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DEEP Report 3.00

Energy Efficiency Surveys

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Executive summary

Surveys and air tests were performed at 160 solid and cavity walled homes in Northern England, which had a mix of insulated and uninsulated walls. Blower door tests and Pulse tests were compared and used to quantify the airtightness of the homes. An evaluation of how building characteristics affected the results was performed, and common leakage pathways were identified. Data was also collected on the condition of the homes, potential barriers to external wall insulation (EWI) retrofit, as well as perceptions of occupants.

This research agreed with previous findings that the average airtightness of UK homes is around 11 $m^3/(h \cdot m^2)$ @ 50Pa [1]. However, this may not be a useful metric when considering how airtightness improvements may benefit homes. The range in air permeability was found to be between 0.9 and 25 $m^3/(h \cdot m^2)$ @ 50Pa; 78 % of homes had performance below the UK Building Regulations limiting value for new build homes of 8 $m^3/(h \cdot m^2)$ @ 50Pa; and twenty of the homes had measured air permeability exceeding 15 $m^3/(h \cdot m^2)$ @ 50Pa, indicating excessive overventilation. However, finding which homes require airtightness improvements is challenging. Building characteristics such as wall type, glazing type, and EPC score had no correlation to airtightness; nor did building age, except in homes built after 2000, which were generally more airtight. However, homes with suspended timber floors did tend to have marginally worse airtightness, though homes of any floor types can have very low levels of airtightness. 70 % of all homes had detectable air leakage at the ground floor and wall junction (behind skirting boards), or directly between floorboards in the case of suspended timber ground floors.

Thus, infiltration rates are dependent on the quality of internal details in homes. For instance, over two thirds of homes had air leakage around fenestrations, and a third had leakage behind wall mounted items in kitchens and bathrooms, which would be costly and inconvenient to remove. It is not possible to identify the magnitude of leakage pathways during air tests, and several thousand homes would be required to approach a representative sample. However, only sealing up accessible leakages, such as draught-stripping openings and access hatches, sealing around service penetrations and poorly fitting vents etc., may not address a home's main leakage pathways.

Low pressure Pulse tests showed similar results to the blower door, though the findings suggest the CIBSE TM23 (2022) conversion factor may not appropriate for homes with air permeability above the Building Regulations' limiting value (8 $m^3/(h \cdot m^2)$ @ 50Pa). More investigation to understand how non-solid floors affect Pulse testing is needed. However, Pulse results may not be as affected by inter-dwelling air exchange as individual dwelling fan pressurisation tests. Almost all homes surveyed had barriers to EWI, almost two thirds would require utilities to be moved by specialists, a third had architectural details meaning EWI designs would need adapting, and one in ten had access issues to installing EWI. Funding for EWI schemes therefore needs to account for these as standard.

The sample size of occupant surveys was too small to draw generalisable conclusions, though it suggests occupants heat to between 19 °C and 21 °C, and occupants generally are comfortable, regardless of their levels of airtightness. The condition of lofts was also observed, indicating that although 70 % of lofts are insulated, the performance varies considerably: around one in five homes had less than 100 mm of loft insulation and many homes had

variable thicknesses or disturbed insulation. Although the sample is not representative, it suggests loft top-ups may be a useful retrofit measure for many homes.

1 Introduction

This report presents the findings from airtightness tests, thermographic surveys, and retrofit barrier audits, which were undertaken in 160 homes across the UK. It provides insights into the relationships between building characteristics and a home's current and potential energy efficiency. It also provides a comparison of blower door and low-pressure Pulse airtightness measurement technologies.

The surveys that were undertaken were designed to begin to answer specific questions as part of the DEEP project including:

1. *What is the current state of airtightness in homes in the UK?*
2. *How effective is the low-pressure Pulse test as an alternative to the blower door test?*
3. *What building features may act as barriers to the future retrofit of homes, and how common are they?*
4. *Can occupant satisfaction or thermal comfort be linked to airtightness or other characteristics?*

This report is structured into sections addressing each question in turn.

1.1 Survey protocol

Since the survey had four purposes, a protocol was developed to allow data capture on multiple levels including:

- General building survey and photos (building dimensions and age; damp identification; observations of fabric and glazing condition; record of ventilation and renewables present, etc.)
- Blower door test according to ATTMA TS1 [1] and low-pressure Pulse test [2]
- Thermography to support air leakage identification
- Loft inspections
- Cavity inspections using a borescope
- Historic EPC for the property
- Occupant survey

The surveys were developed by Leeds Beckett researchers and undertaken by both Leeds Beckett and Thermal Image UK (TIUK) following an induction to the protocol and handover.

1.2 Survey sample

The project does not attempt to characterise the airtightness of the UK housing stock, but to explore how different building characteristics may be affecting airtightness in homes. The sample selection was blind to tenure type, but aimed to collect a stratified sample of:

- 50 uninsulated solid walled homes: to explore airtightness levels, and identify major air leakage pathways and barriers to future solid wall insulation retrofits
- 50 solid walled homes with either internal or external wall insulation (IWI or EWI) to investigate how insulation affects airtightness levels and air leakage pathways, but also to explore the condition of insulation installed in homes over the previous decades
- 50 insulated cavity walled homes to investigate the condition of existing cavity wall insulation; as well as compare airtightness levels, and air leakage pathways with solid walled homes.

The final sample did not display such uniform subgroups owing to the limitations in recruitment, though still displayed sufficient variation to enable statistical comparisons between construction types. The sample included: 77 solid walled homes (10 with IWI, 13 with EWI, one with both, 53 uninsulated); 75 cavity walled homes (55 insulated, 20 uninsulated); and eight homes with mixed or unrecorded wall construction (two with cavity wall insulation, one with IWI, two uninsulated, three not recorded).

It is relevant to note that the COVID-19 pandemic also placed a serious limitation on the ability to be selective in choosing survey locations. Although only insulated cavity walled homes were requested, on inspection, several of these were observed to have not been filled.

In total, 145 homes were surveyed by TIUK and when added to the 15 baseline DEEP case study homes discussed in the DEEP case study reports and surveyed by Leeds Beckett, this brought the total sample to 160 homes.

Homes were sourced using convenience and snowball sampling via advertisement across Leeds Beckett University networks; direct requests to landlord groups; and social media campaigns. As a result, homes were predominantly located in the West Yorkshire region and were representative of regional building archetypes. This should be considered in terms of extrapolation and external validity of findings. Householders were provided with a £50 incentive to take part and given access to the results.

As can be seen in Figure 1-1, a range of tenure types were recruited: social and private tenants, landlords, and owner occupiers. The majority of the sample were owner occupiers. Flats were not a major part of the sample, and given their unique constructions, the results found here may not be generalisable to these multi-dwelling buildings. Similarly, only a few bungalows were included in the sample, and so there may be specific construction features of bungalows that affect airtightness that are not captured in this survey.

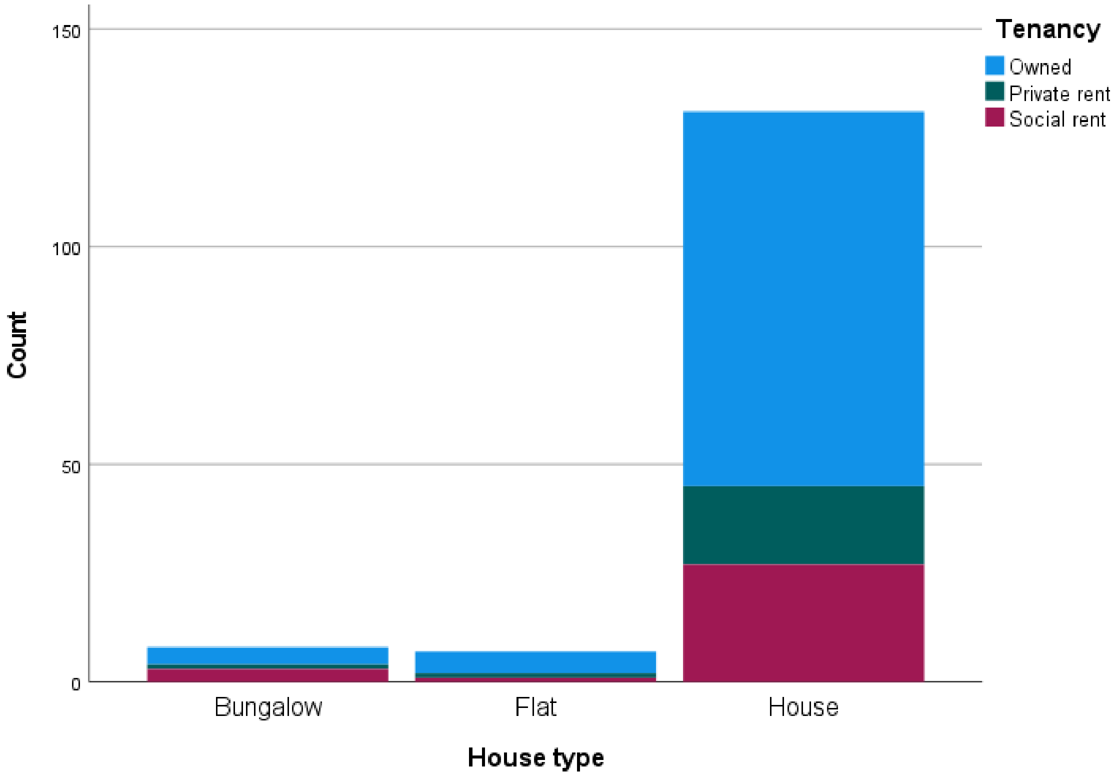

Figure 1-1 DEEP survey house type by tenure

The sample included a range of dwelling ages, as shown by Figure 1-2, although the majority fell between 1890-1960 construction, with limited examples of recently constructed dwellings.

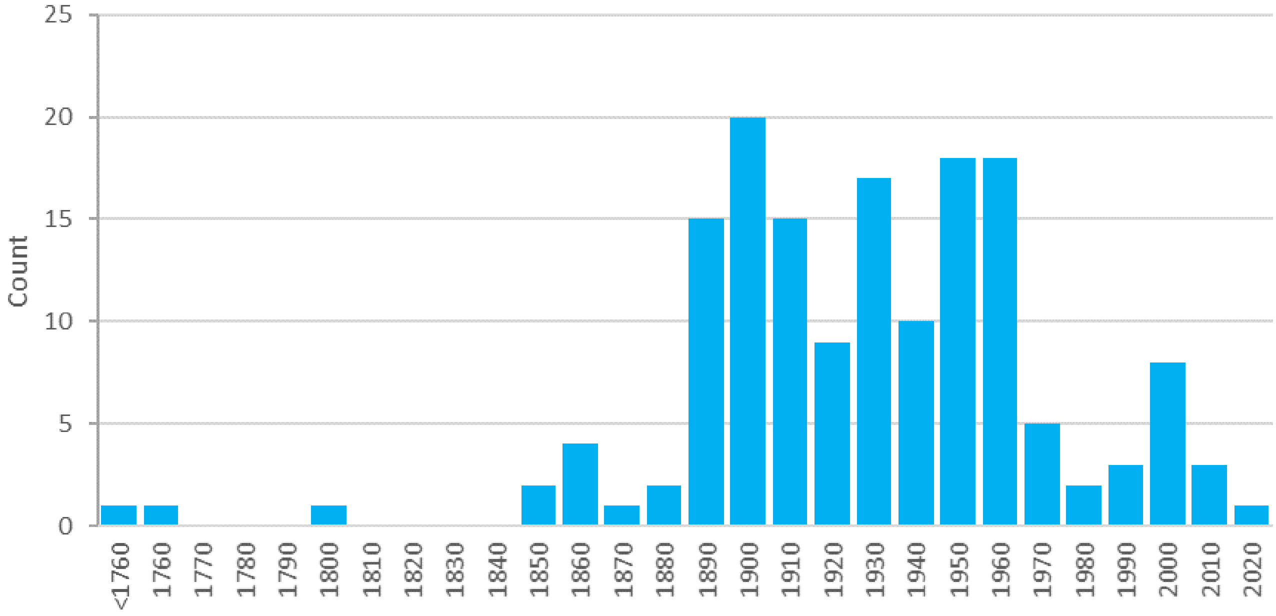

Figure 1-2 DEEP survey homes by age

As can be seen in Figure 1-3, a large amount of the cavity-walled homes surveyed were discovered to be uninsulated during the visits (27 %). Recruitment material asked for only insulated cavity walls, so this points to landlords and homeowners perhaps not knowing if their walls are insulated or not.

The English Housing Survey indicates that 70.5 % of cavity walls in the UK are insulated in some way [3], suggesting that this survey bears good resemblance with the national landscape; with only a slightly higher proportion of insulted cavity walls (73 %) in the sample.

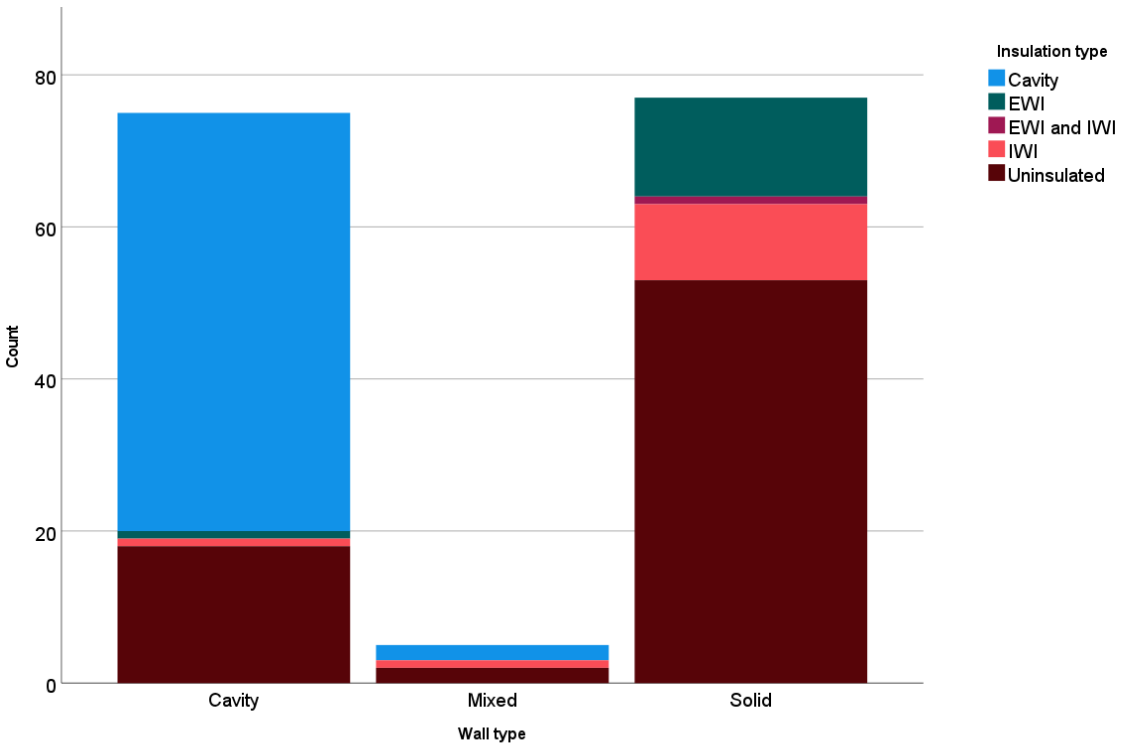

Figure 1-3 DEEP survey homes by wall type

Interestingly, five of the 160 homes had a combination of both cavity and solid walls. This reflected modern cavity wall extensions built on solid wall homes in the present sample, as opposed to changes in construction on the same façade. Of the solid walled homes, most were uninsulated, though a range of EWI and IWI, and one instance of a hybrid insulation solution was observed.

No obvious correlation existed between tenure and if the walls were insulated or not, as can be seen in Figure 1-4 or Figure 1-5.

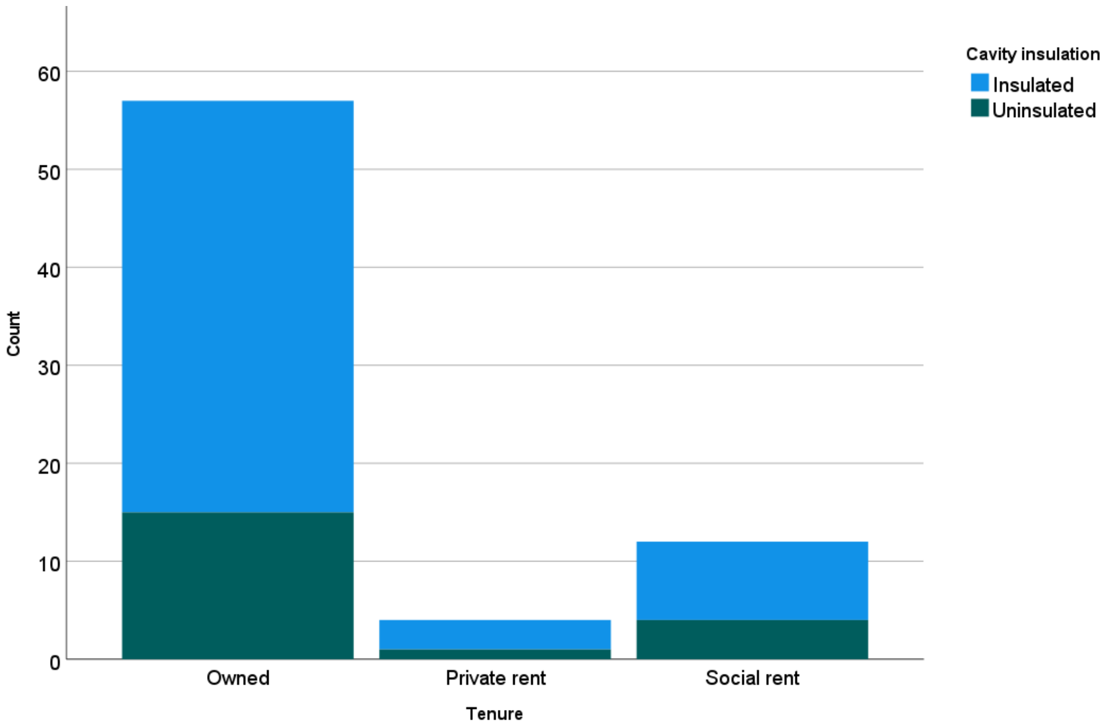

Figure 1-4 Tenure and presence of cavity wall Insulation

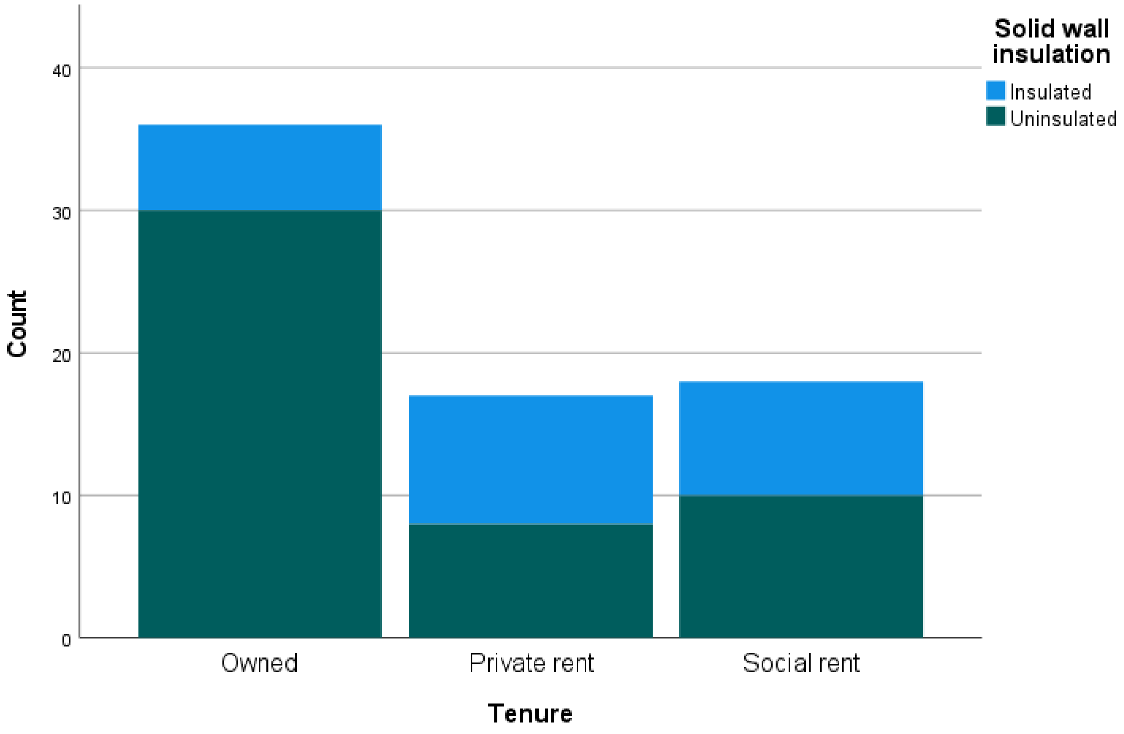

Figure 1-5 Tenure and presence of solid wall insulation

1.3 Sample loft condition

114 loft inspections were undertaken across the sample – in some homes loft access was not available, others had converted lofts. 77% were observed to have less than the minimum top up loft insulation thickness of 250 mm, as recommended by Part L of the Building Regulations. The distribution of insulation thickness is shown in Figure 1-6.

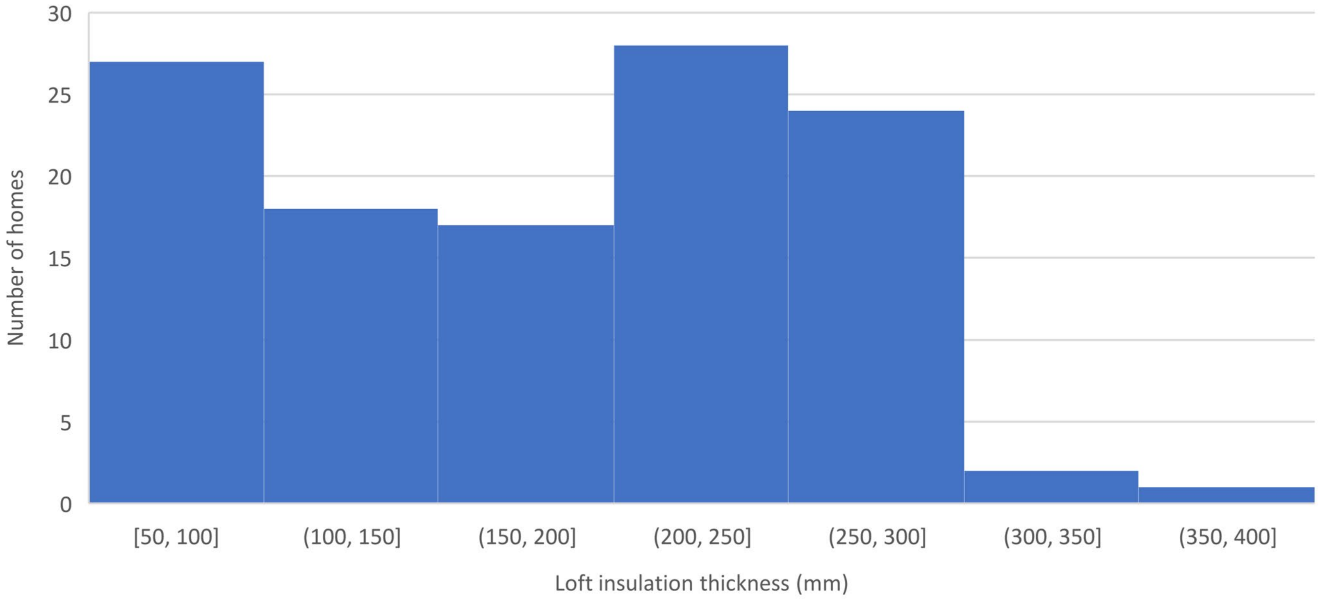

Figure 1-6 Frequency of loft insulation thickness

This indicates that although 70% of lofts are insulated, the performance varies considerably, and that a loft top-up retrofit measure is likely to benefit a large number of homes.

Loft insulation in more efficient homes tends to be thicker, as shown in Figure 1-7, and as may be expected, since loft insulation is an important contributor to EPC score. E and G rated homes (no homes in the sample were rated band F), tend to have more insulation than Band D, but these tended be solid walled homes which drives the EPC score more than loft insulation.

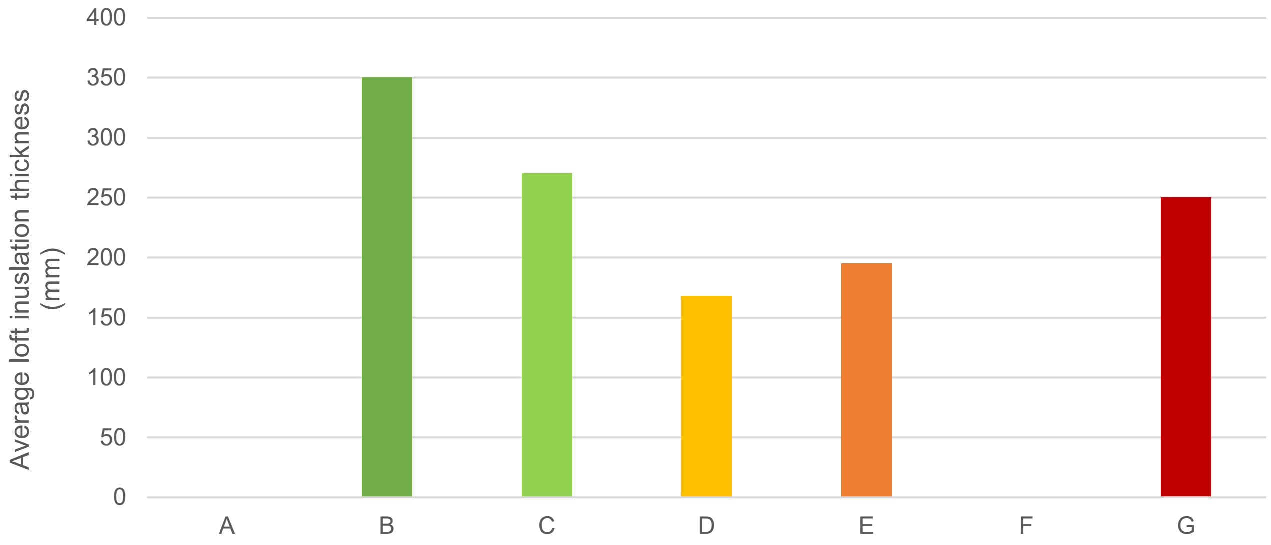

Figure 1-7 Average loft insulation thickness per EPC score

1.4 Sample ventilation and damp condition

During data collection the surveyors identified signs of damp in 42 homes, though there were only three instances of mould. Figure 1-8 shows the distribution of where damp concerns were recorded. It is not possible to indicate the severity or cause of these issues, nor if they are representative for other samples of homes, but they are indicative of where issues were reported.

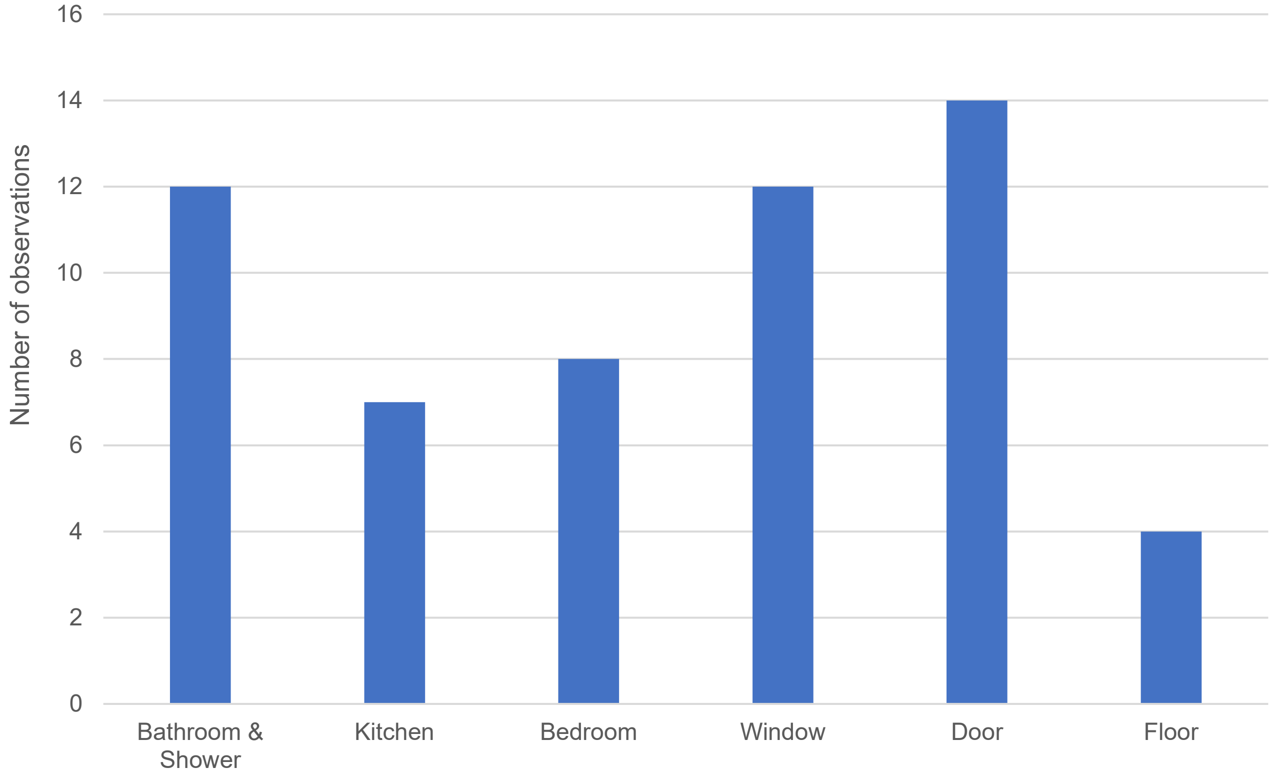

Figure 1-8 Frequency and location of damp observations

Damp is inextricably linked to ventilation, and although the surveys were not intended as full investigations into the damp risk in the homes, the ventilation types in the homes were noted and are shown in Figure 1-9.

In 19 of the 160 homes, no record was taken of any ventilation type (i.e. unrecorded), though there was a positive identification of ‘none’ in 23 homes. Additionally, there were only four homes seen to have trickle vents and only 13 homes had mechanical extract vents (of which eight were private or socially rented homes). It is worth noting that surveys were in occupied homes, so it may be the case that some ventilation types were hidden from view behind furniture.

These findings suggest that there is a low proportion of homes with no ventilation in this sample. The low number of homes with trickle vents is perhaps surprising, given that many of the homes have had double glazing retrofits, indicating most have been installed without trickle ventilation. This suggests that the glazing retrofit occurred prior to trickle vents being commonplace within window design.

No significant difference was found in airtightness between homes with or without visible damp observed in the survey. Due to the small size of the survey sample, it is not possible to conclude whether higher rates of air exchange are beneficial in avoiding damp (i.e. expelling warm, damp, moisture laden internal air direct to outside) or make damp more prevalent (i.e. colder, external air entering buildings and cooling down surfaces, promoting condensation). It is relevant to note the difference between ventilation and airtightness in this regard: with ventilation providing intentional, controlled air movement to improve internal conditions; and airtightness referring to uncontrolled, typically unwanted air movement.

It is not known how consistently the survey was noting down ventilation types; however, large numbers were recorded for some ventilation types. For instance, 57 homes were observed to have air bricks under suspended timber ground floors. This correlates to the 64 homes with suspended timber floors, indicating that the seven remaining homes either had no sub-floor void ventilation, or these were simply not noted during the survey (potentially due to being obscured from view).

Similarly, a relatively large number of homes had wall air bricks, which may not be representative of the UK housing stock but may be more due to the sample containing older homes, where this was the main purpose ventilation provided.

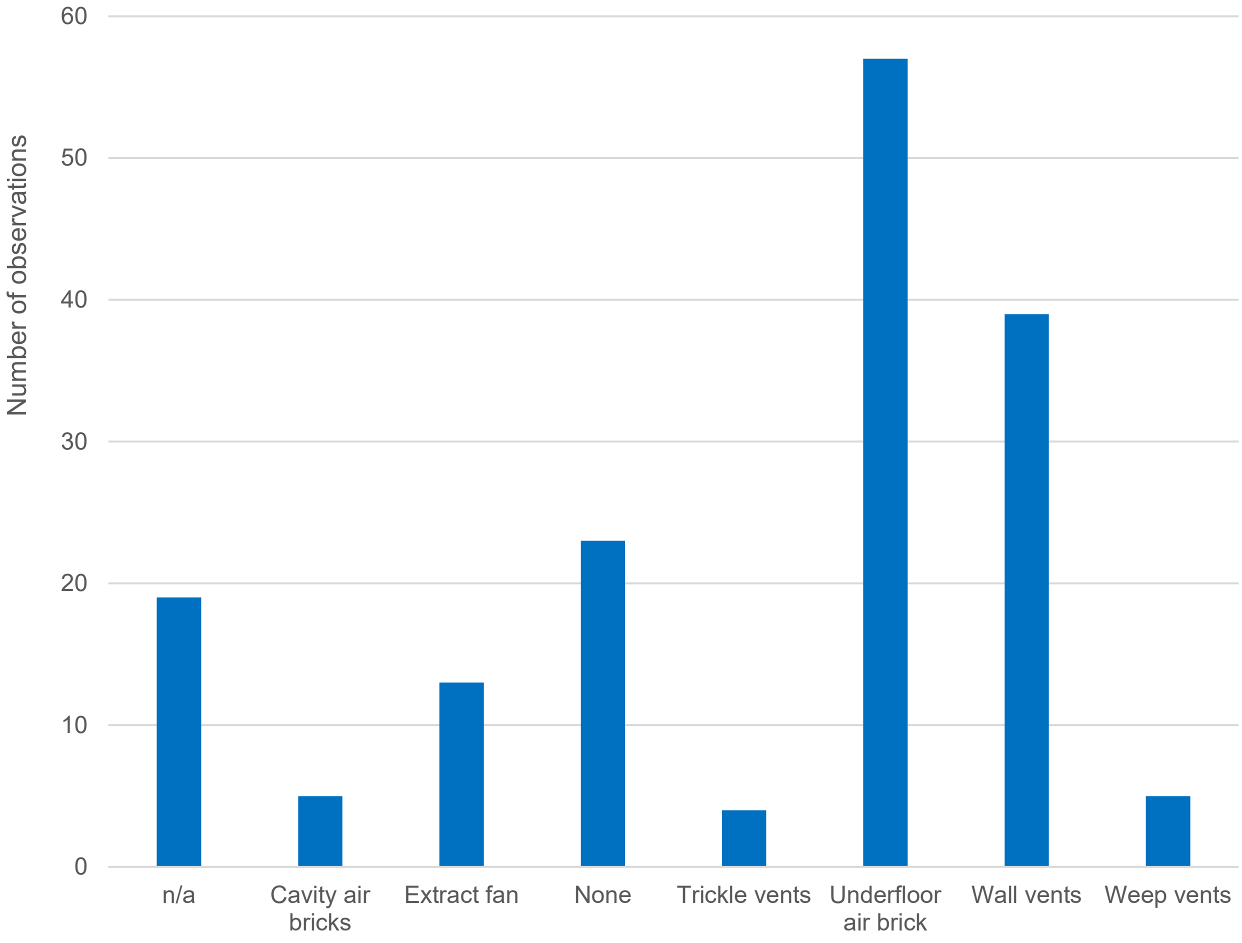

Figure 1-9 Ventilation types in sample

2 Airtightness of the homes

Heat loss via air leakage is an essential component of a home's fabric energy efficiency. Research has shown that there can be heterogeneity in the airtightness of homes, even where they are of the same size, form, and share similar physical characteristics. Few large data sets exist from which to draw generalisations regarding the air leakage of UK dwellings. This chapter describes the sample of dwellings surveyed and how building characteristics relate to airtightness.

2.1 Airtightness and building characteristics

Blower door tests were successfully undertaken in 146 of the 160 homes. A wide range of air permeability was measured across the sample, ranging from 0.9 $m^3/(h \cdot m^2)$ @ 50Pa to 25 $m^3/(h \cdot m^2)$ @ 50Pa, with a mean of 11.07 $m^3/(h \cdot m^2)$ @ 50Pa.The mean of this sample concurs remarkably well with the findings from Stephen [4] who found an average of 11.5 $m^3/(h \cdot m^2)$ @ 50Pa based on a sample of 384 homes. The range of results are shown in Figure 2-1.

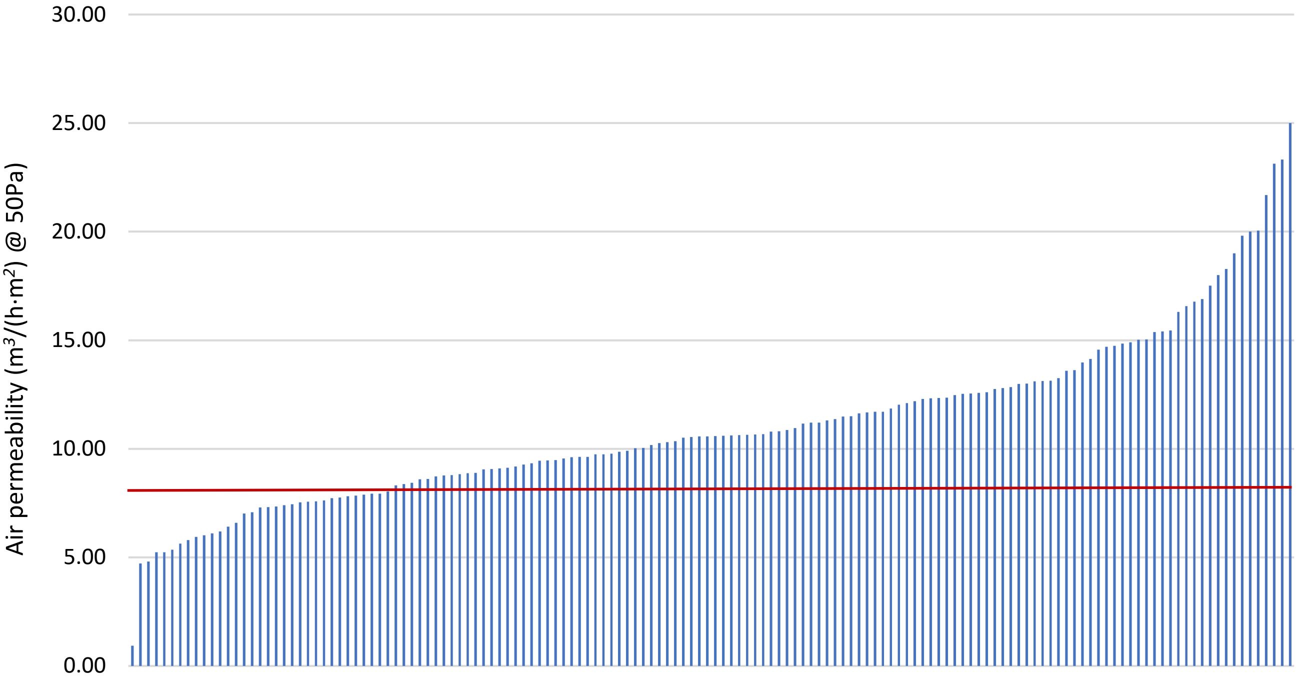

Figure 2-1 Sample airtightness values (red line = Building Regulations new build air permeability limiting value)

The majority of the homes that underwent a blower door test (114 or 78 %) had airtightness levels exceeding the current Building Regulations air permeability limiting value for new build homes of 8 $m^3/(h \cdot m^2)$ @ 50Pa (shown by the horizontal red line in Figure 2-1) with only 32 (22 %) of the homes having air permeability below this threshold. Under the previous Building Regulations air permeability threshold limit of 10 $m^3/(h \cdot m^2)$ @ 50Pa, 63 homes (43 %) would have been within threshold limits [5].

Of the remaining 83 homes, 63 would be considered to have relatively poor airtightness with measured air permeability between 10 and 15 $m^3/(h\cdot m^2)$ @ 50Pa, while 14 homes had high levels of air leakage with measured air permeability between 15 and 20 $m^3/(h\cdot m^2)$ @ 50Pa. Six of the homes were measured to have excessive air permeability above 20 $m^3/(h\cdot m^2)$ @ 50Pa.

The distribution of the data can be seen in Figure 2-2. This shows that there is a clustering of homes between seven and 13 $m^3/(h\cdot m^2)$ @ 50Pa, with few homes below this, but a relatively long tail of homes with very poor levels of airtightness up to 25 $m^3/(h\cdot m^2)$ @ 50Pa. The Stephen [4] data set exhibited a broadly similar frequency distribution, though had a slightly longer tail of homes at higher levels of air leakage.

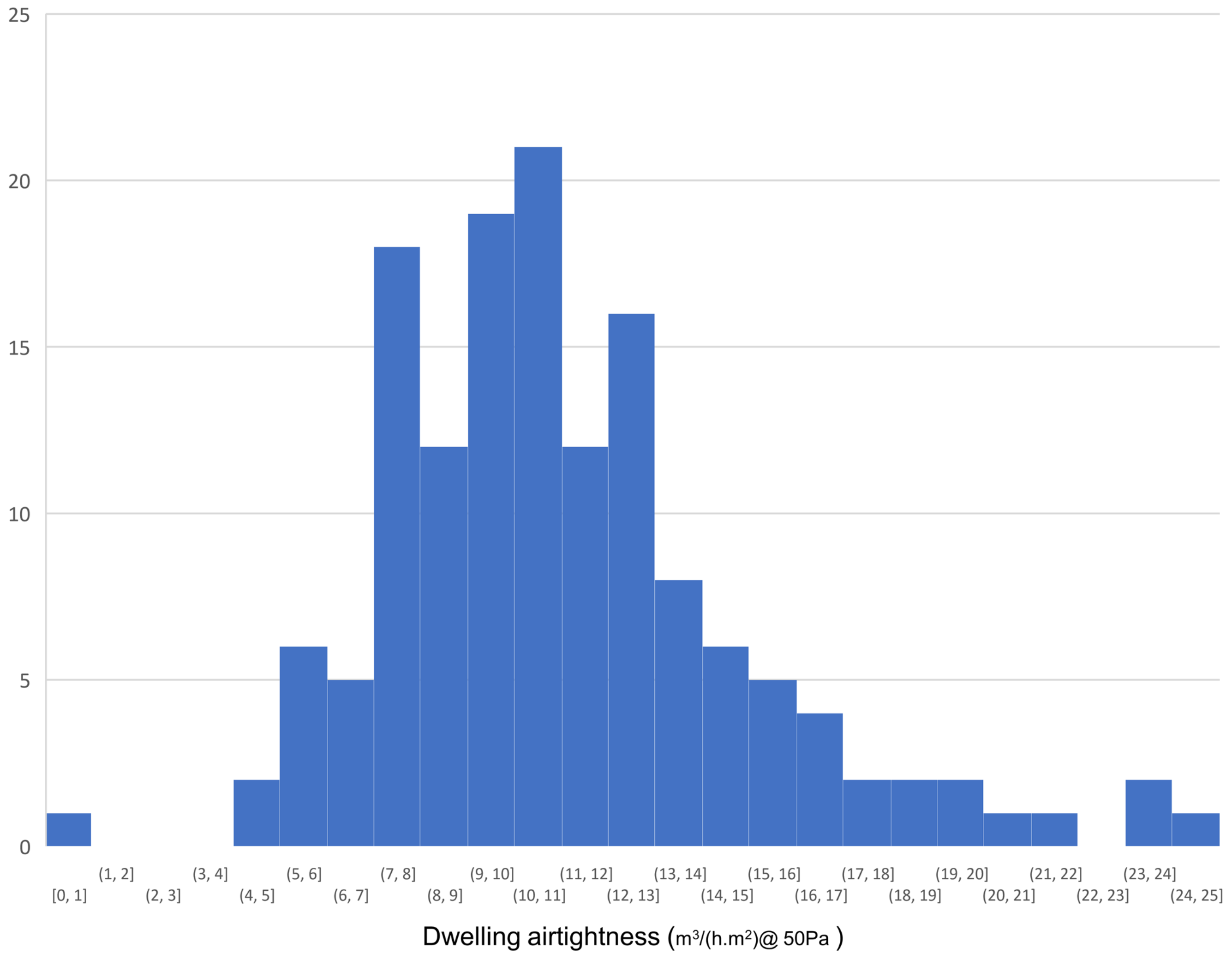

Figure 2-2 Distribution of airtightness test results for cohort

When considering the airtightness of the existing building stock, it is relevant to consider the effect of building characteristics. The following sections discuss how airtightness varied according to different characteristics of buildings, to understand what may be behind the variability.

For comparison of airtightness between different building characteristics, statistical tests have been applied. Where the data satisfy assumptions for use of parametric methods, independent t-test and ANOVA have been applied to compare characteristics, together with Pearson's R for evaluation of correlations.

Where data are not suitable for parametric methods, for example, due to skewed distribution or unequal samples, non-parametric Mann-Whitney *U*, Kruskal-Wallis *H* with Bonferroni correction and Spearman’s Rank tests have been applied. Details for methods used during both data collection and analysis may be found in further detail in the supporting methodology report for the DEEP project.

2.1.1 Building age

142 homes had a valid blower door test together with details of the decade when the home was built. Building age, categorised into decade of construction, showed a weak negative correlation that was significant at the 0.05 level (r_s (142) = -0.182, p=.028). This suggests that, across the sample measured, newer buildings were marginally more airtight. However, the relationship was not strong and as can be seen in Figure 2-3, the airtightness across each decade grouping is very varied, which should be considered when generalising this finding.

Stephen [4] similarly did not find a good correlation between the age of dwellings and airtightness, though they noted homes post 1980 appeared to be more airtight. Although the sample size is small, this data suggests that homes built post 2000 were notably more airtight. This broadly correlates with the introduction of airtightness compliance testing and limiting infiltration rates in the Building Regulations in 2002, which became mandatory in 2006 [5].

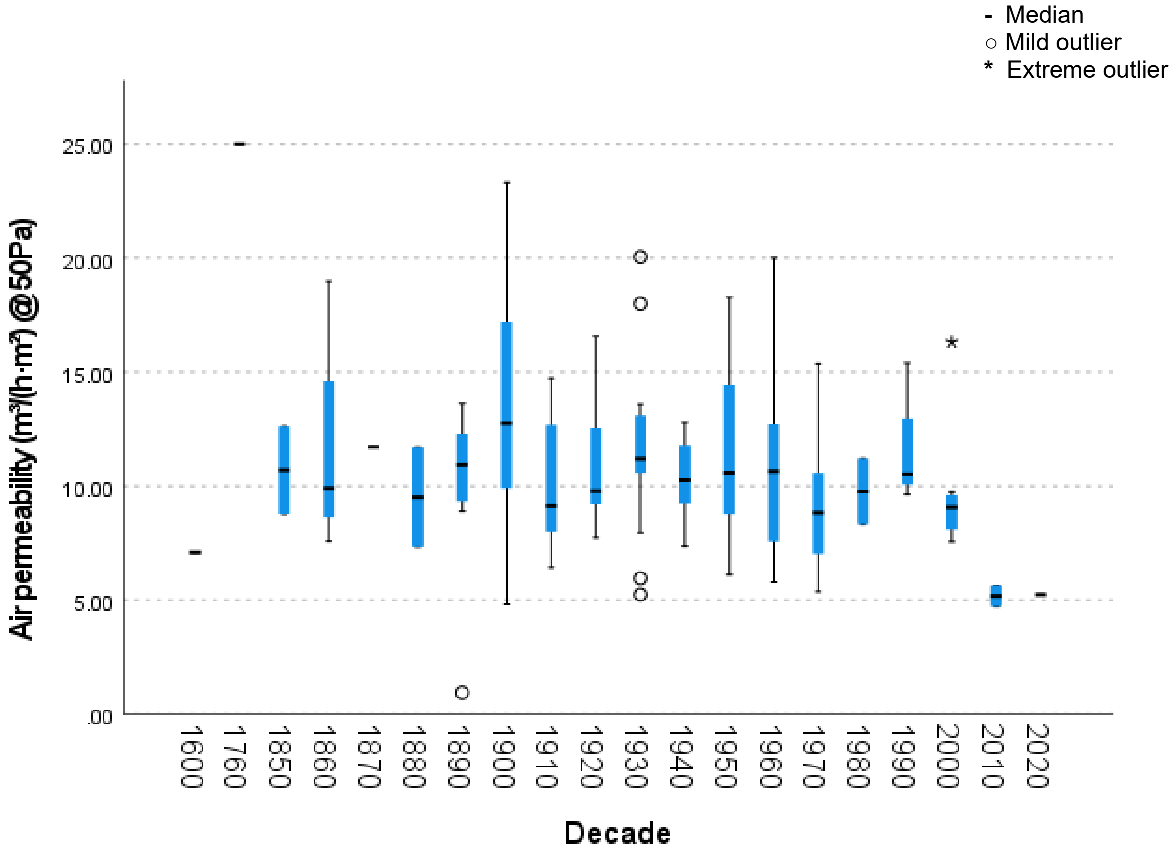

Figure 2-3 Airtightness distribution of homes per decade

Chimneys in dwellings are sealed when undertaking the airtightness tests, so in older dwellings that have chimneys, during normal occupation, the dwellings will be leakier than measured using the blower door tests. This may have substantial impact on heat loss during occupation, and work to disaggregate the contribution of chimney heat loss is an area for further research.

2.1.2 Wall construction and material properties

No significant difference in airtightness was observed between main wall material and construction types or materials, although it should be noted that most homes tested were brick and of solid or cavity construction, and none were timber-framed, which limits the potential for comprehensive comparison with other construction types or data sets. The sample characteristics and airtightness distribution of wall types is shown in Figure 2-4 and Figure 2-5.

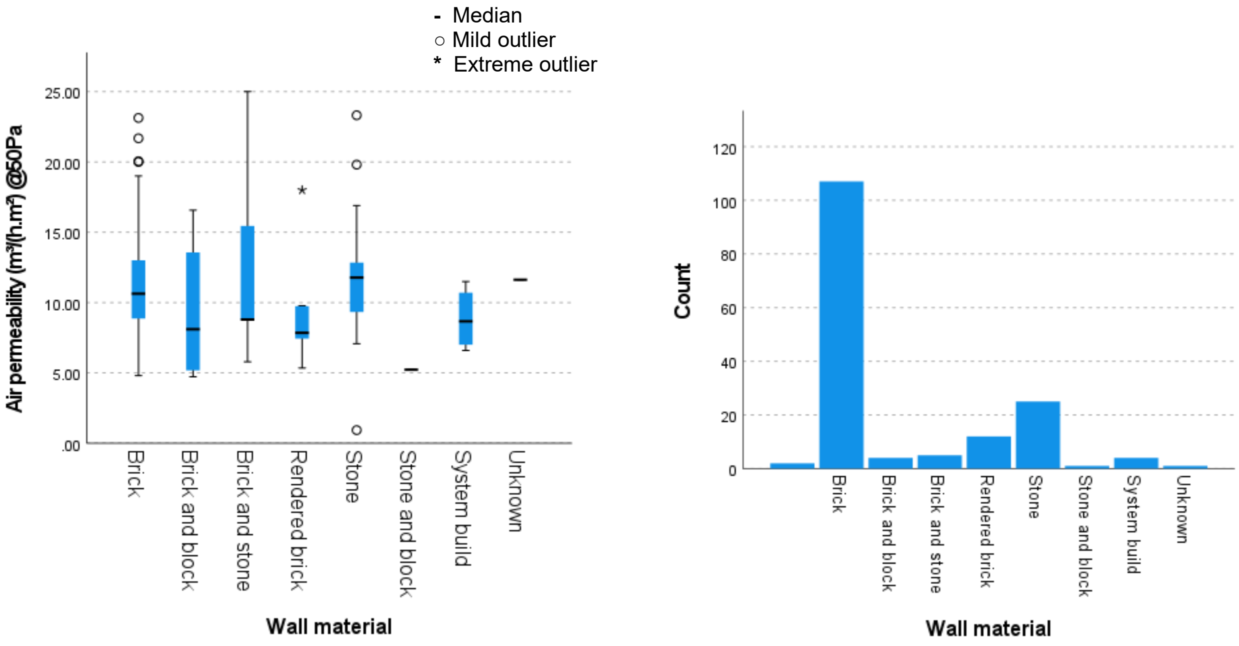

Figure 2-4 Airtightness per wall material

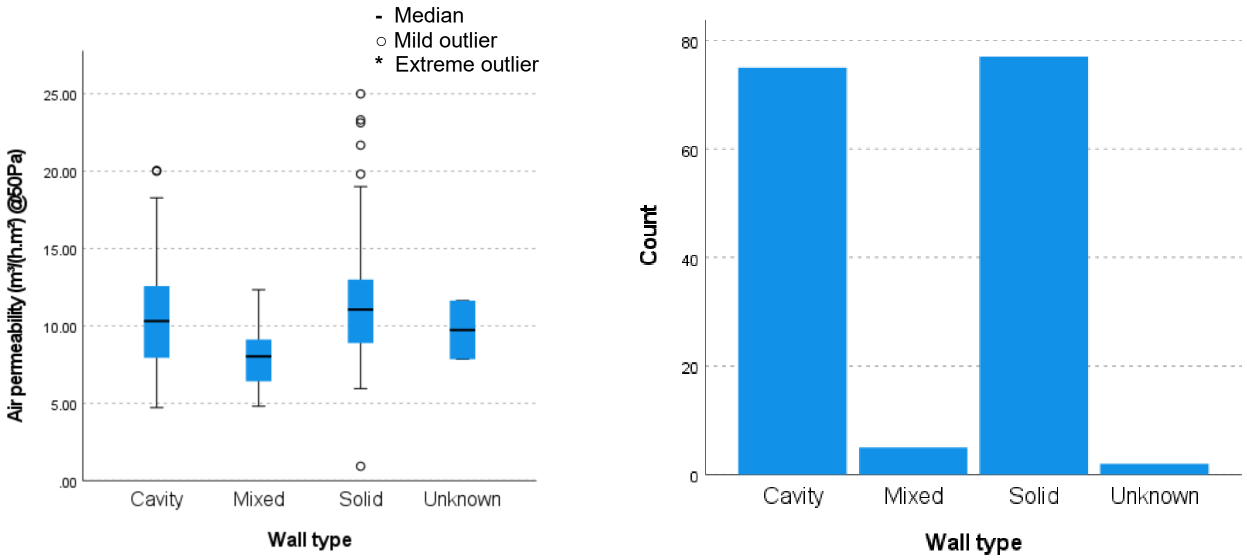

Figure 2-5 Airtightness per wall type

2.1.3 Internal wall finish

Although the main construction of the external walls themselves did not return a significant difference, there was observed to be a significant difference in airtightness between different types of internal wall finish (H (2) = 7.898, p = .019).

This difference was most pronounced for mixed methods of internal finishing, which displayed an average air permeability of 14.3 $m^3/(h{\cdot}m^2)$ @ 50Pa, although this was across a small sample (n=6) as shown by Figure 2-6. Mixed finish displayed a significant pairwise difference to both wet plaster (p = .019) and dry-lined (p = .086) plasterboard finish.

Where mixed finishes are present, it is likely that there has been some form of extension or refurbishment in the home. Since these homes tend to exhibit greater levels of air leakage, it may be that the integration of the old and new air barrier was not effective. However, the sample size is too low to draw generalisations and more investigations are needed.

Air pathways behind skirting boards and behind dry lining (e.g. dot and dab plaster boards) are commonly cited weaknesses in homes. These areas often link to gaps and cracks in the external walls and wall cavities, as well as directly with ground floor voids, intermediate floor voids, service voids, and the loft space. However, in this study, dry-lined homes were not observed to have significantly different levels of airtightness than wet plastered homes. Median values were observed to be similar, with a difference of only 0.31 $m^3/(h{\cdot}m^2)$ @ 50Pa. It is worth noting, however, that the range in both finish types was very large.

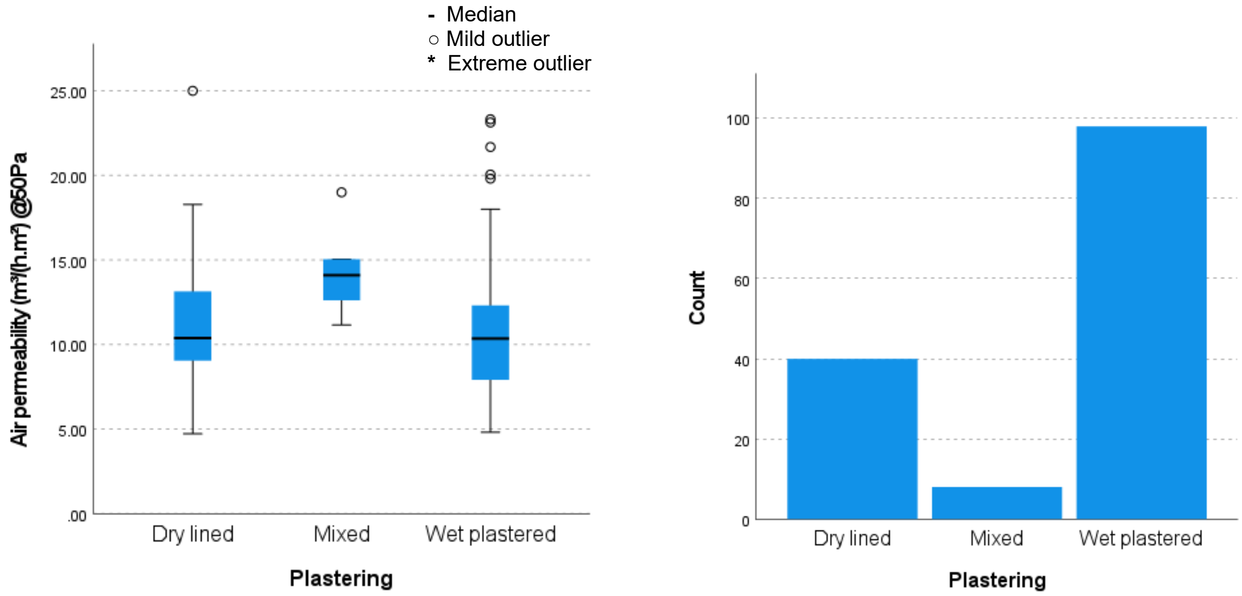

Figure 2-6 Airtightness and internal plaster finish

2.1.4 Ground floor

The ground floor type was observed to significantly influence how airtight a home was. A significant difference was observed between the three floor types: suspended timber, solid, and mixed (*H* (2) = 17.779, *p* = <.001). Mixed floor construction had both solid and suspended floors, either as part of the original house design or owing to extensions or modifications to the original dwelling.

Solid floors were significantly more airtight than suspended timber floors (*U* = -36.49, *p* = <.001), which confirms the perception that suspended timber floors tend to be major air leakage pathways in homes. This is also consistent with the work undertaken by Stephen [4].

Mixed floors were also significantly more airtight than suspended timber floors (*U* = -21.524, *p* = .045) following pairwise comparison with Bonferroni correction, i.e. even if homes have only a partial solid floor, they may be more airtight. Further investigation into the reasons for this is needed, however. It may be that homes with mixed floors have less underfloor void ventilation, or because there is a smaller proportion of the floor with plain-edged floorboards through which infiltration often occurs.

The distribution of observed floor types is shown in Figure 2-7 and, taken with the test statistics, illustrates the lower level of airtightness for the suspended timber ground floor properties.

The type of suspended timber floor covering itself was not noted i.e. plain edged floorboards vs. tongue and groove sheets (the latter being noted as a more airtight option), so it is not possible to relate the airtightness to the type of floor covering or to distinguish between infiltration occurring through the floorboards or at the ground floor perimeter.

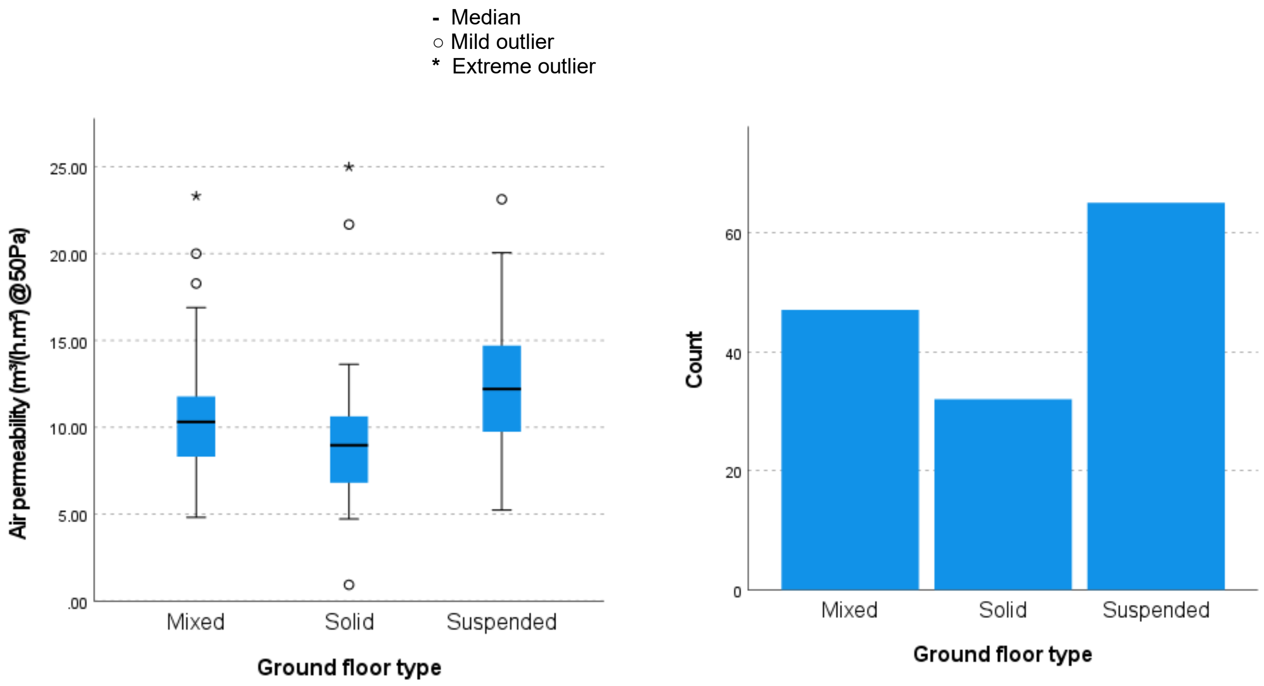

Figure 2-7 Airtightness per floor type

2.1.5 Dwelling form and party elements

The importance of dwelling form and attachment type did return a significant difference (*H* (10) = 21.021, *p* = .021). In very broad terms, detached and semi-detached homes appear to have higher levels of airtightness than mid-terraced homes. However, the usefulness of this statistic is questionable given the number of attachment types observed, together with the small and uneven sample sizes, shown in Figure 2-8. This relationship is weak, and when compared pairwise, differences were not found to be significant with corrected p-values.

In order to achieve a more useful comparison, attachment types were grouped into number of party elements (i.e. shared by two adjoining properties). The distribution of airtightness by number of party elements is shown in Figure 2-9. No significant difference was observed during statistical comparison, which suggests that other factors related to the overall dwelling form, are likely to be more significant than the number of party elements.

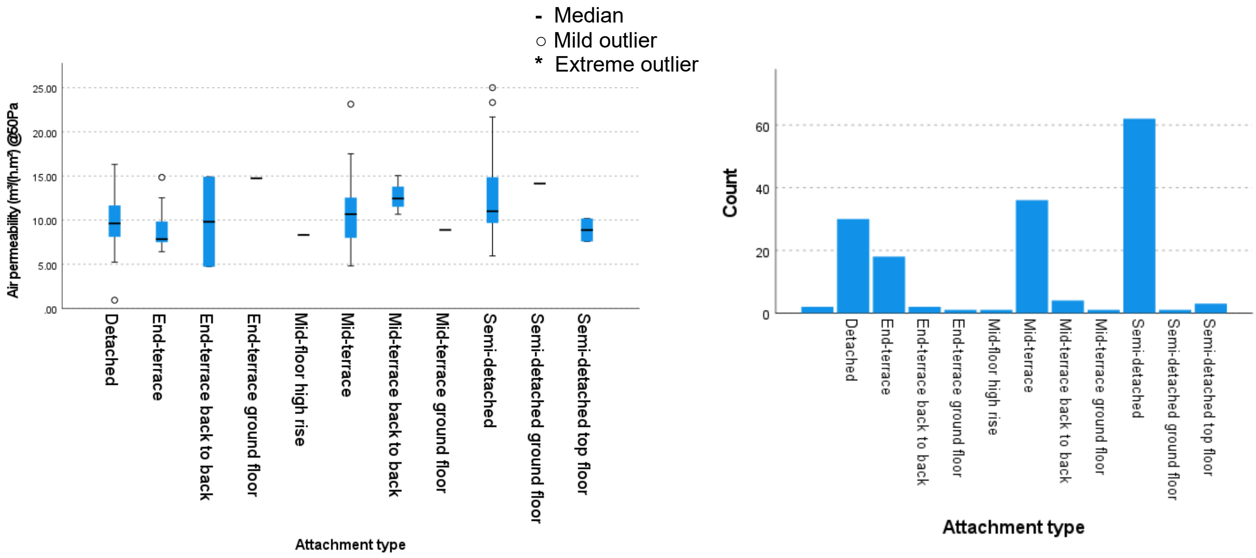

Figure 2-8 Airtightness according to attachment type

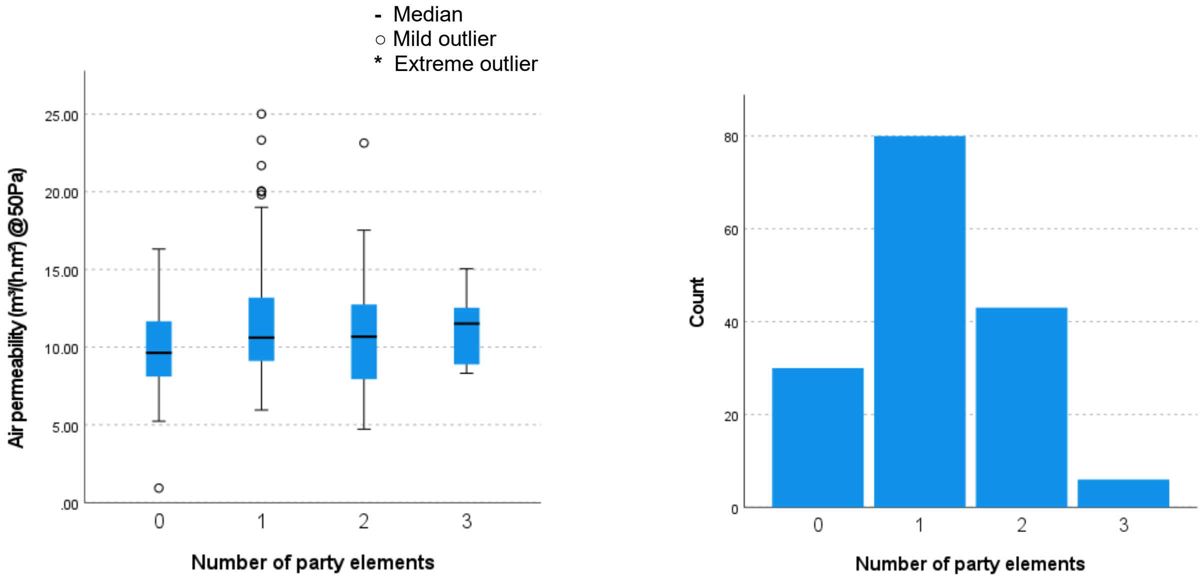

Figure 2-9 Airtightness according to number of party elements

2.1.6 EPC score

It may be presumed that homes with higher EPC scores are more airtight. A higher EPC score infers better build quality, and increased airtightness is an aspiration of better build quality, since it results in a lower degree of unintentional, uncontrolled air movement. However, neither air leakage rate nor air permeability is an input into EPCs when RdSAP is used, instead default values are assumed. Only EPCs for new build homes, which use full SAP, can consider measured airtightness levels. In this sample of older homes, the EPCs were based on RdSAP. Not all homes in the survey had EPCs that were available, so the sample size is significantly smaller for this analysis (n=39). Figure 2-10 and Figure 2-11 show the available EPC and EIR (Environmental Impact Rating) scores for the homes in the sample and illustrate the airtightness variability present.

No significant correlation was observed between the airtightness of dwellings and their RdSAP score (based on fuel bills) or EIR score (based on carbon emissions). These results therefore suggest that airtightness is not being addressed when homes are being retrofitted. More data is needed to explore this relationship.

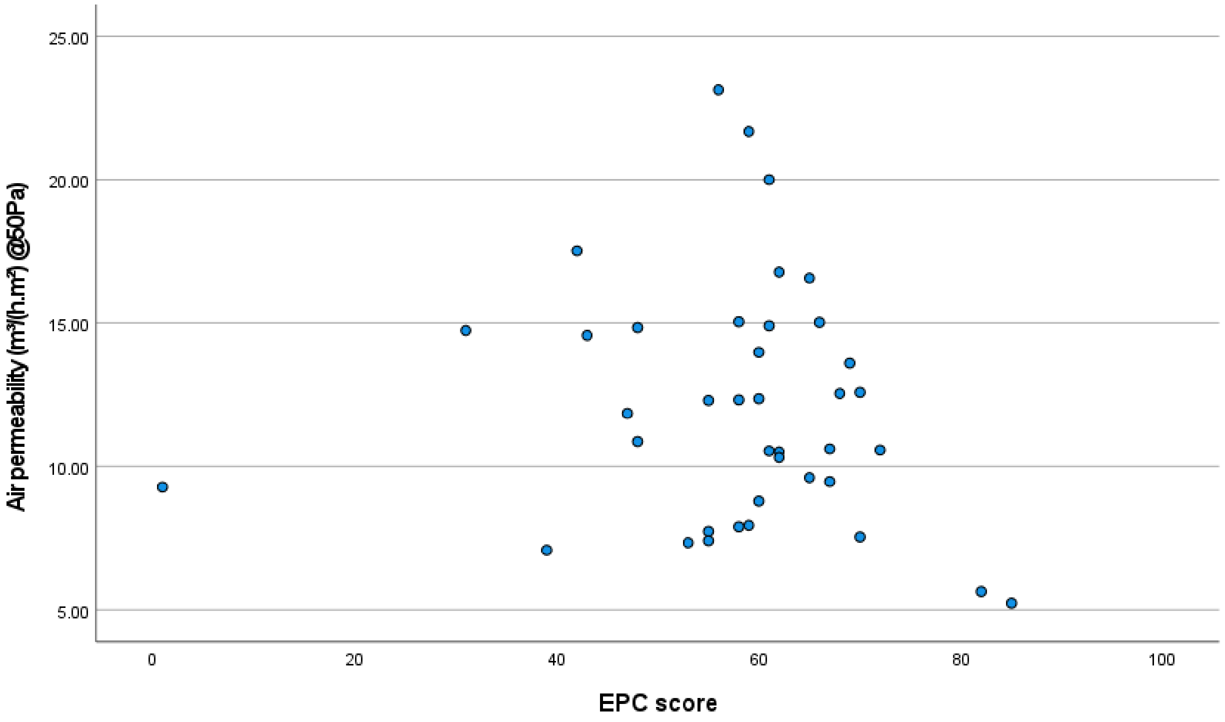

Figure 2-10 Airtightness and EPC score of homes

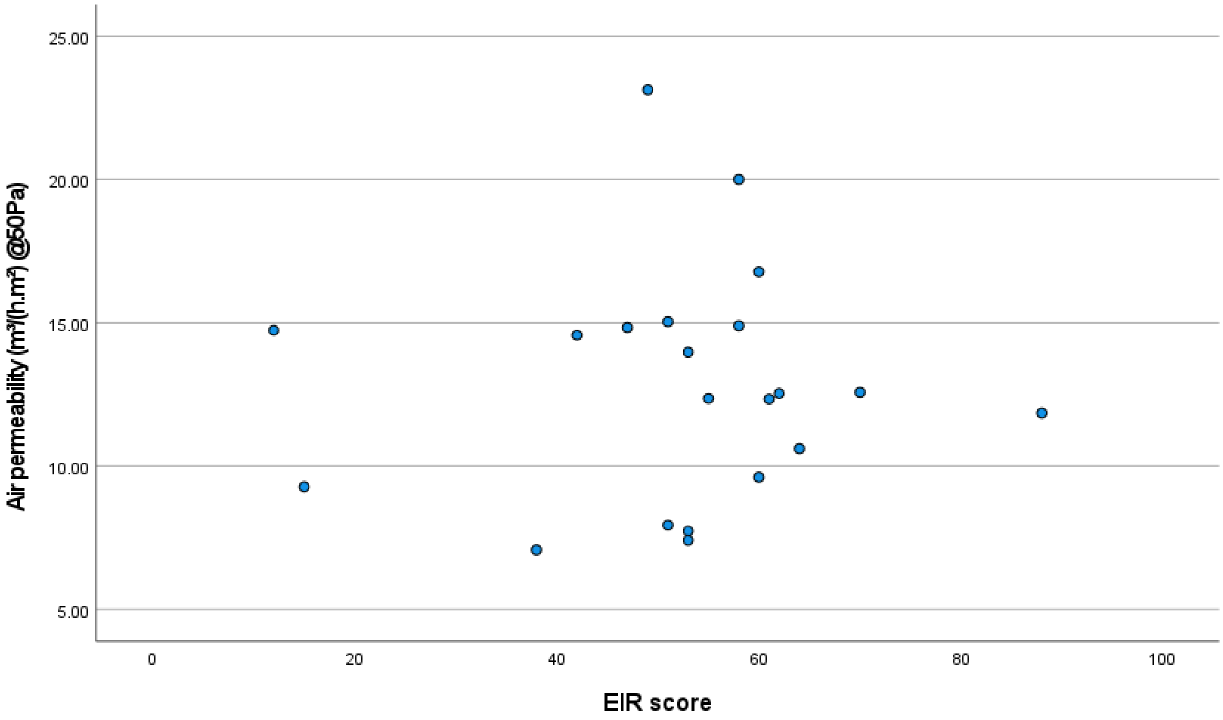

Figure 2-11 Airtightness and EIR score of homes

2.1.7 External window and door condition

No correlation or significant difference was found when considering airtightness and the condition of external windows and doors (as observed by the surveyor) in the sample, the distribution of which can be seen in Figure 2-12 and Figure 2-13. This observation is noteworthy given the influence of openings on air movement in dwellings. However, it must also be considered critically, as the subjective evaluation of quality was based upon a visual inspection only, and no consistent standard was applied to the range of observed window types and models.

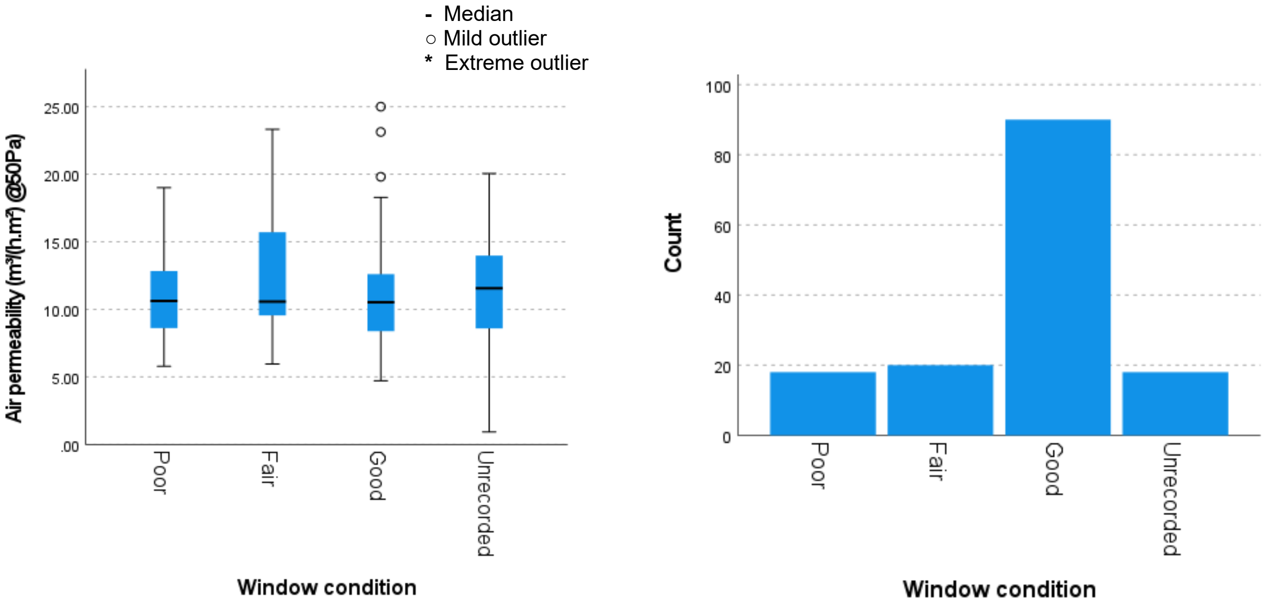

Figure 2-12 Airtightness and external window condition

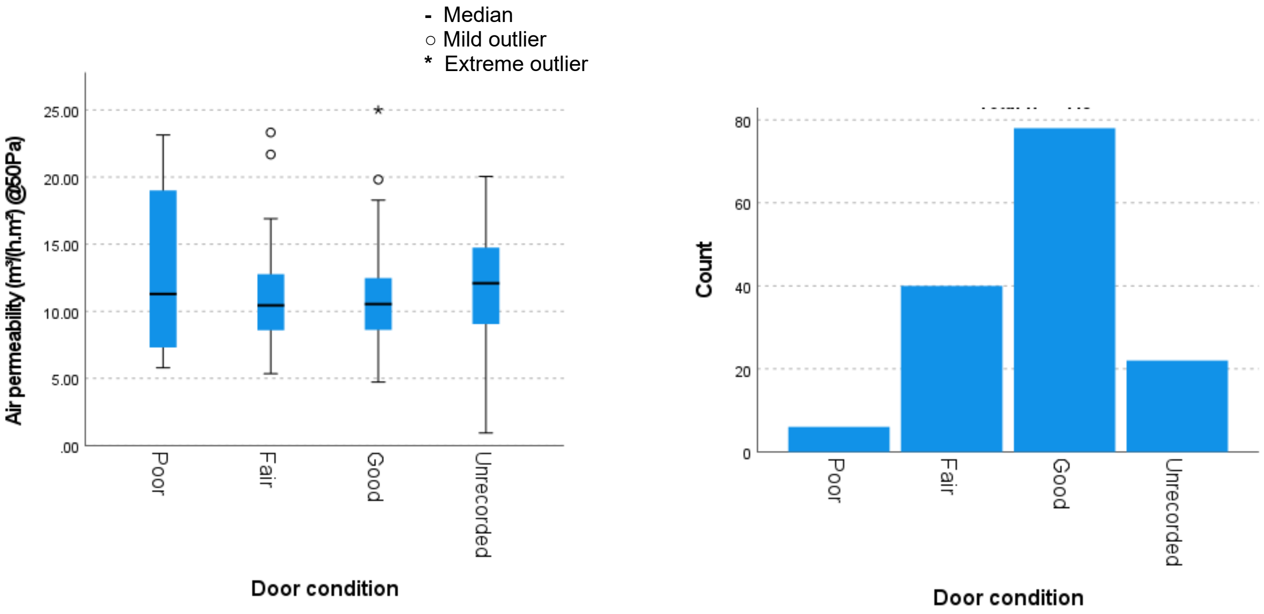

Figure 2-13 Airtightness and external door condition

Additionally, there was no significant difference in the mean air permeability found between homes with single glazing (11.6 $m^3/(h \cdot m^2)$ @ 50Pa) and double glazing (11.12 $m^3/(h \cdot m^2)$ @ 50Pa). However, the two homes with triple glazing were more airtight with mean air permeability measured at 6 and 9 $m^3/(h \cdot m^2)$ @ 50Pa.

2.2 Air leakage pathways

Having established the aggregated airtightness of dwellings, it was also the intention of the surveys to identify specific leakage pathways. Whilst a total airtightness figure gives an indication of total heat loss via air movement, the location and nature of specific air movement pathways are significant for numerous reasons.

Firstly, draught occurrence is a key contributing factor in occupant comfort and wellbeing, and can influence energy use. Similarly, by identifying the pathways of air movement, it is possible to undertake targeted remedial action. Finally, locations of air movement are typically critical areas for damp and mould formation, as cooler air entering the property causes cooler surfaces in a locality, promoting condensation and damp.

The surveyors, therefore, undertook air leakage detection during depressurisation, using thermography. From these a keyword search was performed to identify the most frequently occurring terms used to describe the air leakage pathways. Figure 2-14 shows those keywords that were mentioned at least 10 times.

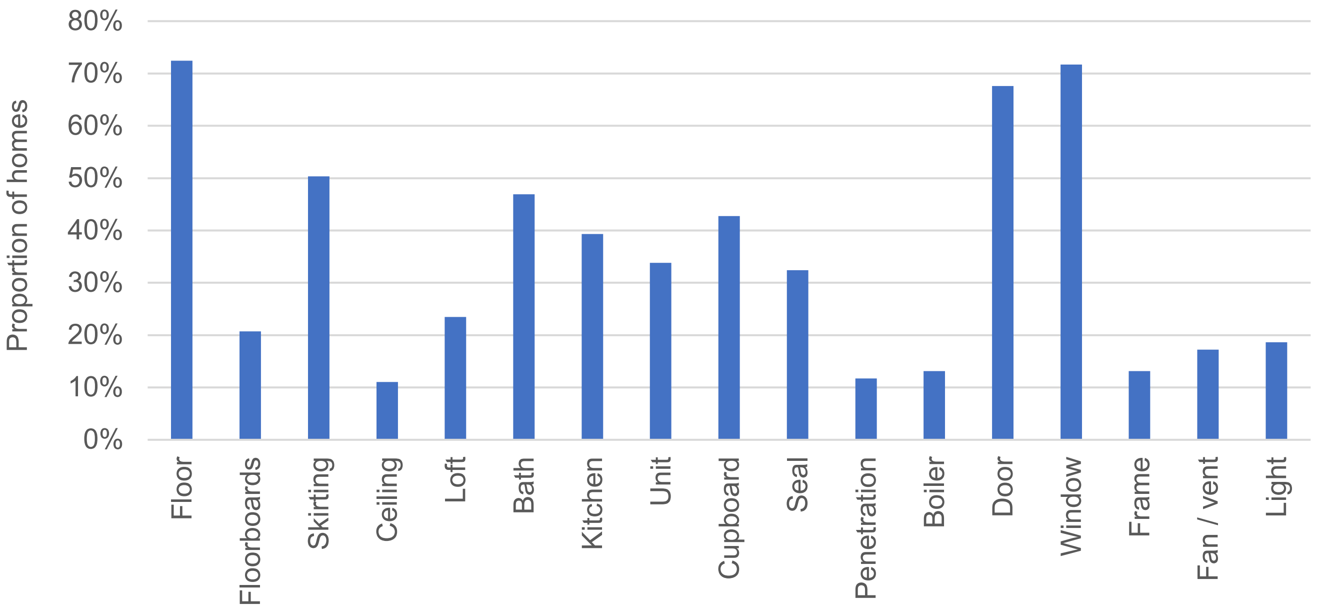

Figure 2-14 Most common air leakage pathways

It is not possible to quantify the scale of leakage at each pathway or compare which is more significant, only to identify which were commonly occurring. As can be seen, a large proportion of homes had air leakage through the ground floor and its perimeter.

More than a third of homes had air leakage pathways behind wall fixed units and cupboards (including the bath panels) in bathrooms and kitchens, where pipework often penetrates through external walls.

Other noteworthy leakage pathways were doors and windows, which were both mentioned in over two thirds of homes. Up to one in five homes had at least one leakage pathway related to seals which may have failed, as well as leakage around penetrations for wall or ceiling mounted items such as fans, boilers, lights, and loft hatches. The following sections show examples of some of these commonly occurring air leakage pathways.

2.2.1 Suspended timber floors

Figure 2-15 shows air movement through a suspended timber floor, with cooler air passing through unsealed gaps between the plain-edge floor boards. This type of air infiltration was common for homes both with and without basements below and often lead to the carpets lifting under depressurisation. It is also relevant to note the impact that carpets and sealed flooring may have on reducing air movement under typical conditions (i.e. not under forced depressurisation).

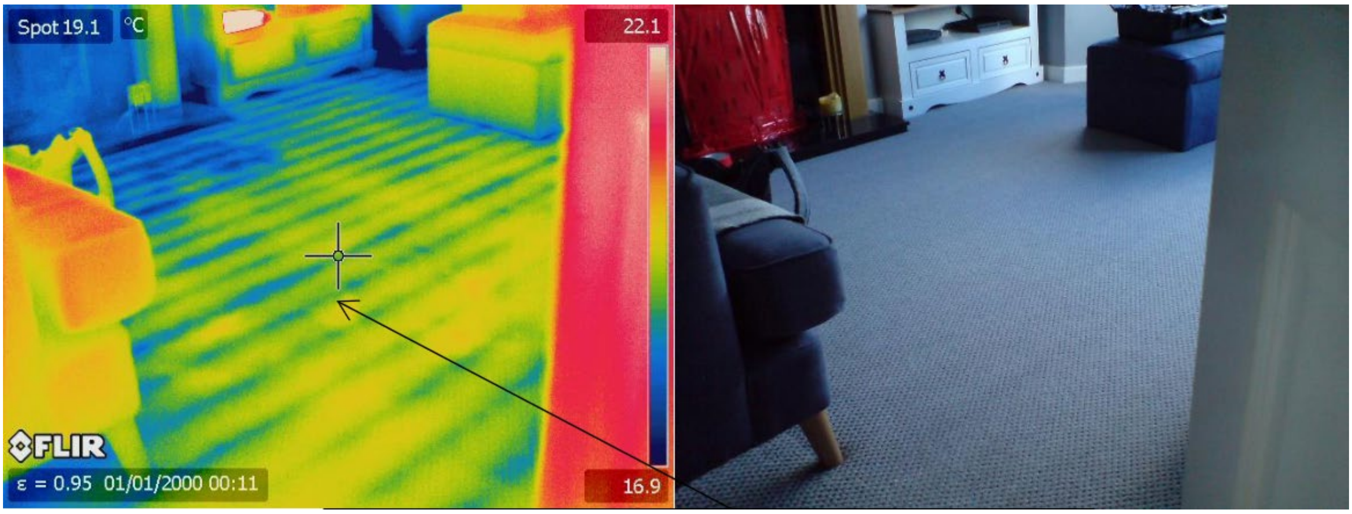

Figure 2-15 Air movement through a suspended timber floor

2.2.2 Skirting

Substantial air movement was observed behind skirting at ground floor perimeters, as illustrated in Figure 2-16. This air movement was present in both suspended and solid floor dwellings, with infiltrating air at the external wall/ground floor junctions being drawn through gaps and cracks to eventually emerge at the ground floor perimeter.

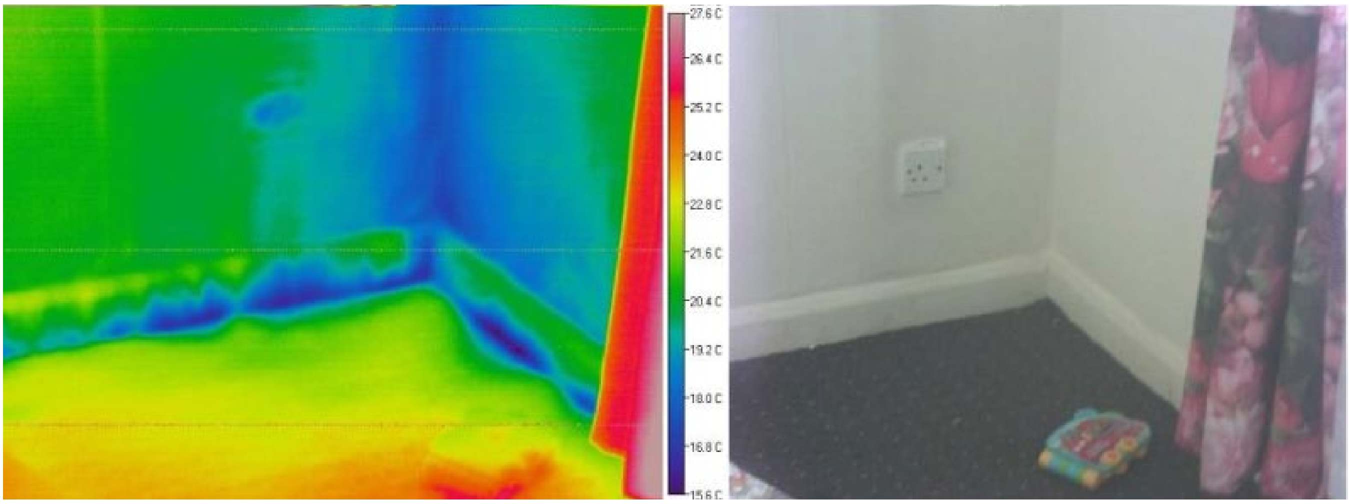

Figure 2-16 Air movement behind skirting

2.2.3 External window frames

Many of the homes surveyed displayed air movement around the junctions between the window frames and the external wall openings, as illustrated by Figure 2-17. This air pathway concerns the sealing of the junctions between the window and the wall, with air movement through these gaps and emerging at both jamb and sill. Some leakage was seen around deteriorated seals between the glazing and the window frames, though these were less common than the leakage around the frame and external wall which suggests often the windows themselves may be airtight, and leakage is due to how they were fitted.

Figure 2-17 Air movement around window casement and seal

2.2.4 Ventilation seals

During the blower door test, purpose-provided ventilation is temporarily sealed using low-tack tapes. This is to ensure that the test only identifies unwanted air movement and differentiates between uncontrolled air leakage and purpose-provided ventilation. It was common to observe issues with purpose-provided ventilation even when they were sealed, as shown by Figure 2-18. Extract fans or air vents should be adequately sealed to the wall, so that air movement is exclusively through the unit and not around it. As can be seen, this was often not the case, with air movement at the interface between the vent and the external wall.

Figure 2-18 Air movement around purpose-provided ventilation

2.2.5 Doors

Similar to the issues observed with external windows, doors presented substantial unwanted air movement. Two types of doors were commonly observed showing issues. These were uninsulated basement doors and external doors, shown by Figure 2-19 and Figure 2-20 respectively.

Unlike with windows, the infiltration was mainly occurring between the door and the frame (especially thresholds) rather than the frame and the external wall suggesting seals were not adequate. Added issues for doors were unsealed letter boxes and keyholes, and where draught-stripping was fitted it often missed areas at hinges and locks.

Commonly cellar doors are internal quality doors and therefore have lower quality seals and thermal performance than external doors and they tend not to have any threshold frame, resulting in a gap between the door and the floor.

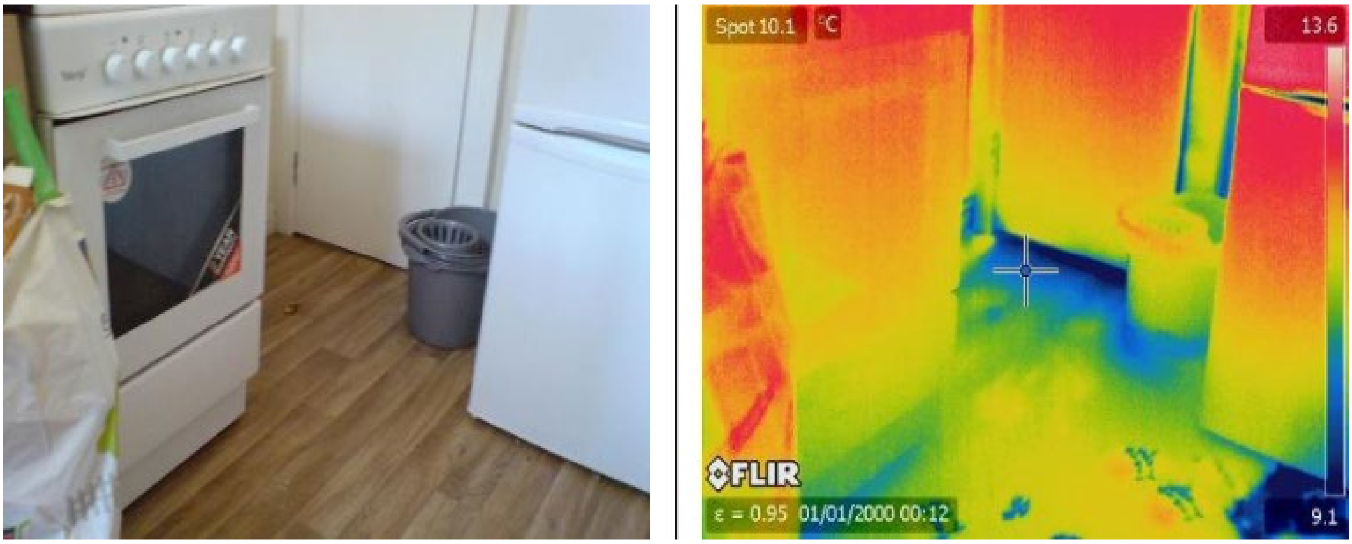

Figure 2-19 Air movement under a basement door

Figure 2-20 Air movement across an external door

2.2.6 Loft hatch

Figure 2-21 shows an example of air movement around a poorly fitting loft hatch. This is a common issue for cold pitched roof properties, where a simple wooden loft hatch was generally laid over the loft entrance with little sealing in place. This particular air movement pathway will accelerate heat loss, bypassing any insulation that may be in the loft space. Most of the lofts had loft insulation retrofitted, yet the loft hatch was not upgraded as standard at the same time, suggesting there is a large proportion of leaky and uninsulated loft hatches in UK homes.

Figure 2-21 Air movement around a loft hatch

2.2.7 Electrical fittings

Another common air pathway into the loft space was unsealed electrical fittings, such as lighting and alarm systems as shown by Figure 2-22. These fittings are often only screwed into place with no sealing and conceal a gap in the ceiling that provides a route for air movement into the loft space. This may also be a problem on lower floors, where air may pass into intermediate floor voids and then escape at the building perimeter. It is not clear how well articulated the issue of airtightness is for electricians fitting lights and other items to walls and ceilings, or how commonly airtightness products are used to address this air leakage.

Figure 2-22 Air movement around electrical fittings into loft space

2.2.8 Service penetrations

Air leakage at service penetrations such as pipework and ducting were a common observation, as shown in Figure 2-23. These penetrations should be sealed where they compromise the building fabric; however, it was common to see an insufficient seal, deteriorated sealing, or a lack of sealing entirely. Air movement at service penetrations can be significant, as it is often a direct pathway to the external environment and the openings can be large. It is not clear how well articulated the issue of airtightness is for plumbers installing pipework through walls and ceilings, or how commonly airtightness products are used to address this air leakage.

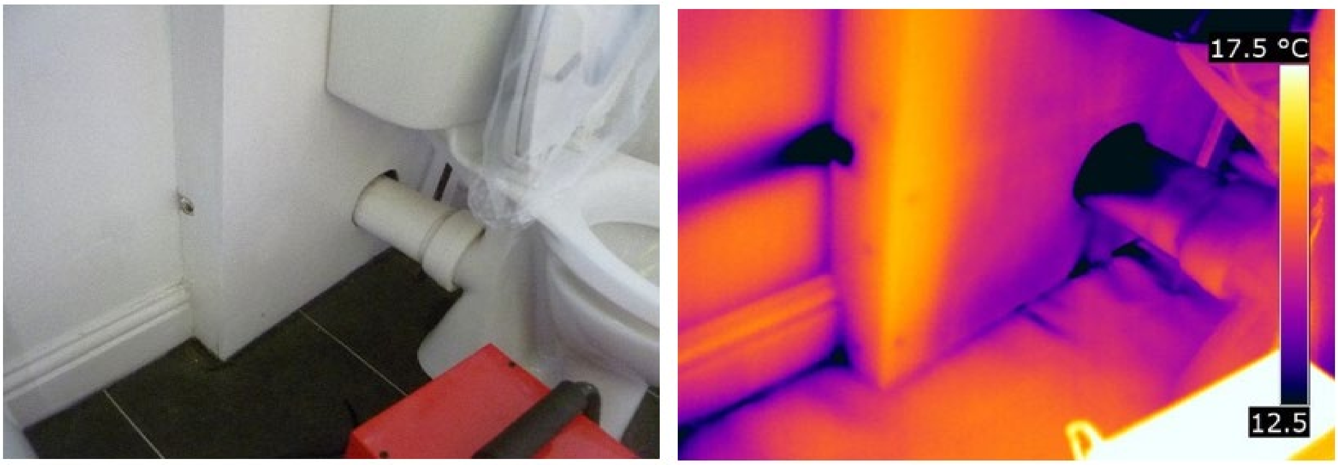

Figure 2-23 Air movement around pipework service penetration

2.2.9 Kitchen Units

Related to service penetrations, substantial air movement was observed behind kitchen units. with air emerging under their plinths as illustrated in Figure 2-24. Kitchen units often conceal several service penetrations and can channel incoming air if they are interconnected. Additionally, the flooring underneath a kitchen unit may not be covered, which can result in additional incoming air through a suspended timber floor. Also, the junction between the wall and floor may is less accessible and may not be treated to the same level of detailing as visible areas. The same phenomenon was also common behind bath panels and boxed in services. Without removing this, which is relatively disruptive, tackling these air leakage pathways is difficult.

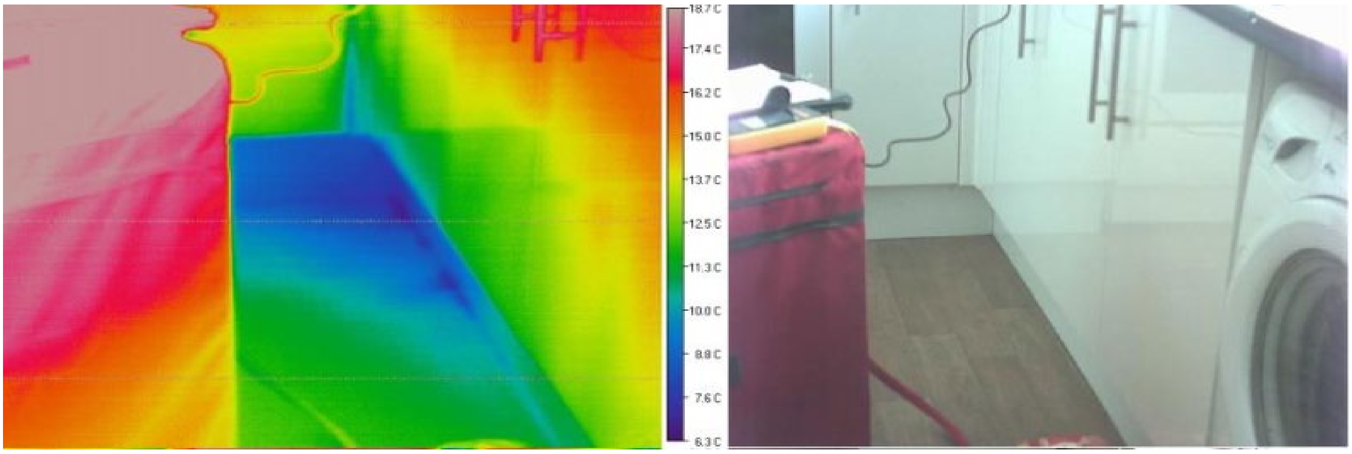

Figure 2-24 Air movement behind kitchen units

2.2.10 Bypass behind plasterboard

It was often the case that it was not possible to identify the specific source of incoming air due to bypassing behind the plasterboard dry lining, as shown in Figure 2-25. Air enters the dwelling, often via the suspended timber floor perimeter or via a crack, gap, or service penetration in the perimeter of the building envelope and moves into and behind the plasterboard dry lining until it can emerge at an unsealed point such as skirting, light fittings, or electrical switches.

Air movement of this nature is difficult to address in existing dwellings beyond ensuring that the plasterboard dry lining is well sealed. Commonly, plasterboard installers leave a gap between the floor and the boards so that the boards can be fitted “plumb”. Since floors are often not perfectly flat, if the board and floor junction is not then sealed, the only barrier to avoid air entering behind the plasterboards is the skirting board seal. Removing skirting boards to apply seals here may be disruptive.

Figure 2-25 Air movement behind plasterboard drylining

2.2.11 Inter-dwelling air leakage

Co-pressurisation tests involve performing blower door tests on two neighbouring houses simultaneously, with readings only recorded when the internal/external pressure differentials in both houses are similar (<1.0 Pa difference). While blower door tests on individual dwellings induce pressure differences on all elements of the building envelope, co-pressurising removes the drivers for inter-dwelling air movement across a party/separating element.

Co-pressurisation tests were undertaken on 10 of the 15 detailed case study homes investigated by Leeds Beckett. These revealed reductions in air permeability results of between 9 % and 29 % compared to individual blower door tests on the same properties.

Air exchange between neighbouring homes might not always represent a heat loss, since both homes may be heated similarly; however, neighbouring heating patterns may differ, or conditioned spaces may be adjacent to unheated spaces next door. Hence, the infiltrating air from an attached house is not necessarily external air but may already have been conditioned by the neighbour. Therefore, when using blower door tests to understand heat lost to the outside, it may be useful to remove the inter-dwelling air exchange by undertaking co-pressurisation tests where practicable.

Airtightness of homes summary

The findings support previously published average airtightness levels of existing dwellings in the UK of around 11 $m^3/(h \cdot m^2)$ @ 50 Pa. Additionally, 78 % of homes had more air leakage than the limiting threshold air permeability of 8 $m^3/(h \cdot m^2)$ @ 50Pa in Part L of the Building Regulations for new build homes.

The study also suggests that the range in performance is substantial, from 0.9 to over 25 $m^3/(h \cdot m^2)$ @ 50Pa, and that 14 % of homes within the sample may have severe air leakage problems, with air permeability greater than 15 $m^3/(h \cdot m^2)$ @ 50Pa.

The data suggests that using an average airtightness value to represent a cohort of homes will mask high or low levels of airtightness in a significant proportion of homes.

The findings also suggest that it is difficult to predict if homes will be airtight, or not, based on building age, form, archetype, or even their EPC score. Of all the construction features analysed, ground floor construction type was the best predictor of airtightness in homes, i.e. homes with full suspended timber floors have greater air leakage.

There was a difference between attachment types, i.e. mid-terraced homes may be marginally more airtight than semi-detached and detached homes. There was also a very weak correlation that newer homes were more airtight, though this is mostly due to homes that were built post 2000, when Building Regulations first set performance standards for airtightness.

There was also no difference between infiltration rates for homes with double versus single glazing, though homes with triple glazing tended to be more airtight.

Instead, the findings suggest that the presence, quality, and condition of internal features, rather than their construction are driving high or low levels of infiltration. Specific pathways observed in these studies were similar to those commonly reported elsewhere, with the most frequently observed being through and around suspended timber floors, between window frames and wall openings, around doors and their frames, and behind kitchen and bathroom units.

Other notable leakage pathways were poor seals around loft hatches, electrical fittings and service penetrations. However, it was not possible to identify which leakage pathways were more significant than others.

Co-pressurisation tests revealed significant inter-dwelling air leakage between connected dwellings at blower door test pressures.

3 Comparing low pressure Pulse and blower door tests

This chapter presents the comparison between the airtightness test results and the low-pressure Pulse test results to investigate if they are comparable, or if there are building characteristics which may be causing variability in the relationship between the two tests. It will also investigate the appropriateness of the factor for converting the Pulse airtightness test at 4 Pa to an equivalent blower door test result at 50 Pa.

Low pressure Pulse tests were incorporated into CIBSE TM23 in 2022 with the Pulse method acknowledged as an acceptable test for Building Regulations compliance testing for the air leakage rates of new build homes [3]. The comparability of Pulse tests with blower door tests in existing buildings is less well understood; although some work has been undertaken in this area it has prioritised more airtight dwellings [6]. This report outlines the results of the Pulse tests that were attempted as part of the surveys undertaken in this project.

The initial Pulse units provided were found to be faulty after some use and this resulted in a failure to collect valid Pulse test results from homes until new units could be sourced. The failures were due to both hardware and software issues linked to previous versions of the Pulse equipment. Many of these have been resolved in the new Mark 2 equipment which has superseded the original Mark 1 units.

Pulse tests were successfully undertaken in a 51-home subset of the main sample, of which 21 were solid walled, 26 were cavity walled, 3 were mixed and 1 home had an unrecorded wall type. Figure 3-1 shows the ages of the buildings in the sample. A further 45 homes had Pulse tests attempted, however, owing to hardware and/or software problems no valid reading was obtained in these homes. These technical problems were resolved midway through the project by switching to the latest Pulse test equipment.

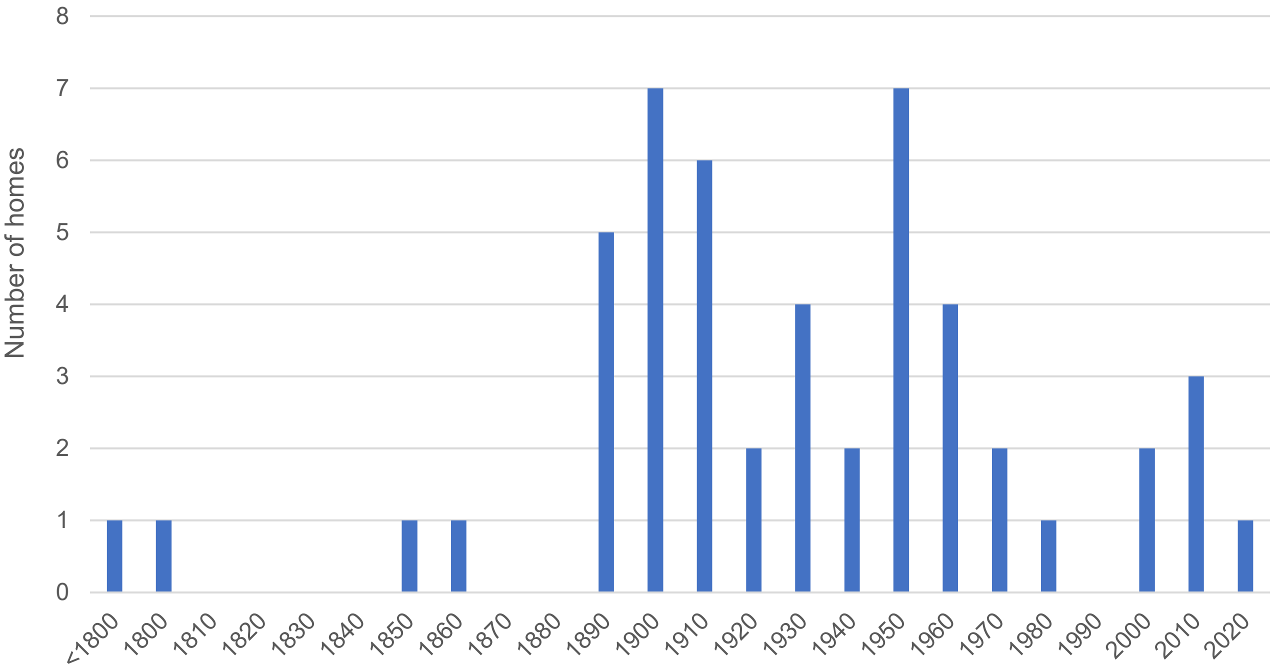

Figure 3-1 Number of homes with valid Pulse test results per decade of construction

3.1 Low-pressure Pulse versus blower door results

Figure 3-2 shows the Pulse test results adjusted to 50 Pa from 4 Pa using the conversion factor detailed within CIBSE TM23, compared to the blower door results at 50 Pa, for the homes where both tests were successfully undertaken. Only Pulse results determined to represent valid test results are used.

As can be seen, there is a relatively good correlation between the two methods, but the data suggests that the Pulse method often reports a lower value than blower door. This may be expected since inter-dwelling air exchanges may take place under high pressures, as observed in the DEEP case studies, which can lead to the blower door test over-reporting air leakage. The low-pressure Pulse test may be less susceptible to this phenomenon, though more investigations are needed to further explore this.

It also shows that for individual tests, the values can differ significantly. Investigation into specific tests, where results provided a particularly poor correlation, did not reveal any distinct patterns or commonalities between these test homes.

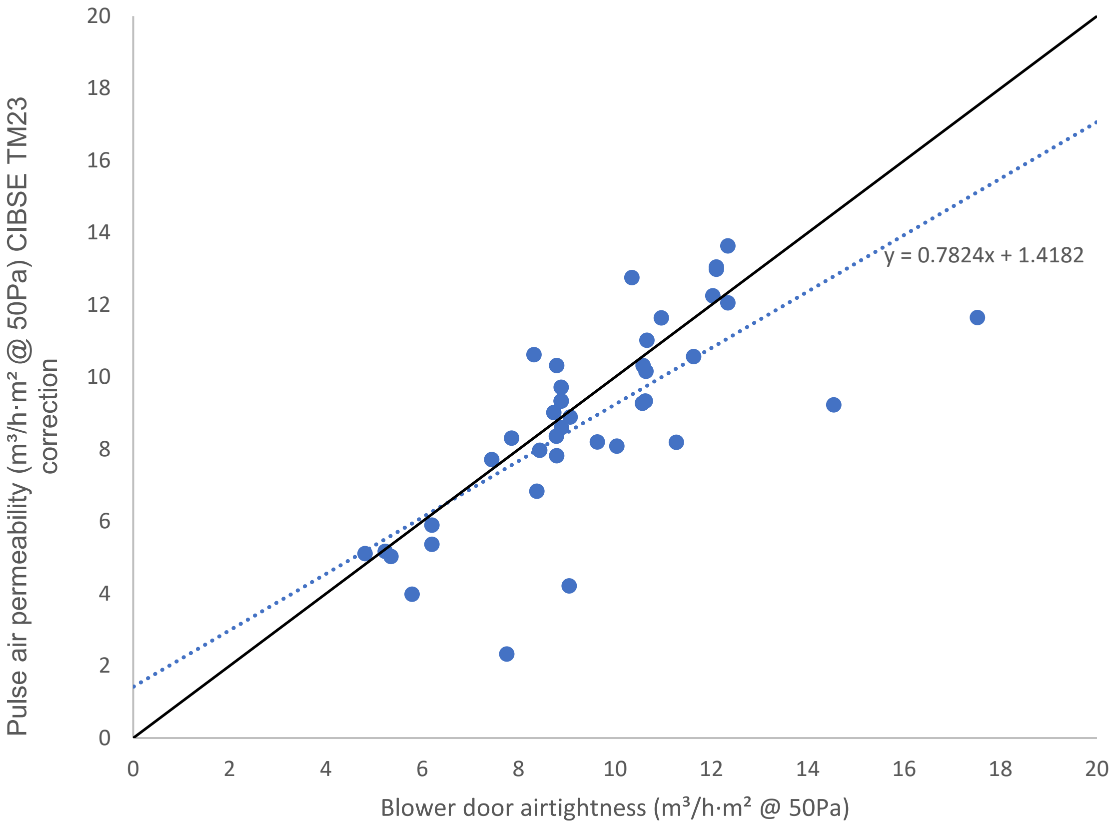

Figure 3-2 Comparison of airtightness derived by the Pulse test and the blower door test; black line indicates a 1:1 ratio

3.2 Observations of the low-pressure Pulse test

The previous assessment of the blower door test assessed multiple building characteristics to evaluate if these had an impact on airtightness. The same assessment has been undertaken on the Pulse tests to identify if these characteristics similarly affected the Pulse test result, as the building envelope at higher pressures induced during a blower door test may differ from that under the lower induced pressures of a Pulse test.

Age, wall finish, and attachment, which were found to marginally affect the blower door test, did not affect the Pulse test results. However, as with the blower door test, ground floor type (Figure 3-3, appears to have some impact on the Pulse test result, though, the sample size is too small to draw any clear conclusion.

Indeed, the reason fewer characteristics were found to affect the Pulse test may be due to the substantially smaller sample size, which has made statistical analysis difficult. The small sample size also means that the inferences shown in the following section should be considered with caution.

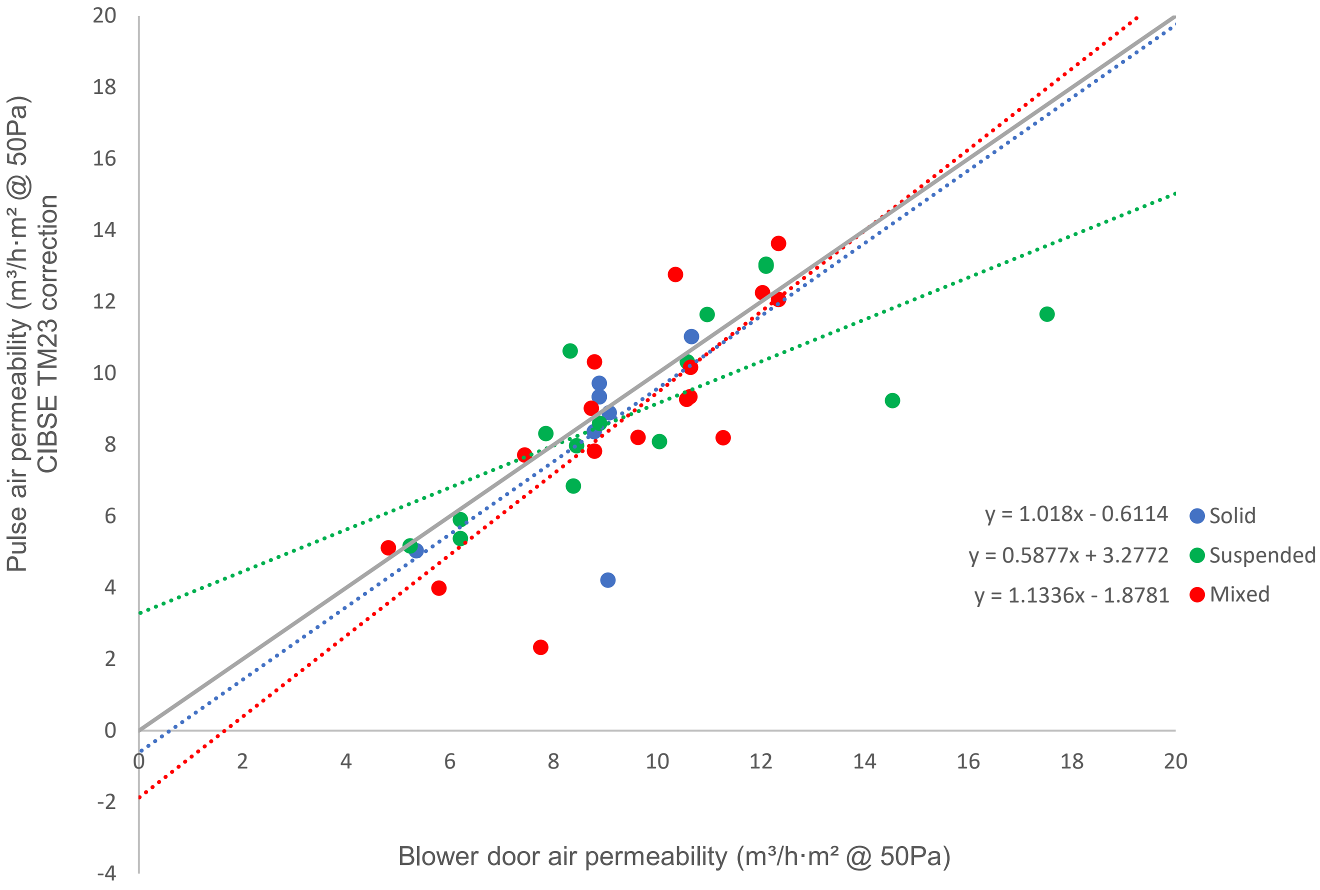

Figure 3-3 Comparison of blower door and Pulse results for different floor types

Pulse and blower door summary

Comparing the Pulse test results to the blower door test results suggests that the stated conversion factor in CIBSE TM23 may be suitable on average, for existing homes, but more data is needed to confirm this.

Significantly, the results show that for any individual test, the difference between blower door and Pulse tests can be very large.

The findings appear to suggest that Pulse tests in suspended timber ground floor homes may exhibit a different correlation with blower door tests, though more investigation would be needed to explore this difference.

Air exchange between neighbouring dwellings takes place when blower door tests induce high pressures. Consequently, blower door tests can overestimate the amount of indoor to outdoor air exchange taking place in adjoined homes if a co-pressurisation test is not undertaken; which is a limitation of the current regulatory test method. These results suggest Pulse tests may not be causing inter-dwelling air exchanges at the same level as blower door tests (because they operate at lower pressures).

This could be an advantage of the Pulse test over the blower door test method. However, it also means that an alternative conversion factor may be needed for Pulse tests undertaken in detached homes compared to attached homes, unless a correction factor is applied to the blower door test to account for inter-dwelling air exchanges.

4 Barriers to solid wall retrofits

Retrofit installation rates are much lower than they may need to be in order to achieve net zero carbon targets. There are many financial, political, and socio-technical reasons for this, but there are also a number of physical barriers or obstacles in homes. This chapter quantifies the variety and frequency of these potential physical barriers and discusses the implications of these for retrofit potential and installation costs.

A wide range of barriers to retrofit were observed as part of the 160 surveys that have taken place. As previous work undertaken for DESNZ has investigated the barriers to internal wall insulation [7], the surveys during the DEEP project focused on barriers to external wall insulation (EWI), given the significant need to address the efficiency of uninsulated solid wall homes.

To facilitate the analysis of barrier prevalence, the disparate individual barriers that were observed were grouped into the categories defined in

Table 4-1 below:

Table 4-1 Retrofit barriers

Barrier group	Individual barriers identified in surveys
Utilities	Gas, electric, water, dish/aerials, telecoms, broadband, metering
Waste/water	Guttering, drainpipes, soil pipes, drainage
Security	Lights, alarms, cameras, key box
Ventilation	Extracts, airbricks, fans
Systems	Flues, condensate pipes, heat pumps
Foliage	Trellis, trees, climbing plants
Architectural	Corbelling, extensions, porch/canopy, decorative stonework, cladding
Access	Public right of way, roads, neighbouring buildings/infrastructure
Disrepair	Visible damp, crumbled masonry
Conservation	Heritage status
None	No observed barrier to insulation

Figure 4-1 shows the distribution of the different barriers that were observed across the sample. As may be expected, water and waste goods such as gutters and drainpipes were commonly observed to be a barrier, with the majority of homes having externally located rainwater goods and especially below ground drainage.

These items need to be removed and repositioned during an effective EWI retrofit, a factor that is commonly avoided due to the additional work and disruption required. As such, it is common for EWI to be cut out around guttering and pipework, leaving thermal bridges in its absence. In estimating the cost of EWI projects, it therefore seems reasonable to always account for some element of relocation of waste and water goods.

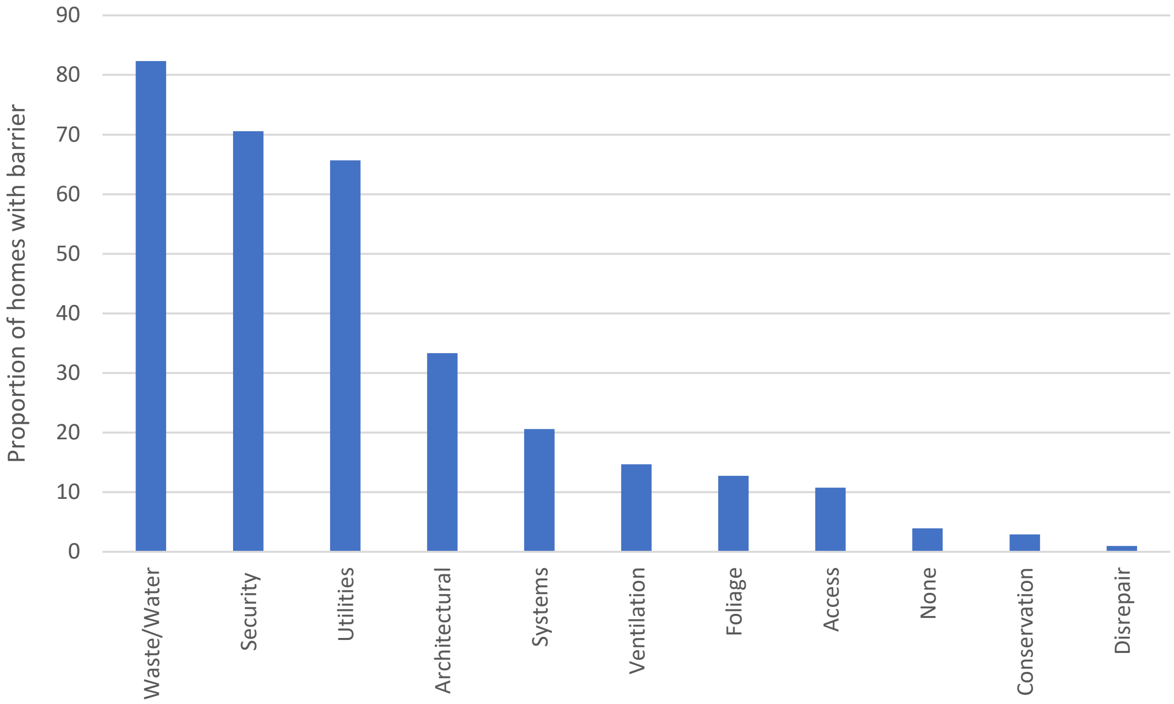

Figure 4-1 Prevalence of retrofit barriers

The second most prevalent barrier to EWI observed was wall furniture for security purposes, such as alarm boxes, CCTV systems and lighting. These items can be removed and replaced during EWI retrofits, although they may present a challenge if they are mains as opposed to battery powered, as an electrician or specialist may be required. The requirement to bring an additional trade onto site can cause additional costs and time delays, and cause sequencing problems. Given the high frequency of security related wall furniture, it would be prudent to require that any installation guidance documents for EWI systems incorporate instructions for electricians or specialist trades. It may also be recommended that the electrician's or specialist trade's time is accounted for in standard costing models for EWI.

Utilities were the third most prevalent barrier in homes, plus there were often multiple utilities per home, meaning they were the most numerous barriers as shown in Figure 4-2. This is significant, as utilities cannot be moved by a homeowner or retrofit contractor but require a specialist qualified practitioner. In the case of gas, electricity, and water supply, this can incur significantly more cost and time delay than simply bringing in an extra trade. Additionally, many utilities cannot be moved or relocated in a simple way due to their connection with the existing mains supply or a requirement for directional location (e.g. in the case of a television dish or aerial). With these factors in mind, utilities are likely to present the most significant barrier to EWI retrofit. The retrofit installers have little influence in resolving utility barriers.

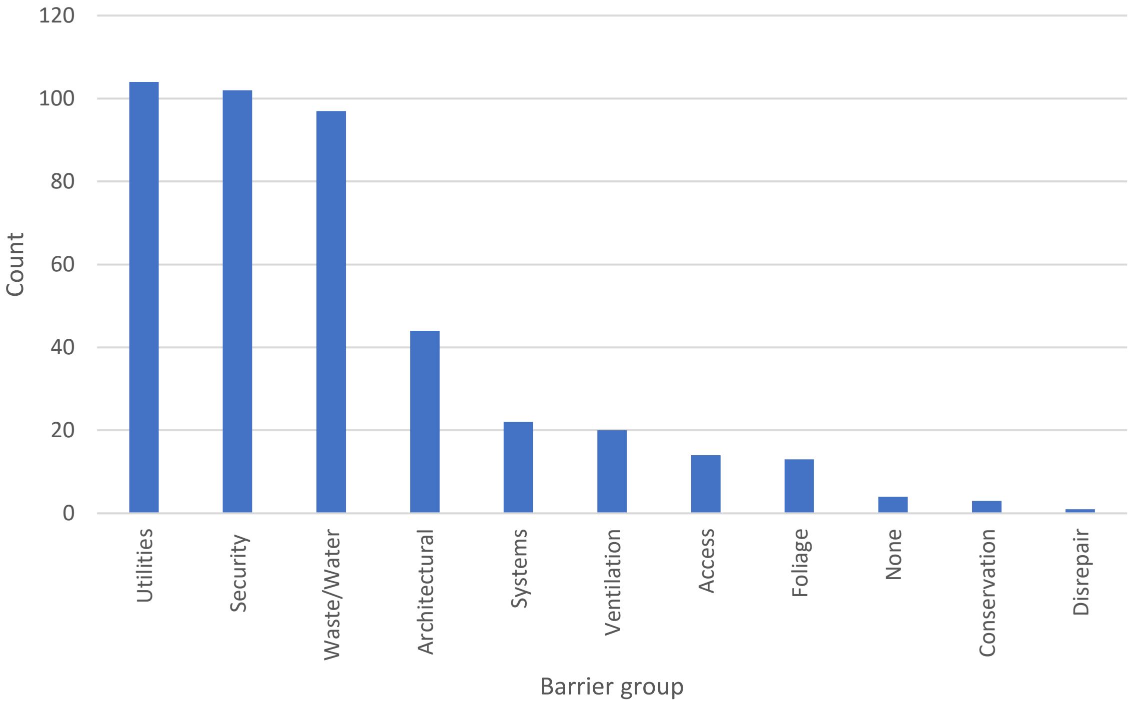

Figure 4-2 Frequency of retrofit barriers

Architectural barriers were present in around a third of homes surveyed. Features such as extensions and porches make maintaining continuity of the insulation layer a challenge, depending on the insulation characteristics of the extension. For example, a conservatory may not be thermally insulated, i.e. it may not be separated from the main building by an external-quality door, meaning the large surface of original wall obstructed by the extension will bypass any EWI insulation.

Decorative architectural details such as corbelling would also need to be removed or avoided, leaving large thermal bridges at the perimeters. One in three homes fall into this category in this sample. However, it is not clear how significant this finding is when considering national domestic retrofit policy and targets, since the sample size in this study was small and not nationally representative.

Systems and ventilation barriers are similar in that they are a penetration through the external wall, either to provide ventilation or for a flue or pipe. Any EWI retrofit would have to accommodate these penetrations and will typically lead to a point thermal bridge with EWI cut around the necessary area. It is possible to avoid this using insulated boxing and embedding pipework in the EWI, but this will incur additional cost and complexity.

Access issues also limited the ability to install EWI. This barrier concerns the ability to safely erect scaffolding and undertake necessary work, with consideration for encroachment onto public highways. Although less commonly observed in the sample, for the 1 in 10 homes where this is a significant challenge, it may mean that EWI cannot be installed. A similar number of homes are affected by foliage i.e. nearby trees and plants affecting the ability to safely access the property. Removal of these may sound trivial but can add hundreds or thousands of pounds to the cost of EWI projects.

Conservation status was observed in a small number of homes, which would limit the ability to modify the external appearance of the dwelling. This is interesting, since conservation constraints (e.g. heritage / listed building / planning etc) can be cited as barriers for the potential for EWI. Although this survey suggests this may not be a prevalent barrier, the results are limited to the small sample of homes, so are not representative (since conservation barriers can be highly contextual to the local area).

Only one home was observed to have a defect that would need to be resolved prior to retrofit. This suggests that defects may be unidentifiable until the works begin, which is potentially problematic as such defects typically incur additional time and cost to retrofit.

Only a very small proportion of the dwellings surveyed (4%) had no notable and observable barriers to EWI retrofit. This suggests that funding for EWI schemes should anticipate the costs associated with overcoming the barriers identified in this survey as part of their funding models.

Barriers to retrofit summary

The results obtained for this sample of homes are indicative of the type and frequency of barriers to external wall insulation that homes may face. However, interpretations should be made in the context of the small sample in the survey, which was not representative of the UK housing stock.

The most frequent barriers observed relate to wall mounted items, affecting over 80 % of the homes surveyed. These can often be dealt with relatively simply, though over 65 % of homes in the survey would need to employ specialist contractors to deal with wall-mounted utilities, adding significant costs (hundreds or thousands of pounds) to projects. More significant still is the time delay these can cause if sequencing problems occur. Lead-in times for specialists can be many weeks or months, which could cause substantial disruption to retrofit programs.

A more streamlined approach to dealing with utility companies and their role, responsibility, and accountability in retrofit policy may be an essential part of successful future retrofit policy. Additionally, guidance to restrict the mounting of utilities on walls generally would also support future EWI retrofits.

Other than wall furniture, a third of homes had architectural features (e.g. extensions) making them hard to treat. 1 in 10 homes also have access limitations and a similar number have vegetation, causing obstacles. This can mean that EWI cannot be installed at all, or that hundreds or thousands of pounds in additional costs are needed before even starting the retrofit.

5 Occupant satisfaction and thermal comfort

The surveys undertaken presented an opportunity to gather additional information from occupants on their heating behaviour and their perceptions of the heating and insulation in their home. This chapter covers the findings of a 1-page questionnaire exploring these topics.

During surveys, participants were invited to complete a 1-page questionnaire to provide their perception of the heating and insulation systems within their home. The questionnaire is in Appendix 1. A total of 47 participants took part in the questionnaire.

When responding to the question: ‘What is your typical heating set-point during winter?’, participants overwhelmingly favoured a set point of 19 °C to 22 °C as shown by Figure 5-1, which is consistent with the findings of the most recent EFUS study [8]. There were no significant differences in set points observed amongst age or sex groups.

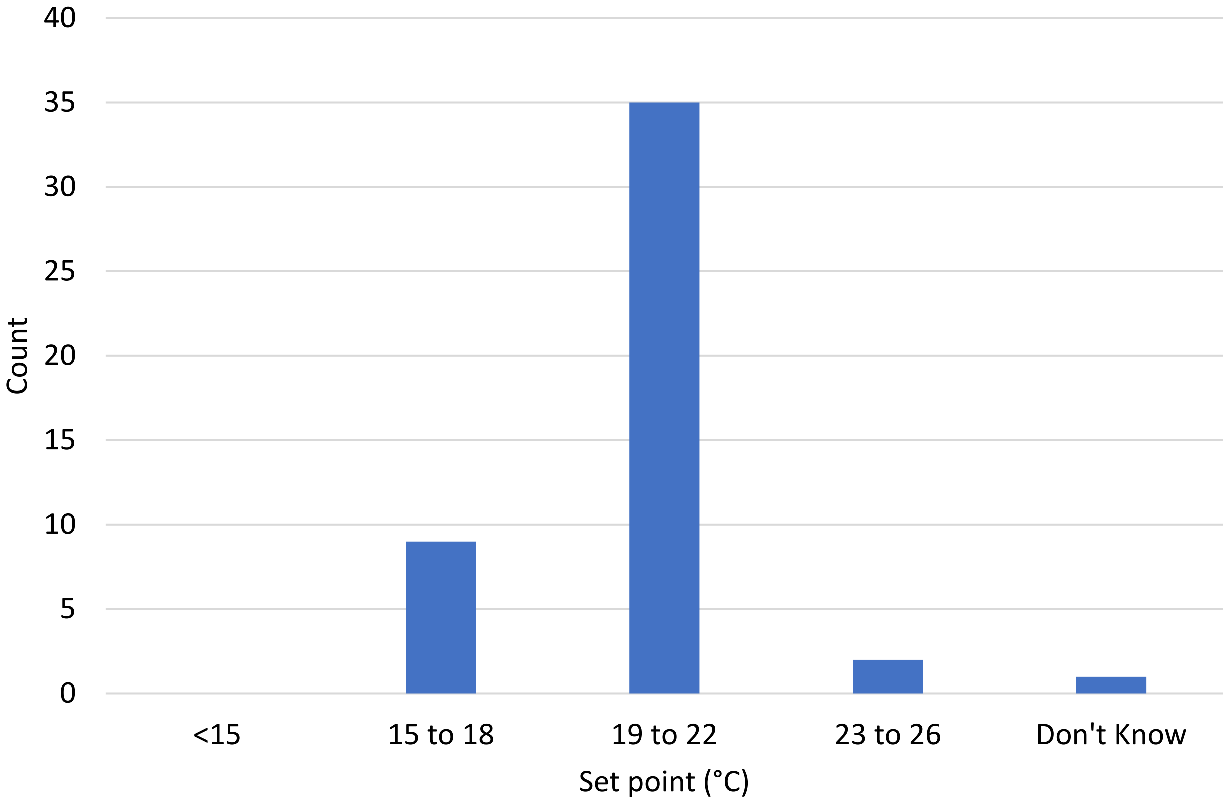

Figure 5-1 Set point responses

Figure 5-2 shows the responses to the question: ‘How good or poor is your heating and insulation at keeping your home warm in the winter?’ This found that occupant perception favoured a positive rating. This is despite many of the homes displaying poor levels of airtightness and inadequate existing insulation. Unfortunately, the sample size was insufficient to elucidate trends between the perception of heating and insulation effectiveness and different types of insulation (obtained from the physical survey of the dwellings).

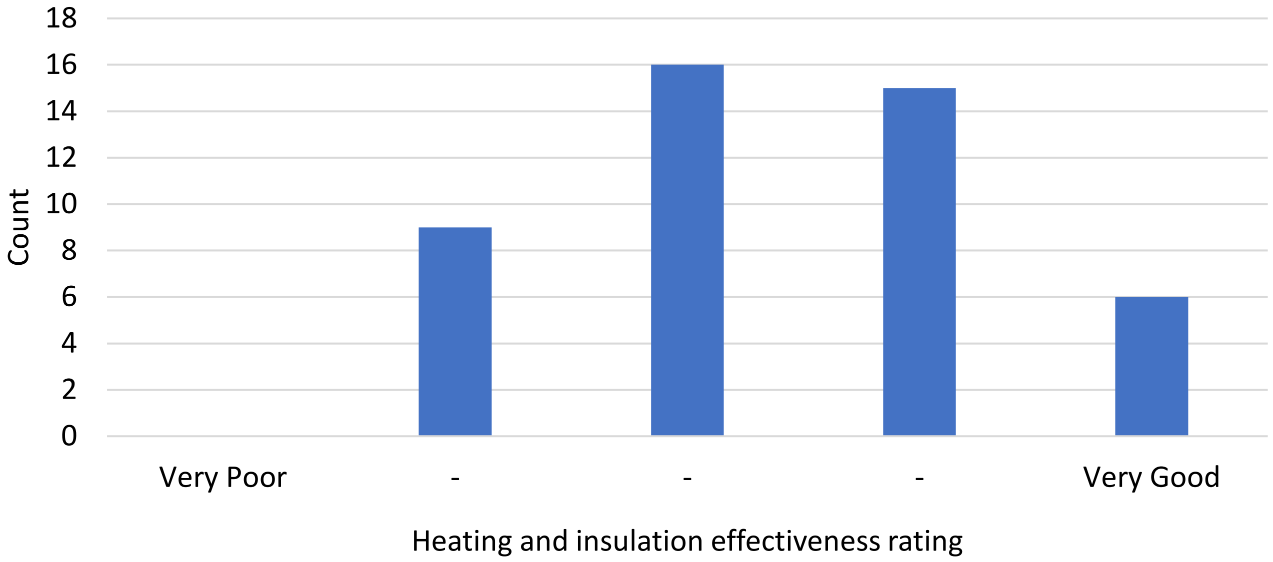

Figure 5-2 Perception of heating and insulation effectiveness

Figure 5-3 displays the response to the question: ‘In general, how do you find the temperature in your home in winter?’. The majority of participants (81 %) reported a sense of comfort, which corresponds with the proportion of participants who felt their heating and insulation effectiveness was average or better. As may be expected, negative winter comfort skewed towards being too cold. Nine occupants perceived that the temperature of their home in winter was too cool. No correlation was found between comfort perception and airtightness of the homes.

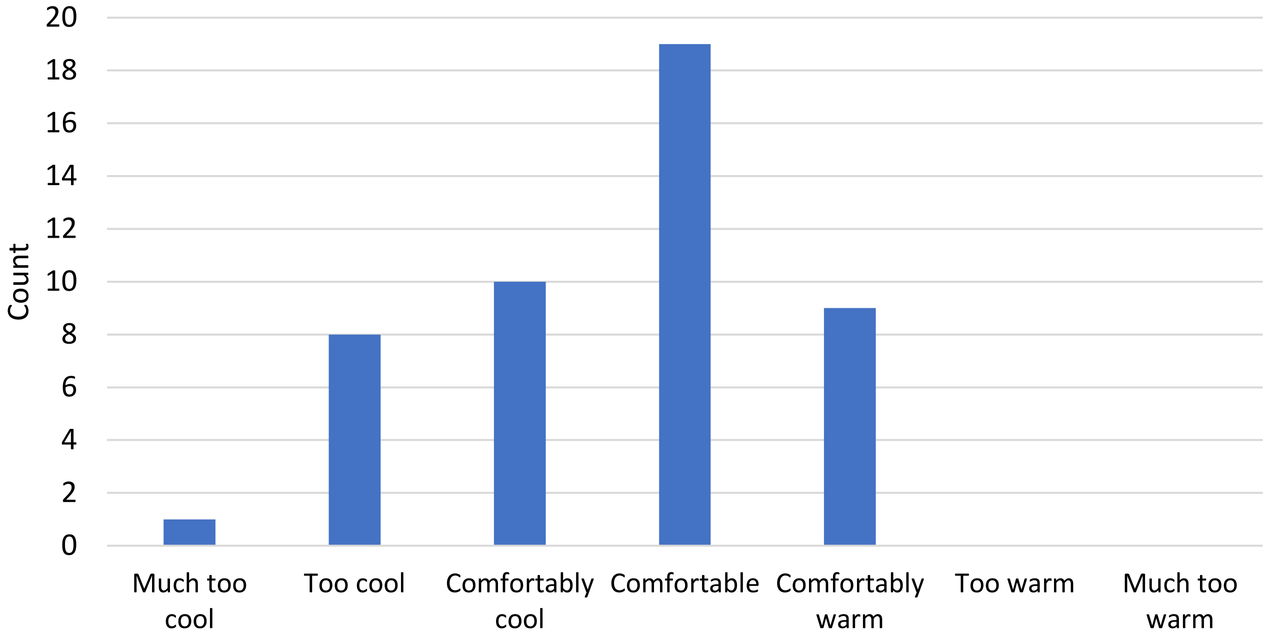

Figure 5-3 Comfort perception

A significant correlation was observed between comfort perception and effectiveness rating in the sample (r_s (46) = 0.593, p = <.001), with this relationship illustrated in Figure 5-4. This suggests that participants with increased warmth perception also thought their heating systems and insulation were effective.

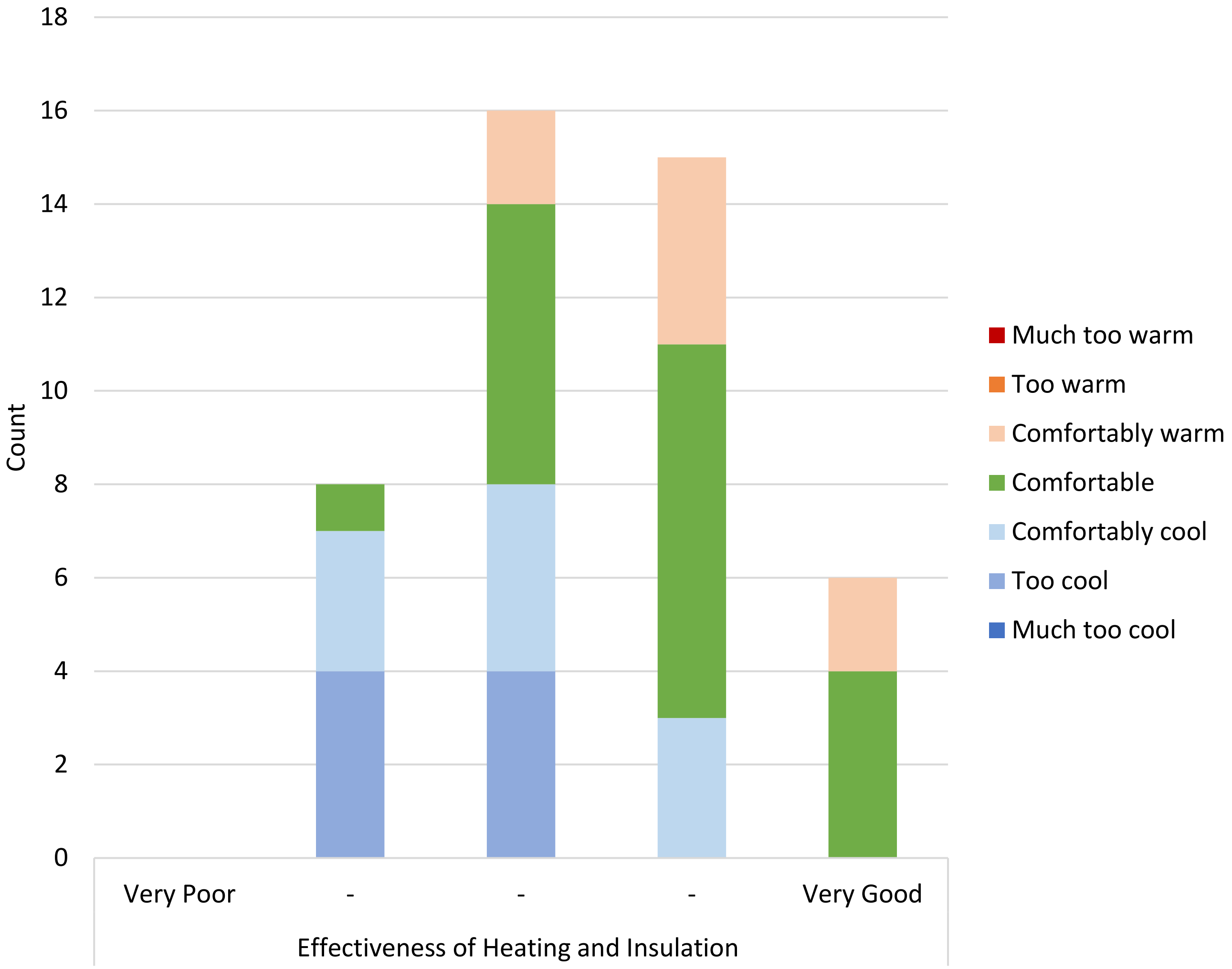

Figure 5-4 Relationship between comfort and perception of heating and insulation effectiveness

Participants were asked the question: ‘Do you feel your home is draughty?” and “Do you have any issues with damp or mould?’. The responses are shown in Figure 5-5 and Figure 5-6 respectively. No significant difference in airtightness was found within either set of groups, nor between occupant perception of draughts and measured airtightness value. This suggests that in the present dataset, living in a home that had high levels of air leakage did not correlate to a perception of having more draughts.

The lack of relationship may be partly explained by the nature of draught perception, being an ingress of cold air from a specific point that affects the occupant rather than the aggregated airtightness of the dwelling measured by the blower door. Further detail would be required from the occupant to identify the areas that are perceived as draughty to trace back to the air movement pathways. Similarly, no relationship was observed between airtightness and damp perception.

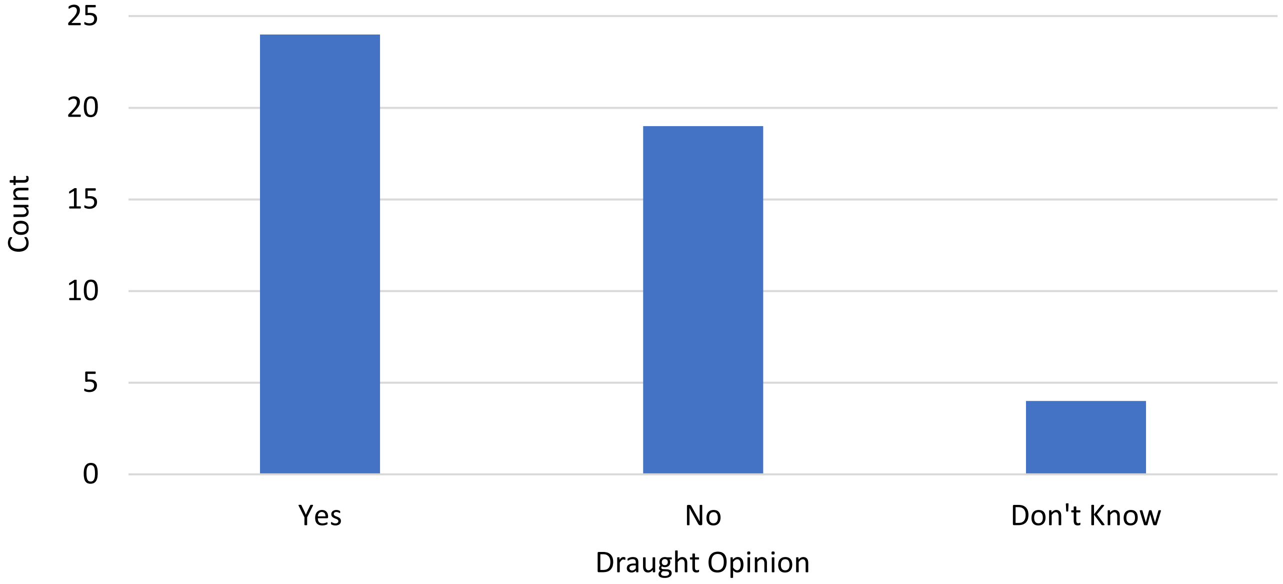

Figure 5-5 Draught perception

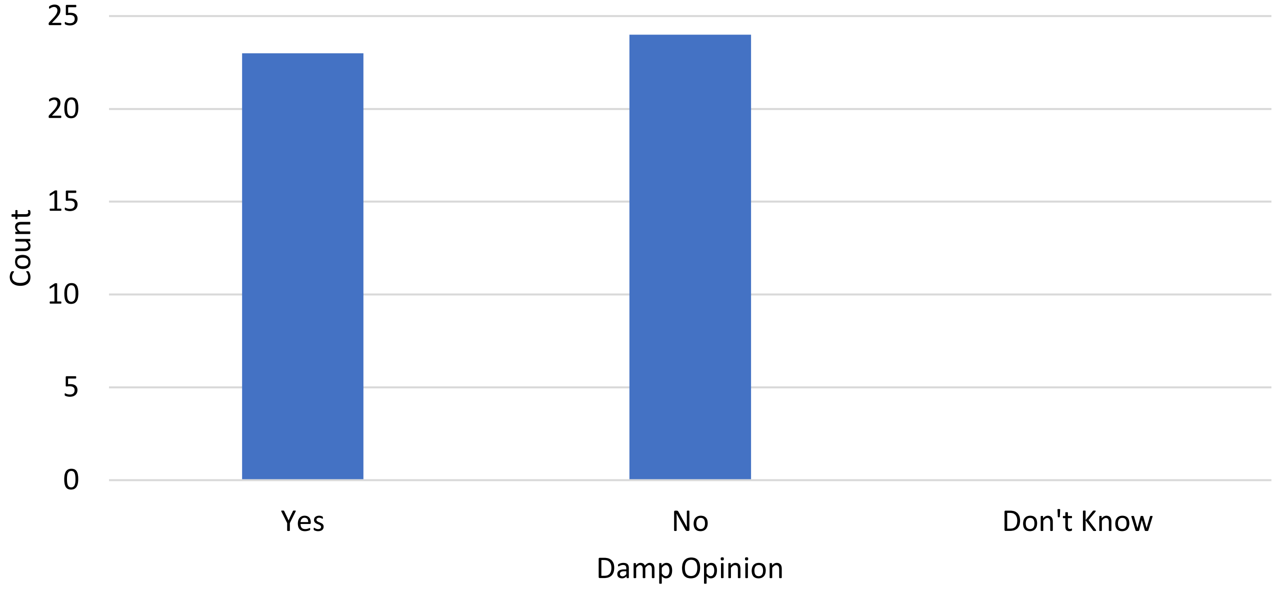

Figure 5-6 Damp perception

As a final question, participants were asked: ‘How affordable is it to heat your home in winter?’. As shown by Figure 5-7, participants responded that the cost of heating their home was towards the expensive end of the response scale. An analysis confirmed that there was no significant difference between answers to this question and the home’s actual airtightness level, perceived performance of energy systems, or comfort perception.

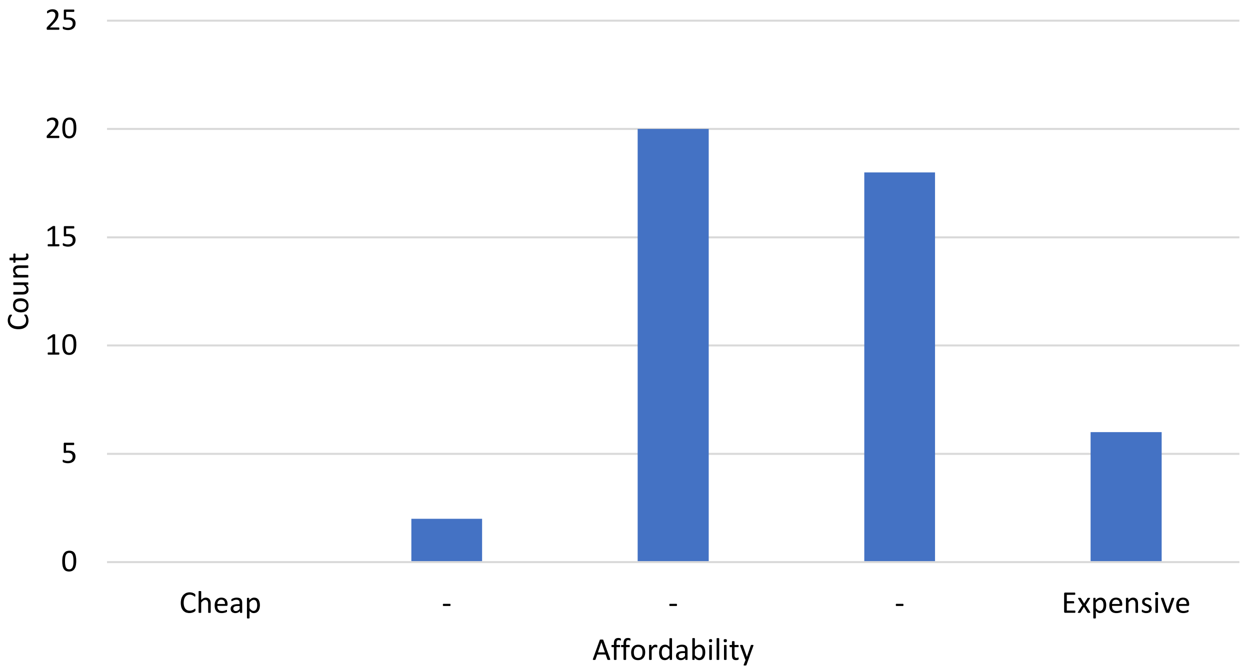

Figure 5-7 Affordability

Post occupancy evaluation summary

The survey of 47 householders has found that people tend to prefer their heating to be between 19 °C and 22 °C, which is consistent with other national surveys [8].

There was no discernible link between the measured level of airtightness of the homes and the perception of thermal comfort or presence of draughts or damp.

Most respondents indicated that they were able to maintain an acceptable level of comfort, though it was expensive to do so.

This survey suggests that comfort can be achieved even in draughty homes, though this should be treated with caution given the small sample size. Additionally, the perception of thermal comfort is highly personal, affected by multiple factors. A deeper understanding of the role of demographic characteristics, such as ability to pay for heating to compensate for excessive heat loss, was not the focus of the present research but would provide valuable context in future studies of this nature.

These indicative results are useful, though a larger sample with more contextual data about the homes and occupants would be needed to identify indicators to predict thermal comfort levels in homes, and if airtightness is a major factor.

6 Conclusions

This report presents the results of airtightness tests and energy surveys in 150 homes. Although not nationally representative, the sample includes a mix of solid wall and cavity wall homes, as well as a mixture of walls that are insulated and uninsulated. The survey explores building characteristics affecting airtightness, identifies common air leakage pathways, compares blower door and Pulse test methods, makes observations on barriers to EWI in the homes, and attempts to understand how building characteristics affect perceived comfort of occupants.

Average airtightness

146 successful blower door measurements were undertaken and the results concur with previous studies that the average air permeability of homes is around 11 $m^3/(h \cdot m^2)$ @ 50Pa. More significant is that the range of performance is very large (from <1 to >25 $m^3/(h \cdot m^2)$ @ 50Pa) and 14 % of the homes sampled have severe air leakage problems, with mean air permeability in excess of 15 $m^3/(h \cdot m^2)$ @ 50Pa, i.e. high levels of air leakage are a significant problem for a minority of homes.

The air leakage in a home does not appear to correspond to building form, wall type, or EPC score. There is a very slight correlation between age and airtightness, but this is driven by homes post 2002 when airtightness tests were introduced into Building Regulations. Most causes of air leakage cannot be linked to specific building features that are easily observed. Ground floor type gives the strongest indication of performance, with suspended timber ground floors tending to be less airtight than solid ground floors. Homes with mixed internal wall finishes, i.e. wet plaster in some areas and plasterboard in other parts of the home, tend to have slightly higher air leakage. The reasons for this are not fully understood; observations suggest the interface between old and new buildings where extensions have been built could be an issue, and retrofitted plasterboard dry lining on dabs (where the original wet plaster has been removed) may not be as airtight as the original wall covering.

More significant to a home’s airtightness is the quality and condition of the internal features, mainly seals around ground and intermediate floors, windows, doors, thresholds, loft hatches, electrical fittings, service penetrations, and behind plasterboard dry lining. These features will not normally be visible unless thermography or other leakage detection is performed under depressurisation, which can be a costly activity to undertake. This suggests that leakage detection may be needed before the benefits of airtightness measures can be estimated. However, even when the air leakage pathways are identified, their severity cannot be quantified in advance of any retrofit taking place.

It is clear from the survey data that airtightness retrofits could have the potential to provide a substantial benefit to some homes. However, it is a major challenge for policy development if it is not possible to determine the benefit that particular airtightness improvements may provide for individual houses until after the work is undertaken, and when before and after air leakage tests can be compared; as potential energy savings will carry significant uncertainty.

Low pressure Pulse tests

Results were obtained for 51 of the homes and suggest that there is on average a moderately good agreement between Pulse tests undertaken at 4 Pa to a blower door test result performed at 50 Pa. However, for individual tests the difference between the tests can be significant.

Suspended timber ground floors might be affecting the Pulse test results but more data on different house types would be needed in order to explore this relationship in more detail. Blower door tests often cause inter-dwelling air exchanges due to the high pressures that are induced, which can lead to an over-estimation of air exchange between inside and outside. The results obtained from the test sample suggest that the Pulse tests may not be subject to this limitation.

Retrofit barriers

In all 160 surveys observations were made on potential barriers to future EWI retrofits in the homes. Almost all homes surveyed had some wall furniture (drainage) that need accounting for when costing for EWI projects. More significantly, over 60 % of dwellings in the sample need utilities to be removed or relocated, which can add complications and potentially months of delays to retrofit schedules if not considered in the initial programme. A more streamlined interaction between utility companies and retrofit installers may be needed, if EWI is to be undertaken on a national level.

One third of the homes surveyed had architectural features that would mean EWI needed to be adapted. This is important when considering the homes that can be cost effectively insulated. Based on the results of this survey, the data indicated that at least one in 10 of the homes surveyed will likely have access problems that could also add costs and delays to retrofit projects.

The survey findings suggest that most EWI projects will invariably involve a substantial additional cost that is not directly associated with the installation of the product.

Occupant satisfaction

In a subset of homes (47) occupants responded to a post occupancy evaluation questionnaire on their perceptions about their home. The results are therefore only indicative of this sample and may not be generalised to the broader population. In some respects, however, the survey results are consistent with those obtained from other national surveys, for instance, indicating that most homes aim to achieve an internal temperature of between 19 °C and 21° C.

The results also suggest that the air leakage in a home is not directly proportional to comfort levels. However, comfort is a complex and personal concept and so larger data sets are needed to confirm if this is the case. The findings also suggest that most householders are able to stay comfortably warm, and this was true for homes that had both good and poor levels of airtightness.

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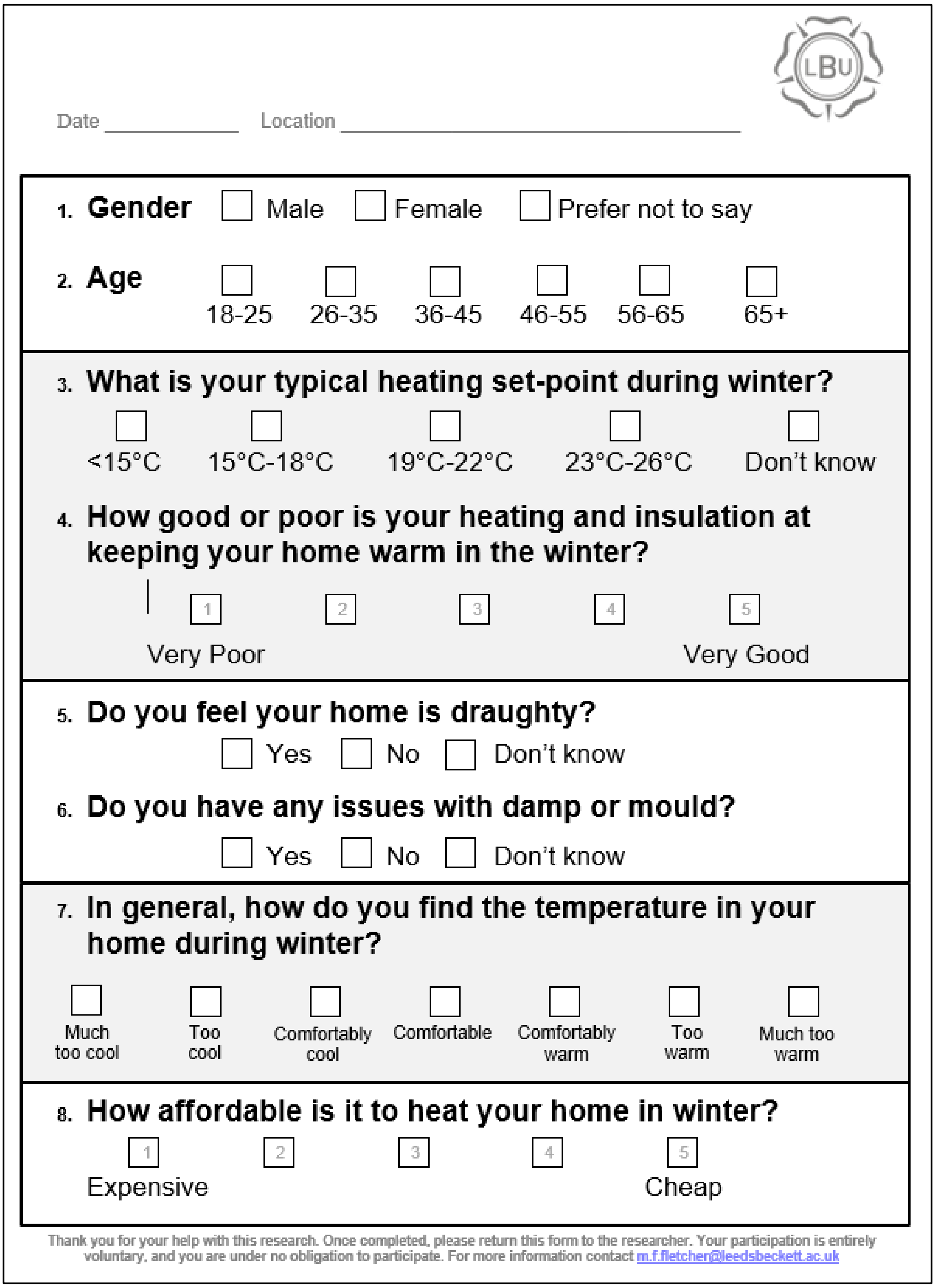
Appendices

Appendix 1 Post-occupancy evaluation questionnaire



Date ____________ Location ____________________________________

1. **Gender** ☐ Male ☐ Female ☐ Prefer not to say

2. **Age** ☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ 56-65 ☐ 65+

3. **What is your typical heating set-point during winter?**
☐ <15°C ☐ 15°C-18°C ☐ 19°C-22°C ☐ 23°C-26°C ☐ Don't know

4. **How good or poor is your heating and insulation at keeping your home warm in the winter?**
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Very Poor … Very Good

5. **Do you feel your home is draughty?**
☐ Yes ☐ No ☐ Don't know

6. **Do you have any issues with damp or mould?**
☐ Yes ☐ No ☐ Don't know

7. **In general, how do you find the temperature in your home during winter?**
☐ Much too cool ☐ Too cool ☐ Comfortably cool ☐ Comfortable ☐ Comfortably warm ☐ Too warm ☐ Much too warm

8. **How affordable is it to heat your home in winter?**
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Expensive … Cheap

Thank you for your help with this research. Once completed, please return this form to the researcher. Your participation is entirely voluntary, and you are under no obligation to participate. For more information contact m.f.fletcher@leedsbeckett.ac.uk