwellings to higher levels of the Code for Sustainable Homes (CLG, 2008).

23 175mm of external mineral wool insulation with a polymeric render coating was to be fitted to all external walls of the property from the dpc level (one brick course below the ground floor level) up to the eaves, where extension of the roofline would be necessary to allow for the additional wall thickness. Further alterations would be required at junctions with the adjoining property, where the external wall insulation (EWI) continues to the plane of the midpoint of the party wall, and to the roofline at the gable end of the single storey rear extension. An additional 70mm of extruded polystyrene insulation was to be fitted below the mineral wool EWI, to below the external ground level, to reduce thermal bridging through the floor perimeter. The resultant external wall U-value was calculated to be 0.15 W/m^2K for the architects' SAP purposes.

24 Both the assumed un-insulated solid ground floor and the suspended timber ground floor were to be removed and replaced with an insulated solid ground floor to a U-value of 0.195 W/m^2K throughout.

25 The loft insulation remained the same as in the stage 1 renovation, however, the roof extension work necessary to accommodate the EWI would require an associated extension of the loft insulation to meet up with the wall insulation and provide greater accessibility to the tops of the external wall cavities to allow them to be closed off more effectively.

26 The windows were designed to be replaced with new argon-filled triple glazed timber windows throughout (average total window U-value 0.83 W/m^2K) and the external and kitchen to garage doors replaced with composite insulated doors (U-value 1.2 W/m^2K). A decision regarding the width of the preformed metal external sill had to be made at the time of and as part of the order for the triple glazed windows and, thus, it was agreed at this time that a 200 mm wide sill would allow the windows to be fitted on brackets on the 'front' edge of the existing openings, close to external face of the existing brick walls and mainly in the same plane as the external wall insulation (EWI), to minimise thermal bridging. This was fully discussed and agreed at that time with the window suppliers, the window fitters and the EWI suppliers. With no detail drawings made available to the research team prior to their installation it was not possible to perform any thermal modelling or raise any specific concerns, such as those regarding continuity of the air barrier, and perform

calculations on the reduction in thermal bridging at these details to validate the architects' decision to reduce the y-value in their SAP calculations from 0.15 to 0.08 W/m^{2}K. The insulation of the bay mullions was not so clear cut and appeared to rely on the vision and experience of the site foreman rather than a pre-determined design.

27 The target air permeability for the dwelling at the end of the stage 2 renovations was 5 m^3/(h.m^2) @50Pa. No specific airtightness measures were undertaken to achieve this reduction. It was anticipated that measures taken such as the new solid ground floor, the replacement windows and the EWI providing a potential secondary air barrier, together with continued good workmanship internally, would result in the required reductions.

28 A whole-house mechanical ventilation system with heat recovery was to be installed, with a loft-mounted unit with intake and exhaust passing through vents in the main roof, supply vents in the lounge/dining area and all 3 bedrooms and extract vents in the kitchen and bathroom.

29 The architects' calculations provided a SAP rating of 89 (Energy Band B) after the stage 2 renovation work, with estimated annual emissions of 1269 kg CO_2 (a 77.93% reduction on the initial dwelling assessment) and a DER of 13.11 kg CO_2/m^2/yr.

Figure 3 Front and rear elevations following stage 2 renovations

Construction observations

30 Site observations commenced in July 2009, with an initial pressurisation test while the house was still occupied, and were undertaken throughout the construction and coheating test periods. Specific visits to the site were arranged to coincide with items of interest in the works programme, but access was granted to the research team throughout the entire project. With the research team regularly visiting the adjacent prototype dwellings and allowed to also view construction on the existing dwelling at the same time, maintaining a fairly thorough photographic record of the construction process was possible. In addition to the 20 visits to site made during the coheating tests, opportunities were taken for the research team to observe the renovation work on 30 additional days. Any issues raised during the visits to site were firstly discussed with the site foreman to clarify whether these concerns were justified.

Stage 1 Renovation construction issues

31 The stage 1 renovation was intended to carry out any necessary repairs on the property and to replicate energy saving measures that could easily be performed by occupants of dwellings similar to this dwelling. Most of the renovation work was performed by the client's own staff, with only the injection of the cavity wall insulation (CWI) subcontracted out.

32 Blown mineral fibre insulation was installed into the original external cavity walls, including the original cavity walls which are no longer external walls. This was intended to bring the U-values of these walls down from 1.68 to 0.45 W/m^{2}K, assuming a nominal 70 mm cavity. A local CIGA approved contractor was appointed to install the CWI in the same manner that they had installed it in many similar dwellings over a number of years. This being an uninhabited dwelling drilling and injection was performed from the inside of the property for ease of access. Figure 4 shows the front elevation during the 1st coheating test, prior to the injection of the CWI, Figure 5 shows the same detail during the 2nd coheating test, after the installation of the CWI in the original front wall of the house. Whilst a direct comparison of the 2 thermal images is not straightforward, due to the

differing environmental conditions, it can clearly be seen that the process had had very little effect on the thermal conductivity of the wall, and had certainly not reduced it by the 73% assumed in the design calculations.

Figure 4 Front elevation during coheating test 1, 27-Oct-09, prior to cavity wall insulation installation.

Figure 5 Front elevation during coheating test 2, 17-Dec-09, following cavity wall insulation installation.

33 The alterations necessary for the stage 2 renovations provided additional opportunities to view the cavity insulation. The extension of the eaves to allow for the 175 mm of external wall insulation exposed the tops of the external wall cavities and permitted viewing of how far up the insulation had penetrated; similarly, during the replacement of windows and doors the horizontal spread was exposed. What was observed was a very uneven level of fill throughout the dwelling with a number areas having very little, if any, insulation present. The standard drill pattern used appeared to comply with the relevant CIGA and BBA documentation, and it appeared that some insulation had been injected through each drill hole. This phenomenon was not totally unexpected, with the research team having observed uneven fill patterns in a retro-filled cavity wall in a project funded by Eurisol the previous winter (Wingfield et al., 2009), of greater concern was the level of variation in fill densities and expanses of un-insulated wall observed in this instance. The removal of the old solid concrete floor allowed viewing of the cavity below floor level to see how far down the blown fibre had filled beneath the drill holes. Figure 6 shows the original rear wall of the dwelling after the floors had been removed. Looking along the cavity it was possible to see some insulation extending down to the bottom of the cavity, but this only occurs in about 300 mm of a 1.6 m length of wall, but where the floor joists had been removed there was only evidence of insulation at one of the holes. In the areas where insulation was observed the fill density was also suspect.

Figure 6 Removal of the original floors for Stage 2 renovation revealed the depth of penetration of the cavity wall fill.

34 Borescope investigations, additional thermal imaging and heat flux measurements were performed by the research team to investigate why the some of the CWI issues had arisen. In some areas highlighted by thermal imaging as potential causes for concern 10 mm inspection holes were drilled and a Hawkeye Pro Videoscope (manufactured by Gradient Lens Corporation), with 4-way tip articulation, inserted to view the inside of the cavity. Figure 7 shows a particularly poor example where the CWI did not spread through the cavity, instead just clustering around the injection hole. Additional borescope investigations of other areas of cavity wall showed a wide variation from very patchy fill to completely filled with insulation. One possible cause for the incomplete fill appeared to be the poor quality of the inner leaf brickwork and the amount of debris present in the cavity. The inner leaf brickwork displayed a number of instances of bricks crumbling and surfaces falling off around drill holes, possibly made worse because the installers drilled from inside the property so could not follow their normal practice of drilling through mortar joints rather than bricks/blocks where possible; this only added to the other debris in the cavity which ranged from bricks, mortar and other building waste to bird nests (Figure 8). The one area of wall where there was little variation in fill density and an apparent much more complete fill was the internal cavity wall between the garage/bedroom 3 and the hall/stairs/bedroom 1, where the original external brick outer leaf had been replaced by blockwork when the side extension had been erected.

Figure 7 Borescope investigation of the external wall showing insulation clustered around the injection hole, but not filling the cavity.

Figure 8 Debris in the cavity wall included masonry detritus and bird nests.

35 The incomplete fill of the CWI was not only due to the poor state of the cavities and the inadequate flow of the blown fibre through them. Thermal images captured using a FLiR ThermaCam B4 infrared imaging camera revealed a major cold spot at the 1st floor junction of the external and party wall at the rear of the property. Borescope investigations confirmed that there was no insulation at the sites shown in Figure 9 where heat flux sensors were placed even though there appeared to be adequate injection holes. Following conversations with the CWI installers it transpired that a vertical cavity brush had not been fitted at the party wall junction, allowing the CWI to fall sideways into the adjacent neighbour’s wall cavity. An additional result of these conversations was that the CWI installers returned to the site in January 2010 to install the vertical brush and to drill additional holes and inject extra insulation at areas of poor fill identified through thermal imaging by the research team.

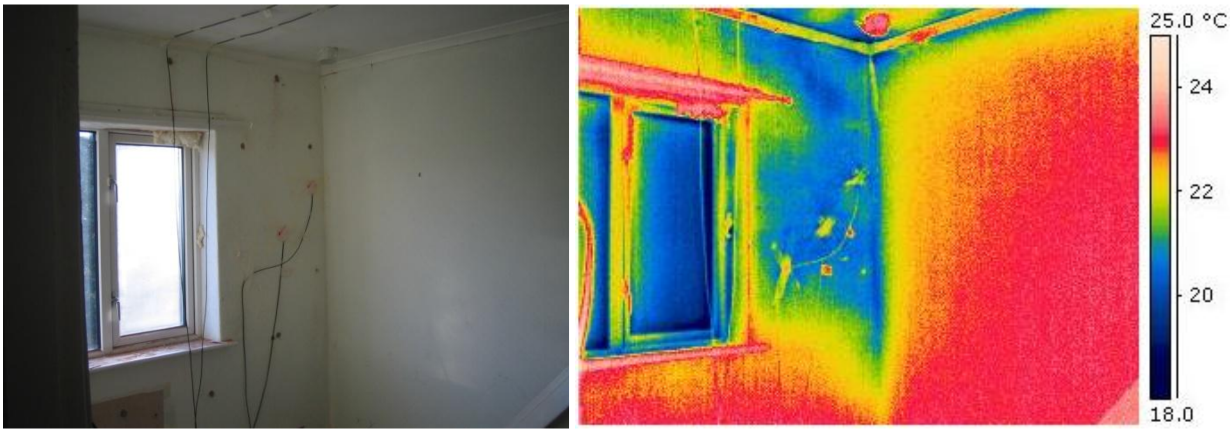


Figure 9 Heat flux sensors and thermal imaging of the external and party wall junction in bedroom 2.

36 The partial boarding in the main loft was removed along with the majority of the old compressed loft insulation and debris; 400 mm of mineral wool quilt was laid and an insulated access hatch installed. The design suggested that 100 mm thickness of mineral wool quilt was to be laid between the joists and a 300 mm layer perpendicular to the joists for the best fill and fit, what appeared to have been installed was a double layer of 200 mm thickness. This provided additional air pockets in the insulation layer which will have degraded the performance. Of greater concern was that the insulation did not extend fully into the eaves and was some distance off meeting the cavity wall insulation to provide a continuous thermal barrier. The full extent of these gaps in the insulation layer was exposed when the roof tiles at the eaves were lifted during the stage 2 renovations (Figure 10) with gaps between the lower 200 mm of insulation and the wall cavity averaging around 300 mm and the upper 200 mm of insulation being inset by a further 300 mm. A loft ladder was also installed which was not fully compatible with the new increased depth of insulation, with the ladder mechanism disturbing the insulation to the hinged side on operation. The bay roof in bedroom 1 was also insulated during the stage 1 renovation work with 150 mm of mineral wool quilt laid between the roof joists.

Figure 10 Loft insulation not extending fully into the eaves and air spaces around the insulation.

37 To reduce the effects of thermal bypassing in the cavity walls the gaps at the top of the cavities were intended to be closed by packing with cavity stop socks after the existing insulation had been removed and prior to the cavity fill and new loft insulation installed. With the site staff under pressure to get the house in a state where it was possible to perform the 2nd coheating test, this edge sealing of the top of the internal cavity wall was overlooked. Figure 11 shows the top of the cavity wall between the bathroom and bedroom 2 at the end of November 2009 with the old insulation removed and the following week with the cavity filled, new loft insulation laid, but no edge sealing along the top of the cavity.

Figure 11 The top of the internal cavity wall with the old insulation removed and with the cavity filled and new loft insulation laid.

38 The insulation in the rear extension loft space was relocated and changed from a nominal 100 mm between the ceiling joists to 75 mm phenolic foam placed under the rafters (Figure 12). Transforming this void from a cold to a warm space was intended to provide a simpler continuation of both the thermal layer and the air barrier once the stage 2 renovations were completed with external wall insulation applied. The newly placed insulation providing a direct link between the EWI at ground and first floor levels, and the services running through this roof void were now all internal to the air and thermal layers so no longer penetrated the primary air barrier. An “intelligent” air tightness membrane was sourced rather than the standard membrane used elsewhere in the dwelling to regulate the potential for condensation due to its placement on the cold side of the insulation, between the insulation boards and rafters.

Figure 12 The rear extension insulation was relocated from mineral wool between the joists to phenolic foam beneath the rafters.

39 Both Figure 13 and Figure 14 show the effect of the movement of the insulation from ceiling level to rafter level at the ground floor rear extension. During the 1st coheating test thermal imaging highlighted a substantial cold area at the eaves where the mineral wool insulation did not extend fully into the junction to meet up with the wall insulation (Figure 13). The replacement phenolic foam at rafter level overcame this problem, with the thermal image (Figure 14) showing no such cold bridge at this junction.

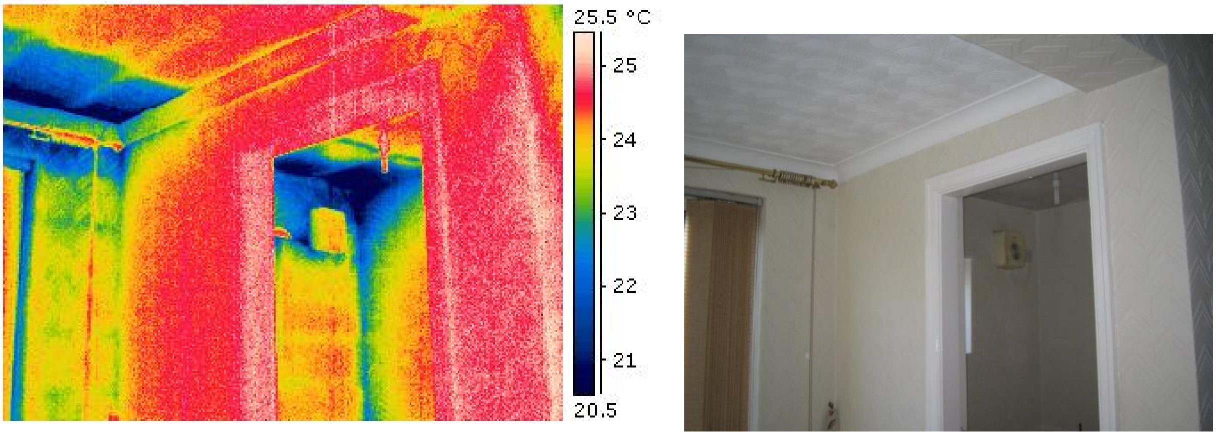


Figure 13 Eaves at the rear extension during the 1st coheating test with the mineral wool insulation not fully filling right into the eaves.

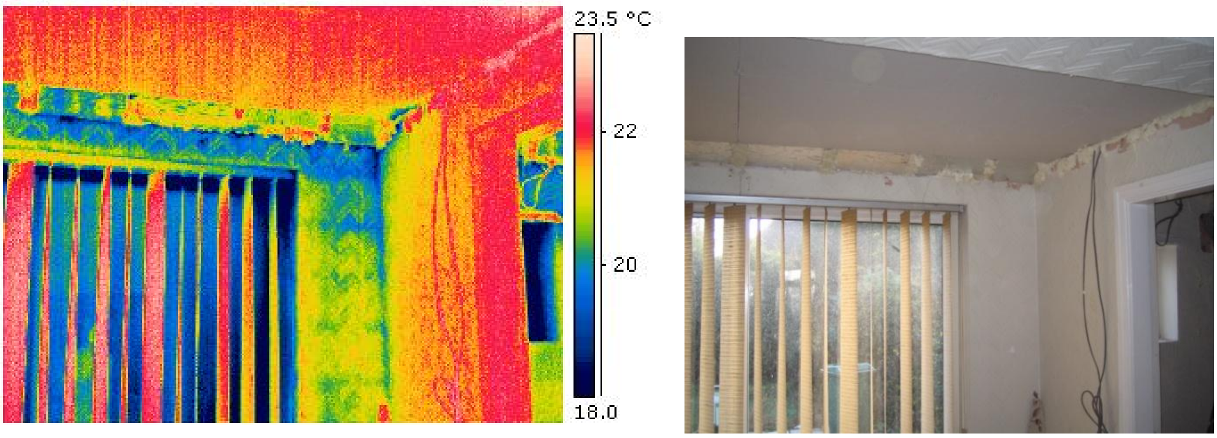


Figure 14 Eaves at the rear extension during the 2nd coheating test with the insulation and air barrier relocated to rafter level.

40 Reparatory work was carried out to level the intermediate floor of the side extension and provide new floor decking, with insulation in the floor above the garage being replaced with fresh mineral fibre and under drawn with 75 mm phenolic foam. The intermediate floor joists were replaced and sealed around where they were built into the external and internal cavity walls. There were numerous gaps into these wall cavities which were exposed upon removal of the intermediate floor, not only around the joists but also around many of the service penetrations. Sealing and filling of these gaps will have had a significant impact on the airtightness of the dwelling and raised questions about the airtightness of penetrations in the intermediate floor void perimeter throughout the rest of the dwelling which would be addressed in the stage 2 renovations. The removal of the gas boiler from the garage, prior a replacement being fitted in the kitchen, also negated the requirements for many of the penetrations between the garage and the dwelling interior, these were also sealed prior to being covered over by any subsequent work.

Figure 15 The boiler and associated pipework were removed and a new intermediate floor constructed over the garage.

41 The windows and doors were left unaltered as part of the stage 1 renovation work. As double glazing was already fitted throughout the property it was not considered sensible to replace them at this stage, as they would have had to have been removed for the next stage renovations. The door between the kitchen and garage was temporarily replaced with a sheet of phenolic insulation board, fixed in position and sealed around using expanding foam, but was then replaced with an un-insulated one-hour fire door rather than a door which was suitably insulated as it forms the barrier between conditioned and un-conditioned space.

42 Thermal imaging of the loft during the 1st coheating test had showed a thermal bypass in operation via the front chimney stack (Figure 16). The rear chimney breast had been removed beneath the ceiling level so there was no upward movement of warm air as can clearly be deduced was occurring in the front stack. It was hoped that the sealing of the fireplace in the lounge would reduce this, but it was not possible to cap the chimney and fill the flue with insulation to eliminate the bypass without additional investigative work as the next door neighbour's chimney may also have been affected. The thermal images of the same detail during the second coheating test (Figure 17) revealed that the bypass was still in operation after the fireplace had been sealed and additional work was still required to stop this heat loss mechanism from operating.

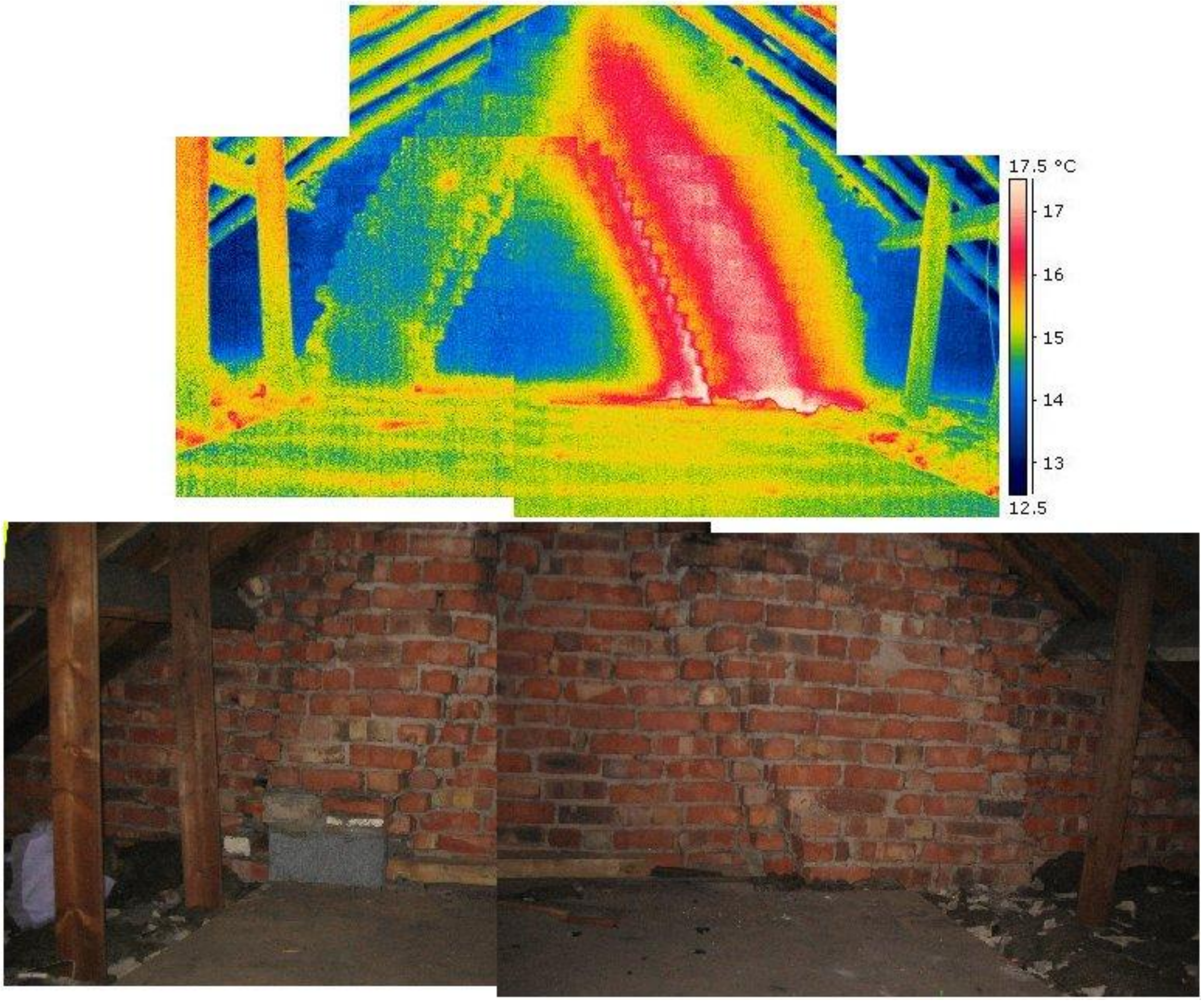


Figure 16 The bypass via the open flue chimney during the 1st coheating test contrasting with the rear chimney which had been closed off at ceiling level.

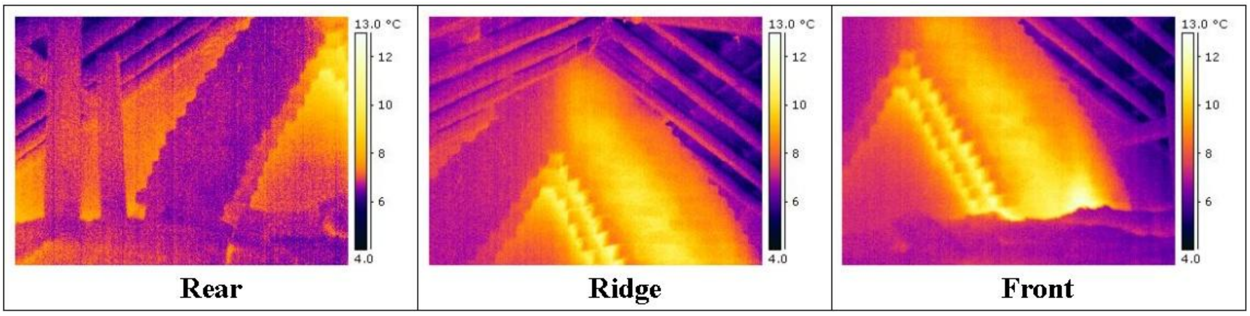


Figure 17 Thermal images of the chimney bypass during the 2nd coheating test.

43 Various additional measures were designed to improve the airtightness of the dwelling beyond those normally carried out as part of a decent homes upgrade. The suspended timber ground floor was sealed using a temporary hardboard covering with expanding foam edge sealing and taped joints. Figure 18 shows the living room floor in its original condition with cold air infiltrating between the floorboards during the heat-up period for the 1st coheating test and the sealed floor during the 2nd coheating test. Service penetrations through the external wall were removed and either temporarily sealed, patched up or filled with expanding foam, these included bathroom and kitchen waste pipes and the recessed lights in the bathroom ceiling. Opportunities were taken to seal gaps and air leakage paths as they came about. An example of this is shown in Figure 19, where the exposed intermediate floor void above the living room bay window allowed the joists to be sealed around and the cracks and gaps in the inner leaf brickwork to be pointed up.

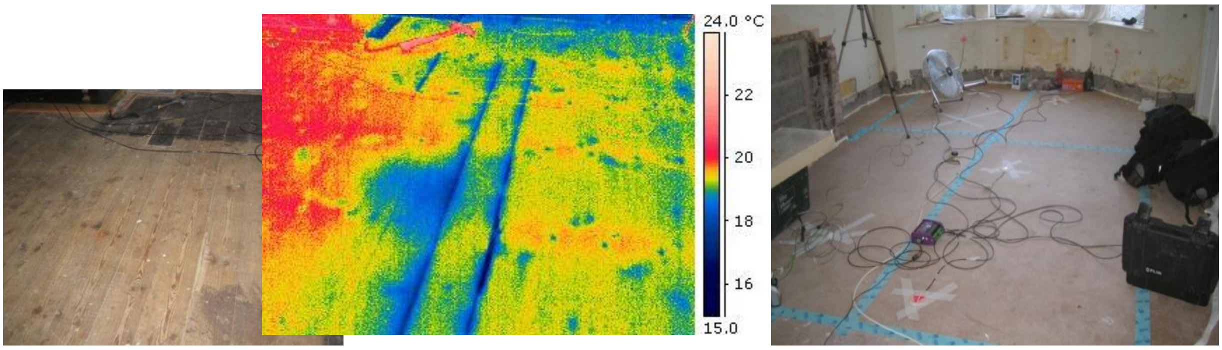


Figure 18 Living room floor during phase 1 and phase 2 coheating tests

Figure 19 Void above the living room bay window re-pointed and sealed around the joists to reduce air leakage

Stage 2 Renovation construction issues

44 The stage 2 renovation was intended to achieve an 80% reduction in CO_2 emissions from those prescribed to the dwelling in its original condition, and bring it roughly in line with the 2 prototype dwellings. Some of the measures taken involved high capital costs; this, coupled with the huge disruption would prevent most of these measures being replicated by occupiers but are of greater interest to social landlords looking to raise stock dwellings to higher levels of the Code for Sustainable Homes (CLG, 2008).

45 Both the assumed un-insulated solid ground floor and the suspended timber ground floor were removed and a replacement solid ground floor to a U-value of 0.195 W/m^2K installed throughout. The removal of the suspended timber floor proved straightforward as plumbing and electrical services previously located in the floor void were either re-routed or decommissioned. Removal of the solid concrete floor in the dining area and kitchen was more difficult and time consuming, with particular problems at the room perimeters and where internal masonry walls had been constructed on top of the old slab (Figure 20). Laying the new floor did not appear to present many problems apart from the large amount of moisture generated which proved difficult to remove given the extremely cold weather and that the windows were only open whilst workers were present, due to security issues. The new floor was laid in a single slab without any expansion joints and subsequently a crack developed in the doorway between the kitchen and dining area. This crack appeared to affect just the top surface of the floor and did not appear to penetrate by more than a few millimetres; subsequent leakage detection performed during air tightness tests did not identify the crack as a significant air leakage path.

Figure 20 New ground floor construction in the dining area and previous downstairs WC.

46 Additional blown fibre cavity wall insulation was installed where thermal imaging and heat flux measurements taken during the 2nd coheating test had highlighted issues, many of which had been confirmed as areas of incomplete insulation fill by borescope investigations. A vertical brush was installed at the rear of the property at the party wall junction to resolve the issues observed at the external wall in bedroom 2 (Figure 9) and the CWI topped-up. Supplementary injection holes were drilled at the ground floor perimeter to enable insulation to be injected at a lower level than during the original cavity fill (Figure 21). However, with no coheating test being performed between the rectifying of the CWI issues and the application of the external wall insulation it was not possible to quantify the success of these remedial measures.

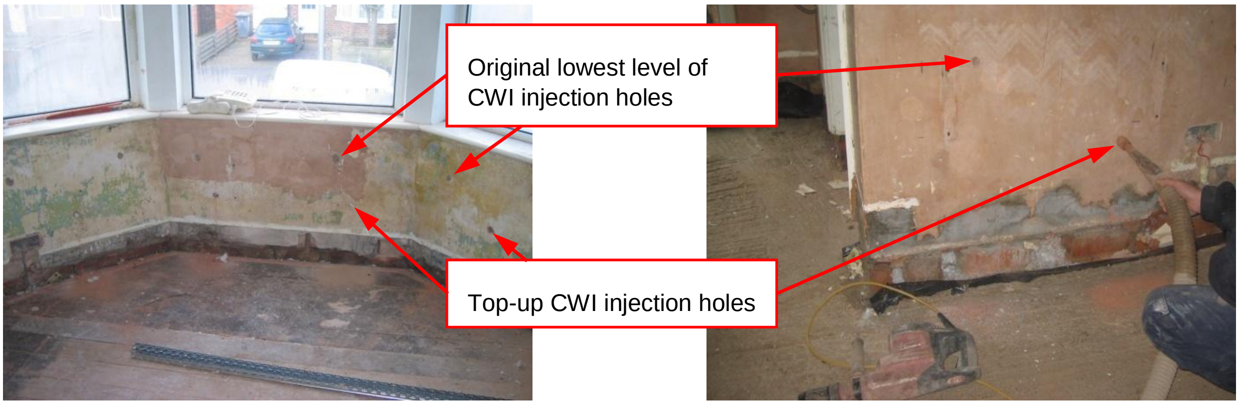


Figure 21 Top-up CWI at the ground floor bay and internal rear cavity wall.

47 To achieve the required U-value of the external walls 175 mm of mineral wool insulation, with a polymeric render coating, was to be fitted to the outer surface of all external walls of the property from the dpc level (one brick course below the ground floor level) up to the eaves. An extension of the roofline was necessary to allow for the additional wall thickness. Further alterations were required at junctions with the adjoining property, where the EWI continued to the plane of the midpoint of the party wall, and to the roofline at the gable end of the single storey rear extension. An additional 70 mm of extruded polystyrene insulation was fitted below the mineral wool EWI, to below the external ground level, to reduce thermal bridging through the floor perimeter. The EWI application process shown in Figure 22 commenced with the fixing of a galvanised metal tray at dpc level which acted as a guide for the base layer of insulation batts. High strength, rock mineral wool slabs with a water-repellent additive specifically designed for use in external wall insulation systems (1200 x 600 x 100 mm, λ-value 0.038 W/mK) were then attached to the outer brickwork using the slab manufacturer's recommended multi-functional base coat render as an adhesive which was mixed on site immediately prior to application. Sufficient adhesive was applied to the inner face of the insulation slabs to limit air movement in the recessed mortar joints of the facing brickwork. The slabs were tapped into position to ensure a good fit against the wall and any excess adhesive immediately struck off. A second layer of insulation slabs of 75 mm thickness was fixed to the outer surface of the first layer soon afterwards using the same adhesive before mechanically fixing both layers of insulation to the outer brickwork. Around junctions, penetrations and openings

the insulation batts were dry-positioned and marked to allow them to be sawn to the correct size prior to applying the adhesive directly to the batt and then fitting it into position. This method appeared to be very successful in minimising the gaps around penetrations and junctions; where small gaps did emerge, the insulation material was rigid enough for the installers to cut thin slivers of insulation which were worked into any spaces to maintain the continuity of the insulation layer. Once the insulation layers were completed they were covered with a purpose-designed fine mesh polymeric scrim, attached to the EWI using thin dabs of the same adhesive, and finished with a pre-coloured and pre-mixed textured silicone resin render.

Figure 22 EWI installation, February to March 2010.

48 There was a lack of pre-installation detail design of the EWI which resulted in many of the details being made up on site by the installers with consultation from the site manager, with discussions with the clients and design team deemed unnecessary unless there were issues of aesthetics or additional cost. For example, problems including the repositioning of external drainage appeared to be handled adroitly on site, whereas the treatment of the bay mullions prompted lengthier discussion with more interested parties. Particular areas of concern with performance issues were at openings and at the junctions involving the rear ground floor extension roof and front bay roof. With the replacement windows fitted prior to the EWI there was always going to be some thermal bridging which had not been fully considered in thermal calculations. The overlap between the window/door frames and insulation was not optimal, due to a compromise having to be achieved between thermal performance and structural issues. Of particular concern was the treatment of the thresholds where the 175 mm of mineral wool EWI stopped at the jambs, and only the 70 mm polystyrene insulation around the slab perimeter continues under the sills. In all 3 cases the polystyrene insulation did not extend right up to the frame leaving exposed brickwork externally and some degree of thermal bridging (Figure 23 and Figure 24). None of these details were fully completed at the time of the phase 3 coheating test, so may have displayed a marginally better performance than those shown in the thermal images in Figure 23 and Figure 24 if they had been entirely finished at the time of the test. The junctions involving the rear ground floor extension and front bay roofs both involved linking the vertical wall insulation to insulation in a different plane in a variation on the methods prescribed in EWI system manufacturer's standard details (Marmorit,

2006); if relevant detail drawings or thermal calculations had been prepared, they were not made available to the research team.

Figure 23 Patio door threshold during construction, on completion, and the external view and internal thermal image of the detail during the phase 3 coheating test.

49 Thermal bridging at the floor perimeter could have been reduced by extending the 175 mm mineral wool to further below the floor level, but it would have been impractical to have continued it across the thresholds. The external polystyrene slab perimeter insulation did continue right across each threshold between the foundation brickwork and the brickwork of the external steps but the paving slabs forming the doorstep surfaces linked directly to the masonry wall, and the resultant thermal bridge may present a condensation risk given the low thermal conductivity of the surrounding areas. The extent of the thermal bridges is shown in the thermal images in Figure 23, where the threshold is some 5º lower than the ambient internal temperature, and Figure 24, where the external temperature of the brickwork at the threshold is as high as that of the door which has a U-value of 1.2 W/m^2K (the higher temperatures indicated at the sides of the door are partly a result of the front door being opened briefly, shortly prior to the thermal image being captured).

Figure 24 Front door threshold during construction, on completion, and the external view thermal image of the detail during the phase 3 coheating test.

50 The EWI detail at the party wall junction had been a concern at design discussions due to the protrusion of the insulation from the external wall and the associated extension of the eaves and bay roof to accommodate the increase in wall thickness. The anticipated difficulties in detailing at the rear of the house, due to the extended eaves of both the main roof and the ground floor extension, appeared to present little problem to the insulation installers once the extensions to the eaves had been completed. A discontinuity in the external insulation layer resulted at the junction of the rear extension roof and the first floor EWI (Figure 25), although this did not appear to be a major issue in thermal images taken from either inside or outside the house during the 3rd coheating test. At the front of the property the EWI edge detail at the party wall was more straightforward, and any concerns over the aesthetics of the increased wall thickness compared to that of the adjoining property were allayed (Figure 26). Similarly, concerns over the appearance of the bay window mullions with EWI fitted prompted much discussion, but the finished detail (Figure 27) met with the approval of all concerned.

Figure 25 Junction of EWI with the rear extension roof at various stages of construction, and a thermal image of the completed detail captured during the 3rd coheating test.

Figure 26 The edge detail of the EWI at the party wall junction at the rear and front elevations.

51 The finished party wall detail with the 175 mm protrusion of the EWI appears unremarkable when viewed from the roadside, but very noticeable when viewed using a thermal camera. In Figure 27 the internal temperature in the test dwelling was 25 ºC (298 K) throughout, the temperature in the ground floor front room of the adjacent dwelling was 21 ºC whilst the temperature in the bedroom above it was not known. However, it must be stated that some of the differences in the wall

temperatures between the two properties observed in the thermal images in both Figure 25 and Figure 27 will also be due to the lower emissivity of the newly rendered surface.

Figure 27 Finished party wall EWI detail and thermal image, front elevation.

52 The bulk of the loft insulation remained unchanged following the stage 1 renovation; however, the roof extension work necessary to accommodate the EWI presented an opportunity for an extension of the loft insulation to meet up with the forthcoming wall insulation. With the roof tiles removed and felt lifted back (Figure 28) it was possible to observe how short the loft insulation fell from meeting up with the CWI to create a continuous insulation layer at this junction. Prior to the tiles being re-laid additional mineral fibre insulation was installed at the eaves to provide a link between the loft insulation and the EWI. Although the need to extend the roof for the EWI incurred additional costs it was fortunate from a thermal point of view, as it would have been highly unlikely to achieve the same level of integrity of the thermal layer without this advantageous access being acquired. Figure 29 and Figure 30 show the North East corner of bedroom 3 before and after the stage 2 renovations with the thermal images both displaying a 5 K range in temperature, they underline the beneficial effect of maintaining a continuous insulation layer between the walls and loft by the reduction in apparent thermal bridging at this junction. Some bridging is still evident through the roof timbers in Figure 30, but most of the large differences in internal surface temperature at the eaves junction observed in Figure 29 had been eradicated. Lifting the tiles for the main roof extensions at the eaves also provided an opportunity to close the tops of the external wall cavities which was not fully undertaken, this would have further reduced the likelihood of undesirable air movement in the external cavities and any associated bypassing effects.

Figure 28 Eaves extensions to the main roof at the rear and side elevations under construction, and with the roof extension completed prior to the EWI installation.

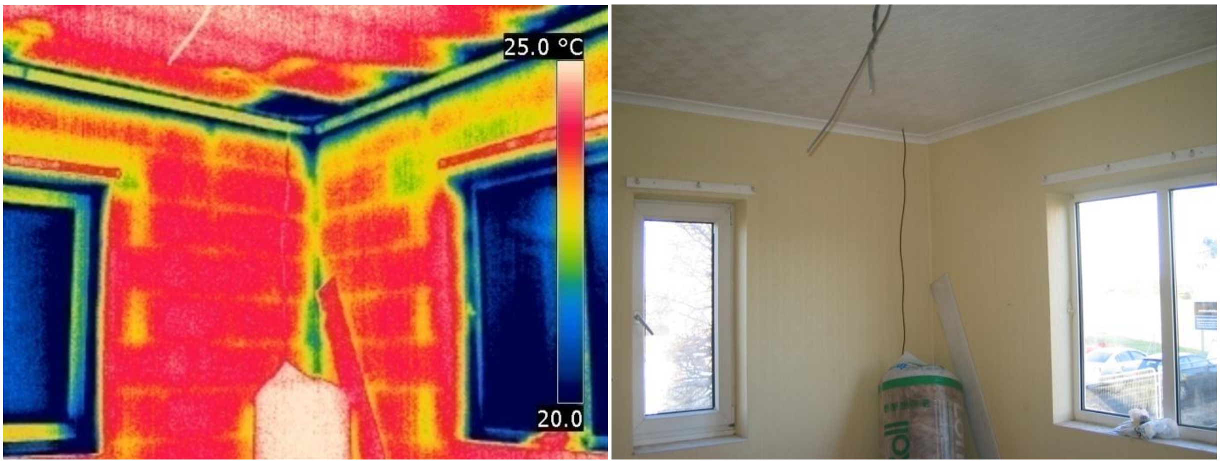


Figure 29 Bedroom 3 junction of front and side walls with the ceiling during the 2nd coheating test.

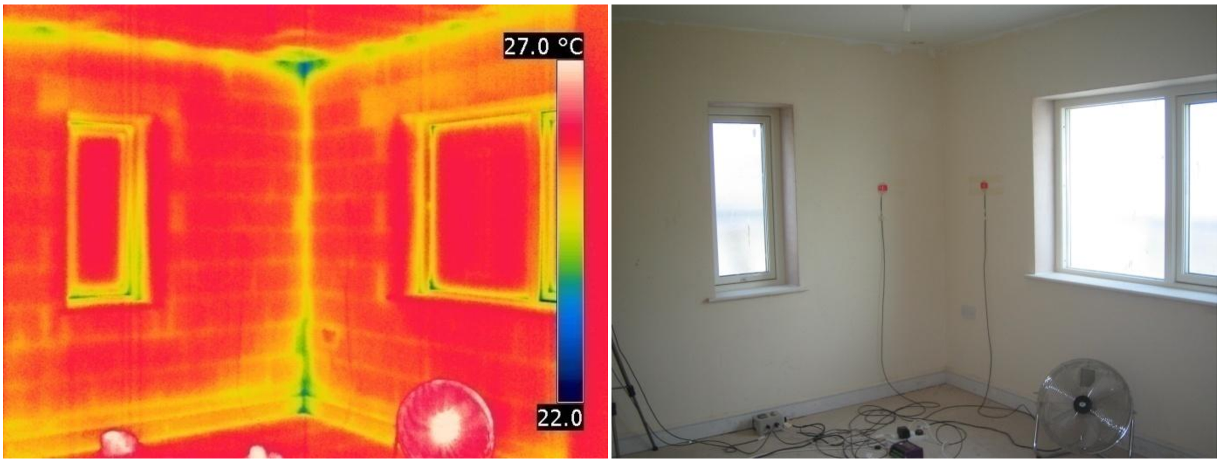


Figure 30 Bedroom 3 junction of front and side walls with the ceiling during the 3rd coheating test.

53 Figure 29 and Figure 30 also emphasize the difference in the thermal performance of the original windows and their replacements and the reduction in thermal bridging and/or air movement at the jambs, heads and sills resulting from the stage 2 renovations. The existing double glazed units were replaced with new argon-filled triple glazed timber windows throughout (U-value 0.83 W/m^{2}K) and the external doors replaced with composite insulated doors (U-value 1.2 W/m^{2}K). The kitchen to garage door was temporarily replaced. Placement of the windows in the external walls to more in line with the external wall insulation took place, but was limited by the weight of some of the replacement units. The replacement windows were planned to be fitted on brackets to extend them out into the insulation layer to optimise thermal performance, this was not always possible, with a number of windows fitted by screwing directly through the frames into the brickwork. This practical solution was decided upon by the window installer and site foreman and although the window placement was not optimal, it appeared acceptable as Figure 30 shows that there was no significant thermal bridging around the window frames. Similarly, with no formal design drawing, the insulation of the bay mullions appeared to rely on the vision and experience of the site foreman and no excessive thermal bridging observed during the final coheating test.

Figure 31 Installation of triple glazed replacement windows showing the air barrier.

54 Without any specific detailed drawings to guide the window fitter, it was left to him and the site manager to agree a practical solution as how to best achieve an airtight fit whilst keeping thermal bridging to a minimum. Airtightness was assisted by using a vapour barrier taped to the window/door frames prior to installation which was then returned and taped into the reveals using suitable adhesive tapes (Figure 31). This method of minimising air leakage was adopted both where window and door frames were secured by brackets or by screwing through the frames directly into the brickwork. Thermally, the expected optimum position for the frames would have been fully in line with the EWI to minimise thermal bridging through the frame and opening. However, the compromise between thermal performance and structural stability resulted in a final overlap between the frames and EWI varying from 30 – 70 mm (Figure 32) and appearing to depend on the size (or weight) of the window, with smaller (lighter) windows being placed further out into the EWI than the larger (heavier) windows and doors. No thermal bridging calculations were made available to the research team regarding the window placement, so it is uncertain whether the decrease in thermal bridging was in line with the estimated reduction in y-value from 0.15 W/m^2K to 0.08 W/m^2K used in the SAP calculations.

Figure 32 Rear and front elevation window frame positioning, showing potential for overlap with the EWI.

55 The target air permeability for the dwelling at the end of the stage 2 renovations was 5 $m^3/(h.m^2)$ @ 50 Pa. It was anticipated that this would be achieved by additional measures to the primary air barrier; including sealing around built-in joists at intermediate floor when opportunities arose (Figure 33), measures taken such as the new solid ground floor and the more airtight replacement windows, and continued good workmanship internally around service penetrations. Supplementary secondary sealing such as sealing floor wall junctions with mastic sealant was avoided, and no

specific effort was put into the possibility of the EWI providing a secondary external air barrier, instead reliance was put on the primary air barrier of the ground floor, the plaster lining of the external walls, the 1st floor ceiling, the garage ceiling and the newly installed membrane in the sloping roof of the rear ground floor extension. The suspended timber ground floor was a major leakage path in the initial pressure test and was temporarily boarded over for the 1st stage renovations, for the 2nd stage renovations a new insulated solid concrete ground floor was laid throughout the dwelling which minimised air leakage through this detail. The airtightness of the external walls was vastly improved by the replacement windows and doors, where infiltration through and around the original windows was significantly reduced, and sealing around the intermediate floor joists was addressed wherever opportunities arose. Air leakage through the 1st floor ceiling was reduced by removing the bathroom recessed lighting and existing penetrations to the loft-sited hot water cylinder. Further measures at this detail included replacing the loft hatch with a hinged and lockable hatch and ensuring that new penetrations into the loft space, including MVHR ductwork, solar hot water pipes and the bathroom soil stack, were all adequately sealed around. Some discontinuities in the primary air barrier remained after the 2nd stage renovations, most notably there were gaps between the plaster in bedroom 3 and the newly installed garage ceiling which had now become part of the primary air barrier, and the junctions of the rear ground floor extension sloping roof membrane with the internal plaster at the rear of the house, although the house was expected to approach or even achieve the airtightness target with these issues not fully resolved.

Figure 33 Rear wall of bedroom 2 before and after sealing work around the intermediate floor joists.

56 A whole-house mechanical ventilation system with heat recovery (MVHR) was installed, necessitating reparatory work to the disturbed loft insulation around the area where the MVHR unit had been positioned (Figure 34) and also to the loft insulation displaced by the MVHR ductwork. The MVHR system installers appeared to show little concern for the placement of the insulation; throwing the insulation into large piles when requiring access to grilles and ducts and not re-laying it adequately. The insulation was re-laid by a member of the client’s workforce to allow the 3rd coheating test on the property to proceed. As a result, much of the insulated flexible ductwork used in the loft still runs below the loft insulation rather than over it, displacing some of the loft insulation, creating additional air pockets and reducing the insulation’s thermal performance. Additional reparatory work was required where an MVHR service engineer inadvertently broke through the ceiling of Bedroom 1 whilst setting up the unit for commissioning. Further disturbance to the loft insulation was made where a steel support was inserted at ceiling level underneath the rear chimney stack, but here some attempt was made to re-lay the insulation albeit not quite to the original standard. The overall effect of the additional structural steelwork and displacement and disturbance of the loft insulation will have been a decrease in the performance of the loft insulation between the 2nd and 3rd coheating tests which was not possible to quantify given the scope of this project.

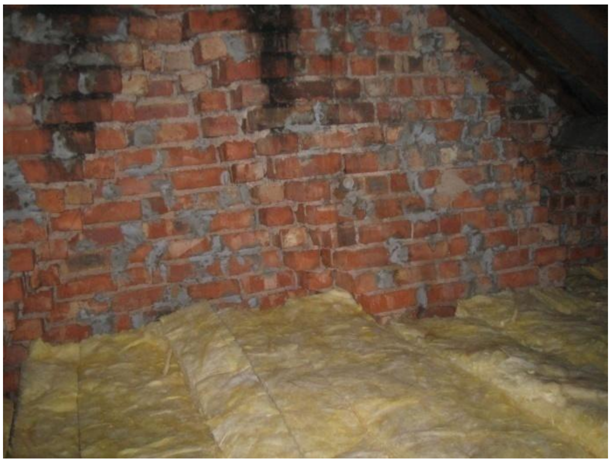



Figure 34 Loft insulation when laid (07-Dec-09) and after MVHR unit installation (02-Mar-10).

57 In general, the workmanship observed on site was to at least as good a standard as that observed in the Temple Avenue project prototype dwellings (Miles-Shenton et al., 2010). Problems that did arise were often due to lack of detail design which was invariable quickly resolved by the site team, or issues relating to time constrictions placed on the operatives by the pressures to get work completed to fit in with the testing regime or through protracted decision making by the clients, often both.

Fabric performance testing

Airtightness testing

58 Airtightness tests were conducted by Leeds Met, in accordance with ATTMA TS1 (ATTMA, 2007)[4], at a number of stages, prior to the occupants vacating the dwelling, both prior to and immediately following each of the coheating tests, with an additional test conducted prior to the Phase 3 coheating test to facilitate some of the secondary sealing work. The test dates and results are listed in Table 1.

Table 1 Pressurisation tests performed on the existing dwelling.

Test Date	Pressurisation Only			Depressurisation Only			Mean	
	Air Permeability	Air Leakage	Correlation	Air Permeability	Air Leakage	Correlation	Air Permeability	Air Leakage
	$m^3/(h.m^2)$@50Pa	h^{-1}@50Pa	r^2	$m^3/(h.m^2)$@50Pa	h^{-1}@50Pa	r^2	$m^3/(h.m^2)$@50Pa	h^{-1}@50Pa
01/07/2009	15.02	16.60	0.997	16.50	18.22	0.998	15.76	17.41
06/11/2009	21.33	23.56	0.997	19.99	22.08	0.999	20.66	22.82
07/12/2009	11.67	12.89	0.997	8.97	9.91	0.999	10.32	11.40
21/12/2009	10.41	11.50	0.999	9.26	10.23	1.000	9.83	10.86
08/03/2010	6.77	7.47	0.993	6.51	7.19	0.996	6.64	7.33
10/03/2010	5.91	6.53	0.993	5.58	6.16	0.998	5.74	6.35
24/03/2010	5.61	6.20	0.989	5.23	5.77	0.996	5.42	5.99

59 The initial pressurisation test performed in July 2009 was carried out with the dwelling still inhabited and fully carpeted and produced a mean air permeability test result of 15.76 $m^3/(h.m^2)$ @ 50Pa. It was only possible to perform a very limited amount of leakage detection to avoid undue disturbance to the occupants and potential damage to furnishings from the handheld smoke generators. Particularly poor performing areas appeared to be the lounge, hall, dining area,

[4] ATTMA TS1 (2007) was superseded in October 2010 by ATTMA TSL1 (ATTMA, 2010), the test procedure used by the LeedsMet research team is also in accordance with this revised testing protocol.

bedroom and bathroom floor perimeters; any service penetrations through the external walls and 1st floor ceiling; at both loft hatches and both around and through the external windows and doors and the door from the kitchen into the garage.

60 The substantial increase in air permeability recorded following the 1st coheating test, in November 2009, to 20.66 $m^3/(h.m^2)$ @ 50Pa was due to a number of factors. The physical act of performing the coheating test and keeping the house at 25 ºC for a 16 day period my have resulted in some shrinkage and worsening of the airtightness, although this effect is thought to have been limited in a “dry” existing dwelling. Of far greater significance was the removal of the carpets throughout the dwelling, which revealed gaps between floorboards and at floor perimeters and enabled less impeded airflow into the intermediate floor void and the void beneath the suspended timber ground floor. In the bathroom this effect was exacerbated by the exposing of additional leakage paths around the bath and shower (Figure 35). Also two first floor windows, the front facing window in bedroom 3 and one window in bedroom 2, appeared not to be tightly closed for this pressurisation test due to faulty mechanisms. Neither of these was noted for the initial test and may go some way to explaining the much larger increase in the pressurisation test over that observed for depressurisation; as under depressurisation the windows would have benefited from being pulled shut, whereas under pressurisation the opening lights would have been forced further away from any sealing.

Figure 35 Air leakage around the bath in July 2009, using smoke detection under pressurisation, and cooler air being drawn in under depressurisation in November 2009.

61 Two pressurisation tests were conducted after the stage 1 renovation work had been completed on 7th and 21st December 2009, immediately prior to and following the 2nd coheating test. The resulting mean air permeability from these tests was 10.32 and 9.83 $m^3/(h.m^2)$ @ 50Pa respectively, marking a vast improvement in airtightness over the previous tests. Substantial increases in the airtightness resulted from many of the stage 1 renovations, not just those that were specifically aimed at addressing this issue. Of the measures explicitly designed to improve the airtightness, perhaps the most effective was the decision to seal the suspended timber ground floor using a temporary hardboard covering with compressible edge sealing and taped joints in the lounge, dining area, hall and under-stairs cupboard. This is shown in Figure 36, which also shows the fireplace in the lounge was permanently blocked up prior to these tests, rather than relying on the temporary sealing used in previous tests, where adhesion of the temporary sealing masking to the masonry hearth and fireplace surround was unreliable and may also have had an important impact on the test results.

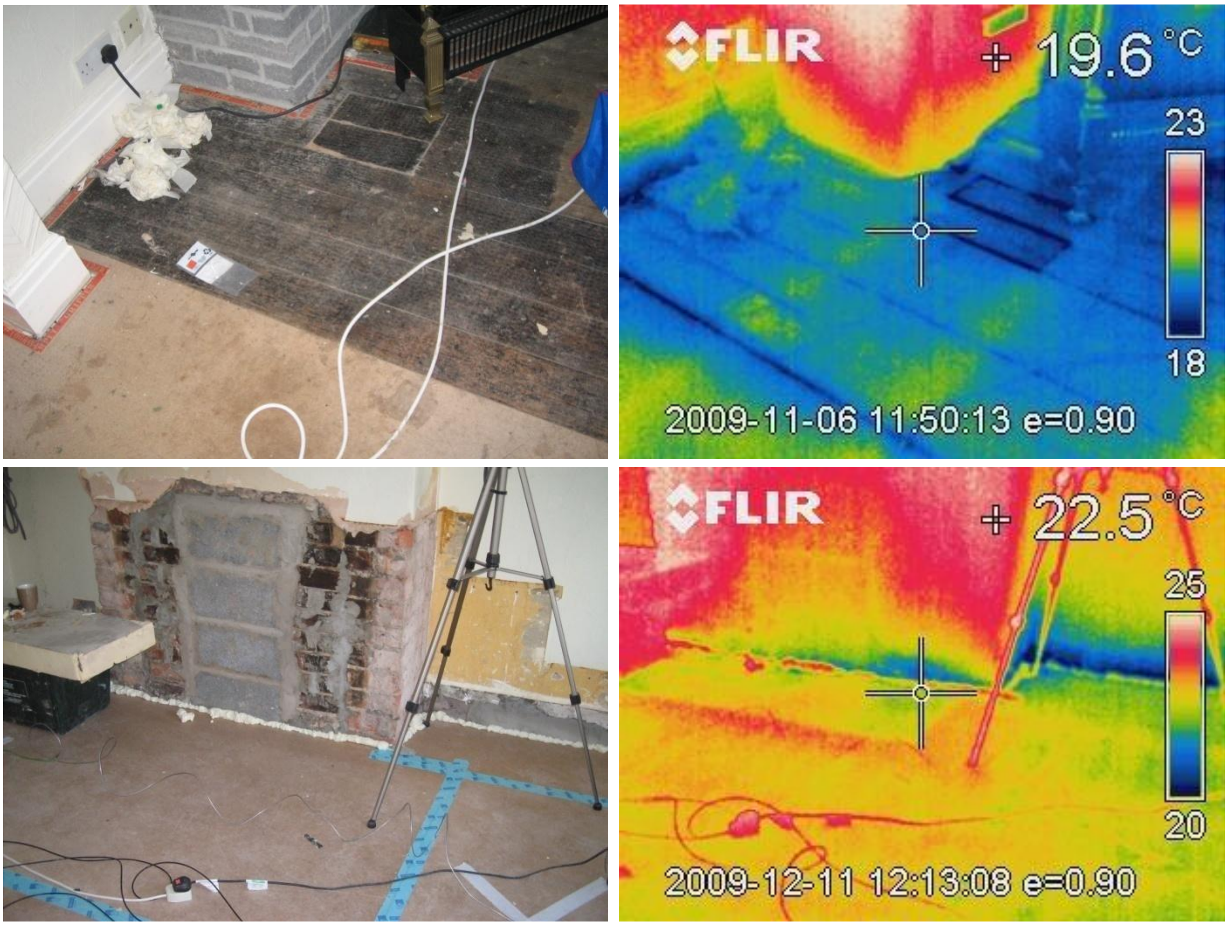


Figure 36 Infiltration, under depressurisation, through the original suspended timber ground floor following the 1st coheating test was addressed for the 2nd coheating test with a temporary floor covering.

62 Additional renovation work that had significant beneficial effect on the December 2009 airtightness test results included the removal of the boiler from the garage (Figure 15) and the hot water cylinder from the loft along with their associated pipework; this allowed service penetrations into the garage and loft to be sealed, either by patching up the walls or filling the gaps with expanding foam. Other service penetrations which had provided direct air paths to outside were also removed, including; bathroom, downstairs WC and kitchen waste pipes; kitchen and downstairs WC extraction fans; the downstairs toilet and the recessed lights in the bathroom ceiling. The moving of the air barrier at the rear extension from ceiling level to rafter level meant that some gaps in the external wall outer leaf now became gaps in the air barrier and needed to be repaired. Figure 37 shows a hole where service penetrations into the extension roof void were not sealed around for the 1st coheating test then sealed with expanding foam for the subsequent tests, as this effectively became part of the air barrier. Questions also arose regarding other linking up of the edges of the new airtightness membrane to the existing air barrier of the internal wet plaster linings. Reparatory work performed to level the intermediate floor of the side extension allowed further leakage paths to be addressed, but also delivered some missed opportunities. Removal of the original flooring allowed some sealing to be performed around the intermediate floor perimeter joist-ends and service penetrations. However, gaps were filled with expanding foam (for speed and convenience) rather than a more robust mortar and mastic which would have sealed better into corners and provided a better link between the wet-plastered 1st floor walls and the new garage ceiling. A mortar or mastic seal would have been more successful in achieving a continuous air barrier, and may also have coped better with the dirt, dust and debris. Whilst the floor decking was removed the opportunity to effectively seal the opening into the cavity of the original external gable wall by the top of the stairs was also missed.

Figure 37 Gaps in the external wall in the rear extension loft space effectively became part of the air barrier and required sealing due to the movement of the air barrier from ceiling to rafter level in the rear ground floor extension.

63 The partial boarding in the main loft and the old compressed loft insulation and debris were removed in late November 2009, and only some of the opportunities to address airtightness issues undertaken. With the boarding and old insulation removed, but prior to installation of the replacement insulation, it would have been possible to seal around penetrations through the ceiling from the loft space where access was difficult when performed from the first floor rooms, such as MVHR ducts and electrical penetrations positioned close to walls (Figure 38). The opportunity to seal along the tops of the old cavity external walls and internal partition walls was also not undertaken, this could have assisted in maintaining continuity of the air barrier by providing a link between internal wet plastered surfaces and helped to prevent indirect air leakage into the loft.

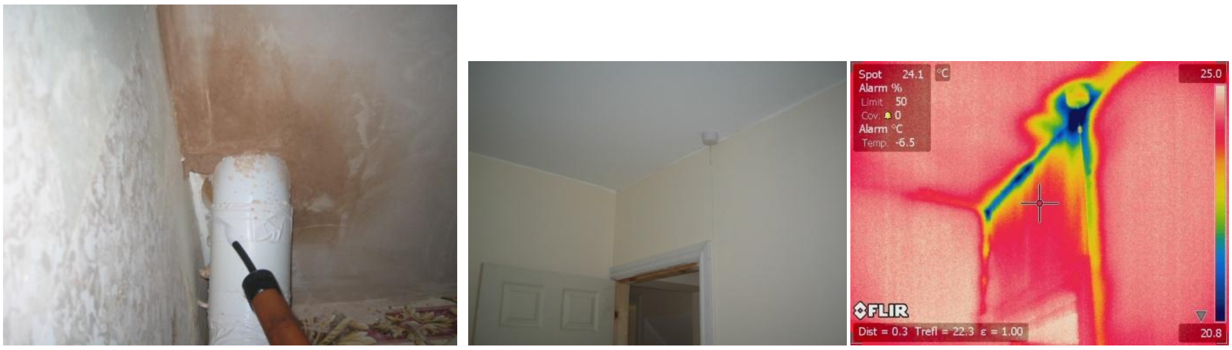


Figure 38 Air leakage into the loft which could have been sealed more effectively from inside the loft than from the 1st floor rooms.

64 One area where there was deterioration in the airtightness for the December 2009 airtightness tests came as a result of the mineral fibre insulation installation into the original external cavity walls. Air leakage was detected into the cavity at many of the injection holes which had been drilled into the cavity from inside the dwelling. Whilst a few of the holes had not been plugged with mortar and allowed significant air exchange between cavity and habitable areas, the majority had been loosely plugged and still allowed small amounts of air movement. These would be resolved when the dwelling was re-plastered.

65 The doors and windows were left unaltered for the 2nd coheating test, so still performed relatively poorly for airtightness. However, the door from the kitchen to the garage was temporarily sealed and air leakage around it reduced significantly; draught-stripping a door which was due to be replaced for the next stage refurbishment was considered an inefficient use of resources.

66 The aim of these measures performed prior to the 2nd coheating test was to reduce the mean air permeability of the dwelling from 20.66 $m^3/(h.m^2)$ @ 50Pa to below the figure of 10 $m^3/(h.m^2)$ @ 50Pa outlined in the 2006 Building Regulations, this was pretty much achieved and highlighted some areas where further improvements could be carried out, most notably around the untreated remainder of the intermediate floor perimeter and the doors and windows. These were regarded as two of the worst performing details and the anticipated reduction in air permeability from the new

windows and doors and additional sealing at the intermediate floor perimeter was expected to bring the house towards the final target level of 5 $m^3/(h.m^2)$ @ 50Pa.

67 A fifth pressurisation test was carried out on 8th March 2010 to inform the site team where there efforts were best spent prior to the 3rd coheating test being conducted, and how much additional work was required to attain the final air permeability target figure of 5 $m^3/(h.m^2)$ @ 50Pa. Two further pressurisation tests were conducted on 10th and 24th March 2010, immediately prior to and following the 3rd coheating test, the results of which were 5.74 and 5.42 $m^3/(h.m^2)$ @ 50Pa.

68 The stage 2 renovations were carried out between January and March 2010, with a number of the renovations having an impact of the airtightness. The entire ground floor was replaced with an insulated solid concrete ground floor leaving only potential air leakage paths at the floor perimeter. The temporary boarding-over of the suspended timber floor, as part of the stage 1 renovations, had gone some way to simulate the improvements in airtightness resulting from the new floor; however, the new floor was laid in a single slab and proved to be airtight leaving only a small amount of air leakage at the floor perimeter (Figure 39). The stage 2 renovations included replacing all the windows and both external doors; these had been a major source of air leakage in all the previous tests. The new windows and doors were of a very high standard and air leakage relating the replacement windows was limited to a small amount around the bay window sills, no air leakage was detected through the window units themselves (as seen in Figure 30). The doors were of an equally airtight construction, but some air movement persisted particularly at the thresholds; as with the bay windows this was not due to any defect in the units themselves but was due to gaps around the openings. In bedrooms 1 and 2 the floor boards were lifted to allow some sealing around the built-in joists and other gaps in the external walls at the intermediate floor void perimeter (Figure 33), other areas were not accessible due to floor joists running closely parallel to the walls restricting access. Other improvements in airtightness were observed with the replacement loft access hatch, the patching up of the internal plaster finishes, the re-roofing of the upstairs bay and the removal and/or sealing of the few remaining obsolete plumbing, sanitary and electrical penetrations. Certain other works increased the potential for air leakage including the new kitchen and bathroom installations, particularly for the new boiler, the installation of the MVHR system and associated ductwork, new electrical fixings and penetrations, and the installation of the solar thermal system and its related penetrations. No evidence was observed as to whether or not the EWI could have improved the airtightness by providing a secondary air barrier on the outside of the dwelling, as the air leakage paths observed into the external walls appeared to be into the existing cavities which had not been sealed at the top when the opportunities had arisen.

Figure 39 The hall and cupboard under the stairs, under depressurisation, showing the difference between the suspended timber ground floor and the replacement insulated solid concrete ground floor.

69 The pressurisation test conducted on 8th March 2010 revealed unsealed penetrations in the cylinder cupboard which were sealed with expanding foam prior to the pre-coheating air test 2 days later. Some additional sealing was also performed around kitchen, bathroom and MVHR penetrations, and at floor/wall junctions at service voids and thresholds. These measures resulted in bringing the mean air permeability down from 6.64 $m^3/(h.m^2)$ @ 50Pa on the 8th to 5.74 $m^3/(h.m^2)$ @ 50Pa on the 10th March. Additional sealing to gaps around the patio door threshold, the unfinished detail at the back door and leaks around the door between the kitchen and garage were not performed until after the test result on 10th March had been obtained, with a member of the site

staff using a mastic gun to seal some of the gaps being observed by the Leeds Met research team as they performed leakage detection around the property. This could go some way to explaining why the pressurisation test performed on 24th March, immediately following the 3rd coheating test produced an even lower result for mean air permeability (5.42 $m^3/(h.m^2)$ @ 50Pa) than at the start of the coheating test, when the elevated temperatures for the 2 week duration of the coheating test usually induce an increase in air permeability due to accelerated drying and shrinkage.

70 Whilst the replacement windows saw the anticipated reduction in airtightness realised, air leakage persisted at the external doors. Some air leakage was due to the back door not being fully sealed at the time of the final pressurisation tests, as an incorrect, outward-opening, door had been supplied. The site foreman was reluctant to expend too much effort in sealing around the door in the knowledge that it would be removed and replaced shortly after the testing schedule had been completed. The door would then be fully sealed and an improvement in airtightness expected. The front door and patio door threshold detailing was also not fully completed externally (Figure 24 and Figure 23), this may have provided a further improvement on completion, although this benefit may only be limited as the air leakage from the dwelling around these openings appeared to be into the existing wall cavity. The door between the kitchen and garage was only a temporary replacement and as such had not been draught-stripped or sealed at the sill as no floor covering had been applied in the kitchen. The temporary sealing did not adhere fully to the unfinished floor surface and would also expect to improve on full completion. With all the door detailing complete the dwelling may achieve the necessary reduction in mean air permeability to meet the target figure of 5 $m^3/(h.m^2)$ @ 50Pa.

Figure 40 Infiltration around the door between the kitchen and the garage at the November 2009 and March 2010 pressurisation tests.

71 The lofthatches into the main loft and into the ground floor rear extension were a major source of air leakage in first phase tests. For the tests in March 2010 the lofthatch into the rear extension roofspace had been removed from the primary air barrier, as the air barrier now followed the roofline; the lofthatch into the main loft had been replaced with an insulated and draught-stripped lockable unit. The result was that air movement into the main loft, from between the door and trap, had been reduced considerably, but not entirely (Figure 41); also some leakage around the hatch surround was detected where it was not sealed to the ceiling, but is expected to be reduced upon full decoration and caulking.

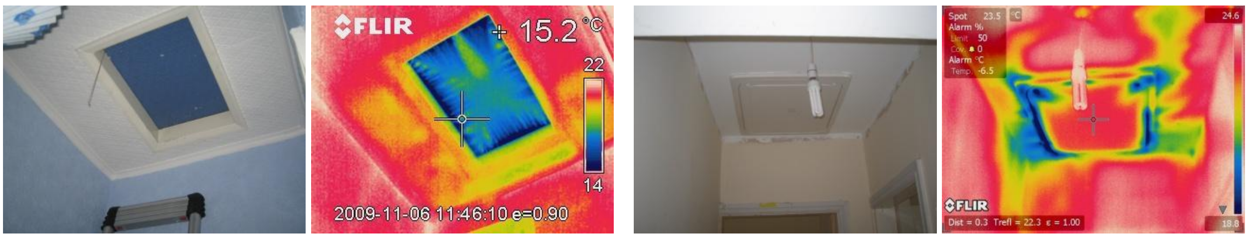


Figure 41 The original lofthatch into the main loft and the replacement, both under dwelling depressurisation.

72 Although most of the internal walls in the property were of masonry construction, a number of the 1^{st} floor internal walls were non-load bearing timber stud partition walls. Air leakage into the loft space had been observed into the loft at these partition wall heads in earlier pressurisation tests and was still present at tests performed in March 2010 (Figure 42). The ideal opportunity to seal the partition wall heads when the old loft insulation had been removed (and seal the open top of the cavity wall in the loft) was not programmed into to any schedule of works, so was missed. This was observed as a minor leakage path in November 2009 when the mean air permeability of the dwelling was over 20 $m^3/(h.m^2)$ @ 50Pa and would have been relatively low priority; however, by reducing the mean air permeability to 5 $m^3/(h.m^2)$ and successfully reducing most of the more obvious leakage paths what was a minor path had become much more significant

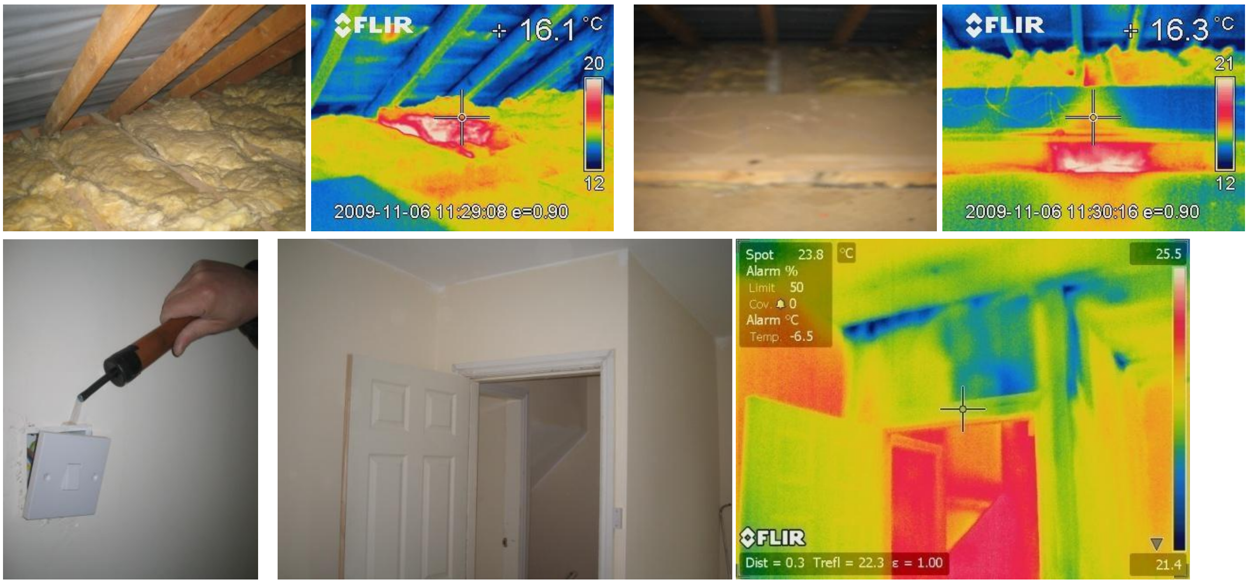


Figure 42 Hot air escaping through the partition wall heads into the loft in the 2^{nd} pressurisation test in November 2009 under dwelling pressurisation. And in March 2010, air leakage into the 1^{st} floor partition wall voids; via an electrical pattress under dwelling pressurisation and from the roof space under depressurisation.

73 A number of issues surrounding both kitchen and bathroom penetrations had been resolved prior to the air pressurisation tests in March 2010; however, some issues did remain and new concerns introduced. The removal of plumbing and sanitary services to the downstairs WC and the re-routing of waste pipes to minimise penetrations through the external walls in both the kitchen and the bathroom had solved obvious direct air leakage problems. However, air leakage into the soil stack risers and service voids was still an issue, with boxed in service penetrations appearing to end up not being sealed as well as those which remained visible. Figure 43 shows the benefit of removing the waste pipe penetration through the external wall in the bathroom, but thermal imaging of the renovated bathroom still showed cooler air being drawn in indirectly from service voids. A number of these indirect leakage paths were detected in the pressure test performed on 8^{th} March 2010, and the subsequent secondary sealing around the junctions and penetrations into the service voids will have helped to reduce the mean air permeability recorded in the ensuing 2 tests. Some of the other original leakage paths observed in previous test still remained, or had been removed only to be replaced by leakage paths around new penetrations, junctions and detailing (Figure 44).

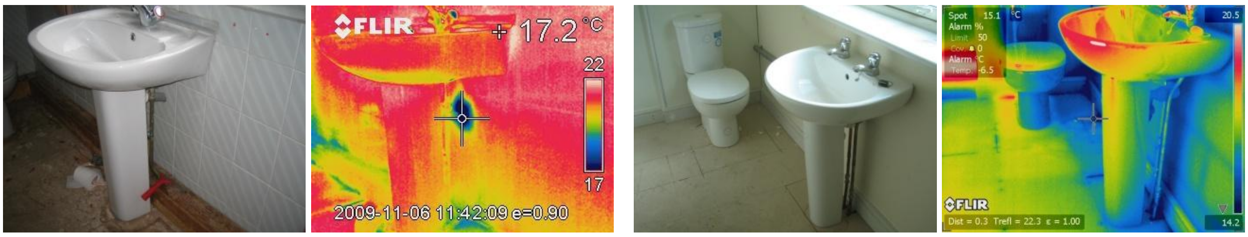


Figure 43 Air leakage at the bathroom hand basin waste pipe in November 2009, and the equivalent detail in March 2010, under dwelling depressurisation.

Figure 44 Air leakage under the kitchen units and around the extract vent in November 2009 (top), and at the same locations in March 2010, both under dwelling depressurisation, with the new boiler flue situated where the extractor fan had been positioned previously.

74 In summary, over the course of both stages of renovation work there were airtightness issues which had been addressed in full, partially and left un-tackled. Those airtightness issues fully addressed included:

a) Ground floor – Air leakage was eliminated through the ground floor after the entire ground floor had been replaced with an impermeable solid concrete floor.

b) Windows – The replacement windows performed exceptionally well with regard to airtightness and were far superior to those replaced, the membrane fitted between the frames and openings generally ensured only minimal air leakage at jambs, heads and sills.

c) Fireplace – Blocking up and re-plastering over the existed fireplace in the lounge eliminated it as a direct source of air leakage.

Airtightness issues which had only been partially addressed included:

d) Ground floor perimeter – Some air leakage was still evident at this detail, but far less than was observed for the existing ground floor.

e) Doors – Air leakage remained due to these details remaining unfinished at the time of the final airtightness test performed. The door between the kitchen and garage was also not fully finished, and was temporarily sealed awaiting a draught-stripped replacement door and frame to be fitted on completion. It is expected however, that some of the air leakage detected at the edges of the door thresholds will still remain even after completion.

f) Lofthatch to main loft – The replacement lofthatch to the main loft was hinged and had a catch and compressible seal, it performed much better than the previous unsealed lofthatch. Although air leakage was detected around the hatch surround, this is expected to be much reduced with the final decoration and caulking.

g) Intermediate floor void perimeter – Most of the gaps in the external walls around the intermediate floor void perimeter were sealed, where accessible, with expanding foam. This reduced the airflow through these holes considerably, but did not totally eradicate it. Where joists ran closely parallel to the external wall it was not possible to seal any holes effectively.

h) Ceiling penetrations – The removal of the bathroom down-lighters and the loft-mounted hot water cylinder had a significant beneficial effect on the airtightness, the small amount of leakage through central-light wiring was not tackled. The positioning of risers and MVHR ductwork close to walls left areas around the penetrations between the walls and pipe/duct unsuccessfully sealed; the opportunity to seal these from inside the loft, when the original loft insulation was removed, was either not undertaken or not possible due to the build sequence adopted. Penetrations through the new cylinder cupboard were only partially sealed at the time of the last pressurisation test conducted as part of this project.

Some of the airtightness issues were not addressed, these included:

i) Partition walls heads – As with the ceiling penetrations, these could have been addressed from inside the loft. This could have been carried out during the short period of time when the original loft boarding and insulation had been removed and they were all fully exposed and accessible from above.

j) Junction of intermediate floor with old gable wall cavity – The opportunity arose to seal the cavity when the intermediate floor on the landing was lifted. This was not carried out and air movement between the intermediate floor void and the old gable wall cavity remained.

k) Air barrier discontinuities – Some of the renovations included the introduction of materials which constituted the primary air barrier, but were not linked directly to the existing primary air barrier. The sloping roof membrane in the rear extension linked directly to the air barrier on the ground floor external wall (the internal plaster finish), but not directly to the air barrier at the side walls and 1st floor rear wall. The new garage ceiling did not connect directly to the plaster finish in bedroom 3 above it (Figure 45), leaving the intermediate floor void perimeter to complete the discontinuity in the primary air barrier.

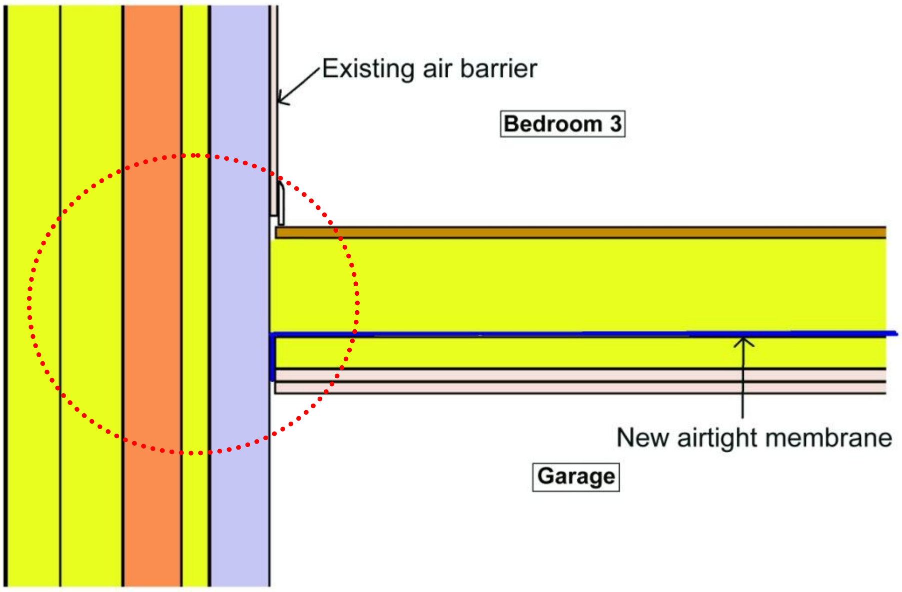


Figure 45 Discontinuity in the primary air barrier between the new garage ceiling and the wet-plastered wall finish in bedroom 3 at the gable wall.

Coheating tests

75 To fit all the renovation work and 3 coheating tests into one winter involved careful planning and scheduling of the retrofit programme, as the window of opportunity for conducting the coheating tests is limited to the winter period. Warmer external temperatures and increased solar insolation occurring outside of this period reduce the efficacy of the data obtained. Figure 46 shows the daily mean external temperatures recorded at the weather station located at the client's maintenance depot, and illustrates the time window available for coheating tests. It is not until late October that the mean daily temperatures are low enough to provide the >10 K temperature differential required for accurate measurement and analysis of the coheating data, and by April the external temperatures are regularly above the levels required to maintain the desired ΔT. The schedule adopted utilised the maximum time window available and coheating testing of the dwelling took place over 3 phases between 20-Oct-09 and 24-Mar-10, the dates for each individual coheating test are listed in Table 2. The procedure followed that described in the Whole House Heat Loss Test Method (Coheating) (Wingfield, Johnston, Miles-Shenton and Bell, 2010), the same procedure followed in testing the Temple Avenue project prototype dwellings. Although the research team requested that access to the house during these periods was limited to emergencies only, there were days when the clients required access to the property and the data for these days may have been compromised. All of the available data have been included in the analysis provided for this report, but may be removed from any subsequent analyses should the effects of these interventions prove significant.

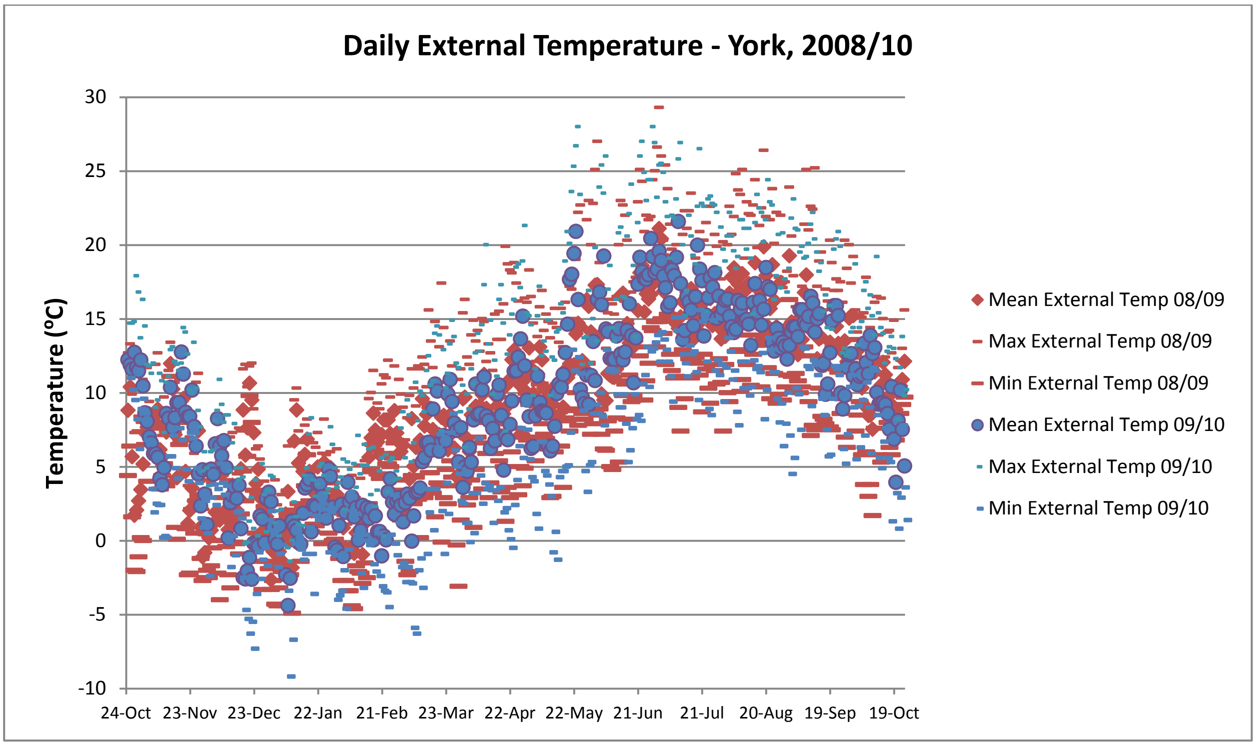


Figure 46 Mean daily external temperatures recorded at the weather station sited at the client's maintenance yard in York.

Table 2 Coheating tests performed on the existing dwelling.

Coheating Test	Start Date	End Date	Description
Phase 1	20-Oct-09	06-Nov-09	Original dwelling condition
Phase 2	07-Dec-09	21-Dec-09	Following Stage 1 renovation
Phase 3	10-Mar-10	24-Mar-10	Following Stage 2 renovation

76 For the phase 1 coheating test the equipment used for the test duration was arranged around the dwelling as indicated in Figure 47 with the typical equipment set up as shown in Figure 48. Slight adaptations to this layout were performed for subsequent tests. For the phase 2 test the under-floor temperature/RH sensors were replaced by thermocouples fed through pre-drilled holes in the hardboard covering of the suspended timber ground floor. For the phase 3 test additional circulation fans were situated in the bathroom and bedroom 2 to disperse the additional heat accumulating in these areas during periods of high solar insolence, and the external temperature/RH sensor was relocated from the front elevation of the test dwelling to the gable wall of the house on the opposite side of the street, less than 20 m away (Figure 49). The relocation of the external temperature/RH sensor to a slightly more sheltered and more easterly facade may have had a slight effect on the readings obtained but with the sensor tip housed in a Stephenson screen the difference is thought to have been negligible in this instance. External temperature and RH measurements taken in tandem, from the weather station sited at the client's maintenance yard, showed no obvious change in variation between the sets of readings taken simultaneously with those at the site. Wind and solar insolation measurements were also obtained from the weather station at the client's yard, for all 3 phase coheating tests.

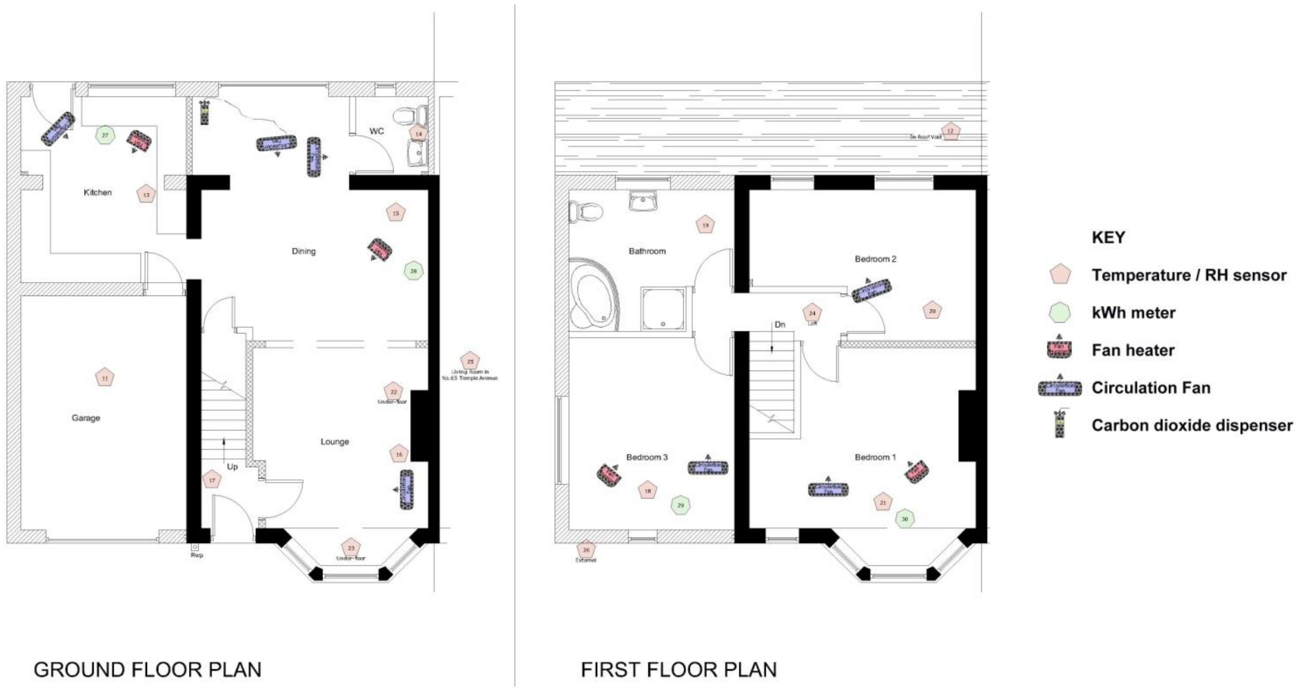


Figure 47 Phase 1 coheating test equipment layout

Figure 48 Coheating test equipment set-up in bedrooms 1 and 3.

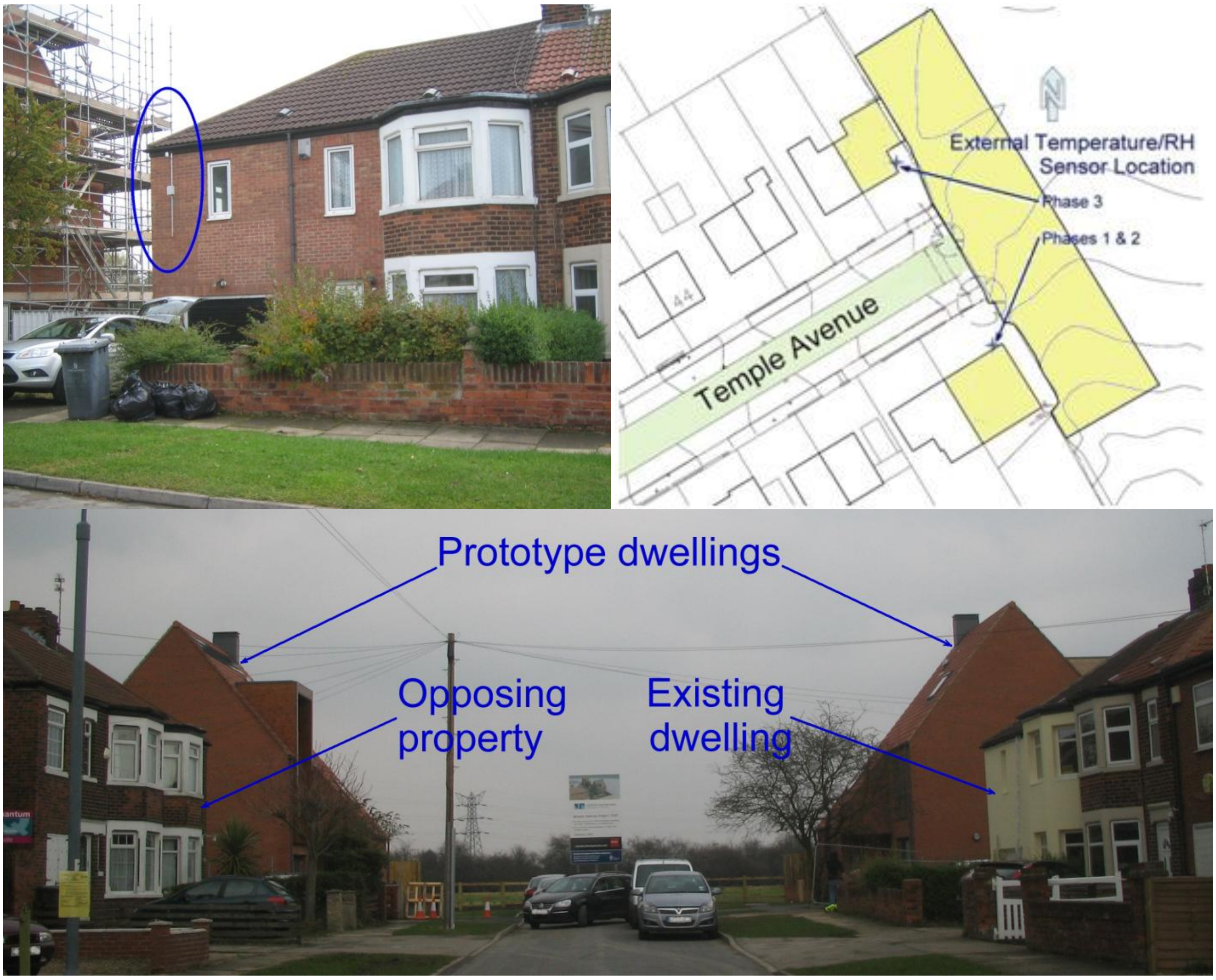


Figure 49 External temperature and relative humidity sensor was re-located from the front elevation of the test dwelling to the Gable wall of the opposing dwelling for the phase 3 coheating test.

77 The results from the data collected over the test periods outlined in Table 2 are shown in Figure 50, where both the predicted and measured heat losses of the dwelling during each coheating test are compared. Figure 50 plots the total daily heat input into the dwelling against the average daily internal/external temperature difference. The total daily heat input includes all electrical input into the dwelling, from resistance heaters, circulation fans, data-logging and communications equipment, and is compensated for solar gain by a value calculated using a multiple regression analysis. The internal/external temperature differential (ΔT) is calculated using the mean daily external temperature, measured from the external sensor at Temple Avenue, and the mean daily internal temperature, calculated from the mean internal room temperatures and weighted by each room's internal floor area. The measured data is manipulated to force the intercepts through zero; it is assumed that no heat loss occurs when ΔT = 0. The heat loss coefficient is simply the amount of power, in Watts, required to maintain a given ΔT, in Kelvin (or Celsius); the values for heat-loss coefficient realised (both predicted and measured) for each phase are represented by the gradient of each of the lines plotted in Figure 50.

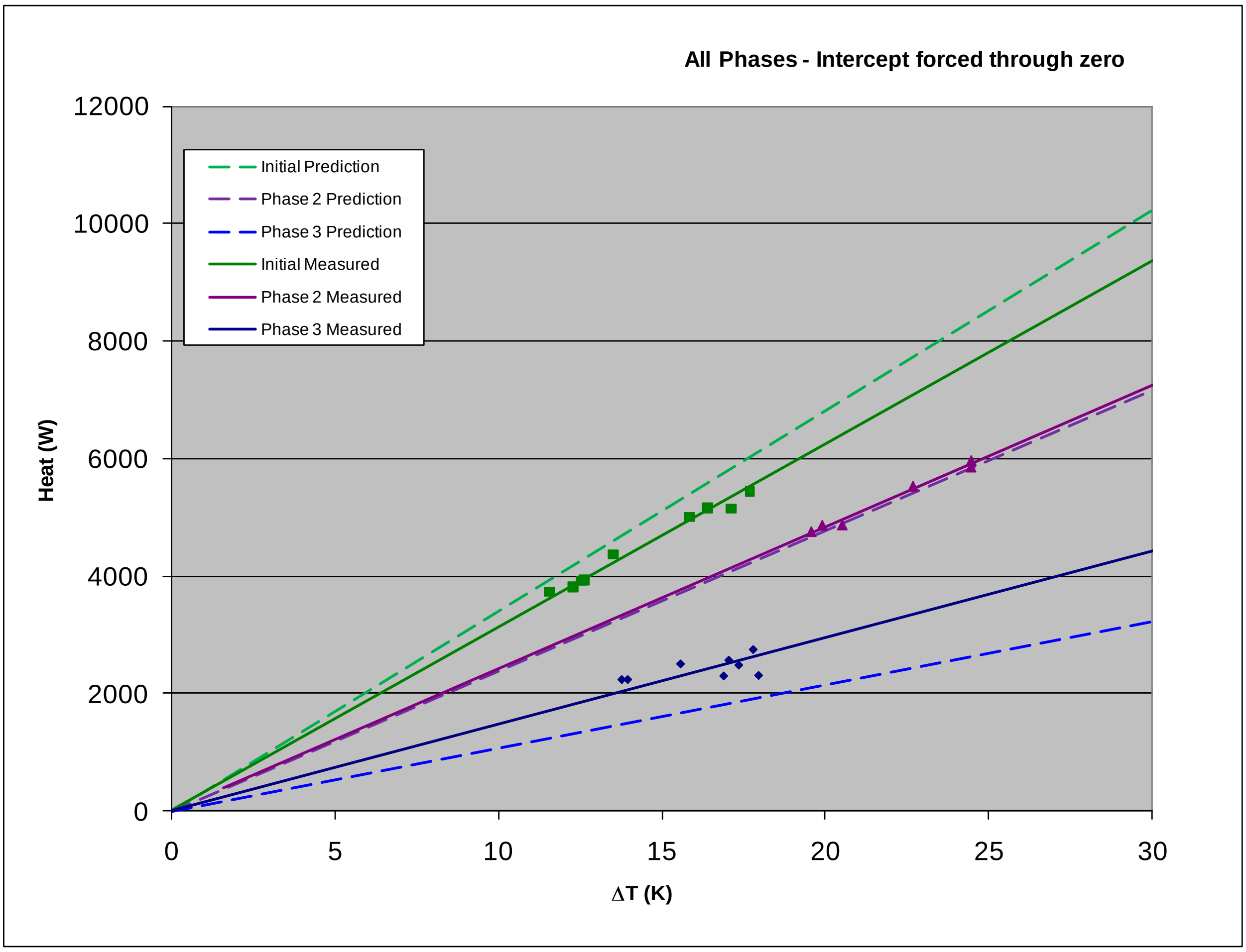


Figure 50 Comparison of predicted[5] and measured[6] heat loss for the 3 coheating tests performed on the existing dwelling.

78 What is immediately obvious from Figure 50 is that the measured heat loss coefficient is less than predicted for phase 1, roughly similar to the predicted figure in phase 2 and greater than predicted in phase 3. More importantly, in neither of the renovation stages did the measured reduction in heat loss coefficient achieve the reduction that had been predicted. This can be explained by either experimental error, underperformance of the renovation works undertaken, inaccuracies in the estimations made for the prediction of heat loss values, or a combination of any of these. The coheating test protocol used by the research team is a proven methodology, and there were no significant variations between the 3 test procedures followed. This indicates that the variations observed between the measured and predicted heat loss are a result of either underperformance of the measures introduced or inaccuracies in the predicted performance data, or both.

79 The predicted heat loss figures used in the analysis are based on a combination of estimations in the architects' original draft SAP calculations, manufacturer's claimed values, some additional U-value calculations performed by the research team where no stated or claimed value could be found and measured values for air permeability; the values relating to fabric heat loss elements are listed in Table 3. Each coheating phase in Table 3 has entries for elemental U-value and heat loss, the heat loss figure obtained being a product of the stated U-value and the heat loss area defined in the drawings supplied by the architects; mean U-values and total heat loss figures use the same calculated areas.

[5] The predicted heat-loss includes ventilation heat loss calculated using measured mean air permeability results (the arithmetic mean of pressurisation tests performed prior to and immediately following the coheating test).

[6] The measured heat-loss is the total electrical energy input, minus a correction for solar gains.

Table 3 Elemental U-Values and predicted fabric heat loss

	Initial Phase		Phase 2		Phase 3	
	U-Value (W/m^2K)	Heat Loss (W/K)	U-Value (W/m^2K)	Heat Loss (W/K)	U-Value (W/m^2K)	Heat Loss (W/K)
Solid Ground Floor	0.881	19.66	0.881	19.66	0.195	13.75
Suspended Ground Floor	0.365	11.93	0.365	11.93		
Floor over Garage	0.253	4.58	0.200	3.61	0.200	3.61
Mean Floor U-Value	**0.49**		**0.48**		**0.20**	
Total Floor Heat Loss		**36.17**		**35.21**		**14.34**
Main Roof	0.517	29.02	0.110	6.17	0.110	6.17
Rear Extension Roof	0.517	6.74	0.170	2.22	0.170	2.22
Bay Roof	1.986	2.90	1.986	2.90	0.170	0.25
Mean Roof U-Value	**0.55**		**0.16**		**0.12**	
Total Roof Heat Loss		**38.66**		**11.29**		**8.64**
Original Front Wall	1.680	35.37	0.450	9.47	0.150	3.16
Original Rear Wall	1.680	10.20	0.450	2.74	0.150	0.92
Original Rear Wall to Extension	0.622	3.14	0.391	1.97	0.150	0.76
Newer Front Wall	0.645	5.48	0.645	5.48	0.150	1.27
Newer Rear Wall	0.645	10.26	0.645	10.26	0.150	2.39
Newer Rear Wall to Extension	0.391	1.57	0.391	1.57	0.150	0.60
Gable Wall	0.645	15.84	0.645	15.84	0.150	3.68
Modified Gable Wall to Garage	0.622	8.31	0.200	2.67	0.200	2.67
Newer Wall to Garage	0.391	3.16	0.200	1.62	0.200	1.62
Mean Wall U-Value	**0.88**		**0.48**		**0.16**	
Total Wall Heat Loss		**93.33**		**51.62**		**17.06**
Windows & Patio Doors	2.70	43.62	2.70	43.62	0.83	13.41
External Doors	2.85	10.56	2.85	10.56	1.20	4.45
Door to Garage	3.00	5.10	3.00	5.10	3.00	5.10
Mean Window/Door U-Value	**2.75**		**2.75**		**1.06**	
Total Window/Door Heat Loss		**59.28**		**59.28**		**22.96**
Thermal Bridging		40.78		40.78		21.75
Total Predicted Fabric Heat Loss (reduction on original value)		**268.21**		**198.18** (-26.11%)		**84.74** (-68.41%)

80 The U-values listed in Table 3 are simple steady state approximations and do not consider dynamic effects such as thermal bypassing and any potential heat recovery resulting from bulk air movement. For example, the suspended timber ground floor U-value of 0.365 W/m^2K is the default value, used by the architects from the NHER software, this may not reflect the full extent of any heat recovery resulting from infiltration of adventitiously pre-heated air from the under-floor void. Air leakage through the suspended timber floor was seen as a major air leakage path for the phase 1 coheating test; with the ground floor acting as an infiltration zone under normal environmental conditions, heat lost to air in the under floor void through conduction will be recovered by the

warmed up air entering the dwelling (rather than air entering at the cooler external temperature, as is assumed in the energy calculations) as infiltration[7]. Whether this pre-warming of infiltrating air should cause a reduction in the predicted fabric heat loss or in the ventilation heat loss is debateable, but either way it results in an over-estimate of heat loss from the dwelling for the initial phase coheating test not present for either the phase 2 or phase 3 coheating test.

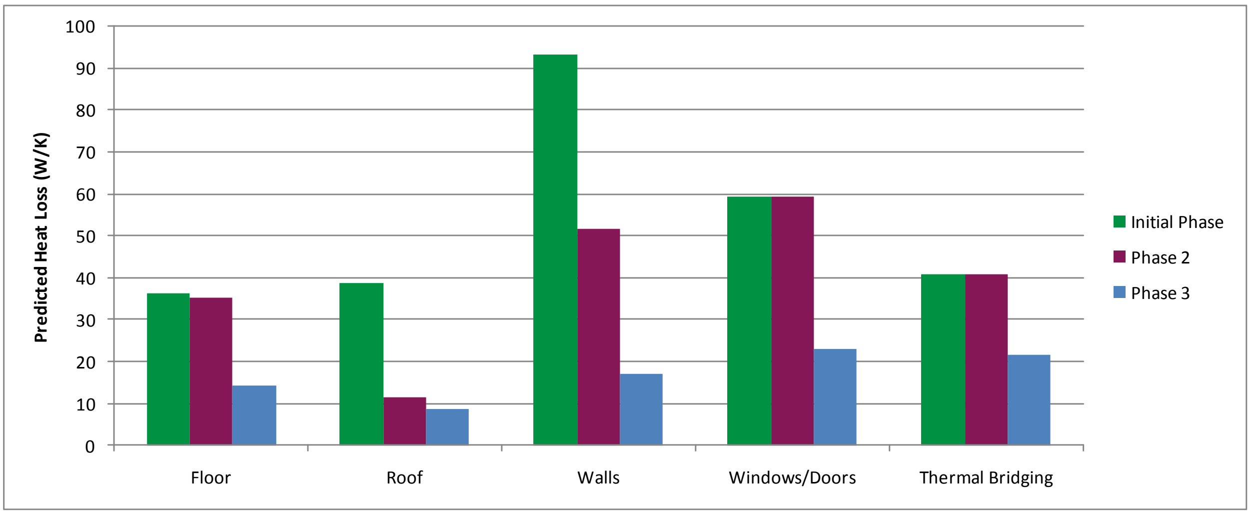


Figure 51 Predicted heat loss, by element, for each coheating phase.

81 The single largest predicted heat loss element for the initial phase coheating test was the external walls (Figure 51) and a number of issues exist relating to the accuracy of their predicted thermal performance. The estimated U-values of the insulated cavity walls in both the initial phase and phase 2 coheating tests were calculated using an assumed 25 mm of partial fill mineral wool cavity insulation in a 70 mm cavity between either a brick or block inner leaf and a brick outer leaf, with U-values >0.6 W/m^2K. Once building work commenced it became clear that the partial fill insulation batts were nominally 50 mm thick (Figure 52). This is perhaps where the majority of the over-estimation in predicted heat loss coefficient for the initial phase coheating test occurs, with some over-estimation still present for the phase 2 coheating test (those wall values which remained unchanged in Table 3 between the initial phase and phase 2). The over-estimates for phase 2 will however be offset by the problems encountered with the retro-filling of the original cavity walls with blown fibre insulation as part of the stage 1 renovations, which will have resulted in a level of performance substantially below those predicted. Also, no adjustments to the U-values and heat loss figures in Table 3 have been made to take into consideration any thermal bypassing occurring in the cavity walls. Further evidence of existence of these bypasses and indications of their magnitude is discussed in more detail later (paragraphs 97 to 100).

[7] Natural pressure differentials induced through thermal stack and wind effects will drive air leakage under normal environmental conditions, with infiltration mainly occurring at the δP+ ground floor and leeward sides of the building and exfiltration at the δP- top floor and leeward side of the property.

Figure 52 Cavity insulation at the front door, gable wall, and rear extensions wall was revealed during renovations works and shown to be thicker than originally estimated (photographs taken during relocation of the front door lintel, installation of the new extension floor and removal of the existing kitchen service penetrations).

82 The predicted single largest heat loss element for the phase 2 coheating test was the windows and doors (Figure 51) which were unchanged from the initial phase coheating test. The comparison of the thermal images in Figure 29 and Figure 30 provide a clear illustration in the improvements in performance made by the new windows as part of the stage 2 renovation. Although there were no questions over the replacement window performance; as was observed with airtightness, issues remained around the replacement doors which had not been fully finished at the time of the final coheating test. The unfinished details around the replacement doors will have increased thermal bridging (as seen in Figure 23 and Figure 24), and the door between the kitchen and garage was an un-insulated one-hour fire door rather than the recommended replacement with a door of similar performance to the external doors.

83 The Table 3 values provided for thermal bridging were default values for the initial and 2nd phases of coheating, with the SAP2005 Appendix K (BRE, 2005) default y-value of 0.15 W/m^{2}K applied, and an improved y-value of 0.08 W/m^{2}K for phase 3. Given the large variation in external wall U-values over the initial and 2nd phases it is likely that this value overestimates the additional linear transmission heat losses in the initial phase coheating test when compared to phase 2. The scope of the project did not extend to resource-consuming thermal modelling of Ψ-values of individual details, but given that the EWI installed during the stage 2 renovation and relocation of the windows within the external walls will have significantly reduced much of the thermal bridging for the phase 3 coheating test relating to the external walls and windows, it is unlikely that the reduced value accurately represents the additional heat loss for this instance, although it may provide a more accurate estimation for other building elements.

84 Inaccuracies in predicted values affect the size of the variation between them and the measured heat loss, but anomalies between the two are also due to the as-built details and elements not achieving their specified design performance for a variety of reasons; including construction faults and modifications, possible design and process issues, and variations in the physical properties of the building itself throughout the course of the coheating tests. Additional measurements taken during the coheating tests assisted the estimation of the extent of some of these issues; airtightness issues were shown up by pressurisation tests before and after the coheating test and through the use of CO_2 as a tracer gas during the tests, changes in the moisture load through drying of the building fabric were monitored through constant recording of relative humidity and degradation of fabric U-values was investigated by measuring heat flux through elements of the fabric to measure the actual effective U-values at given points using heat flux sensors. Potential inaccuracies in the prediction of ventilation heat loss in each coheating test was overcome by using a mean air permeability figure based on dwelling pressurisation tests performed at the start and end of each coheating test period. The n/20 rule of thumb (as used in SAP2005) and a sheltering factor of 0.85 were used to convert these mean air permeability values into the ventilation heat loss figures used in the predicted values displayed in Figure 50. As there are always likely to be changes in ventilation heat loss over the course of the tests, daily CO_2 concentration curves were used to record how the actual ventilation rate varied by means of a pulsed CO_2 release and measurement of its subsequent decay (Roulet & Faradini, 2002). The measurement of ventilation rate via this technique allowed the research team to see if there were any sudden step changes in ventilation rate indicating changes in the fabric airtightness. The CO_2 decay method utilised a single source of gas sited in the dining area with 2 CO_2 sensors, in the lounge and bedroom 1; 15 minute pulses of CO_2 were released each afternoon to raise the concentration to over 1000 ppm and the decay to background levels logged. Table 4 compares background ventilation heat loss values using both techniques, along with calculations based on the target levels of airtightness for

each stage of renovation. The CO_2 decay method provided higher mean air change rates than was calculated using the air permeability values, but not significantly higher. It also displayed a very similar trend in decreasing ventilation through the 3 coheating tests as the airtightness of the building fabric was improved.

Table 4 Heat loss through ventilation

	Initial Phase	**Phase 2**	**Phase 3**
Initial air permeability	15.76 $m^3/(h.m^2)$@50Pa	10.32 $m^3/(h.m^2)$@50Pa	5.74 $m^3/(h.m^2)$@50Pa
Final air permeability	20.66 $m^3/(h.m^2)$@50Pa	9.83 $m^3/(h.m^2)$@50Pa	5.42 $m^3/(h.m^2)$@50Pa
Mean air permeability	18.21 $m^3/(h.m^2)$@50Pa	10.07 $m^3/(h.m^2)$@50Pa	5.53 $m^3/(h.m^2)$@50Pa
Background ventilation heat-loss (1)	**73.22 W/K**	**40.49 W/K**	**22.44 W/K**
CO_2 decay - mean air change rate	0.83 h^{-1}	0.51 h^{-1}	0.27 h^{-1}
Background ventilation heat-loss (2)	**78.21 W/K**	**48.25 W/K**	**25.54 W/K**
Target air permeability		10 $m^3/(h.m^2)$@50Pa	5 $m^3/(h.m^2)$@50Pa
Background ventilation heat-loss (3)		**40.21 W/K**	**20.10 W/K**

85 The background ventilation heat loss value from Table 4 used for the predicted total heat loss value was that obtained from mean air permeability (background ventilation heat-loss (1) in Table 4), as this covered the entire test period and the whole house; the CO_2 decay method was based on readings from only 2 rooms, not recorded every day (11, 8 and 9 days of useable data were available for the 1st, 2nd and 3rd coheating tests respectively) and was more susceptible to changes in wind conditions. Table 5 lists the total predicted heat loss calculated as the sum of the predicted fabric heat loss from Table 3 and ventilation heat-loss from Table 4. The architects' calculated gross floor area of 112.06 m^2 (listed by the architects in their draft SAP worksheets) was used to calculate a heat-loss parameter, and a total envelope area of 316.71 m^2 for the initial coheating test and 311.85 m^2 for the phase 2 and phase 3 tests was used to calculate an effective predicted mean fabric U-value[8]; the effective mean U-value being the predicted heat-loss divided by the heat loss area and is also listed in Table 5. The 2 values shown for effective mean U-value represent heat-loss areas including and not including the party wall as part of the overall heat loss area of the building envelope.

Table 5 Predicted total heat loss and heat loss parameters

	Initial Phase	**Phase 2**	**Phase 3**
Fabric heat loss	268.21 W/K	198.18 W/K	84.74 W/K
Ventilation heat loss	73.22 W/K	40.49 W/K	22.44 W/K
Total predicted heat-loss (reduction on original value)	**341.43 W/K**	**238.67 W/K** (-30.10%)	**107.18 W/K** (-68.61%)
Predicted heat-loss parameter	**3.05 W/m^2K**	**2.13 W/m^2K**	**1.15 W/m^2K**
Predicted effective mean fabric U-value	**1.08 W/m^2K** (1.23 W/m^2K)	**0.77 W/m^2K** (0.88 W/m^2K)	**0.34 W/m^2K** (0.40 W/m^2K)

86 The daily total energy used by all the equipment (not only the resistance heaters, but circulation fans, control and CO_2 timer release systems, and data-logging and communication equipment) was included in the calculations of energy utilised to maintain the internal temperature for each of the coheating tests. This provided the raw data values illustrated in Figure 53, plotted against the mean daily temperature differential. However, this was not the only energy acting on the dwelling to

[8] Fabric envelope area calculations were derived from the architects' drawings, the difference between the 2 values was a result of the thermal and air barrier in the rear extension moving from ceiling and external wall to rafter level.

maintain the internal temperatures; the solar gain also needed to be taken into account. The solar-correct values are also displayed in Figure 53, where it can be seen that the solar insolence experienced for the initial phase and phase 3 coheating tests far exceed those endured in the phase 2 test. This was to be expected given the time of year in which each of the coheating tests was undertaken (Table 2). The values derived for solar gain was added to the measured raw data to help obtain the solar-corrected measured heat loss coefficients, listed in Table 6, of 312.2 W/K for the initial coheating test, 241.8 W/K for the phase 2 test and 147.5 W/K for phase 3. This represents a measured thermal envelope performance 8.5% better than predicted in the initial test, but measured underperformance of 1.3% and 37.6% for the subsequent tests. Measured values for heat-loss parameter and effective mean U-value are also included in Table 6, using the same areas used for the values listed in Table 5.

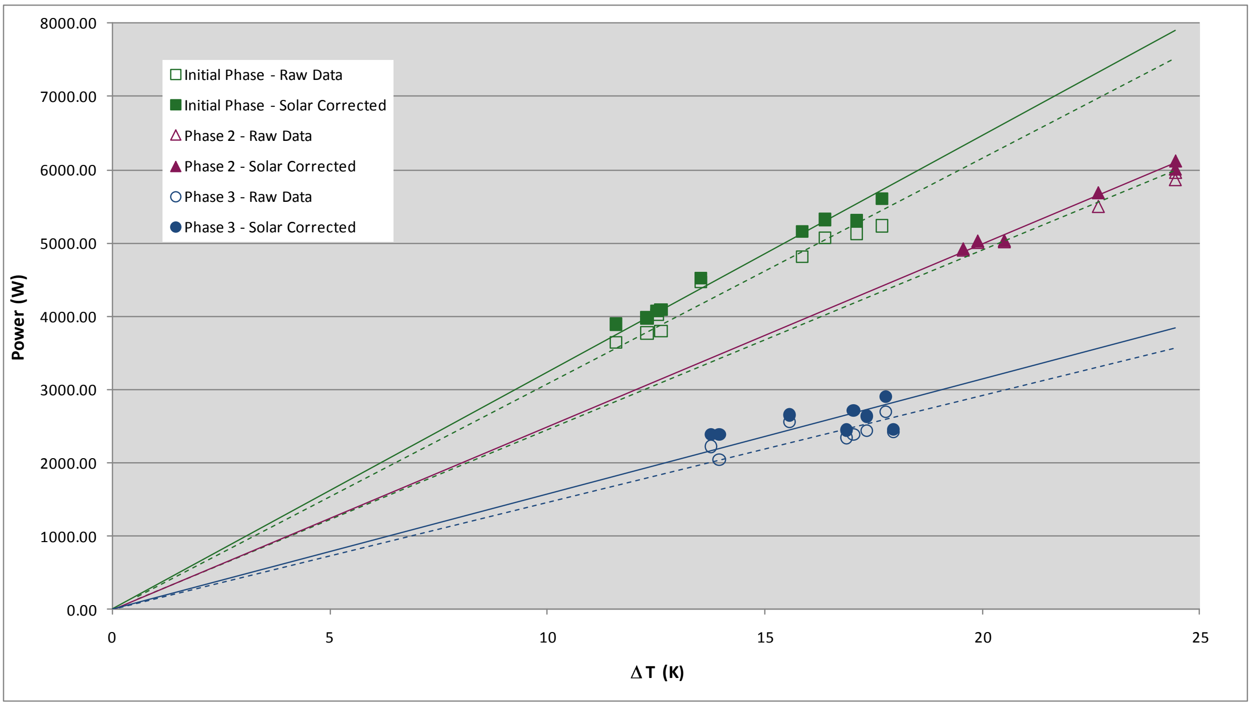


Figure 53 Raw and solar-corrected data for each phase coheating test.

Table 6 Difference between predicted and measured heat loss

	Initial Phase W/K	**Phase 2** W/K	**Phase 3** W/K
Total predicted heat loss (1)	341.4	238.7	107.2
Raw measured heat loss (2)	309.3	245.7	147.3
Correction for solar gain (3)	+ 15.4	+ 3.5	+ 11.7
Wind & party wall adjustment (4)	- 12.5	- 7.4	- 11.5
Solar-corrected measured heat loss (5)	**312.2**	**241.8**	**147.5**
Difference between predicted and measured heat loss (1) – (5)	**+ 29.2** (+ 8.5% of (1))	**- 3.1** (- 1.3%)	**- 40.3** (- 37.6%)
Measured heat-loss parameter	**2.79 W/m²K**	**2.15 W/m²K**	**1.32 W/m²K**
Measured effective mean fabric U-value[9]	**0.99 W/m²K**	**0.77 W/m²K**	**0.47 W/m²K**

87 The values listed in Table 6 (and shown graphically in Figure 50) indicate that the difference between predicted and measured heat loss was substantially greater for the phase 3 coheating test

[9] The measured effective mean fabric U-value is calculated including the party wall as part of the heat loss area.

than for the phase 2 test, -37.6% as opposed to -1.3%. Taken at face value this would imply that the measures undertaken in the stage 1 renovation work (the difference between the phase 1 and phase 2 coheating tests) were far more successful than those undertaken in the stage 2 renovation (between phase 2 and phase 3 coheating tests); this was not the case. Figure 54 and Table 7 show the predicted reduction in heat loss as a result of each stage of renovations produced fairly similar rates of underperformance, 31% and 28% respectively. However, when also considering the very dissimilar starting points for each stage of renovations it is difficult to make direct comparisons over the "success" of the measures introduced.

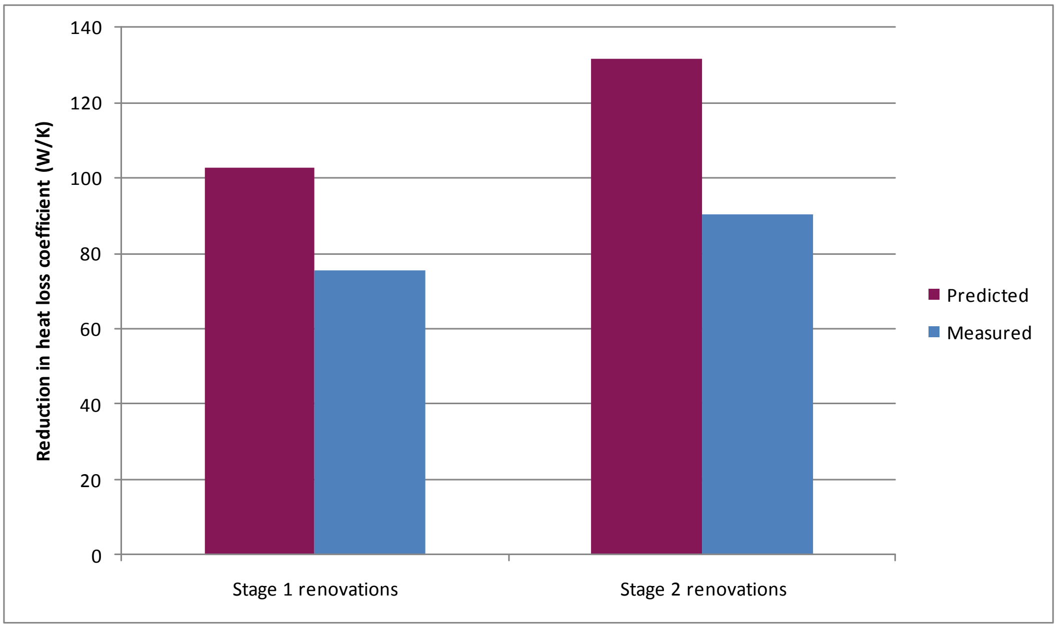


Figure 54 Predicted and measured decreases in heat loss coefficients for each stage of the dwelling renovations.

Table 7 Comparison of predicted and measured reduction in heat loss coefficient of renovation work by stage.

	Stage 1 renovations W/K	**Stage 2 renovations** W/K	**Total (Stage 1 + Stage 2)** W/K
Total predicted heat loss reduction	102.7	131.5	234.2
Measured heat loss reduction	70.4	94.3	164.7
Underperformance	**32.3** (31%)	**37.2** (28%)	**69.5** (30%)

88 The party wall was not listed in Table 3, as SAP2005 assumes no heat loss across a separating wall (U-value of 0 W/m^{2}K), but it will have had an effect on the overall heat loss of the dwelling. With the party wall consisting of a solid brick construction it would not be subject to the thermal bypassing observed in many cavity party walls (Lowe et al., 2007), besides the bypass through the chimney stack shown in Figure 16 and Figure 17, and heat loss through the wall will have been primarily due to thermal conductance to the adjoined property and via bridging at junctions. With an area of 40.32 m^2 the party wall constituted 12.73% of the total fabric envelope area for the initial coheating test (Figure 55), rising slightly to 41.42 m^2 and 13.28% for the subsequent 2 tests; this is a substantial proportion of the dwelling's potential heat-loss area which was not considered in the predictions. A temperature/humidity sensor was placed in the lounge of the house next door for the duration of the project, adjacent to the lounge in the test house; this provided some information on the likelihood of heat loss through the party wall, but not enough information for any adjustments to be fully calculated. Figure 56 shows the temperature difference between the neighbouring properties, with all the temperatures of rooms adjacent to the party wall in the test dwelling and the lounge temperature in the next-door property. It illustrates clearly that there was a temperature differential between the 2 properties during the test periods and so some heat transfer will have occurred, and with temperatures in the test house elevated to a constant 25 ºC for the coheating

tests this was likely to be in the form of heat loss rather than gain. The placement of heat flux sensors on the party wall in the initial phase coheating test was used to provide indications of the possible extent of this heat loss and allow for adjustments to be made to compensate for it.

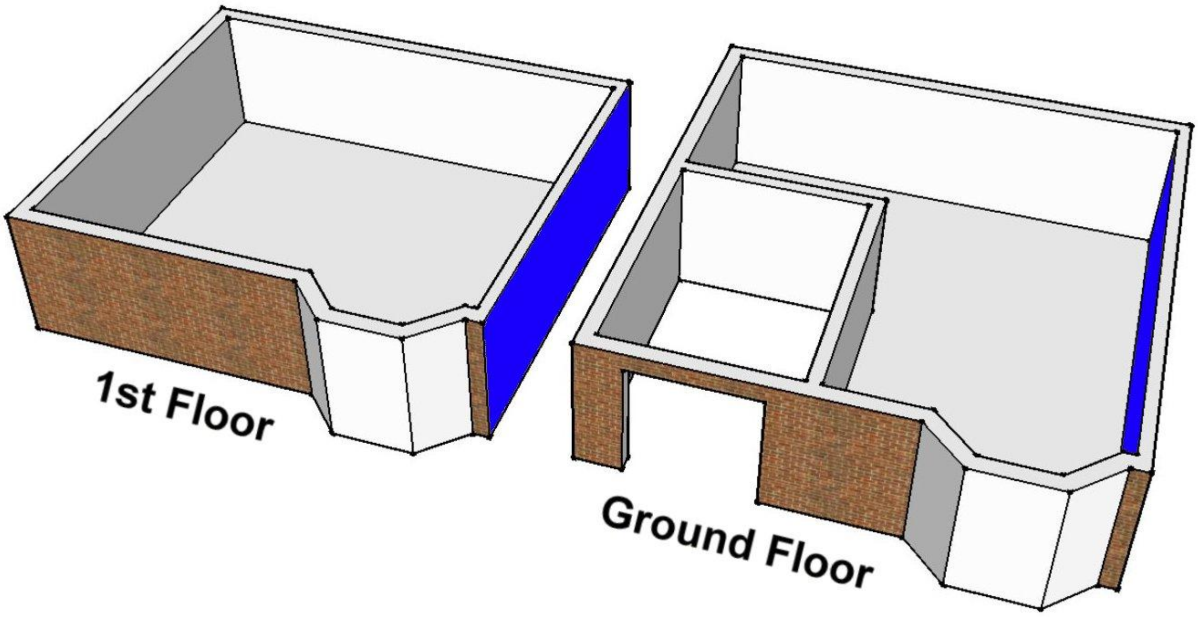


Figure 55 The party wall between the test house and attached property (Initial phase coheating).

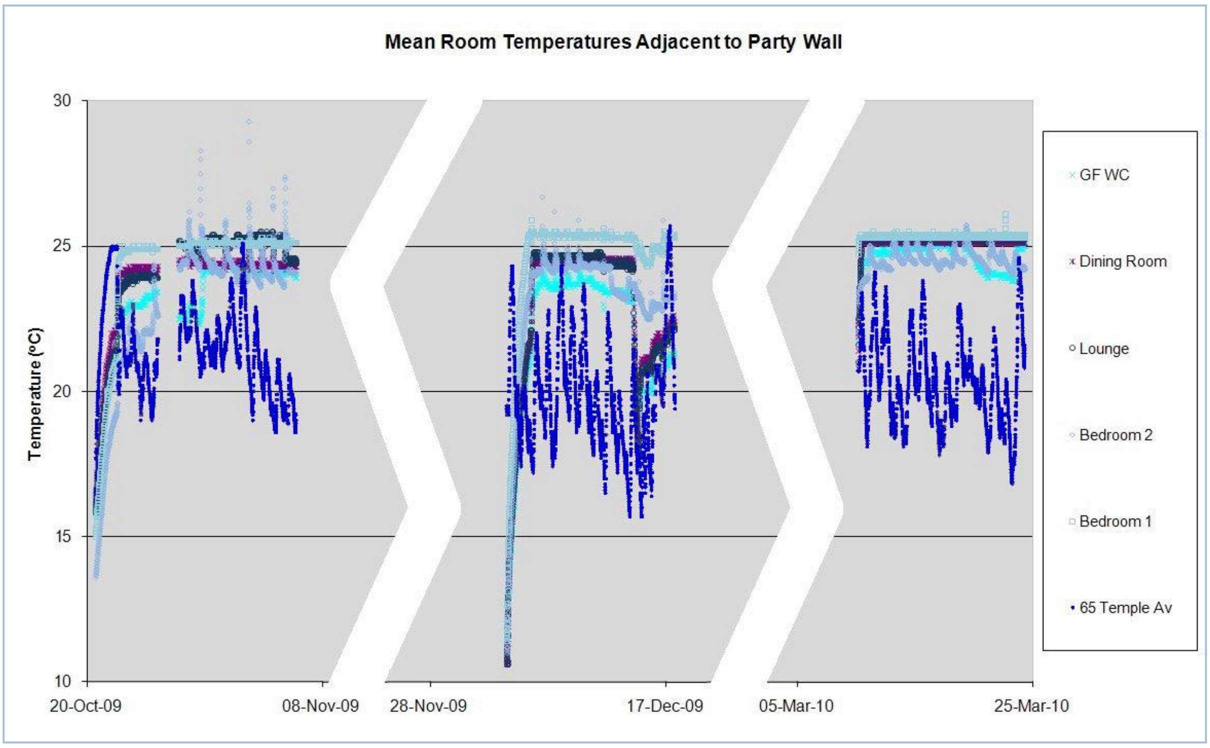


Figure 56 Mean daily room temperatures in rooms adjacent to the party wall during each coheating phase.

89 The measured heat loss figures in Figure 50 and Table 6 include the adjustment to the power consumption, and hence measured heat loss figures, due to the party wall effects. A nominal daily value of 160 W was subtracted from the solar-corrected power consumption to account for heat loss through the party wall. This compensation relied on the assumption that placing the temperature sensor in the lounge of the connected property would record the warmest room temperature on that side of the party wall, however, this may not have been the case and some

overestimation in heat loss through the party wall may have ensued. Figure 57 shows the party wall in bedroom 1 with what appears to be a heat source in the neighbouring property heating an area of wall to above the 25 ˚C ambient internal temperature within the test house. The heat flux sensor placed just above the area shown in Figure 57 measured a minimum daily U-value of 0.09 W/m^2K (sensor No. 3 in Table 8) and the maximum daily U-value of 0.70 W/m^2K recorded in the lounge (sensor No. 1 in Table 8).

Figure 57 Party wall in bedroom 1 during the Phase 3 coheating test.

Table 8 Measured party wall U-values.

	Sensor Location	Sensor No.	Measured Daily U-values		
			Minimum W/m^2K	Maximum W/m^2K	Mean W/m^2K
	Lounge	1	0.39	0.70	0.51
	Dining Area	2	0.31	0.69	0.46
	Bedroom 1	3	0.09	0.37	0.21
	Bedroom 1	4	0.30	0.43	0.37

90 The same power adjustment for the party wall was used in all 3 coheating tests, but there was a slight variation in the average temperatures between the temperatures recorded for the adjoining properties for each of the tests. Table 9 shows how these temperature differentials were some 77% larger for the phase 3 coheating test than for the initial test, suggesting that the actual heat loss through the party wall will have been proportionally larger also.

Table 9 Average temperature differential across the party wall

	Coheating Phase 1	Coheating Phase 2	Coheating Phase 3
	ºC	ºC	ºC
Average – Test house (1)	24.0	23.1	25.0
Lounge - Test house (2)	24.1	22.7	25.2
Lounge - Connected dwelling (3)	21.4	19.8	20.4
ΔT (1)-(3) ((2)-(3))	2.6 (2.7)	3.3 (2.9)	4.6 (4.8)

91 Any variations in internal/external temperature differences between the 3 coheating tests will not have affected the heat loss coefficients and parameters calculated and described above. Although the external temperature profiles for each of the 3 tests differ considerably (Figure 58), the relationship between power input and ΔT is considered linear in nature (Figure 50 and Figure 53)

so does not alter with changes in magnitude. A range of values of ΔT is desirable for each coheating test, these were provided for by the variations in external temperature experienced throughout each test. The values of ΔT recorded were in the ranges 11.6 – 17.7 K for the initial coheating test, 19.6 – 24.4 K for the phase 2 test and 13.8 – 18.0 K for the final test, with respective means of 14.4, 21.9 and 16.3 K; The lower internal temperatures experienced in the phase 2 coheating test were a result of the lower external temperatures at the end of the test period, and there not being enough electrical capacity to provide the energy required to fully heat the entire dwelling to 25 ˚C. Two temporary double 230V sockets had been installed to allow the phase 2 coheating test to proceed, and with four 3 kW fan heaters already operating there was no spare capacity to introduce more heat .The lack of any significant solar gains during the phase 2 test period compounded the problem, but a maximum ΔT of 24.4 K was still achieved. The ranges in ΔT encountered for the phase 1 and 2 coheating tests (6.1 and 4.8 K) were enough for Figure 50 to be compiled and correlation coefficients of r^2 = 0.9696 and 0.9855 for the solar-corrected data derived[10], providing a great deal of confidence in the data and the resulting heat loss coefficients. For the phase 3 coheating test a smaller range in ΔT (13.79 – 17.95 K, range 4.16 K) produced a correlation coefficient of r^2 = -0.238, a negative correlation when the W/K intercept is forced through zero. The phase 3 test was conducted towards the very end of the coheating "season" and the results may well reflect this.

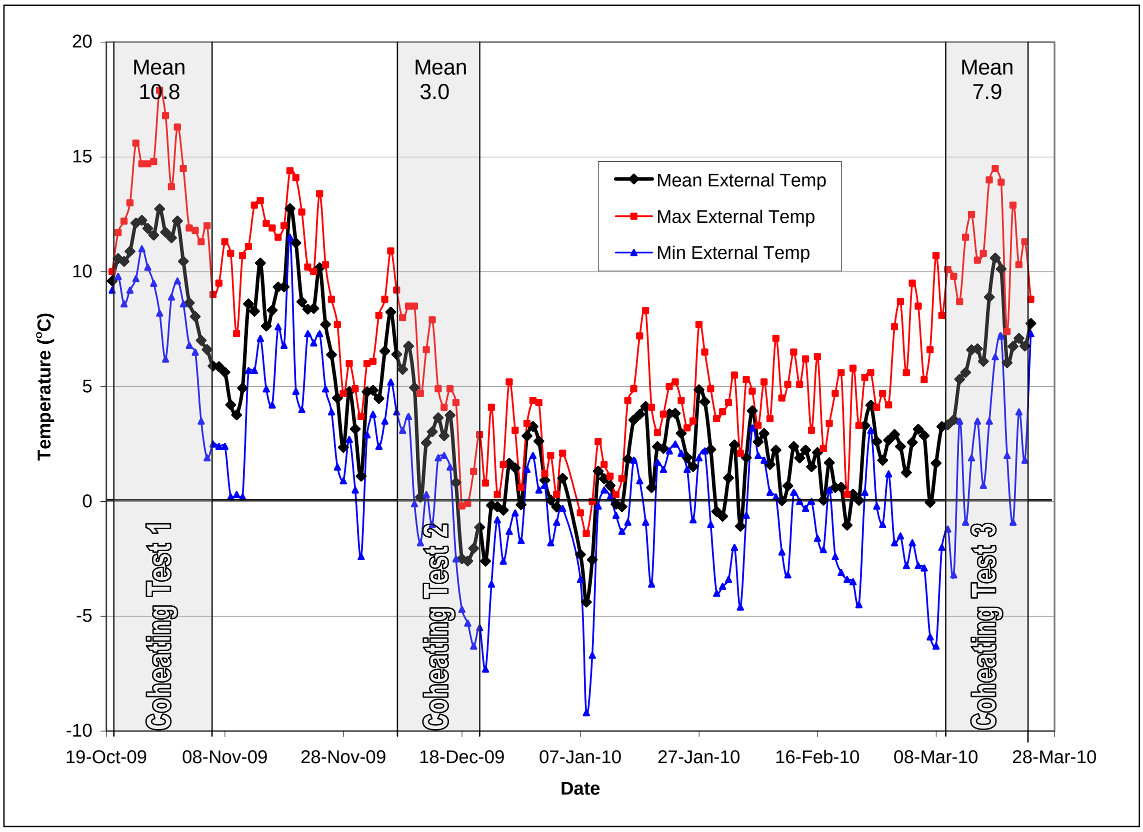


Figure 58 Variation in mean external temperatures over the test period[11].

Moisture loads

92 Variations in the moisture content of the internal air during the coheating test can have a potentially significant effect on the relationship between energy input and internal temperatures. Testing any dwelling in which work has recently been completed by "wet" trades needs due consideration of the impacts, not only on the test results, but also on the potential damage to the property caused by accelerated drying and shrinkage resulting from the elevated temperatures maintained throughout

[10] The correlation coefficients are derived from plots where the W/K intercept was forced through the origin, assuming no heat loss (W = 0) will occur when there is no difference in temperature (ΔT = 0).

[11] The temperatures in Figure 58 were recorded at a weather station sited at the clinet's maintenance yard, 3.5km NNE of the existing dwelling site,

the test period. To limit such effects; an extended heat-up phase was undertaken prior to the 2nd coheating test following extensive re-plastering work, and prior to the 3rd coheating test the site team ensured good ventilation and heating of the dwelling (using electrical fan heaters whilst working in the dwelling) from completion of the replacement solid floor in mid-January until commencement of the test in March.

93 Previous research by the Leeds Met team has included coheating tests at Stamford Brook (Wingfield et al., 2008) on both newly completed dwellings with a relatively high moisture content and similar dwellings with a lesser moisture load. Comparable results were obtained between both sets of dwellings, indicating that the test procedure followed is somewhat robust and produces fairly consistent results under both sets of conditions, the same test procedure which was used for all 3 tests on this dwelling.

94 The variations in relative humidity recorded over the course of the 3 coheating tests are shown in Figure 59, and show ranges of relative humidity between around 35% and 55% over the 3 test periods. Whilst our general opinion is that this inconsistency in moisture levels will have had a small effect on the results obtained, the exact amount is unknown, it is possible to compare the results from the 3 tests directly without over-concerning ourselves with these variations. Coheating tests performed elsewhere have shown that extreme levels of moisture load cannot be similarly disregarded. NBT's coheating test on the Natural House was carried out whilst the property was moisture laden with RH recorded between 80 and 90% over the test period with internal temperatures comparable to those maintained during all three coheated tests reported on here (NBT, 2010), an accurate analysis of the data obtained was seriously hindered by these very high moisture loads.

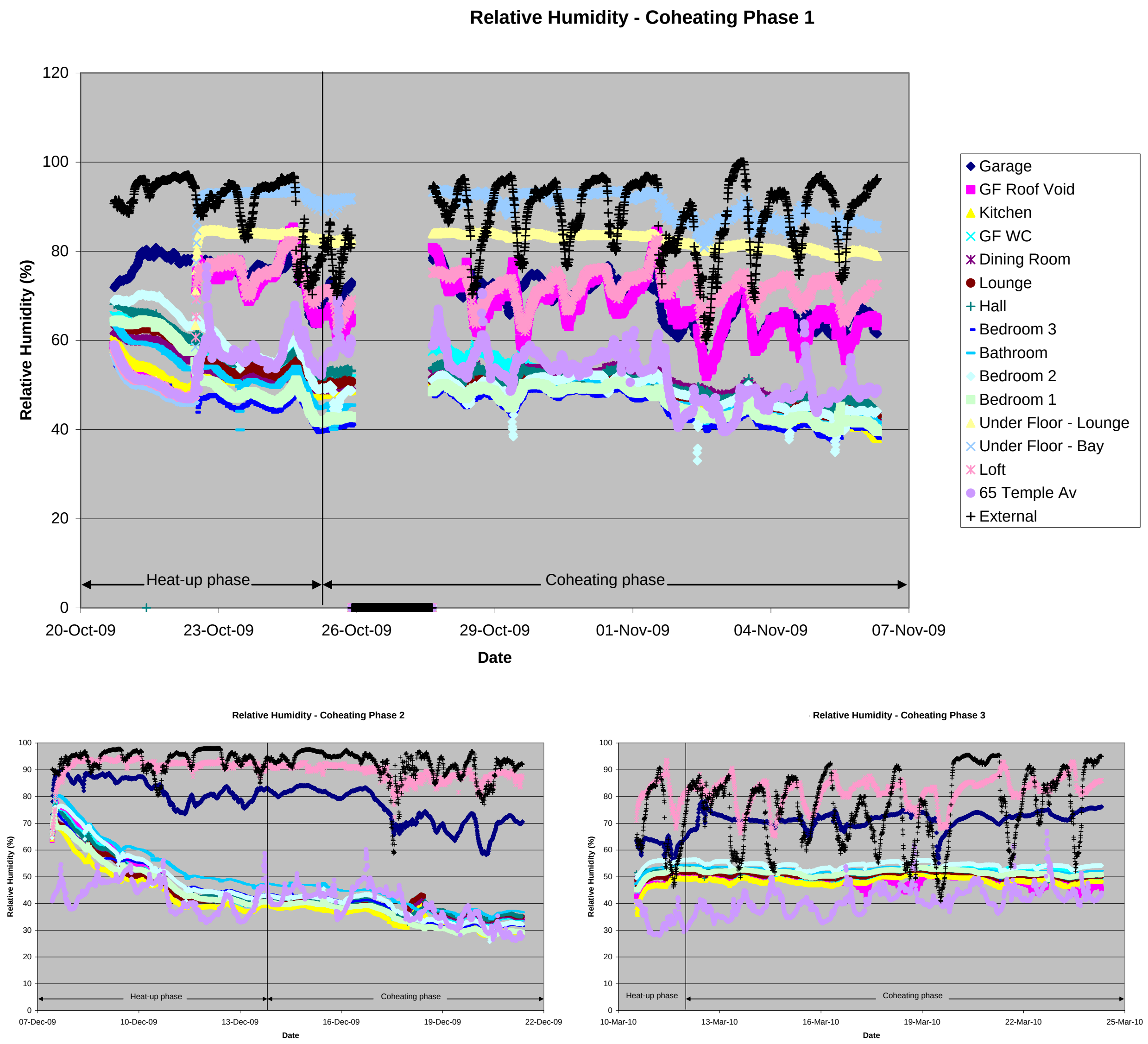


Figure 59 Variations in relative humidity over the course of the 3 coheating tests.

95 For the 3 tests shown in Figure 59, the data collected during the heat-up phases were disregarded for all heat-loss calculations. What appear to be dramatic changes in humidity during the heat-up phases was primarily a function of temperature change rather than any drying effects. The comparatively high RH levels observed in the initial phase coheating test for the underfloor voids in the lounge and ground floor bay were not repeated in the 2 subsequent tests as no RH sensors were placed in similar positions; the higher readings from the initial test for the ground floor extension roof void occurred when that area was ventilated to outside and external to the conditioned space, for both latter tests the air barrier and thermal layer were moved from joist to rafter level resulting in this void becoming part of the conditioned space. The time period in the initial phase test where no data was recorded was a result of a data-logger malfunction and also disregarded from subsequent calculations.

96 For both the initial phase and phase 3 coheating tests the internal RH measurements were relatively consistent throughout the test periods and ranged between 40% and 55%. For the phase 2 coheating test the RH values were similar for the first part of the test, at 40 – 50%, then fell to 30 – 40% for the latter part of the test as the internal temperatures decreased. This drop in RH was almost certainly due to the lower external temperatures resulting in less moisture being contained in any infiltrating air, even though the external RH remained relatively constant. These changes in absolute moisture content of the internal air were not considerable and should not have had any significant effect on the calculated heat loss coefficients.

Cavity wall bypass

97 To establish whether a thermal bypass was operating in the original cavity walls that were now internal partition walls, stand alone dual channel temperature and relative humidity data-loggers (TinyTag Model TGU-1500, manufactured by Gemini Dataloggers Ltd,) were lowered into the wall cavities, from the loft, into the cavities between bedrooms 1 and 3 and between the bathroom and bedroom 2 (Figure 60). Two TinyTag data-loggers were placed in both the front and rear sections of the cavity wall, and data recorded at approximately 1.5 m and 3.5 m below the loft level between 22nd October and 3rd November 2009, to represent 1st floor and ground floor temperatures. With the internal temperatures relatively stable throughout the dwelling at 24 ~ 25 °C over this period, the internal cavities should have displayed similar temperatures if no additional heat loss mechanism was in operation. However this was found not to be the case.

Figure 60 TinyTag data-loggers, suspended on wires and dropped down the internal cavity walls to investigate the potential thermal bypass.

98 The cavity temperatures recorded on the TinyTag data-loggers towards the front of the house showed significantly lower temperatures than those concurrently recorded internally, indicating that some addition heat loss mechanism was in operation, although this was compounded somewhat by the fact that one side of this cavity wall formed the border between the hall and the integral garage, where there was a much greater overall variation in temperatures. However, at the rear of the property the internal temperatures either side of the cavity wall were stable throughout the duration of this investigation. Figure 61 illustrates how the measured cavity temperatures in this rear section of the wall deviated from the internal temperatures.

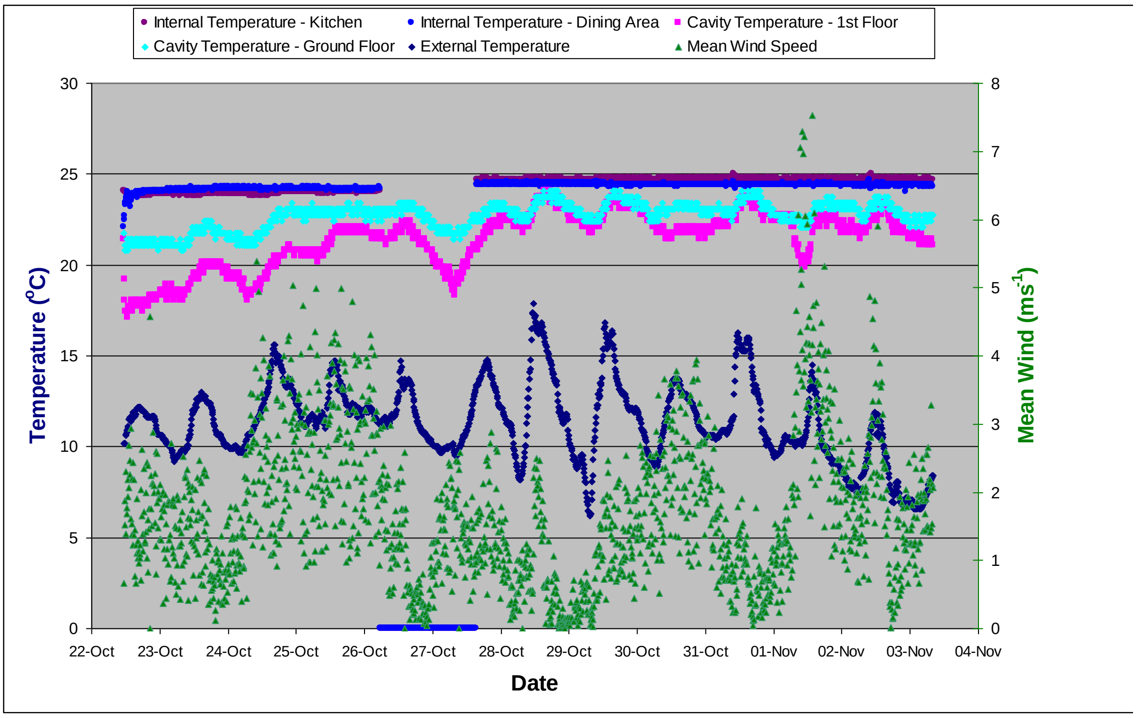


Figure 61 Internal, cavity and external temperatures relating to the rear section of original external wall, now an internal cavity wall.

99 Apart from the brief period on the 26th and 27th October 2009 when an equipment failure prevented the data from being recorded, Figure 61 illustrates how the internal temperatures were relatively constant over the test period, but significant deviation from this was observed in the cavity temperatures recorded. The cavity temperatures appeared to be influenced heavily by the external temperature, and also by the higher wind speeds experienced on both 24th October and 1st November. This clearly shows a bypass in operation and is confirmed by thermal imaging performed in the loft (Figure 62).

Figure 62 Heat escaping into the loft through the top of the internal cavity wall between bedrooms 1 and 2, prior to filling the cavity with blown fibre insulation.

100 Heat flux measurements taken during all 3 coheating phases helped to quantify the effect of the thermal bypassing observed. Figure 63 plots heat flux measurements taken on the hall/stairs wall, which was originally an external gable wall but now backs onto the garage and a 1st floor bedroom. In the dwelling's original condition the calculated average daily effective U-value was 0.54 W/m^{2}K. With the wall subsequently filled with blown mineral fibre cavity wall insulation (CWI), the external wall cavities also filled and additional loft insulation installed, this value had significantly reduced to 0.08 W/m^{2}K. The application of the external wall insulation (EWI) for the phase 3 coheating test reduced the effective U-value of this wall still further to 0.03 W/m^{2}K. The total elimination of this bypass mechanism was not expected without any suitable edge sealing of the cavity, particularly at

the open top of the cavity in the loft (Figure 62), which could have easily been stopped using proprietary cavity socks prior to the installation of the replacement loft insulation.

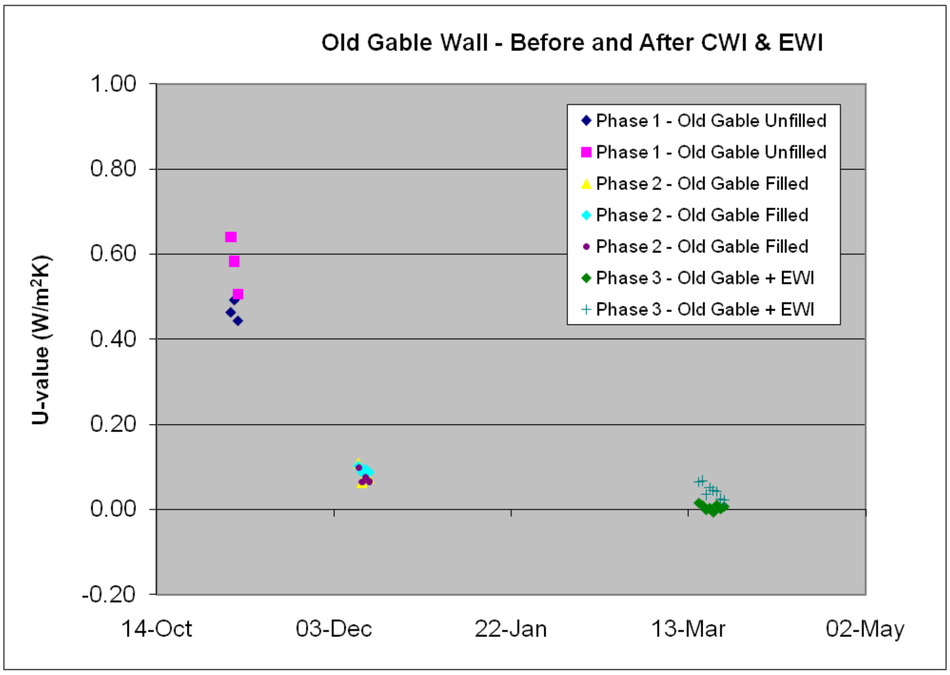


Figure 63 Heat flux measurements of the old gable wall recorded during each coheating phase.

Heat flux measurements

101 To measure actual U-values being experienced, and try to explain some of the differences between design and measured heat loss, Hukseflux heat flux sensors were placed in select locations during each of the coheating tests. These were sited at various locations out of the direct paths of the coheating test fan heaters on the ground and 1st floor at areas identified under thermal imaging as being either representative of that area or of particular interest. Average daily U-values were calculated from the measurements of heat flux at these points. These measurements are indicative of the U-values of the elements stated but for more accurate values a much greater number of heat flux sensors would have been required and strategically placed over the entire surface being analysed.

102 The floor and wall daily average U-values of the dwelling prior to any renovation show a considerable range in values. Figure 64 illustrates the degree of variation in values depending on the sensor location on both the ground floor and external walls, but none of the measured values corresponded to the assumed values listed in Table 3 of 0.365 W/m^{2}K for the suspended timber floor and 0.881 W/m^{2}K for the solid concrete floor. At the front of the living room measured U-values for the suspended timber floor varied from 1.93 ~ 1.19 W/m^{2}K, compared with 1.44 ~ 0.69 W/m^{2}K in the centre of the property adjacent to the party wall. The much lower U-values of 0.69 ~ 0.31 W/m^{2}K obtained for the solid concrete floor in the dining area may be optimistic, as this area was affected by sunlight through the patio doors in the mid-mornings to early afternoons, but generally showed better performance than the adjacent suspended timber floor. The steady decline in observed values over the course of the test period, particularly at the latter two points, may have been due to increased solar insolence and subsequent thermal mass effects. The variation between assumed and measured U-values for the external walls was much smaller, and although the measured U-values at the ground floor bay wall of 2.27 ~1.83 W/m^{2}K were above the Table 3 value of 1.68 W/m^{2}K, the measured values at the first floor bay of 1.85 ~1.42 W/m^{2}K were in line with the estimate. The measured U-values of 0.61 ~ 0.51 W/m^{2}K for the extension wall indicated a slight improvement over the estimated value of 0.645 W/m^{2}K; however this again may have been affected by early to mid-morning sunlight on the external facades slightly reducing the heat loss through the wall at these points.

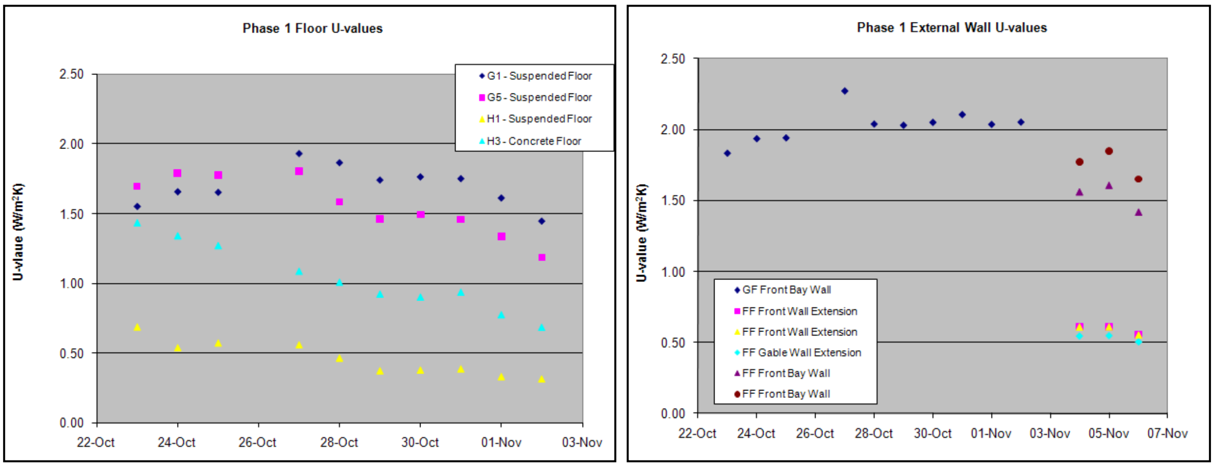


Figure 64 Phase 1 floor and external wall calculated U-values from heat flux measurements.

103 Heat flux data was also useful in assessing the benefits of the CWI by comparing the calculated U-values before and after the installation of the CWI. The ground floor bay wall U-value decreased from an average of 2.03 to 1.66 W/m^{2}K (at the same central location) with the addition of the CWI, on the side wall of the bay adjacent to a CWI drill hole this reduced further to an average of 1.01 W/m^{2}K. This appeared to confirm that the filling of the external wall cavities was not uniform.

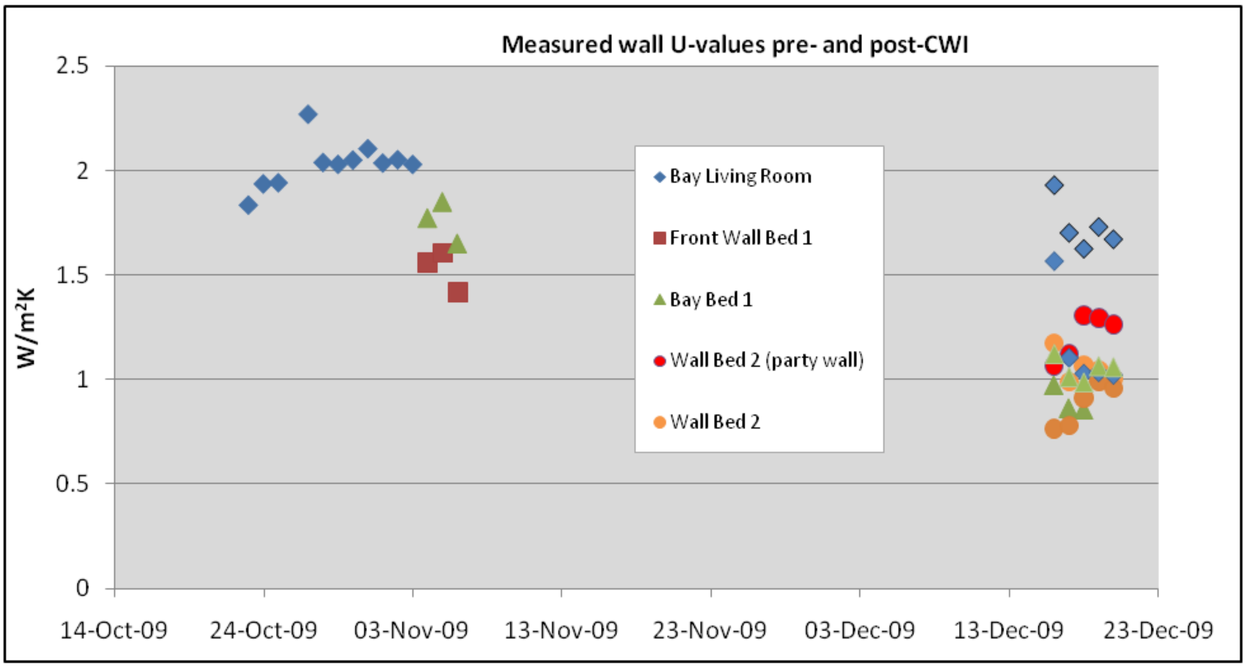


Figure 65 U-values calculated from heat flux measurements, prior to and following installation of cavity wall insulation.

104 In Figure 65 the ground and first floor bays offer a direct comparison between the thermal performance of these details both before and after the installation of the cavity wall insulation, the front bedroom 1 wall was typical of the original construction and provides a comparator to the rear bedroom 2 wall post-CWI. The reduction in U-value seen at the ground floor bay was far less than that seen for the bay on the 1st floor, in both cases the drill patterns were similar and there were no obvious reasons why the results should differ, even the borescope surveys showed variable fill densities in both bay walls. However, post-CWI improvements in the U-values of the bay walls of the magnitude 0.4 W/m^{2}K to 0.7 W/m^{2}K only brought the wall U-values down to 1.6 W/m^{2}K and 1.0 W/m^{2}K, not even approaching the 0.45 W/m^{2}K assumed in the design and listed in Table 3. The original walls in bedroom 1 and bedroom 2 were originally of brick-brick construction with a nominal 70 mm cavity and a pre-CWI measured U-value of 1.5 W/m^{2}K dropping to between 0.7 and 1.3 W/m^{2}K after the CWI had been installed. The post-CWI data points in Figure 65 shown for the external wall in bedroom 2 are differentiated by their proximity to the party wall (the sensor located

next to the party wall is defined as 'Wall Bed 2 (party wall)') and are shown in Figure 9, this was an area that was examined because of the cold area detected during a thermographic survey In this case the variations in the post-CWI U-values could be explained by extreme variations in the fill densities because the lack of installation of a cavity brush allowed insulation by the party wall to fall down the cavity; but again the design value of 0.45 W/m^{2}K was not achieved.

105 With the application of the 175 mm thick EWI the U-value of the external wall was designed to fall to 0.15 W/m^{2}K (based on post-CWI U-value of 0.450 – 0.645 W/m^{2}K); however, with the anticipated U-values for the CWI not being achieved, the reductions in thermal transmittance due to the EWI were unlikely to reach such a level. Figure 66 shows the staged improvements in the measured U-values, with the ground floor bay also benefiting from an additional top-up of the CWI performed in January 2010. A marked improvement in the U-values was observed post-EWI in all instances, although the Table 3 predicted U-value of 0.15 W/m^{2}K was not achieved.

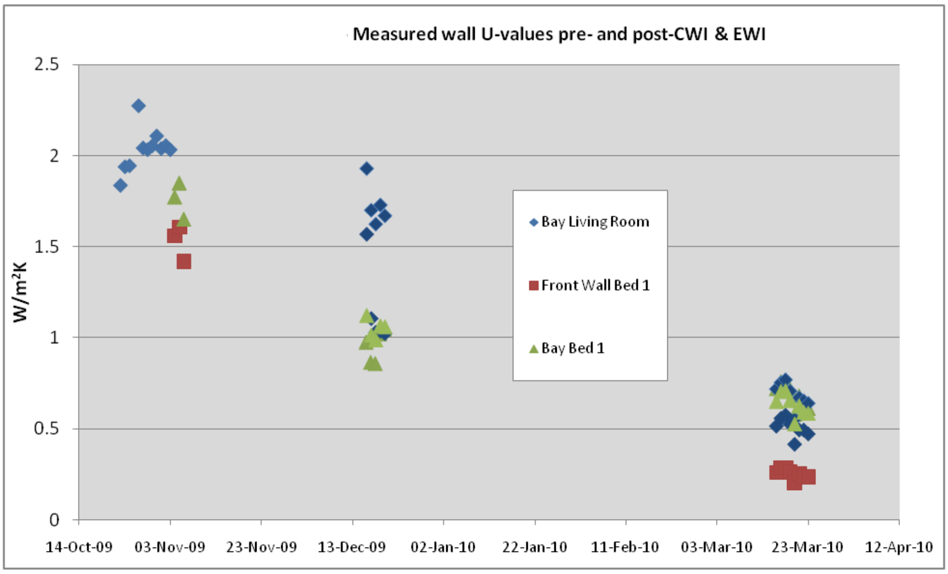


Figure 66 U-values calculated from heat flux measurements, prior to and following installation of cavity wall insulation and external wall insulation.

106 Some predicted values were achieved, with measurements of the U-values of the new ground floor and triple-glazed windows directly comparable to design values. A single heat flux sensor was placed in the centre of the living room floor to evaluate the floor U-value, resulting in a measured figure of 0.31 W/m^{2}K compared to the designed 0.25 W/m^{2}K (sensor D5 in Figure 67). The centre-pane U-value for the front bay window averaged 0.51 W/m^{2}K (D4 in Figure 67) and is consistent with the manufacturer's quoted whole window value of 0.83 W/m^{2}K. The wall U-values also shown in Figure 67 were significantly lower than those prior to the stage 2 renovations but did not achieve the design values. Although the close proximity of some of the heat flux sensors to the window openings and junctions will have had some effect on the measured U-values, by incorporating a degree of thermal bridging, it is very unlikely that the differences between designed and achieved values can be explained by this alone and some additional heat-loss mechanism is also in operation. The most likely cause of the additional heat loss is through air movement in the existing cavity, although further investigation would be necessary to confirm this.

Living Room	Location	Average U-value (W/m^2K)
D1	Bay Wall under window - LHS	0.67
D2	Bay Wall under window - Middle	0.51
D3	Bay Mullion - RHS	0.31
D4	Window Glazing - Centre Bay Window	0.51
D5	Ground Floor	0.31

Figure 67 Phase 3 sensor locations and average U-values – Ground floor

107 On the 1st floor, the change in measured U-values following the EWI was considerable, but again did not reduce to the design value of 0.15 W/m^2K. Figure 68 shows a range of average measured U-values in the external walls between 0.63 and 0.68 W/m^2K for walls under the 1st floor bay window and between 0.23 and 0.34 W/m^2K for the external walls elsewhere. The bypass in the original gable wall (now a cavity wall between bedrooms 1 & 3) had been almost eliminated, with measured U-values of 0.01 and 0.04 recorded for the opposing sides. The heat flux sensor placed on the floor of bedroom 3 was positioned between the joists and recorded an average U-value of 0.15 W/m^2K, well below the design value of 0.20 W/m^2K, although no measurement was made of U-value through the floor directly above the joists to obtain an overall measured floor U-value.

Bedroom 1	Location	Average U-value (W/m^2K)
E1	Bay Wall under window - Middle	0.63
E2	Bay Wall under window - RHS	0.68
E3	Wall between Bay and window	0.25
E4	Wall under window	0.34
E5	Old Gable Wall to Adjacent Bedroom	0.01

Bedroom 3	Logger F	Average U-value (W/m^2K)
F1	Front Wall LHS of window	0.23
F2	Front Wall RHS of window	0.31
F3	Gable Wall LHS of Window	0.26
F4	Old Gable Wall to Adjacent Bedroom	0.04
F5	Floor to Garage	0.15

Figure 68 Phase 3 sensor locations and average U-values – 1st floor

Services

108 Without in-use or simulated in-use measurement any evaluation of services performance is limited in its scope; however, it was possible to measure basic flow rates in the ventilation system and to observe, where possible, its design, installation and commissioning. Some of the issues relating to installation of the MVHR system have already been discussed, including airtightness around

ductwork and the displacement and disturbance of the loft insulation occurring during installation. Similar issues were observed regarding pipework for the solar hot water system.

109 Recent reports by the LeedsMet research team have observed, measured and commented on issues of non-correspondence between post-construction commissioned performance and in-use systems performance in detail at Elm Tree Mews (Bell et al., 2010) and the Stamford Brook Field Trial (Wingfield et al., 2008), lessons learnt from these were discussed at design meetings and many issues were taken on board. The 2 stage renovation of this property resulted in some additional forethought and planning, and consideration to future work was given to any stage 1 refurbishment work by the project manager and site foreman to keep both costs and temporary/break-in/reparatory work to a minimum.

110 Commissioning of the MVHR system was carried out as warranted by Part F of the Building Regulations on 26th March 2010 by an engineer from the system manufacturer, who supplied and fitted the system. After consultation with the project manager the engineer not only ensured that the statutory requirements were met for both trickle supply and boost extraction, which was all that was required for standard system commissioning, but also that the whole house supply and extract flow rates were balanced against each other. Simultaneous flow measurements were taken by the research team, using an Airflow LCA501 vane anemometer with calibrated cone, and confirmed the accuracy of the engineer's readings. Whilst the actual measurement part of the commissioning process was quick and straightforward the balancing of the system caused the engineer to spend approximately 2 hours in total on a system with only 2 extract vents and 5 supply grilles, this was not aided by the prototype MVHR unit having no visual display fitted to show fan speed settings. The scope of this project did not allow for any testing of the heat recovery efficiency of the MVHR system.

111 The replacement boiler and relocation of associated pipework will also have a significant effect of the heat loss from the dwelling, with the boiler, hot water cylinder and related plumbing all moved to inside the thermal envelope; benefits from this are not reflected in measurements of the thermal performance of the fabric and to some extent omitted from the design CO_2 reduction. The design CO_2 reduction (taken from the architects' 18th May 2010 SAP Summary) in Table 10 includes the boiler and control system replacement and secondary heating removal in Stage 1 and the new DHW cylinder and a solar thermal hot water system as part of the stage 2 renovations. The original heating and DHW systems included significant un-insulated pipework runs in the garage, loft and under the suspended timber ground floor which would all have had detrimental effects on overall systems performance. The re-designed layouts repositioned these pipe runs to inside the thermal envelope and minimised primary pipework runs by having the cylinder cupboard directly above the kitchen and close to the new boiler location, their previous positions of garage (boiler) and loft (cylinder) being an almost worst conceivable scenario.

Table 10 Percentage improvement from original condition.

	Stage 1 Renovation %	Stage 2 Renovation %
Design CO_2 Reduction	45.73	77.93
Predicted Fabric Heat-Loss	30.10	68.61
Measured Fabric Heat-Loss	22.44	52.88

Conclusions and recommendations

112 The overall aim of this project was to establish the extent to which an existing 1930s masonry house could be renovated so as to achieve a level of performance commensurate with the advanced energy and carbon standard achieved in the prototype new dwellings constructed in part 1 of the project. The building fabric tests reported on in this report and the Temple Avenue Project Part 1 (Miles-Shenton et al. 2010) are compared in Table 11, with a comparison of the designed differences in heat loss shown in Figure 69. These show that although the design heat-loss coefficient for the existing building following the stage 2 renovation was significantly lower than that of the prototypes, the measured heat loss coefficient was similar. The fabric measures undertaken for the existing dwelling appeared not to achieve quite the same level of success as those undertaken in the two new build properties. This project covers only issues related to the fabric performance rather than any attempt to evaluate the full efficacy of the design CO_2 reductions which would require investigation into additional criteria, such as the solar hot water system on the

existing building or the photo-voltaic systems on the prototypes; this would require a supplementary monitoring project.

Table 11 Comparison of fabric heat-loss coefficients and parameters of the Temple Avenue Project prototype and existing dwellings.

	A1 Prototype	A2 Prototype	Existing Dwelling
	W/K	W/K	W/K
Design heat-loss coefficient	129.30	120.20	107.18
Measured heat-loss coefficient †	149.47	132.86	147.48
	+ **20.17** (15.6%)	+ **12.66** (10.5%)	+ **40.30**(37.6%)
	W/m^2K	W/m^2K	W/m^2K
Design heat-loss parameter	0.85	0.78	1.15
Measured heat-loss parameter †	0.98	0.86	1.32
	+ **0.13** (15.3%)	+ **0.08** (10.3%)	+ **0.17** (14.8%)

† Calculated using measured air permeability, and corrected for solar gain and party wall effects

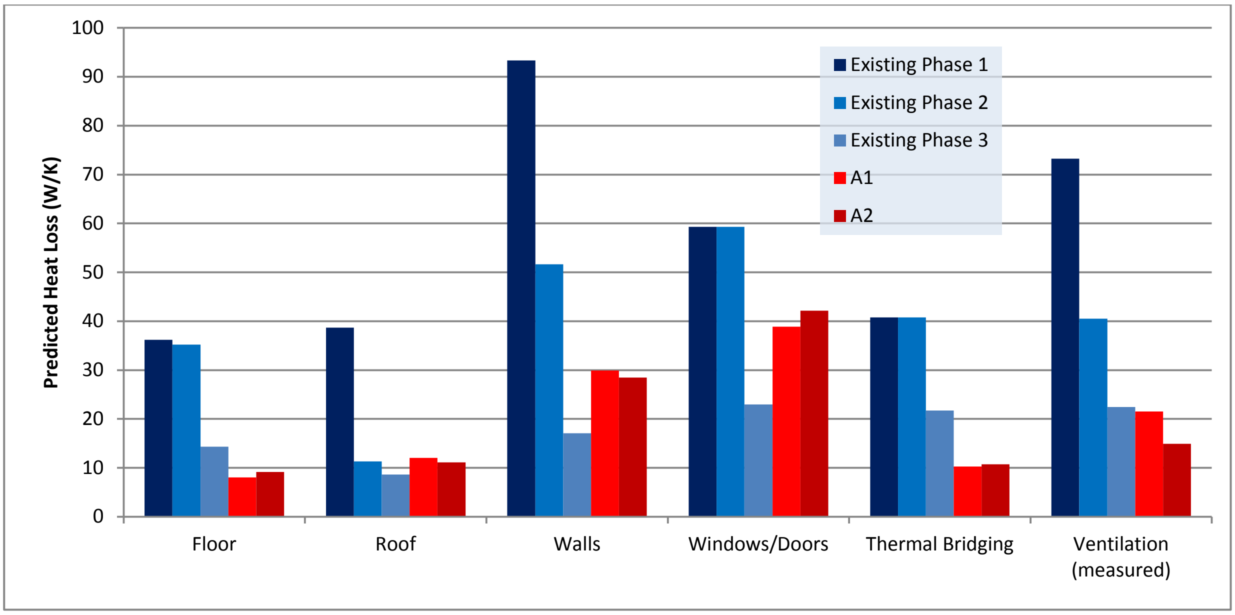


Figure 69 Comparison of predicted elemental heat loss.

113 The LeedsMet research team were involved in the project at all stages, in both an advisory and observatory role; attending project meetings and having input into many of the design discussions. The involvement of LeedsMet had an effect on the project programming, with the schedule needing to be adapted to fit 3 coheating tests into one heating season and performing all renovation work between these periods. This did present some difficulties but was worked around by the project manager and site team and temporary fixes and break-ins kept to a minimum to avoid unnecessary costs. The decision to perform the 2 stage refurbishment; stage 1 comprising necessary repairs and easy to perform improvements, stage 2 bring the level of performance in line with an 80% CO_2 emission reduction, added further complications to the build sequence and programme. It would have been easier, and cheaper, to perform all the refurbishments in a single phase, but important observations would have been missed, such as the shortcomings of the initial CWI installation. Conducting the 2 stage refurbishment, with coheating tests at the end of each phase, allowed greater insight into the effectiveness of each of the measures introduced.

114 Throughout the project a strong clarity of purpose was maintained by all parties, and impacts of design alterations on performance and the efficiency of the design and construction process were almost always taken into consideration. The project was a learning process and modifications to the design as construction progressed were to be expected, however, some of the final design

decisions were made at very short notice and risked incurring additional work and costs. An example being the final decision to apply EWI in stage 2 was not made until after installation of the replacement windows had commenced, the project manager and site manager assumed the EWI would get the go ahead so had already procured extended external sills and positioned the window frames outside the outer leaf brickwork. If the final decision to fit the EWI had been repudiated, the windows would have needed re-installing and external sills replacing.

115 There were no issues arising regarding communication between the research team, the site and the project manager. Constant contact was maintained between all parties, particularly during busy periods and some of the more critical stages of construction. This can be regarded as one of the successes of the project, it is difficult to see how some of the issues would have been resolved without such effective communication. Location and the close proximity of all parties to be able to get to the site at short notice was also extremely beneficial at times, problems could have easily occurred or taken considerably longer to resolve if this had not been the case.

116 As the project consisted of a single dwelling it benefited from micro-management and intensive quality control which would not always be expected with replication of such renovation work on a larger scale. Against this is the possibility that any larger refurbishment schemes might involve central stores (rather than rushing around to find supplies of small quantities of specialist tapes or membranes) and allow for greater flexibility in construction programming. Replication of these measures of a larger scale would introduce economies of scale but may detract from some of the attention to details observed in this project, this should be reflected in any cost or performance estimates and expectations.

117 Some of the experience and lessons learned by the project team, from management through to site operatives, during both renovation stages may only be partially documented, recorded in the client's own records and this report, and in probability will only be read, passed on or disseminated to a limited number of individuals within the organisation. The small team of workers on site gained a far greater understanding of the issues surrounding fabric performance throughout the course of this project, and a significantly increased awareness of how some of the underperforming details can arise and be curtailed, the site team has since applied some of this knowledge into the subsequent upgrading of an adjacent property in the same street. It would be a waste to let these enhanced skills and experiences go underutilised.

Thermal performance

118 Using a comparison of measured vs. predicted heat loss as a measure of the dwellings' fabric performance relies on accuracy of both sets of figures. As the predicted heat loss relies on theoretical performances of materials installed ideally, it is highly unlikely that the predicted performance will be achieved in practice. Given that the thermal performance of the dwelling in its original condition surpassed the measured performance, it can safely be assumed there were inaccuracies in the original heat-loss prediction due to an incomplete knowledge of the actual construction of the existing building. This could only have been improved by a more intrusive initial survey, which was not possible at the time as the dwelling was still occupied.

119 Throughout the project the only change to internal layout was the moving of the thermal and air barrier in the rear ground floor extension from ceiling to rafter level and the introduction of a cylinder cupboard where the shower had been located previously in the bathroom, no changes in layout were made to the masonry external walls. Thus, very similar test equipment layouts were used in each of the coheating test, aiding reliability of results with effectively like for like comparisons of the volumes tested. Differences in the results for each coheating test were direct measurements of the performance of the improvements undertaken to the thermal envelope and not changes due to any structural alterations.

120 Predicted heat loss coefficients of 341.4 W/K, 238.7 W/K, 107.2 W/K were calculated for Phase 1, 2 and 3 coheating tests respectively, the measured values of 312.2 W/K, 241.8 W/K, 147.5 W/K. (after solar correction) are representative of the predicted values but do display some variation. For the initial phase coheating test the measured heat loss was actually less than the predicted value, almost certainly due to underestimation of the thermal performance based on the survey of the dwelling in its original condition; for the phase 3 coheating test the measured heat loss was greater due primarily to overestimation of the performance of the improvements undertaken. In neither stage of improvements did the measured reduction in fabric heat loss achieve the design expectations. The predicted heat loss values are based on steady state calculations using thermal conductance/transmittance values and do not include any dynamic effects such as additional heat loss through thermal bypassing or reductions in heat loss due to heat recovery. In the initial phase coheating test conductive heat loss through the suspended timber ground floor will have heated air

in the void beneath the floor, as this was a significant infiltration zone the effect would have been to pre-heat air infiltrating into the dwelling, recovering a proportion of the heat loss through the floor; the result would be a lowering of the measured heat loss. In the phase 3 coheating test the lack of airtight sealing of the external wall cavities will have permitted some bypassing of the EWI, particularly near junctions and openings, resulting in additional heat loss. Neither of these effects are included in the predicted values, to accurately quantify such effects would require an intensive measurement and monitoring regime beyond the scope of this project.

121 The adjustments necessary for solar correction of 15.4 W/K (initial phase), 3.5 W/K (phase 2), 12.3 W/K (phase 3) reflected the test dates, with the initial phase coheating test commencing in October and the phase 3 coheating test performed in March. For the phase 3 test this represented a 9% increase over the raw measured heat-loss coefficient due to solar insolation, any coheating tests performed later in the spring would inevitably require even larger solar adjustments which may start to overwhelm certain aspects being investigated. This would particularly be the case if the test dwelling was orientated to maximise solar gain and increasing influence on dwellings with a lower heat-loss parameter. External temperatures as high as 17.9 ˚C and 14.8 ˚C were recorded in the initial phase and phase 3 coheating test periods respectively. With the internal temperatures controlled at 25 ˚C for the duration of the tests a ΔT large enough to produce reliable data was achieved. However, shortly outside these test periods (in September 2009 and April 2010) external temperatures in excess of 20 ˚C were recorded. The combination of both these solar effects and ΔT effects prescribe the seasonality of the testing period, and should be the foremost criterion when planning any future coheating tests.

122 An extended heat up was necessary for phase 2 coheating test to allow RH levels to drop following “wet” repairs to the bays, chimney breast and re-plastering of the side and rear extensions, coupled with unhelpful weather conditions and no internal heating and ventilation during the preceding construction period. Large amounts of heat can be absorbed in the evaporation and abstraction of moisture, and it is extremely difficult to extract these from the total heat input to determine the proportion of heat lost through the fabric from that expended through driving out water. Both during and following the stage 2 renovation work the use of fan heaters and increased awareness of ventilation requirements by the site team negated the requirement for a protracted pre-heat phase to the phase 3 coheating test.

123 The measured heat-loss coefficients for the 3 phases of coheating provided effective mean fabric U-values of 0.99 W/m^{2}K for the initial phase, 0.77 W/m^{2}K for phase 2 and 0.47 W/m^{2}K for phase 3, when divided by the total heat-loss area. The phase 3 result compared slightly unfavourably to the mean U-values for the Temple Avenue prototype dwellings of 0.44 W/m^{2}K (A1 – Thin Joint) and 0.37 W/m^{2}K (A2 – SIPs), but the difference was not enormous and would reduce further upon full completion of the renovation work on the existing dwelling. The phase 3 test result was achieved with unfinished insulation detailing at the thresholds which would reduce the final fabric heat loss on completion and some airtightness improvements from the door details and internal finishing and decoration which cause a reduction in the final ventilation heat loss. It is anticipated that the final mean U-value of this existing dwelling, when completed, will be even closer to that of the A1 prototype.

124 Heat-flux measurements taken during the coheating tests revealed a number of issues:

a) The CWI retro-filling of the brick-block original gable wall (now an internal wall) virtually eliminated the thermal bypass, with average U-values dropping from 0.46 – 0.56 W/m^{2}K to 0.01 – 0.04 W/m^{2}K on the cavity wall between bedrooms 1 and 3. The higher values were recorded closer to the external wall and may have been reduced still further if the junction between the walls had been effectively edge-sealed, as is prescribed in the Building Regulations Part L (CLG, 2010) to eliminate heat loss from cavity party walls in new-build dwellings. Fully sealing the cavity at the top would have been favourable as this could have been done quite simply after the existing loft insulation had been removed, but sealing the vertical edges of a cavity in an existing dwelling would almost certainly prove very expensive for a relatively small benefit.

b) The CWI retro-filling of the brick-brick external walls predicted to bring the U-value down from 1.68 W/m^{2}K to 0.45 W/m^{2}K, yet even after filling the measure U-values varied from a highest of 1.93 W/m^{2}K to lowest value of 0.70 W/m^{2}K. These are substantial discrepancies and further investigation of similar cavity filling is suggested to find out whether this is an anomaly or whether this type of overestimation of CWI performance is commonplace. If this level of underperformance of retro-filled CWI is routinely observed it could have serious consequences for the insulation industry.

c) The application of EWI saw significant reductions in all areas where U-values were measured, although the design figure of 0.15 W/m^2K was never achieved. The lowest measured average U-value was 0.23 W/m^2K at the front wall of bedroom 3, the highest 0.68 W/m^2K at the bay wall of bedroom 1; generally higher U-values were seen nearer openings and junctions and lower U-values observed in greater expanses of uninterrupted wall. The pattern of higher U-values nearer openings and junctions suggests that air movement in the external wall cavities is having a detrimental effect on the performance of the EWI and some bypass mechanism is likely to be in operation. This may have been reduced had the edges of the cavities been sealed to a more airtight standard than plugged with lightly compacted mineral wool quilt.

d) The replacement triple-glazed windows with a manufacturer's declared whole window average U-value of 0.83 W/m^2K supplanted the original double glazing which had an assumed U-value of 2.7 W/m^2K. The measured average centre pane U-value of 0.51 W/m^2K replicated the manufacturer's specification for the high performance replacement windows, and with the vast improvement in airtightness also seen with the new windows the choice of replacement windows appears vindicated, at least from an energy efficiency point of view.

e) Measured party wall daily average U-values varied considerably from 0.09 W/m^2K (in bedroom 1, adjacent to a suspected heat source in the adjoining property) to 0.70 W/m^2K. The party wall is of solid masonry construction and no heat loss across this element is included in the heat-loss predictions as no temperature difference is assumed between the dwellings, running the coheating test at elevated temperatures may result in some heat loss being induced which would not occur under normal conditions.

125 Although the predicted values assume no heat loss across the solid separating wall it will have had an effect on the overall measured heat loss of the dwelling due to the elevated temperatures inside the test house being consistently higher than those recorded in the lounge of the house next door. Heat loss through the wall will have been primarily due to thermal conductance to the adjoined property and via bridging at junctions. Although the temperature difference between the 2 adjoined properties was small, the party wall constitutes a substantial proportion of the dwelling's potential heat-loss area. The measured heat loss figures include an adjustment to the power consumption, subtracted from the solar-corrected power consumption to account for heat loss through the party wall. If future coheating tests are to be performed on connected properties it would be beneficial to eliminate having to make similar assumptions, either by heating the adjoining property or properties to the same internal temperature as the test dwelling or by increasing the density of sensors on either side of the separating wall(s) to allow more accurate estimations to be formulated.

Design

126 The 2 stage renovation of the property caused some additional complications to the design process. The stage 1 renovation was intended to carry out any necessary repairs on the property and to replicate energy saving measures that could easily be performed by occupants of similar dwellings, but in this instance also had to take into consideration additional work that was to follow. The stage 2 renovation could have been performed more efficiently had the dwelling not been required to have the stage 1 renovations completed and work stopped for testing. Additional costs and design considerations were incurred as a result of this 2 stage renovation process and would prevent any simple cost benefit analysis of many of the individual measures introduced.

127 The initial dwelling assessment (consisting of a visual inspection and borescope investigation) was conducted with the dwelling still occupied and the survey conducted in a manner which understandably caused minimum disruption to the occupants, baring more resemblance to a valuation survey than a full structural survey. As models and calculations require a higher degree of accuracy than would be required for a valuation survey a more intrusive investigation would have been beneficial. Some incorrect assumptions made regarding the initial fabric performance may have been more accurately made if the initial survey had been performed after the dwelling had been vacated with the surveyors less sensitive any aesthetic damage and subsequent repair work required.

128 The removal of the original loft insulation and loft decking and replacement with 400 mm of new mineral wool should have been sufficient to reduce the U-value in the bulk of the loft to the design values, but there was a lack of detailing available as to how this was to be achieved at the eaves and how the loft insulation was to meet with the external wall insulation to form a continuous thermal barrier. It appeared to be left to the installers and site team to negotiate the more complicated detailing rather than being implicit in the design and specification. Design drawings and specifications stated what was to be achieved but there was little information on how this was to be performed, particularly with issues relating to sequencing, access and buildability absent from

the design material. Such description of build process is perhaps not expected in a project of this size and nature, particularly where design costs are limited, but may require more regard if these processes are to be replicated.

129 Much of the design discussions regarding the external walls centred around concerns over the EWI, in terms of aesthetics, complex detailing and costs. Possibly more efforts should have been expended on how to achieve the best performance from this technology, by sealing off existing cavities to prevent air movement and potential thermal bypassing issues. Again, limitations in the design process resulted in much of the more complex detailing being delegated to the installers and site team.

130 A number of alternatives were discussed prior to agreement on the triple glazed replacement windows with arguments based on a trade-off between cost and performance. Preconceptions that high-performing triple-glazed windows would be prohibitively more expensive than less thermally efficient double-glazed alternatives proved to be unsubstantiated, with the selected replacement windows and doors sourced for comparable cost to good quality double-glazed units with higher U-values. A number of the potential issues involving fitting these windows, particularly regarding airtightness, appeared to be resolved on site during installation rather than at the design stage.

131 The designed air permeability assumed substantial reductions for each renovation stage, down to 10 $m^3/(h.m^2)$ @ 50 Pa for stage 1 and 5 $m^3/(h.m^2)$ @ 50 Pa for stage 2 from an initial 20.66 $m^3/(h.m^2)$ @ 50 Pa after removal of all the internal furnishings. These target values represented the minimum required for building regulations for stage 1 and for stage 2 a value at which the MVHR system becomes more energy efficient. For stage 1, designed improvements included hardboard decking-over of the suspended timber ground floor, and sealing existing penetrations through the first floor ceiling, walls and the open flue in the lounge fireplace, the main designed improvements for stage 2 involved replacing the original doors, windows and lofthatches, and completing the internal finishings to a good standard. It was anticipated that these measures would provide the required reductions in air permeability.

132 The designed renovations appeared not to fully appreciate the full effects of potential thermal bypassing throughout the property. The original cavity walls which were now internal walls were designed to be retro-filled with blown mineral fibre to limit the thermal bypassing effect and closed using mineral fibre, but specific edge sealing of the cavities was not prioritised to reduce the likelihood and severity of any bypasses further. Tightly sealing the external wall cavities at the top would also have reduced any air movement in the cavities which could cause some deterioration in the effective performance of the EWI, packing this with mineral fibre quilt only met with partial success. Other thermal bypassing effects such as that observed in the front chimney were fixed through ad hoc design decisions as the build progressed, and bypassing of insulation into the tops of open first floor partition wall voids was not addressed. The potential for thermal bypassing occurs anywhere that there is not a continuous air barrier contiguous to a continuous thermal barrier, wherever possible these should be recognised at the design stage and designed out.

133 A full analysis of thermal bridging was not performed and a SAP default y-value of 0.15 W/m^2K applied for the initial phase and phase 2 coheating tests, a y-value of 0.08 W/m^2K was adopted following the stage 2 renovations equivalent to construction using accredited construction details. Full thermal simulation of the details would have been prohibitively expensive, but whether these values were appropriate for each respective stage of construction is uncertain and simulation of just a small number or selected details would have provided useful information on whether the y-values used for each stage were appropriate. Thermal imaging surveys suggested that the EWI was extremely effective in substantially reducing, or even effectively eliminating, many of the thermal bridging problems relating to the external walls, but without any appropriate modelling and more intensive measurements it was not possible to quantify the improvements observed.

134 With the project being undertaken as a research project ad hoc design changes and modifications were anticipated, as such a full set of design details was not available for either stage of the project and it would have been unrealistic to expect full sets of up to date drawings being available at all stages of the project. However, it would be extremely useful to have detailed drawings of the final construction to show what had actually been constructed and to allow for these evolved details to be used again, or adapted, for future renovations and refurbishments of similar dwelling types.

135 Although most of the decisions regarding design alterations were discussed and decided upon in advance, some of the finer detail was made on site without thorough consideration of the full effects. This was often necessary to prevent undue construction delays. Fortunately, for this project, communication between site, research team and project management was excellent and the site team were very aware of potential consequences of material substitutions and minor

design modifications. The site team were prepared to discuss any issues arising immediately to check the possible repercussions of their interventions, without such understanding and awareness the design details would have needed to be far more comprehensive and prescriptive with a formal modification process to prevent the risk of detrimental faults occurring.

136 The specification of suitable membranes, tapes, adhesives and sealants was lacking from the design. More detailed design at some of the more complex junctions would have been beneficial to site operatives and to the thermal and airtight performance of the details. Decisions regarding these were often a result of what materials were readily available rather than what materials were best suited to the task. One such consequence of this was the use of expanding foam and multi-purpose sealants where more specialist or substrate-specific products would have improved the final performance.

137 The decision taken at the design stage to preserve the integral garage meant that some of the more complicated junctions were retained, and was taken specifically to address the issues resulting from what is likely to be a commonly experienced extension to similar properties. To have converted the garage into habitable space would have simplified both thermal and air barriers, removing the discontinuity in the air barrier between the garage ceiling and first floor walls and the issues surrounding the door between the kitchen and garage. Maintaining the complexity of incorporating a semi-exposed area into the building volume provided additional learning opportunities which would not have been existed if a simplified dwelling geometry had been chosen.

Construction

138 The stage 1 renovation carried out necessary repairs on the property and replicated energy saving measures that could easily be performed by occupants of similar dwellings. This included installation of cavity wall insulation, the removal of the boiler and hot water cylinder from outside the thermal envelope, sealing of the suspended timber ground floor and open flue in the lounge, repairs to the side extension floor, relocating the thermal barrier in the rear extension and replacement of the main loft insulation. The measured reduction in heat-loss coefficient (from 312 W/K to 242 W/K) was 70 W/K (31%) compared well to a predicted reduction of 102.7 W/K (30.1%). These figures both include proportions for ventilation heat-loss based on the actual air permeability tests, so variations in ventilation was not responsible for any measured underperformance, leaving issues surrounding the installation of the insulation as the most obvious cause. The discrepancy may actually be more significant than these figures imply, given that the thermal bypassing through the internal cavity walls was significantly reduced by the installation of the CWI, but there is no corresponding reduction in the predicted values.

139 The installation of the CWI was intended to bring the U-values of the un-insulated external walls down to 0.45 W/m^2K but met with limited success due to incomplete fill of the cavities, and even though the fill process appeared to be mainly in accordance with BBA and CIGA recommended procedures some of the measured wall U-values saw little change. Thermal imaging surveys and borescope investigations confirmed that the blown fibre insulation had not spread evenly throughout the cavities, particularly in the old brick-brick cavity walls. The CWI installers had to return to site to install a missing cavity brush at the rear of the property and drill additional injection holes to get insulation into areas which had not been adequately insulated in the initial installation. Without the involvement of the research team, and this project, the lack of insulation in large areas of the walls, and subsequent thermal underperformance, may not have been detected. It is unlikely that this is a one-off occurrence, and there could be very many similar properties nationwide where these issues have been repeated, properties where both clients and installers alike remain unaware of the lack of success of their efforts.

140 The designed replacement loft insulation of 100 mm thick mineral wool quilt between the joists and 300 mm thick quilt running normal to this was replaced by 2 layers of 200 mm thickness. This had the effect of increasing the air gaps in the insulation layer around the ceiling joists and so reducing the thermal performance. There was a problem in getting the loft insulation right into the eaves on all 3 sides of the property, and subsequent work revealed that the loft insulation rarely met up with the cavity wall insulation to form a continuous thermal barrier as part of the stage 1 renovation. This was only resolved when the EWI was fitted because access was available to this junction from the outside of the property and additional mineral wool could be installed, a solution which would not have been available in most standard installations.

141 The opportunity to seal the open cavities at the top of the cavity walls in the loft, to assist with the removal of potential thermal bypassing, was not taken. This would have been simple to perform when the original loft insulation and decking had been removed by inserting cavity socks into the

exposed cavities. A similar procedure could also have been performed on the external cavity walls when the tops of these were exposed.

142 The eaves junction of the ground floor rear extension did not have the same problem observed in the main roof as the roof insulation was fitted at rafter level instead of ceiling level, but instead had other discontinuities of the insulation layer where the roof insulation met with the first floor external wall, gable wall and party wall. Linking up the vapour permeable membrane to form a continuous air barrier with the rest of the property provided problems, compounded by the 2 stage renovation process because the site team needed to allow for stage 2 work including extension of the eaves to accommodate the forthcoming EWI. Fitting PIR rigid foam insulation underneath the rafters and between the ceiling joists proved tricky given the limited access and some small distances involved, particularly where the ceiling joists had to be worked around. The result was an over reliance on expanding foam to seal joints and fill small gaps. A more robust solution would have been to fit larger sheets of insulation over the top of the rafters, with sealing of joints performed from the outside, but this would have required the complete removal and replacement of the roof tiles and incurred additional time and expense.

143 Replacing the loft insulation as part of the stage 1 renovations led to some sequencing issues for the stage 2 renovations. It would have been impractical to completely remove the loft insulation after the 2nd coheating test only to re-install it after the MVHR system and solar system pipe work had been installed in readiness for the 3rd coheating test. The newly laid loft insulation had to be disturbed to fit ductwork for the MVHR system and the unit itself, this appeared to be done with little planning or forethought to how the loft insulation would be re-laid. It was left to the site team to try to re-fit the insulation as best as they could, but with much of the MVHR ductwork now positioned inside the insulation layer, and the insulation piled up all around the loft, it was not possible to re-lay it to the same high standard it had been installed to just a few weeks previously. As insulated flexible ductwork was used in the loft it could have been hung from the rafters on wires to minimise displacement of the loft insulation, or in this case facilitate its re-fitting.

144 The stage 2 renovations involved measures incurring higher capital costs designed to bring the property more in line with the prototype dwellings in terms of fabric performance, the major steps taken included the fitting of EWI, the replacement of the ground floor with an insulated solid floor and the replacement of the original double glazed windows and doors with high performance alternatives. The measured reduction in heat-loss coefficient reduced from 242 W/K to 147 W/K due to the stage 2 renovation, a measured reduction of 994 W/K (39%) compared to a predicted reduction of 131.5 W/K (55%). As for the stage 1 renovations, these figures both include proportions for ventilation heat-loss based on the actual air permeability tests so variations in ventilation heat loss was not responsible for any measured underperformance, leaving issues surrounding unfinished details and the effectiveness of the EWI and door/window replacement.

145 The breaking and extraction of the existing ground floor would have been more straightforward if it had all been suspended timber; the suspended timber floor was easily removed but the 2 existing concrete floors presented difficulties due to internal masonry walls, some of which were built on top of the existing concrete floor and others which stood on the foundations and had to be worked around without disturbing the walls. Laying the new floor was more clear-cut, but presented problems with indoor moisture generation, which proved difficult to remove, and programming of other internal works, as opportunities to perform other construction work on the ground floor were limited whilst the new floor was being constructed.

146 The application of the EWI to the external walls was a smooth and efficient process, with minimal gaps between the mineral wool insulation batts and good contact with the existing external brickwork. Concerns by the research team over such gaps emerging were soon allayed once fitting of the EWI began and the envisaged gaps, which would have had a detrimental effect on the thermal performance of the EWI, did not materialise. This provided immediate benefits over more rigid board EWI systems (such as EPS systems) where the research team have observed this as a major problem with the application of EWI. Associated work necessary to accommodate the EWI included moving external drains and soil pipes and extending the roofline at the eaves. This added some complications to the detailing, most noticeably at the bay window roof and party wall junctions, but also provided an opportunistic benefit of gaining access to the eaves from the outside of the dwelling. This enabled additional mineral wool insulation to be installed between the loft insulation and the external wall insulation to provide a more continuous thermal barrier, and allowed mineral wool to be packed into the tops of the external wall cavities much more effectively than had been possible previously. The thermal images in Figure 29 and Figure 30 clearly show the benefit of the additional insulation at the eaves in the reduction of heat loss via the eaves

junction and should be borne in mind for future refurbishment projects, particularly with low pitch roofs or eaves which are difficult to access from inside the roof space.

147 The thermal images in Figure 29 and Figure 30 also show the considerable reduction achieved in heat loss both through and around the windows. This reduction came about through a combination of the improved performance of the glazing units and frames, the reduction in thermal bridging achieved through the placement of the frames more in line with the insulation layer and the application of appropriate tapes and membranes to the frames during the fixing process to limit air leakage at the openings. The sourcing and procurement of such high performance windows, given the restrictions on budget and lead time, was laudable, and much credit must also be given to the site team in managing to fix the windows in such an airtight and thermally effective manner. The additional weight of the triple glazed units resulted in some quite labour intensive handling issues, particularly for some of the larger 1st floor windows; this was exacerbated by the scaffolding requiring additional clearance from the building than would normally be the case, to allow the application of the EWI. The air barrier membrane fixed to each frame prior to installation proved very effective once an adhesive tape suitable to join the membrane to the masonry window opening had been sourced, and the plasterer had found a satisfactory way of finishing the reveals.

148 Most of the problems with the installation of the MVHR system revolved around the build sequence. It would have been advantageous to have installed the ductwork and unit prior to installing the loft insulation. This would have avoided the significant disturbance to the newly laid loft insulation caused by necessary access to the loft space and routing of the insulated ductwork in the loft. It would also have enabled airtight sealing of penetrations through the 1st floor ceiling from inside the loft when access was limited from inside the living space due to the close proximity of the duct runs to the walls. For future installations the MVHR designers and engineers should be made aware of the thermal effects of displacing insulation by positioning ductwork inside the insulation layer, and the financial effects of reparatory work to any insulation that is disturbed which in this case was carried by the client.

Airtightness

149 Airtightness testing was performed at critical stages throughout the project, whilst the dwelling was still occupied, both prior to and immediately following each of the coheating tests, and an additional test conducted prior to the Phase 3 coheating test to facilitate some of the secondary sealing work. The mean air permeability rose substantially from the initial test of the occupied dwelling to that following the 1st coheating test, from 15.76 to 20.66 $m^3/(h.m^2)$ @ 50 Pa. Some of this deterioration may have been due to the constant elevated temperatures during the 17 day coheating test period, but the bulk of this change was probably due to the removal of the carpets and underlay which would have heavily restricted air movement through the timber floors. The biggest step change observed, from 20.66 to 10.32 $m^3/(h.m^2)$ @ 50 Pa followed the stage 1 renovations, with temporary sealing of the suspended timber ground floor, blocking up of lounge fireplace and removal of boiler, hot water cylinder and downstairs WC, and bathroom down-lighters. The next largest step change, from 9.83 to 6.64 $m^3/(h.m^2)$ @ 50 Pa followed the installation of the replacement windows and sealing around the intermediate floor joists as part of the stage 2 renovations. The final figure of 5.42 $m^3/(h.m^2)$ @ 50 Pa was achieved with the dwelling not fully finished, with sealing around the rear door, garage door and some penetrations in the cylinder cupboard still to be carried out, which on completion would be expected to reduce the mean air permeability still further.

150 Throughout the project it was made aware to all concerned what constituted the primary air barrier and where this was situated within the dwelling. As such, there was the limited reliance on secondary sealing measures; this was reflected by the accelerated shrinkage and drying usually observed due to the coheating tests having only a minor effect on the airtightness test results. Preserving the internal temperatures at 25˚C for the duration of the coheating tests generally results in partial failure of many secondary sealing measures, particularly where joints between substrates of differing physical properties are sealed between with flexible or non-flexible sealants or where sealants are applied with inadequate surface preparation. Avoiding reliance on secondary sealing may also have a beneficial effect on the longevity of the airtightness measures undertaken in the longer term, but this could only be confirmed by additional testing of the dwelling in the future. The clarification of what and where the air barrier was came about through dialogue between the parties concerned rather than through the detail designs and any site team's understanding and awareness could not be expected to be replicated for future projects without such dialogue, as this level of communication is unlikely to be present in future projects it is more important for airtightness details to be fully resolved at the design stage.

151 The pressurisation tests carried out throughout the project emphasise the need to perform such tests at air barrier completion when the air barrier is still accessible and repairs can be implemented and not just to rely on compliance testing on completion. As smoke detection performed under dwelling pressurisation only reveals the point at which the air escapes through the internal surface, and not where it actually penetrates the air barrier, it is important to perform pressurisation tests when the air barrier is still accessible if robust repairs are to be made. Performing leakage detection using thermal imaging under dwelling depressurisation was performed immediately following the coheating tests. This benefited greatly from the elevated temperatures sustained during the coheating test increasing the ΔT, thereby enhancing the thermographic imaging, and as the heat applied to the dwelling was not through a conventional heating system there were no hot pipes or radiators to interfere with the thermal imaging of cold air infiltration. The combination of these 2 methods of leakage detection provided a far greater understanding of the overall air leakage paths in the dwelling than would have been possible by using just one of these techniques alone.

152 Some of the sealing work was only initially possible due to opportunistic exposure of the gaps in the air barrier. This was the case with the intermediate floor joists when the new floor was installed in the side extension. The gaps observed in the external wall at the intermediate floor void, mostly around built-in joists and penetrations for services, encouraged the site team to lift perimeter boards in the other 2 bedrooms to allow additional sealing work to be performed. This additional sealing was only possible where the joists ran into the external walls, where the edge joist ran closely parallel to the external wall it was not possible to access the gaps to anything like the same extent. An attempt was made to improve these details by running a bead of expanding foam between the edge joist and the wall but this proved not to be successful in preventing the air leakage and was not repeated.

153 Some opportunities to seal penetrations through the air barrier were not undertaken, these included the chance to seal ceiling penetrations and the tops of the 1st floor partition walls from inside the loft. The build programme was such that the original loft insulation and decking was removed and then almost immediately replaced with the new loft insulation, it may be beneficial in future projects to create some time between these 2 processes to allow work to be performed to ensure continuity of the air barrier across the entire ceiling (and in the case of dry-lined properties at the ceiling perimeter). In this project installation of the new insulation was required to perform the phase 2 coheating tests, but in future projects it could be advantageous to delay the laying of loft insulation until later in the construction schedule. However, it must be borne in mind that any services laid in the loft space would need to be installed with consideration to the subsequent laying of the insulation and not be positioned where insulation is due to be placed.

154 Although significant improvements were made in the airtightness of the dwelling there are still numerous areas with room for improvement, these include:

a) Ground floor perimeter – particularly at unfinished junctions (such as behind kitchen units) and at thresholds.

b) External doors – unfinished details remained around the external and garage doors at the time of the final test.

c) Lofthatch – leakage remained between the door and trap and between the ceiling and lofthatch surround.

d) Intermediate floor perimeter – issues remain around the offset edge joist and the expanding foam used to seal around built-in joists not fully filling the gaps.

e) 1st Floor ceiling penetrations – many of these proved difficult to seal from inside the habitable space due to access problems.

f) 1st Floor partition wall heads – these can only be effectively sealed from inside the loft, the opportunity to do this was not undertaken.

g) Junction of intermediate floor with old gable wall – the opportunity to fully close the link between the open cavity and the floor void when the landing floor was lifted was missed.

155 With the airtightness testing conducted by the research team there was greater flexibility in testing than would have been possible had testing been undertaken by an external contractor. With short time windows available for testing and reparatory work consideration should be given for the clients to develop their own in-house airtightness testing facility, possibly not for compliance testing but as an aid to construction and achieving the more stringent airtightness requirements of low energy housing and dwellings where higher levels of airtightness are required for the efficiency of MVHR systems. Many air leakage paths only become apparent during leakage detection performed under

an induced pressure, and sealing them whilst the air barrier is still accessible is paramount. In-house testing would enable such tests to be performed at convenient times during the construction process and prevent expensive repairs having to be carried out after subsequent work has prevented access to the areas where the attention is required.

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