Crystal Units Salford Energy House Test

Technical Report

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Executive Summary

Tests were performed at the Salford Energy House to measure the thermal performance of a solid wall end-terrace dwelling retrofitted with Crystal Units C.U.in glazing units. Their performance was compared with ‘E’ and ‘A’ rated double glazed units of the same thickness without any change to the window frames.

C.U.in units provided far superior thermal performance to both ‘E’ and ‘A’ rated glazing units. The measured heat loss through the centre of the C.U.in units was 5.4 and 2.5 times lower than the ‘E’ and ‘A’ rated glazing panels, respectively.

Measured whole house heat loss with the C.U.in units installed was 7% and 3% lower than with ‘E’ and ‘A’ rated glazing units, respectively. These reductions are likely to have been greater if the uninsulated frames had been replaced with insulated frames and if the Energy House was a mid-terrace in which glazing constituted a greater proportion of its external heat loss area.

Contents

1. Introduction

This report provides findings from the Crystal Units test that took place at the University of Salford Energy House test facility during the Department for Energy Security and Net Zero (DESNZ) Demonstration of Energy Efficiency (DEEP) Retrofit Project. The test was commissioned and funded by Crystal Units and approved for inclusion within the DEEP project by DESNZ. The purpose of the test was to compare the reduction in fabric heat loss from the Energy House achieved by the retrofitting of Crystal Units C.U.in glazing units with conventional ‘A’ rated double glazing units (DGUs).

Crystal Units C.U.in units incorporate an invisible film within the cavity of a low emissivity coated DGU. The film which splits the inert gas filled cavity into two chambers is intended to provide superior thermal insulation to standard DGUs. Crystal Units C.U.in units are the same thickness and of similar weight to standard DGUs, thus enabling them to be used in place of standard DGUs in new-build and retrofit applications.

2. Methodology

2.1. Test subject

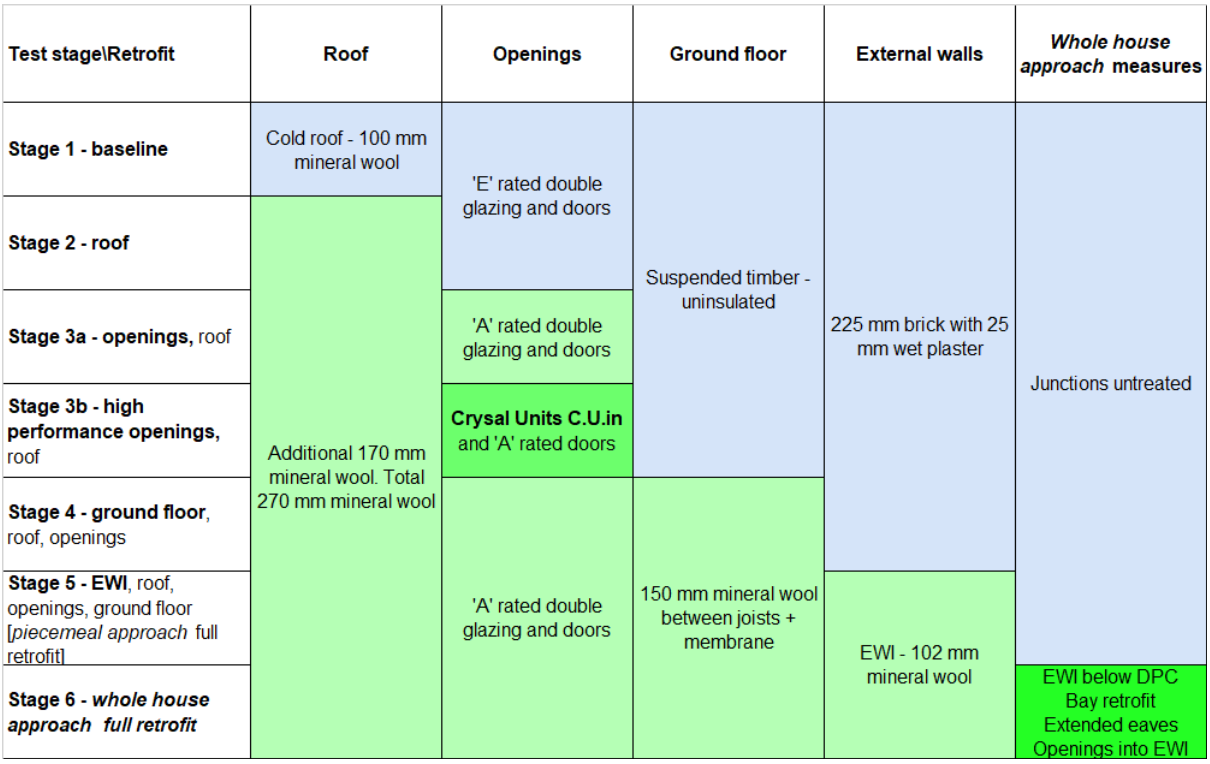
2.1.1. The Salford Energy House test facility

The test took place at the Salford Energy House test facility. It contains the Energy House, a replica Victorian solid wall end-terrace house constructed within an environmental chamber capable of replicating external air temperatures between -12 °C and +30 °C. It was built using reclaimed materials and traditional construction methods of the time and can be retrofitted to most fabric thermal performance standards. The Energy House has a conventional hydronic central heating system with radiators in each room that can be served by a domestic gas condensing combination boiler or an air source heat pump. It has an infrared heating system and can also accommodate other forms of electric space heating. The Energy House shares a party wall with a similar building, referred to as the conditioning void. Environmental conditions in the chamber and conditioning void can be controlled and repeated across multiple test periods. This makes it possible to measure the impact of changes to the Energy House’s building fabric and space heating provision with greater confidence and speed than houses in the field.

Please refer to Appendix C for construction details of the Energy House and Appendix D for floor plans.

2.1.2. Energy House DEEP fabric retrofit

The Crystal Units test took place during a staged full fabric thermal retrofit of the Energy House. Crystal Units were installed at Stage 3b of the test programme. Steady state fabric thermal performance measurements were performed at each stage of the DEEP retrofit. Figure 1 shows the configuration of Energy House fabric at each DEEP test stage.



Test stage\Retrofit	**Roof**	**Openings**	**Ground floor**	**External walls**	***Whole house approach* measures**
Stage 1 - baseline	Cold roof - 100 mm mineral wool	'E' rated double glazing and doors	Suspended timber - uninsulated	225 mm brick with 25 mm wet plaster	Junctions untreated
Stage 2 - roof	Additional 170 mm mineral wool. Total 270 mm mineral wool				
Stage 3a - openings, roof		'A' rated double glazing and doors			
Stage 3b - high performance openings, roof		**Crysal Units C.U.in** and 'A' rated doors			
Stage 4 - ground floor, roof, openings		'A' rated double glazing and doors	150 mm mineral wool between joists + membrane		
Stage 5 - EWI, roof, openings, ground floor [*piecemeal approach* full retrofit]				EWI - 102 mm mineral wool	
Stage 6 - *whole house approach full retrofit*					EWI below DPC Bay retrofit Extended eaves Openings into EWI

Figure 1: Configuration of Energy House fabric at each DEEP test stage

2.2. Energy House openings

2.2.1. Arrangement

The Energy House openings are on the front and rear elevations and represent 10% of the external heat loss area (excluding party wall). The front door is solid, and the rear partially glazed (~30%). Table 1 provides the opening areas for the Energy House.

Table 1: Energy House opening areas

Window area (m^2)	**Glazing area (m^2)**	**Window frame area (m^2)**	**Door area (m^2)**	**Door glazing area (m^2)**
9.92	7.28	2.64	2.94	0.54

2.2.2. Retrofits to openings

The baseline openings in DEEP were specified to simulate a dwelling that had been retrofitted prior to 2010. Window Energy Rating (WER) 'E' rated uPVC double glazed units (DGUs) and Door Energy Rating (DER) 'E' rated uPVC doors were installed as these were the poorest performing openings that were commercially available. DGUs were 28 mm thick comprising 4 mm glazing either side of a 20 mm cavity (4-20-4 configuration). The uninsulated uPVC window frames were retained throughout the DEEP project for practical purposes. So, each retrofit to windows involved the removal and replacement of the window beading and swapping of glazing units. At Stage 3a, 'A' composite doors were installed. This required the door frames to be changed. Table 2 provides the configuration of openings at each DEEP openings retrofit test stage.

Table 2: Configuration of openings at each DEEP openings retrofit test stage

Test stage	Test name	Glazing	Doors
2	‘E' rated openings	‘E’ rated DGUs. Uninsulated uPVC frames	uPVC
3a	‘A' rated openings	Argon filled Low E ‘A’ rated DGUs.	Composite
3b	C.U.in & 'A' rated doors	C.U.in units	Composite

A blower door test was performed after each retrofit. No change in air permeability was measured, so any measured change in fabric heat loss was due to thermal transmission.

2.3. Test methods

2.3.1. Whole building heat transfer coefficient (HTC) measurement

The HTC is the rate of heat loss (fabric and ventilation) in watts (W) from the entire thermal envelope of a building per kelvin (K) of temperature differential between the internal and external environments and is expressed in W/K. HTC measurements were used to quantify the change in whole house heat loss of Energy House resulting from retrofits to its openings. The change in HTC captures the aggregate change in plane element, thermal bridging, and unintentional ventilation (air infiltration and leakage) heat losses from the Energy House. A modified version of the electric coheating test was used to measure the HTC at each test stage. Further details of the HTC measurement method can be found in Appendix E.

2.3.2. In-situ U-value measurement

The thermal transmittance of a building element (U-value) is defined in ISO 7345[1] as the *“Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system”*. In-situ U-value measurements of the openings were undertaken in accordance with ISO 9869-1[2]. Further details of the in-situ U-value measurement method can be found in Appendix F.

Measurements of heat flux density (heat flow rate), from which in-situ U-values were calculated, were taken at four locations on the openings of the Energy House using heat flux plates (HFPs). The centre pane U-value of the glazing was measured on the windows in the kitchen, bedroom 1, and bathroom. The door U-value was measured at the centre of the lower panel on the rear door. It must be noted that the in-situ U-values do not represent the thermal transmission through the entire window or door assembly. Figure 2 shows the HFP on the bedroom 1 window with a C.U.in glazing unit installed.

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[1] ISO (1987) ISO 7345: Thermal insulation –Physical quantities and definitions. Geneva, Switzerland, International Organization for Standardisation.

[2] BSI (2014) BS ISO 9869-1 Thermal insulation. Building elements. In-situ measurement of thermal resistance and thermal transmittance. Heat flow meter method. London. British Standards Institution.

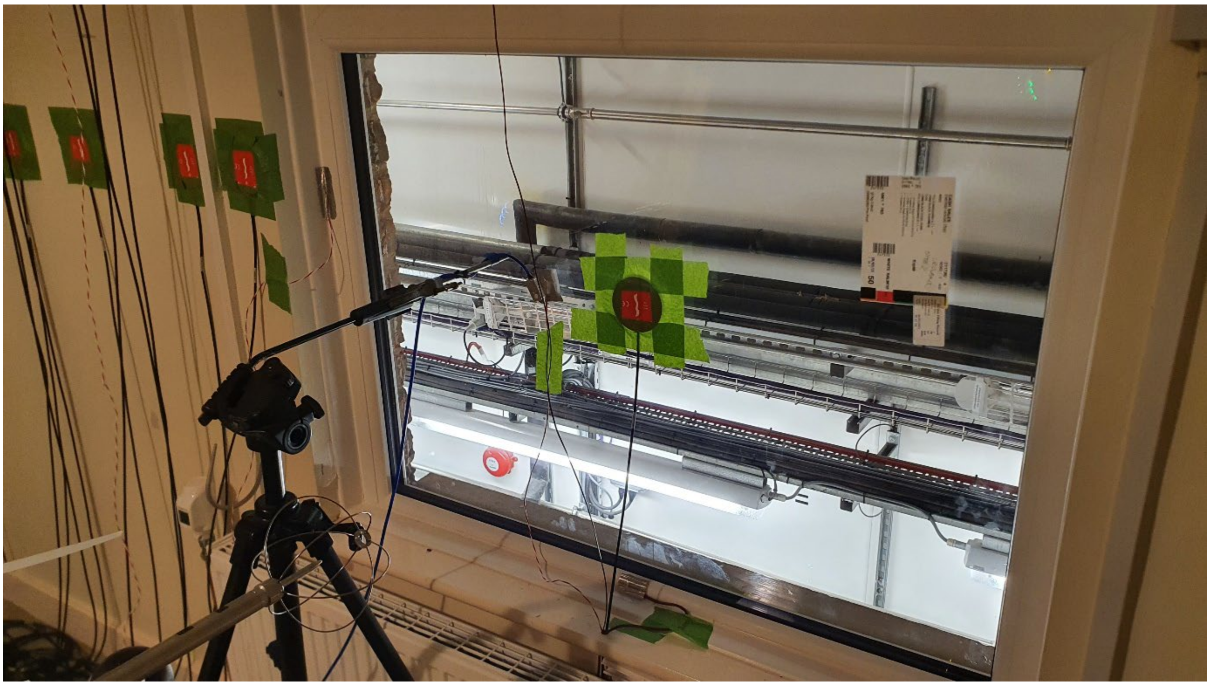

Figure 2: HFP on bedroom 1 window with a C.U.in glazing unit installed

2.4. Test conditions

2.4.1. Internal environment

The Energy House and conditioning void were maintained at 20 °C throughout each steady state measurement period using electric resistance heaters connected to PID controllers with PT-100 RTD temperature sensors. This temperature was selected as it is the average central heating thermostat setpoint for homes in England[3]. Air circulation fans were used to increase air temperature homogeneity within the Energy House. Fans remained in the same location and at the minimum speed setting during each steady state measurement period.

2.4.2. External environment

Table U1 of SAP10 was used to select external temperatures considered representative of the UK average during the winter months (December to February). The chamber HVAC system was set to maintain ~4.5 °C throughout the test programme.

2.4.3. Test duration

Each steady state measurement period was a minimum of 72 hours in duration. Each measurement period concluded once the building heat transfer coefficient (HTC) measured during three successive 24-hour periods differed by less than ±5% from that measured during the final 24-hour period. The uncertainty associated with the HTC measurement during the final 24-hour period had to fall within ± 5% of the HTC for heat transfer to be considered steady state. Reported values for steady

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[3] Shipworth, M., Firth, S., Gentry, M., Wright, A., Shipworth, D. & Lomas, K. (2010) 'Central heating thermostat settings and timing: building demographics', Building Research & Information, 38, (1) 50-69.

state metrics are based on measurements during the final 24-hour period of each measurement period.

2.5. Energy House monitoring

The findings provided in this report are based upon the measurements obtained by the equipment listed in Table 3. Measurements were recorded at one-minute intervals by the Energy House's monitoring system:

Table 3: Measurement equipment used in the Energy House Crystal Units tests

Measurement	Equipment	Uncertainty
Boiler electricity consumption	Siemens 7KT PAC1200 digital power meter	± 1%
Mid-room and chamber air temperature	IC temperature sensor	± 0.2 °C
Heat flux density	Hukseflux HFP-01 heat flux plate	±3%
Air permeability	Retrotec 5100 Blower Door System	±2%

3. Results

3.1. In-situ U-value measurements

Appendix A shows the temperature and heat flux measurements from which the in-situ U-values were derived. Table 4 and Figure 3 provides the glazing centre pane in-situ U-values measured during each DEEP openings retrofit test stage.

Table 4: Glazing centre pane in-situ U-values measured during each DEEP openings retrofit test stage

Glazing	Kit U-value (W/m^{2}K)	Bed1 U-value (W/m^{2}K)	Bath U-value (W/m^{2}K)
'E' rated	2.32 ±0.16	2.62 ±0.17	2.32 ±0.16
'A' rated	1.14 ±0.07	1.30 ±0.23	1.04 ±0.07
C.U.in	0.45 ±0.03	0.46 ±0.16	0.45 ±0.03

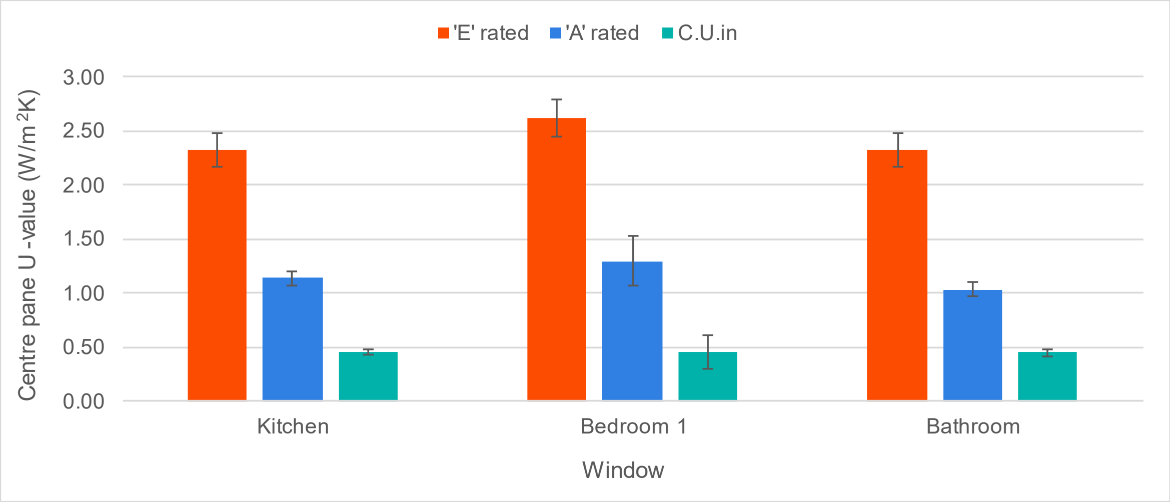


Figure 3: Glazing centre pane in-situ U-values measured during each DEEP openings retrofit test stage

Table 5, Table 6, and Figure 4 show the mean of the glazing centre pane in-situ U-value measurements and door centre in-situ U-value measured at each DEEP openings retrofit test stage.

Table 5: Mean of the glazing centre pane in-situ U-values measured during each DEEP openings retrofit test stage

Glazing	Mean U-value (W/m²K)	Change on 'E' rated (W/m²K)	Change on 'E' rated	Change on 'A' rated (W/m²K)	Change on 'A' rated
'E' rated	2.42 ±0.12	-	-	-	-
'A' rated	1.14 ±0.09	-1.27 ±0.21	-52%	-	-
C.U.in	0.45 ±0.01	-1.97 ±0.17	-81%	-0.70 ±0.13	-61%

Table 6: Door centre in-situ U-value measured during each DEEP openings retrofit test stage

Door	Door centre U-value (W/m²K)	Change on 'E' rated (W/m²K)	Change on 'E' rated
'E' rated	1.02 ±0.07	-	-
'A' rated	0.51 ±0.03	-0.51 ±0.8	-50%

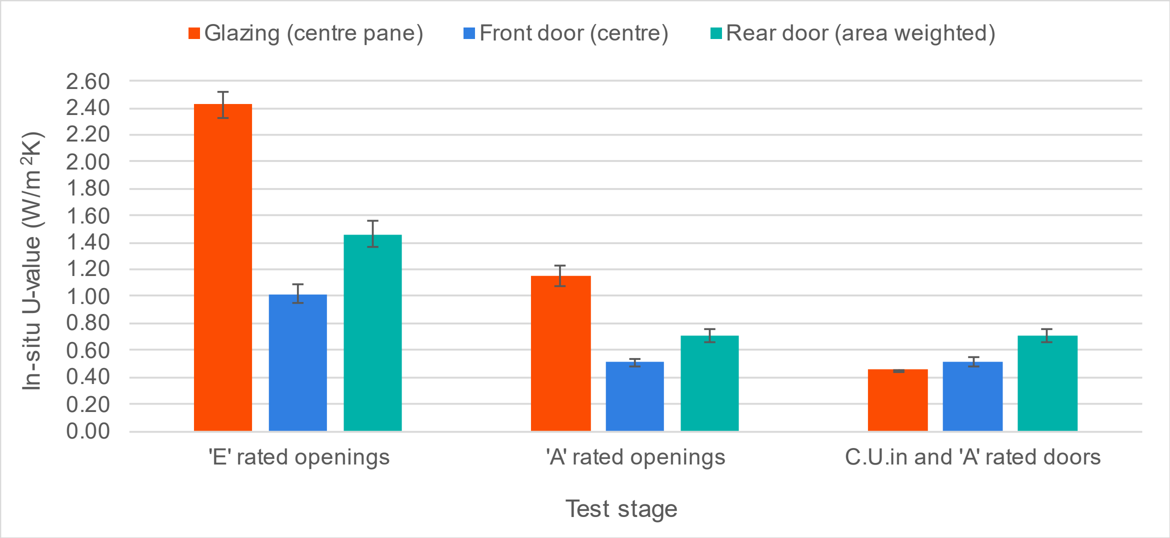


Figure 4: Summary of DEEP openings retrofit in-situ U-value measurements

The C.U.in mean glazing centre in-situ U-value of 0.45 (±0.01) W/m^{2}K represents 81% and 61% reductions in centre pane heat loss on ‘E’ and ‘A’ rated glazing units, respectively.

3.2. HTC measurements

Table 7 and Figure 5 provide the HTCs measured at each DEEP openings retrofit test stage. HTCs measured during each 24-hour period of the steady state measurement period can be found in Appendix B.

Table 7: HTC measured at each DEEP openings retrofit test stage

Condition of openings	Measured HTC (W/K)	Change on ‘E’ rated (W/K)	Change on ‘E’ rated	Change on ‘A’ rated (W/K)	Change on ‘A’ rated
‘E' rated openings	162.7 ±3.1	-	-	-	-
‘A' rated openings	155.1 ±2.9	-7.6 ±4.2	-5%	-	-
C.U.in & 'A' rated doors	151.1 ±1.6	-11.6 ±3.4	-7%	-4 ±3.4	-3%

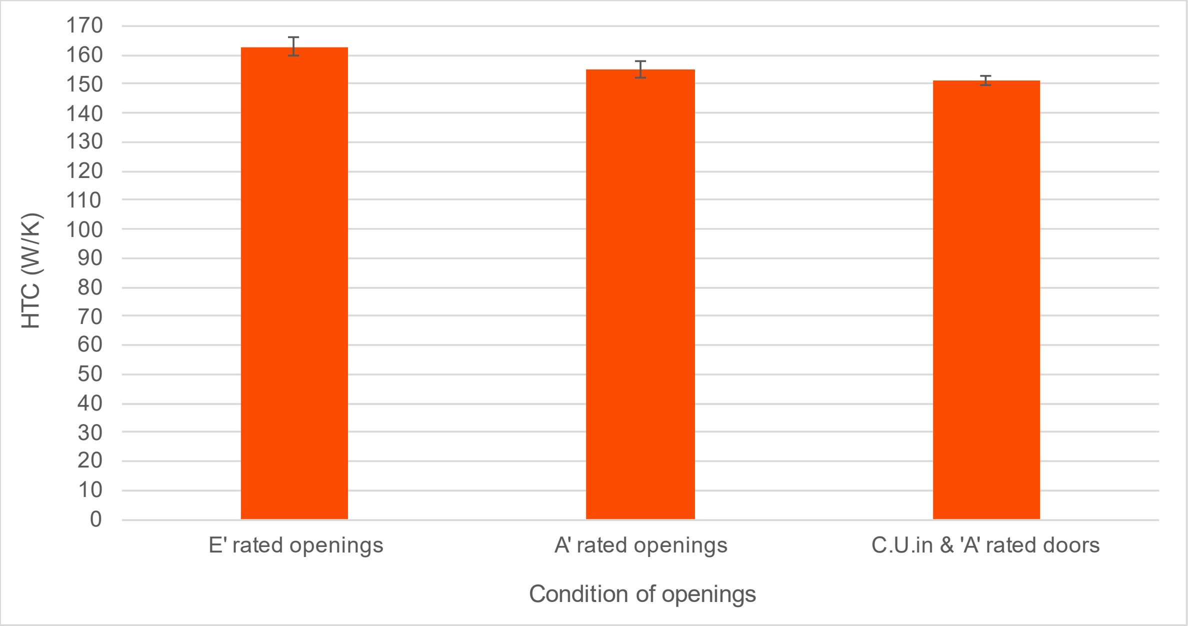


Figure 5: HTC measured at each DEEP openings retrofit test stage

The C.U.in HTC of 151 (±1.6) W/K represents 7% and 3% reductions in whole house heat loss and space heating demand on ‘E’ and ‘A’ rated glazing units, respectively.

3.3. HTC reductions based on in-situ U-value measurements

Table 8 shows the predicted heat loss reductions from measured openings baseline HTC (DEEP Stage 2). Predicted HTCs are based on measured centre pane and door centre in-situ U-value reductions multiplied by the glazing (excluding frames) and door areas, respectively.

*Table 8: Predicted heat loss reductions based on measured in-situ U-value reductions (*denotes measured HTC)*

Condition of openings	**Predicted HTC (W/K)**	**Change on ‘E’ rated (W/K)**	**Change on ‘E’ rated**	**Change on ‘A’ rated (W/K)**	**Change on ‘A’ rated**
‘E' rated openings	162.7*	-	-	-	-
‘A' rated openings	150.6	-12.1	-7%	-	-
C.U.in & 'A' rated doors	145.5	-17.2	-11%	-5.1	-3%

Measured HTC reductions were lower in absolute terms than with those predicted using in-situ U-value measurements. This could potentially be explained by greater heat loss at the perimeter of glazing units that was not captured by the centre pane measurements.

The Energy House is an end-terrace, it’s external walls represent 47% of its external heat loss area. Openings comprise 10%. This limits the potential impact on percentage reductions in HTC resulting from retrofits to the openings. To predict the potential impact of retrofitting the openings of a mid-terrace of similar size to the Energy House, the measured external wall in-situ U-value was multiplied by the area of the gable wall and subtracted from the DEEP Stage 2 HTC. This effectively removed the gable wall heat loss from the HTC, resulting in the Energy House only having two heat loss elevations. In this scenario the external walls comprise 30% of external heat loss area and openings 14%. The same method as before was used to predict the reductions in HTC resulting from retrofits to openings, the results are provided in Table 9.

Table 9: Predicted heat loss reductions for a mid-terrace dwelling of similar size to the Energy House based on measured in-situ U-value reductions

Condition of openings	**Predicted HTC (W/K)**	**Change on ‘E’ rated (W/K)**	**Change on ‘E’ rated**	**Change on ‘A’ rated (W/K)**	**Change on ‘A’ rated**
‘E' rated openings	127.0	-	-	-	-
‘A' rated openings	115.0	-12.1	-9%	-	-
C.U.in & 'A' rated doors	119.8	-17.2	-15%	-5.1	-4%

The findings show that retrofits to openings can have a proportionally greater impact on mid-terrace dwellings or those with a greater proportion of openings.

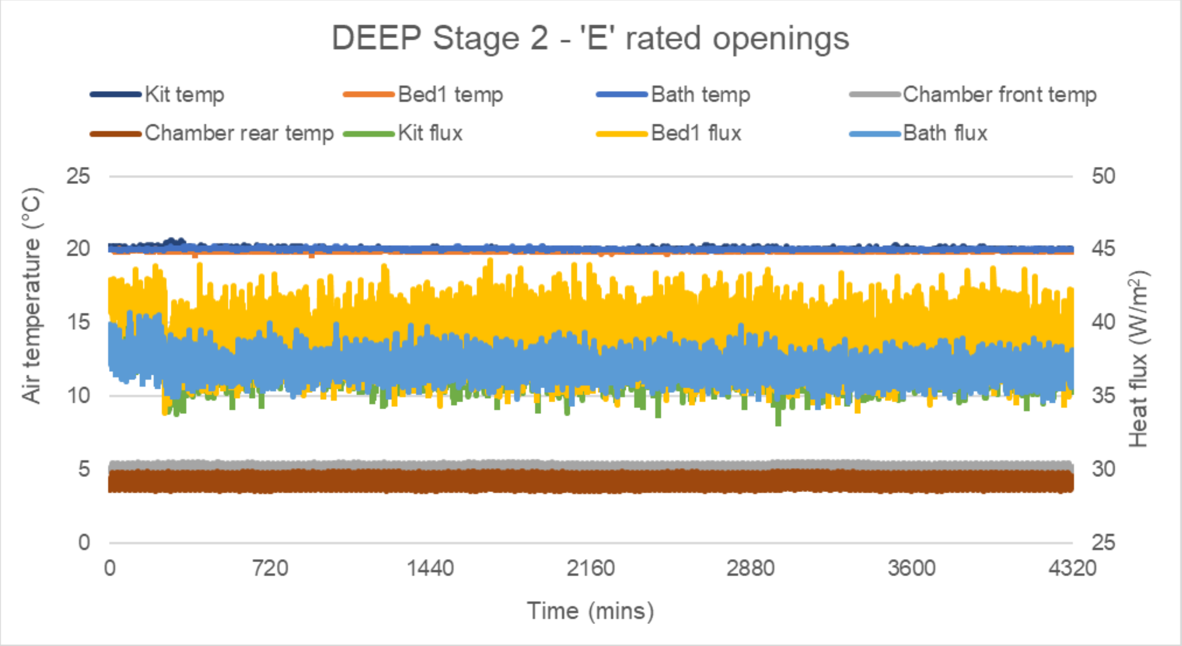
4. Summary

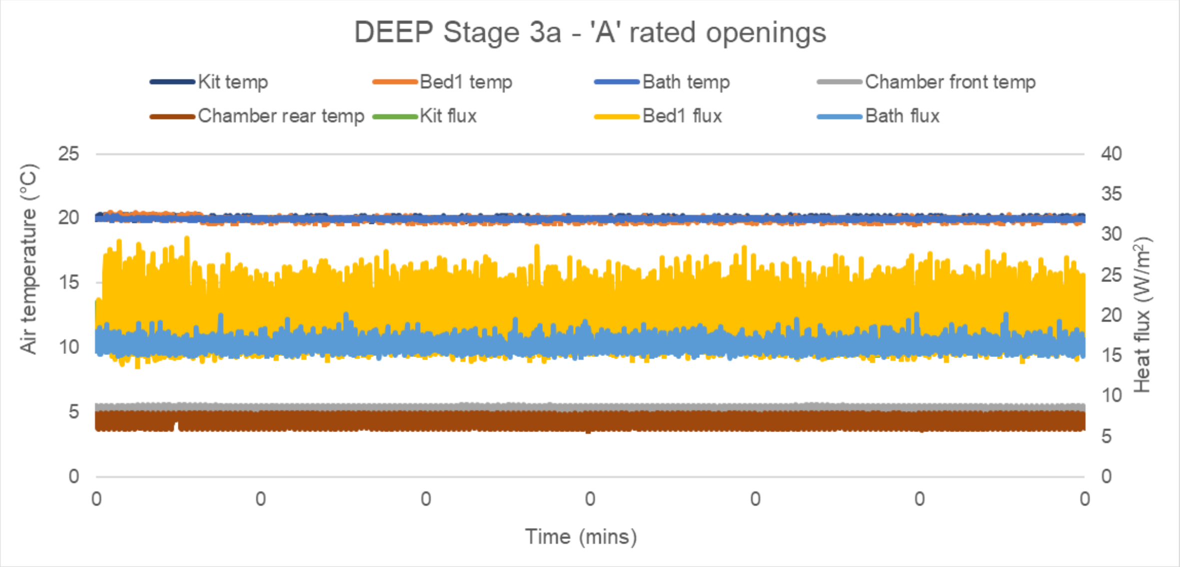
The C.U.in units provided far superior thermal performance to both ‘E’ and ‘A’ rated glazing units. The mean C.U.in glazing centre in-situ U-value of 0.45 (±0.01) W/m^{2}K represents 81% and 61% reductions in centre pane heat loss on ‘E’ and ‘A’ rated glazing units, respectively.

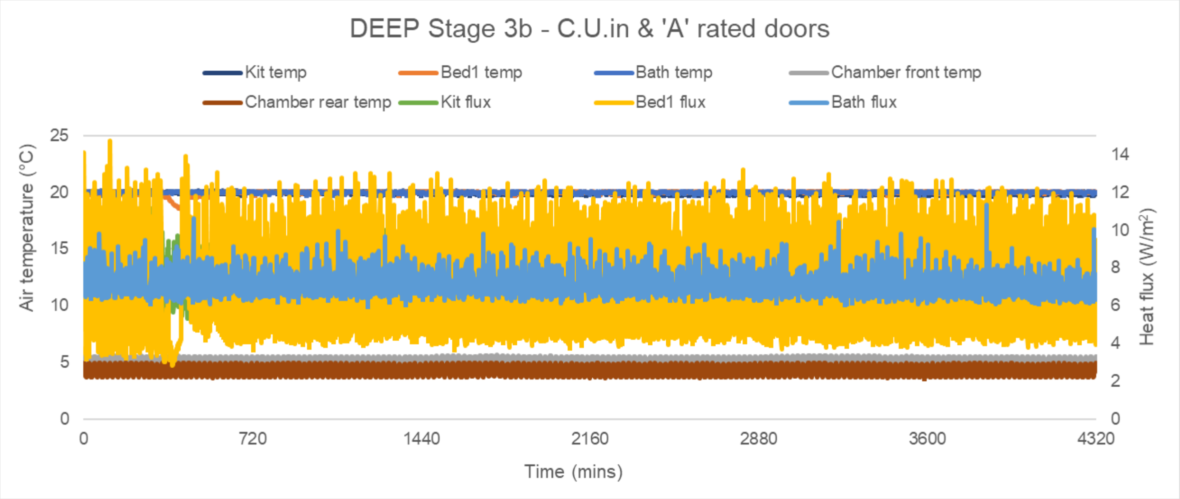
The C.U.in HTC of 151 (±1.6) W/K represents 7% and 3% reductions in whole house heat loss and space heating demand on ‘E’ and ‘A’ rated glazing units, respectively. It must be noted that reductions in HTC from the ‘E’ rated baseline are likely to have been greater if the uninsulated frames had been replaced with insulated frames.

The openings retrofits produced relatively small HTC reductions. This was attributed to the relatively small proportion of heat loss area. Their impact was estimated to be greater for mid-terrace dwellings where openings represent a larger proportion of the surface area. The cost-effectiveness of high-performance windows and glazing for dwellings with a high proportion of glazed areas should be investigated.

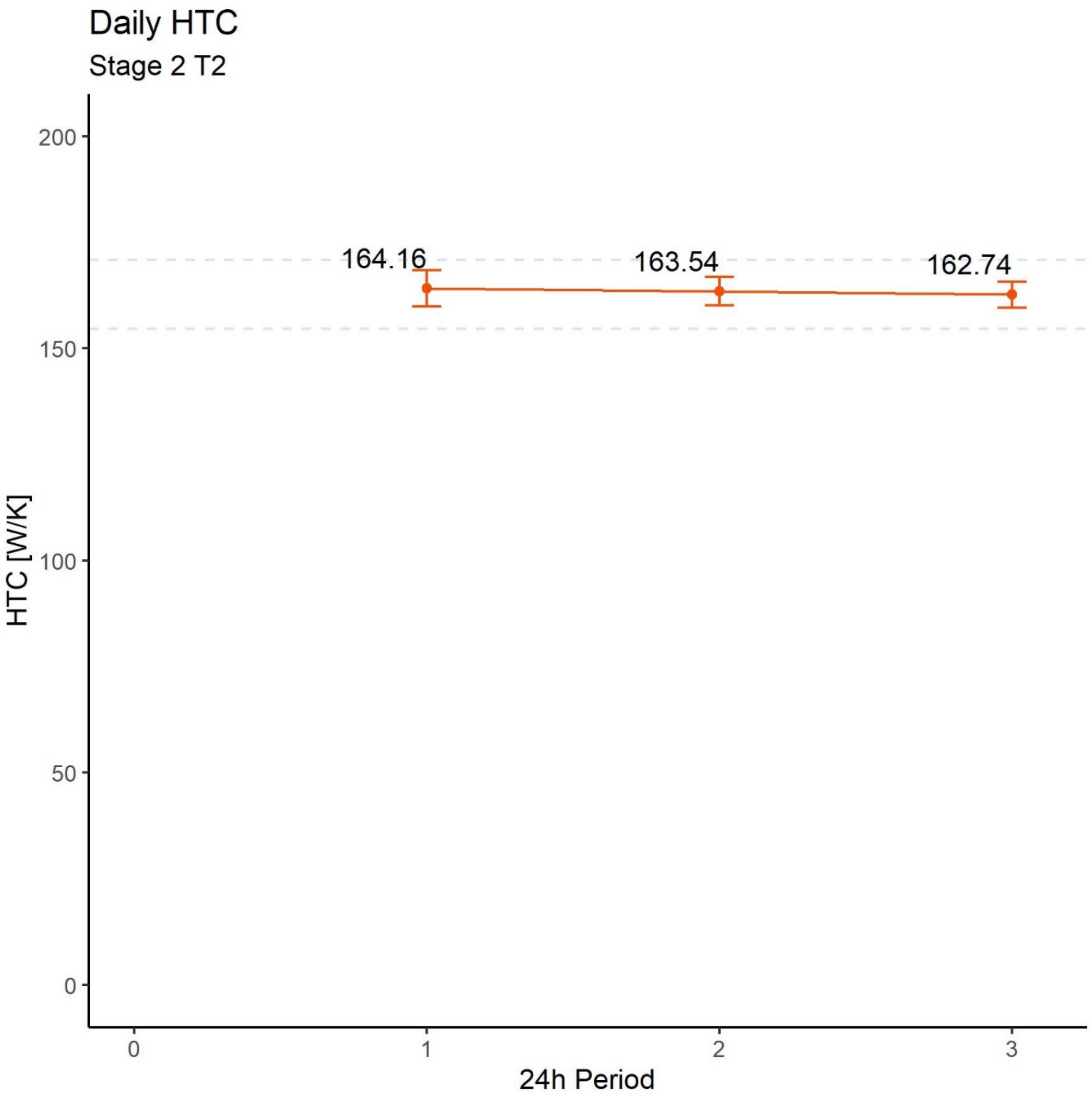
Appendix A: Heat flux and temperature measurements

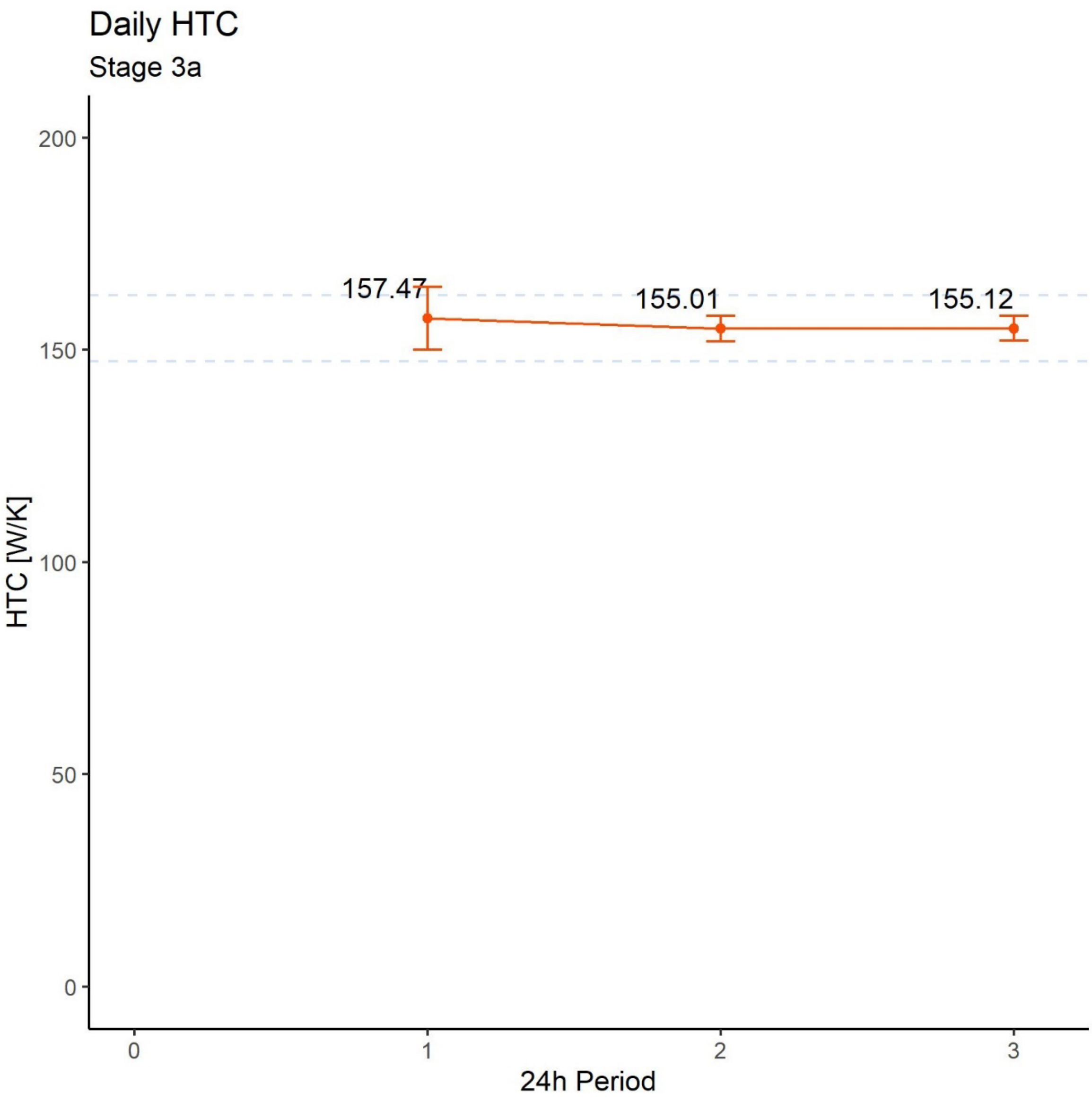


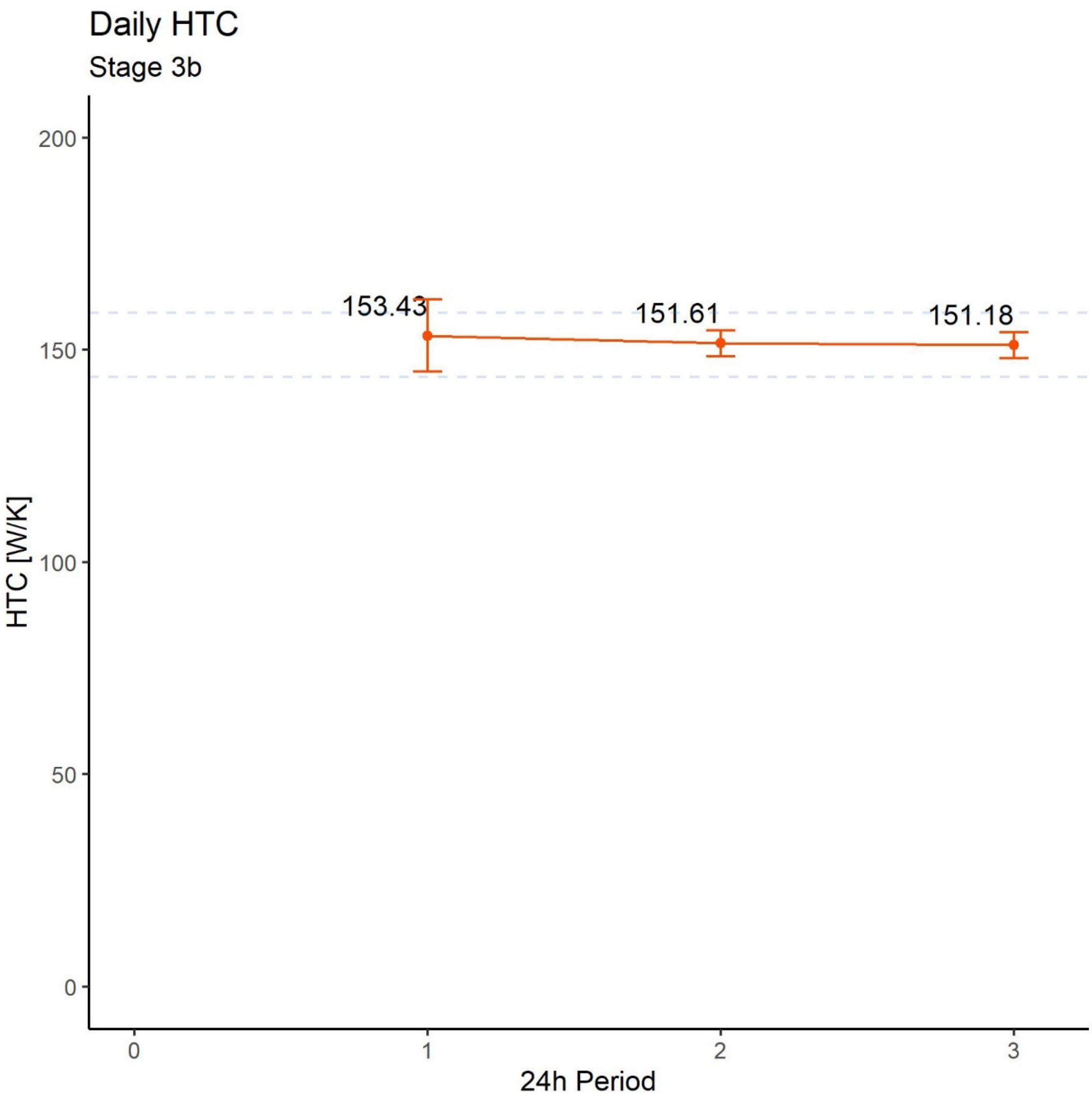




Appendix B: 24-hour HTC measurements




Daily HTC
Stage 3a
HTC [W/K]
200
150
100
50
0
157.47
155.01
155.12
0
1
2
3
24h Period

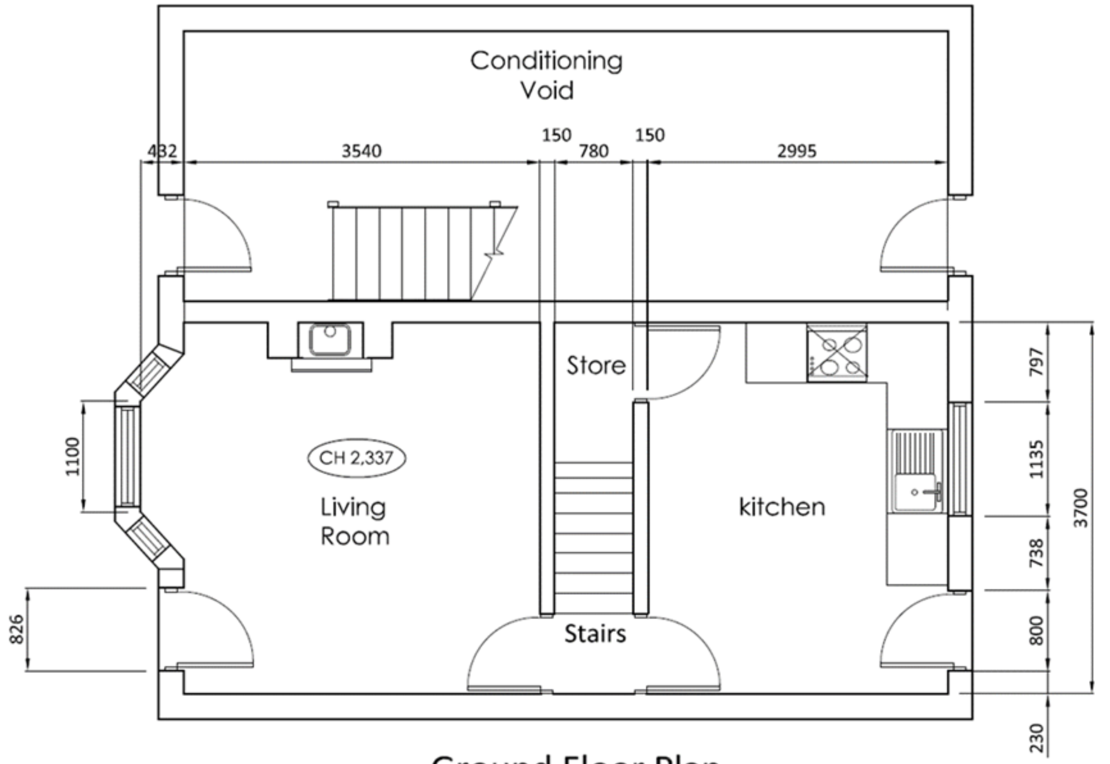

Daily HTC
Stage 3b
HTC [W/K]
200
150
100
50
0
153.43
151.61
151.18
0
1
2
3
24h Period

Appendix C: Energy House construction

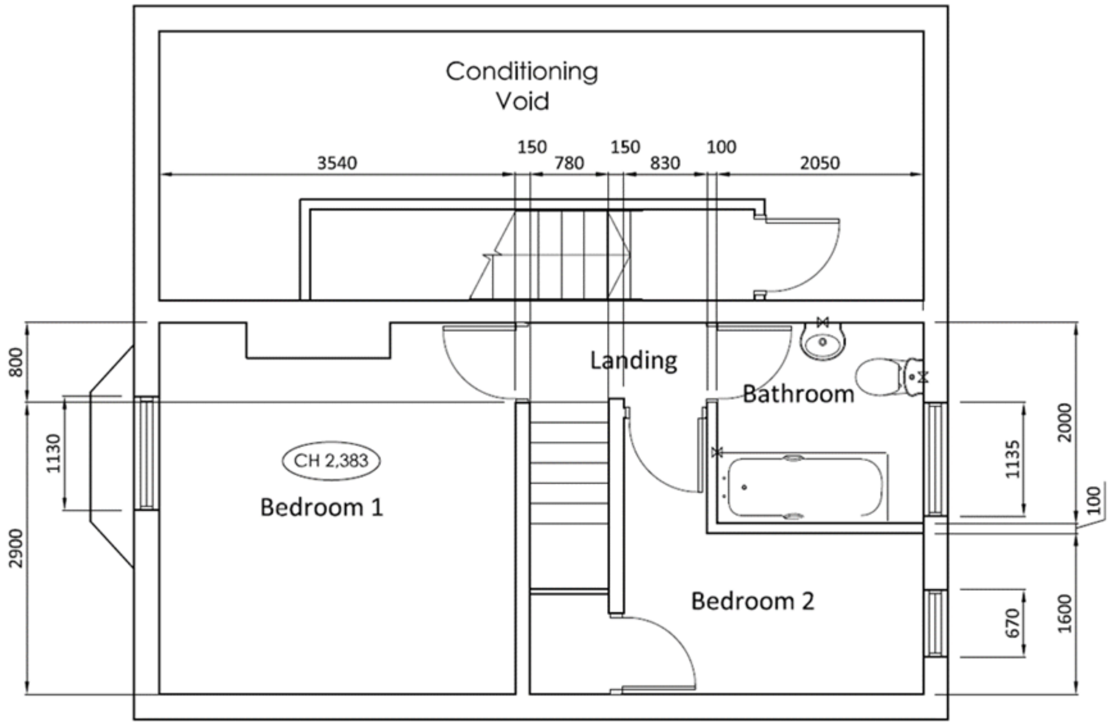
Table C1: Energy House construction details at Stage 2 of DEEP

Thermal element	Construction
External walls	Solid wall – 222.5 mm brick arranged in English bond (5 courses) with 9 mm lime mortar and 10.5 mm British Gypsum Thistle hardwall plaster with a 2 mm Thistle Multi-Finish final coat. The ground and intermediate floor joists are built-in to the gable wall.
Roof	Purlin and rafter cold roof structure with 270 mm insulation at ceiling level. 100 mm mineral wool insulation (λ 0.044 W/mK) between 100x50 mm ceiling joists. 170 mm mineral wool (λ 0.044 W/mK) above and perpendicular to joists. Ceiling joists run parallel to the gable wall at 400 mm centres above lath (6 mm) and plaster (17 mm) ceiling
Ground floor	Suspended timber ground floor above a ventilated underfloor void (20 mm depth). 150x22 mm floorboards fixed to 200x50 mm floor joists at 400 mm centres. Floor joists run between the gable and party wall with joists ends built into masonry walls.
Windows	4-20-4 ‘E’ rated double glazing units in uninsulated uPVC frames.
Doors	Front – ‘E’ rated uPVC. Rear – ‘E’ rated half glazed uPVC.
Party wall	Solid wall – as external walls but with plaster finish on both sides.

Appendix D: Energy House floor plans



Ground Floor Plan



First Floor Plan

Appendix E: HTC measurement method

The HTC is the rate of heat loss (fabric and ventilation) in watts from the entire thermal envelope of a building per kelvin (K) of temperature differential between the internal and external environments and is expressed in W/K. HTC measurements were used to quantify the change in whole house heat loss of Energy House resulting from retrofits to its thermal elements. The change in HTC captures the aggregate change in plane element, thermal bridging, and unintentional ventilation (air infiltration and leakage) heat losses from the Energy House.

At the commencement of testing, no formally recognised standard existed for the in-situ HTC measurement. The 2013 version of the Leeds Metropolitan (now Beckett) University Whole House Heat Loss Test Method[4] was adapted for HTC measurements. The principal differences being the reduction in test duration and analysis of test data.

A coheating test typically assumes the steady state whole house energy balance in the following equation[5].

$$Q + A_{sw}.q_{sw} = (H_{tr} + H_v).\Delta T$$

Where:

Q = Power input (W)

A_{sw} = Solar aperture (m^2)

q_{sw} = Solar irradiance (W/m^2)

H_{tr} = Transmission heat transfer coefficient (W//K)

H_v = Ventilation heat transfer coefficient (W/K)

ΔT = Internal to external temperature difference (K)

At the Salford Energy House test facility, the terms A_{sw} and q_{sw} can be removed from the whole house energy balance, and the equation rearranged to show how at steady state, the HTC can be calculated from measurements of only Q and ΔT. The equation below shows the HTC calculation in Energy House tests.

$$HTC = \frac{Q}{\Delta T}$$

Where:

HTC = H_{tr} + H_v (W/K)

Q = 24-hour mean power input[6] (W)

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[4] Johnston, D., Miles-Shenton, D., Farmer, D. & Wingfield, J. (2013) Whole House Heat Loss Test Method (Coheating), Leeds Metropolitan University, 2013, June 2013.

[5] Adapted from Everett, R. (1985). Rapid Thermal Calibration of Houses, Technical Report, Open University Energy Research Group, Milton Keynes, UK, 1985, ERG 055.

[6] Based on total cumulative energy input to the Energy House over 24-hour period

ΔT = 24-hour volume weighted average internal air temperature (T_{i_vw}) minus the 24-hour average chamber air temperature (T_e)

HTC uncertainty

HTC uncertainty was calculated by considering type A and type B uncertainties.

Type A uncertainty

Type A uncertainty considers statistical variation in the recorded data. To calculate this, the following methods were followed.

Power (Q)

Space heating power input is inherently noisy due to multiple electrical resistance heaters, the limited number of power settings for the heaters, and the sensitivity of their thermostatic controllers. To minimise noise, heaters were placed on the lowest power setting that prevented them being permanently in operation to ensure that the fabric was close to steady state and PID thermostatic controllers were used. The 24-hour averaging period minimises the impact of variation over each aggregation period. However, the standard deviation based on minutely power data over a 24-hour period can overestimate the uncertainty. The “sma()” function from the “smooth” R programming language package is used to create a simple moving average of the power data. This package optimises the moving average by varying the averaging period. It allows uncertainty to capture whether power input over a 24-hour period was significantly different to a previous 24-hour period. The standard deviation of the smoothed data is calculated and taken as the type A power uncertainty.

Volume weighted average internal temperature (T_{i_vw})

The T_{i_vw} is first calculated for every minute of data, using the proportions in Table E2.

The deviation of each individual temperature sensor to the T_{i_vw} is then calculated, denoted by θ.

The standard deviation of all these variations is the calculated and taken as the type A T_{i_vw} uncertainty.

Average external temperature (T_e)

Calculated through a simple mean of the three external temperature sensors located on the front, gable, and rear elevations.

The type A uncertainty of T_e is calculated as the standard deviation of the average external temperature.

Type B uncertainty

Type B uncertainty considers the uncertainty attributed to the accuracy of the measurement device.

The accuracy and standard uncertainty of equipment used in the HTC calculation are stated in Table E1.

Table E1: Accuracy and standard uncertainty of equipment used in the HTC calculation

Variable	Device	Accuracy	Probability distribution	Divisor	Standard Uncertainty
Q [W]	Siemens 7KT PAC1200 digital power meter	1% of measurement	-	-	1% of measurement
T_i [°C]	I.C. sensor	0.4	normal	2	0.20
T_e [°C]	I.C. sensor	0.4	normal	2	0.20

The type B uncertainty of total power input is calculated by taking the 24h average power input (based on cumulative energy data) and multiplying by the stated accuracy (1% of measurement).

The type B uncertainty of both the T_{i_vw} and the average external temperature is calculated using Table E2 and Table E3. The standard uncertainty of each individual temperature sensors is scaled by the same coefficient used in the volume weighting equation. These are then summed following the RSS method.

Table E2: T_{i_vw} type B uncertainty

Zone	Weighting	I.C sensor uncertainty	Scaled uncertainty
Living room	0.252	0.20	0.05
Hall	0.028	0.20	0.01
Kitchen	0.209	0.20	0.04
Bedroom 1	0.237	0.20	0.05
Landing	0.052	0.20	0.01
Bathroom	0.077	0.20	0.02
Bedroom 2	0.105	0.20	0.02
Bedroom 2 cupboard	0.016	0.20	0.00
Understairs	0.025	0.20	0.01
		Quadrature sum (k = 1)	**0.09**
		k = 2	**0.18**

Table E3: T_e type B uncertainty

Elevation	Weighting	I.C sensor uncertainty	Scaled uncertainty
Front	0.333	0.20	0.0667
Gable	0.333	0.20	0.0667
Rear	0.333	0.20	0.0667
		Quadrature sum (k = 1)	**0.12**
		k = 2	**0.23**

Combined Uncertainty

The Type A and Type B uncertainty attributed to each measurement are combined through the RSS method prior to error propagation in the HTC calculation.

$$u_{combined} = \sqrt{u_A^2 + u_B^2}$$

Uncertainty Propagation

The uncertainty propagation of the HTC calculation is given by the following equation:

$$u_{HTC} = \sqrt{\left(\frac{u_Q}{u_{\Delta T}}\right)^2 + \left(\frac{u_Q^2}{\Delta T^4}\right) \cdot \left(u_{T_i}^2 \cdot u_{T_e}^2\right)}$$

Expanded Uncertainty

All prior uncertainties have been given as k=1. When stating the uncertainty on plots, the expanded uncertainty (k=1.96) is stated, such that:

$$U = k \cdot u$$

Such a coverage factor should result in a 95% confidence interval.

Appendix F: In-situ U-value measurement method

In-situ U-value measurements of each thermal element were undertaken in accordance with ISO 9869-1. The thermal transmittance of a building element (U-value) is defined in ISO 7345[7] as the *"Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system"*. To account for thermal storage and release, ISO 9869-1 uses a cumulative moving average of the heat flow rate and ΔT to calculate in-situ U-values. However, steady state conditions at the Energy House allows in-situ U-values to be calculated as defined by ISO 7345 using the following equation.

$$U = \frac{q}{\Delta T}$$

Where:

U = in-situ U-value (W/m^{2}K)

q = 24-hour mean heat flow rate (W/m^2)

ΔT = 24-hour mean internal to external air temperature difference (K)

The heat flow rate was measured using Hukseflux HFP-01 heat flux plates (HFPs). The HFPs were affixed to centre of glazing units using adhesive tape and thermal contact paste. Care was taken to ensure that HFPs were not unduly influenced by excessive air movement by positioning air circulation fans in such a way that air was not blown directly on to the HFPs.

The ΔT for each in-situ U-value measurement was calculated using the internal and external air temperature differential measured in the vicinity of each HFP.

In-situ U-value uncertainty

ISO 9869 applies an uncertainty value of 14-28% to in-situ U-value measurements. However, this uncertainty is based on measurements undertaken in the field without control of external conditions. The ISO 9869 uncertainty calculation was modified for the controlled environment and to include type A and type B uncertainties.

Type A uncertainty

Type A uncertainties consider the statistical variation in the recorded data.

Heat Flux (q)

To reduce noise caused by the operation of electric resistance heaters and fans. the "sma()" function from the "smooth" R programming language package is used to create a simple moving average of the heat flux data. This package optimises moving average by varying the averaging period.

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[7] ISO (1987) ISO 7345: Thermal insulation –Physical quantities and definitions. Geneva, Switzerland, International Organization for Standardisation.

The standard deviation of the smoothed data is calculated and taken as the type A heat flux uncertainty.

T_i and T_e

All U-Value measurements considered a single local internal temperature sensor and a single local external temperature sensor. The standard deviation over a 24-hour period for each sensor was calculated and taken as the type A uncertainty.

Type B uncertainty

Type B uncertainties are based on the sources of uncertainty listed in ISO 9869. Table F1 lists the measurement uncertainties provided by ISO 9869 and modifications that were made for DEEP based on the apparatus and test environment. It must be noted that many of the assumptions regarding sources of uncertainty contained within ISO 9869 are not accompanied with background information as to how they have been derived.

Table F1: Measurement uncertainties provided by ISO 9869 and modifications made for DEEP

ISO 9869 consideration	Notes	% error	Absolute error
Apparatus - Logger	Based on logger accuracy and offset value and DEEP steady state ΔT and heat flux for a U-value of 0.09[8] W/m^{2}K	0.3	
Apparatus - HFP	Hukesflux HFP01 datasheet	2	
Apparatus - I. C. temperature sensor	Based on DEEP steady state ΔT	1.8	0.3
HFP contact	ISO 9869 - unadjusted	5	
Isotherm modification	ISO 9869 - unadjusted	2	
Variation in temp & heat flow	ISO 9869 ~10%. Removed as steady state measurement reported. **Captured in type A uncertainty**	0	
Variation in air (T_i) & radiant (T_r) temperature differences	ISO 9869 suggests 5%. Value halved as air circulation fans increase homogeneity & typical 1-2 °C between T_r and T_a at most locations	2.5	
type B uncertainty	**Quadrature sum**	**6.5**	

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[8] U-value of 0.09 W/m^{2}K is the lowest U-value reported in DEEP and associated with a logger uncertainty of 0.3%. As U-value increases logger uncertainty decreases, therefore the maximum logger uncertainty has been applied to all U-value measurements.

Combined Uncertainty

The Type A and Type B uncertainty attributed to each measurement are combined through the RSS method prior to error propagation in the HTC calculation.

$$u_{combined} = \sqrt{u_A^2 + u_B^2}$$

Expanded Uncertainty

All prior uncertainties have been given as k=1. When stating the uncertainty on plots, the expanded uncertainty (k=1.96) is stated, such that:

$$U = k \cdot u$$

Such a coverage factor should result in a 95% confidence interval.