Improving the Airtightness in an Existing UK Dwelling: The Challenges, the Measures and their Effectiveness

M.C. Gillott[1], D.L. Loveday[2], J. White[1], C.J. Wood[1], K. Chmutina[2], K. Vadodaria[2+]

[1]Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK
[2]School of Civil and Building Engineering, Loughborough University, Loughborough LE11 3TU, UK
[2+]Current affiliation: Faculty of Architecture, CEPT University, Kasturbhai Lalbhai Campus, University Road, Navrangpura, Ahmedabad-380009, Gujarat, India

[1]Corresponding author: Mark Gillott
Tel.: +44 (0)1158467677
E-mail address: mark.gillott@nottingham.ac.uk

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ABSTRACT

Air infiltration, occurring through gaps in the building envelope, can contribute up to one third of total heat losses associated with older UK dwellings [1]. Therefore, reducing the rate of air leakage (i.e. improving air 'tightness') can have a positive effect in terms of decreasing space heating requirements.

This study presents an investigation of the effectiveness of airtightness measures applied in a retrofit context to a UK dwelling. A phased programme of refurbishment work was undertaken to a test dwelling at the University of Nottingham campus, UK. Evaluation techniques, including building energy modelling (SAP 2009), air pressurisation tests and thermal imaging, were performed. The study demonstrates that the use of conventional draught-proofing measures can achieve a reduction in air permeability of over 30% when compared with the house base case value of 15.57 $m^3/(h.m^2)$ @ 50Pa. This reduction was only achievable with close attention to installation detail. Further measures of service penetration and floor sealing enabled the air permeability to be reduced to as low as 4.74 $m^3/(h.m^2)$ @ 50Pa.

Modelling of the test dwelling predicted an initial space heating supply energy requirement of 32,373 kWh, which was reduced to 23,197 kWh by a combination of the air tightness measures, insulation, and system (boiler and ventilation) improvements. Air tightness measures alone contributed to approximately 9% of the predicted total reduction, half of which was due to relatively straight-forward draught-proofing. Other more advanced air tightness measures were considerably more expensive, though cheaper approaches to their application could help reduce payback times.

1. Introduction

The UK Government has set an ambitious target to achieve a reduction in national greenhouse gas emissions of 80% below 1990 levels by the year 2050, alongside a 20% reduction in energy consumption by 2020 [2]. Up to 75% of the total building stock that will exist in 2050 already exists today, and this presents a challenge and opportunity in terms of investigating measures to improve the energy and carbon performance of existing homes [3].

Buildings require an adequate level of ventilation in order to maintain the health, comfort and well-being of the occupants and this involves the supply of fresh air and the removal of stale air and indoor air pollutants. Uncontrolled ventilation, known as air infiltration or air leakage, can occur due to air permeability of the building fabric, via gaps and cracks. This may lead to occupant discomfort and a significant reduction in energy efficiency. Ventilation heat losses can contribute up to 20% of the total heat losses observed in existing buildings, and this value can increase by up to one-third in well insulated properties [1].

The implications of low levels of airtightness in buildings are well documented. The effects can include high infiltration rates, draughts caused by uncontrolled air leakage, a reduction in the effectiveness of mechanical ventilation systems, a possible increased risk of condensation and moisture accumulation, as well as increases in annual energy consumption [4]. Airtightness is therefore of critical importance in improving the energy performance of buildings [5], and is often central to Building Regulations compliance and energy efficiency refurbishment programmes.

The significance of airtightness was emphasised during the consultation process relating to the UK Building Regulations Part L in 2000 [6], with the proposal put forward for a maximum as-built 10 $m^3/(h.m^2)$ @ 50Pa to be attained by all new domestic and non-domestic buildings. This limit for air leakage was subsequently implemented in the 2002 amendments to the UK Building Regulations Part L, and then again in the 2005 (interim), 2006 (full) and 2010 (full) editions.

The current UK residential building stock, consisting of approximately 25 million dwellings, is characterised by properties with a range of airtightness levels. The least airtight dwellings can be up to 10 times more permeable than those achieving the highest standards [5]. The Building Research Establishment (BRE) manages a database that contains information relating to 471 dwellings characterised by different age, size, type and construction. This sample indicates that a very wide range of air permeability levels exists within the UK housing stock, ranging from 2 to 29 $m^3/(h.m^2)$ @ 50Pa [7, 8].

When compared to properties in Europe and North America, UK dwellings are generally less airtight. Airtightness standards are utilised as a benchmark standard in many countries, such as Belgium, Canada, The Netherlands, Norway, Switzerland, and the USA, but the values derived may be based on different testing regimes and unequal criteria. Normalised maximum air leakage criteria for these countries are shown in Figure 1 [8]. It is evident that the UK has less stringent compliance levels than several other nations, meaning that dwellings that qualify as being very airtight in the UK may often be classed as standard practice elsewhere in the world [5]. Pan [9] provides a detailed review of the air tightness requirements in an international context, demonstrating that the UK requirement of 10 $m^3/(h.m^2)$ @ 50Pa is not as onerous as many other nations.

Montoya et al [10] reported an assessment of the accuracy of air tightness measurements through comparison with modelled data for a sample of 483 single family dwellings in France. The work concluded that structure type, the floor area, the age of the building, the number of stories and the insulation type are the characteristics that have the most significant influence on building airtightness. This is in agreement with the work carried out by Sherman, who developed a technique to attempt to normalise blower door test data to account for such variances in dwellings [11, 12].

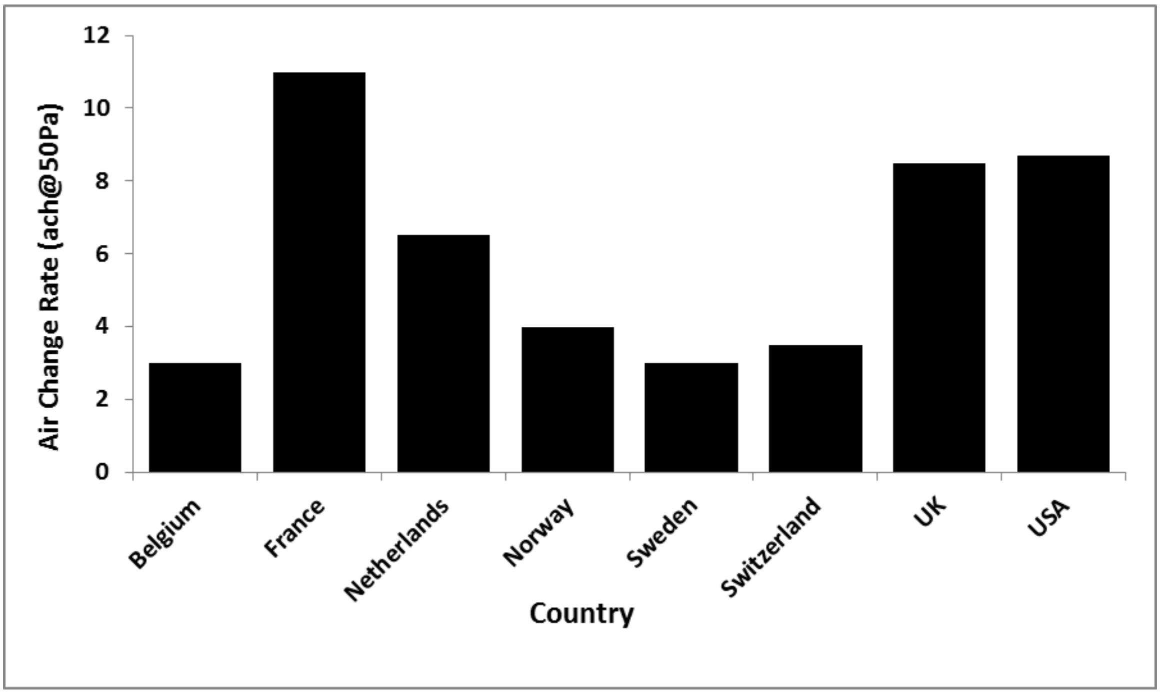

Figure 1 - Comparison of National Data for Normalised Maximum Air Leakage Criteria in Dwellings [8]

With demolition rates at around 1% of total stock [13], and current target new-build construction rates forecast to provide only an additional 9 million homes over the next 15-20 years, it is estimated that approximately 75% of the total building stock that will exist in 2050 already exists today [3]. Therefore, refurbishment work relating to older properties presents a significant opportunity for the UK to reduce its carbon emissions, the RIBA [14] highlighting that improving energy efficiency in existing housing should not be underestimated in terms of importance. Improving the airtightness of a large proportion of the existing housing stock can contribute to this process.

Previous studies have shown that it is possible to reduce infiltration rates by up to 77% through utilisation of retrofit measures [5, 15]. However, when compared with new build dwellings, achieving high levels of airtightness in existing buildings can be very challenging and complex. The air permeability of building fabric is affected by a number of factors, including age, number of storeys, size/complexity of the building structure, longevity, and seasonal variations /environmental conditions. Typical air leakage pathways within a dwelling are shown in Figure 2.

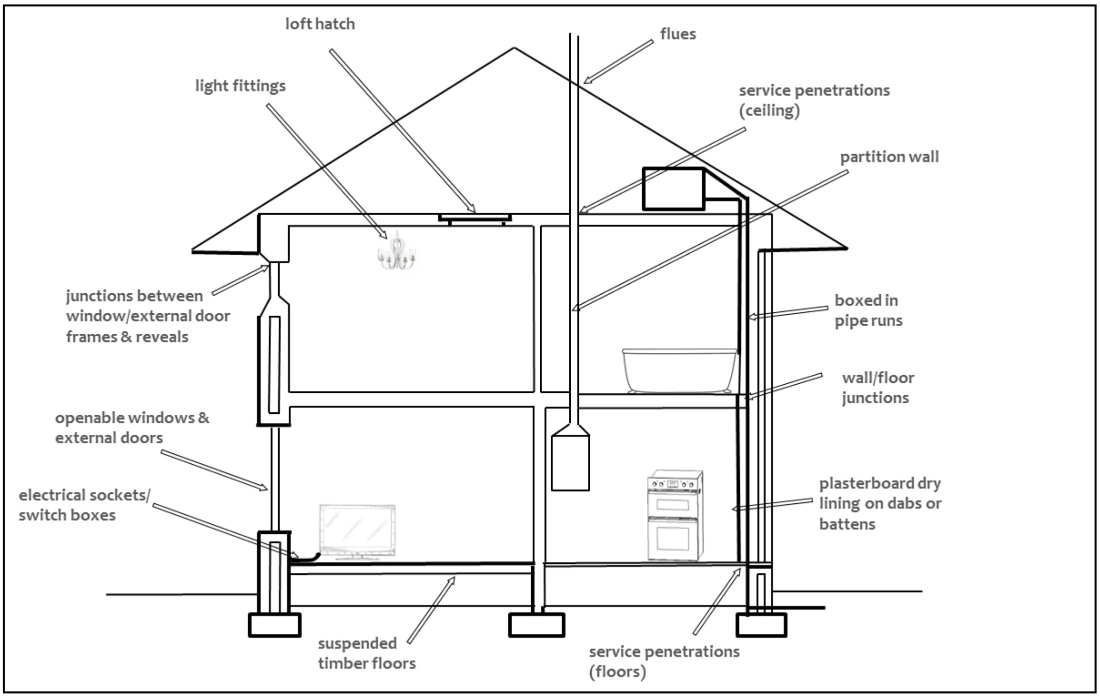

Figure 2 - Typical Air Leakage Pathways in UK Dwellings [16]

The majority of observed air leakage is usually attributable to a combination of a number of cracks, joints and gaps rather than to a single element or component. Building type and structure are therefore found fundamental in the achievement of an airtight building envelope [5], with the contribution of several air leakage pathways quantified in Figure 3, where the remainder refers to fabric and systems improvements.

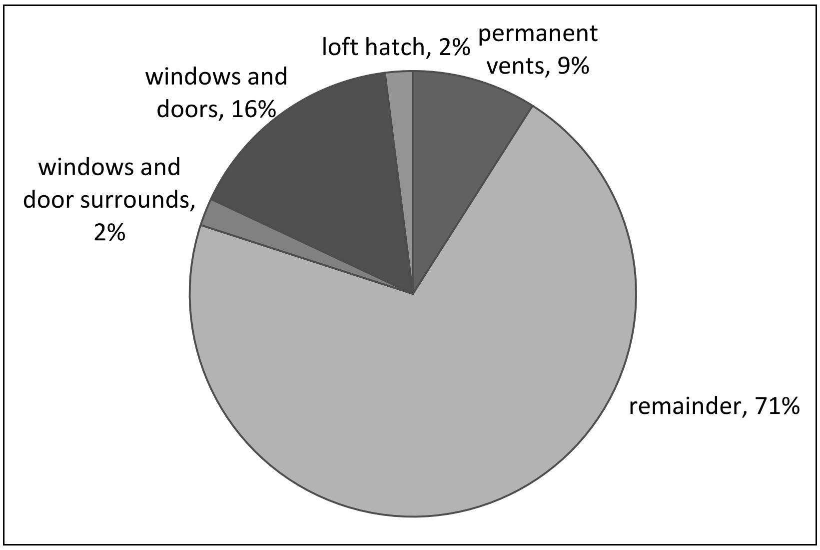

Figure 3 - Component Air Leakage in UK Dwellings [8]

To evaluate the contribution that can be made by improving airtightness, key questions that must be addressed include the following:

1. To what extent can the airtightness of a property be improved within a practical refurbishment context?

2. Which airtightness measures are the most effective?

3. What level and quality of airtightness refurbishment can be expected from a commercial installer?

4. What might be the implications for energy saving, costs of measures, payback, and environmental quality?

In order to develop a greater understanding of the challenges and constraints involved in the improvement of airtightness levels in existing dwellings, a detailed study was conducted as one component within the CALEBRE ('Consumer-Appealing Low Energy technologies for Building REtrofitting') Project. CALEBRE, an RCUK/E.ON-funded multi-partner research project of 4.5 years duration (2008-2013) involved a consortium of six UK Universities: Loughborough, Nottingham, Oxford, Warwick, Ulster and Heriot-Watt ([17, 18]). Project CALEBRE's aim was to address some of the many challenges associated with the energy efficiency refurbishment of the UK's existing homes.

This paper addresses the questions identified above through the application of two methodologies. Questions 1-3 are addressed through measurements conducted in a full-scale test dwelling; question 4 is largely addressed through modelling (SAP 2009). It is noted however, that to answer the above questions fully would require a far wider investigation of properties in a number of different scenarios. This paper investigates a scenario within the UK context.

2. The E.On Retrofit Research House

The University of Nottingham E.On Retrofit Research House formed the case study test dwelling for this research work, and is shown in Figure 4. The house was unoccupied for a large proportion of the programme of study, which allowed unrestricted access and unconstrained opportunity to trial a wide range of refurbishment techniques and technologies. The dwelling forms the basis of the CALEBRE research project (www.calebre.org.uk/) which aims to investigate effectiveness of energy efficiency measures applied to existing dwellings.

Figure 4 - Front and Rear View of the E.On Retrofit Research House

The E.On test house was newly-constructed in 2007 with its design following that of a traditional, two-storey 1930s UK semi-detached property. This type of dwelling forms approximately one third of the current housing stock. The house has a floor area of 108m^2 and comprises two reception rooms, a kitchen and pantry on the ground floor, and three bedrooms, a bathroom and a separate toilet on the upper floor. Due to limited land availability, the property was designed and constructed as one half of a pair of semi-detached dwellings, with a party wall dividing the house from a service zone that is intended to simulate the presence of an attached property. The service zone also provides access to the loft space, where monitoring equipment is located.

The base-case condition of the test house was constructed to re-create the inherent poor thermal performance characteristics that are common in the older UK housing stock [19]. The house utilised typical materials and techniques that would have been integral to the construction of the building fabric of a typical property built in the 1930s. The external walls and party wall were of a 50mm cavity wall construction, whilst internal walls consisted of solid block with a traditional lath and plaster finish. A pitched rafter and purlin roof and single-glazed timber framed windows and doors completed the external envelope.

Inside the property, traditional uninsulated soft wood floor boards and joists were installed throughout the ground and upper floors, with the exception of the kitchen floor which was constructed from a solid uninsulated concrete slab. The suspended timber ground floor sits above an undercroft of 920mm clear height. An access hatch was provided to this area from the hallway, and a concrete screed applied to the floor in the undercroft.

There were open fire places in the living room, dining room and the two larger bedrooms. Heating was further provided by a second-hand 15 year old non-condensing gas fired boiler (seasonal efficiency of 68% as detailed in the Standard Assessment Procedure (SAP) (SAP 2009)). Use of such a boiler maintained authenticity with the current heating situation in many UK dwellings. Further details of the material and systems specifications used throughout the original construction of the test dwelling can be found in the 'Baseline' column of Table 1.

The construction of the property as described formed the basis from which to commence improvements and evaluate their effectiveness in a staged manner. These are described next.

3. Staged Retrofit Improvements

Retrofit improvements were undertaken in five main stages between the years 2010 and 2012, and included upgrades to both the building fabric and integrated systems. Table 1 summarises the key properties of the dwelling and the work undertaken at each stage.

	Baseline	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
External Wall	u-value: 1.29 W/m²k External brick skin, 50mm uninsulated cavity, 100mm solid block with lath and plaster finish	u-value: 0.55 W/m²k Cavity insulated with mineral wool	No change	No change	No change	No change
Party Wall	As external wall	As external wall	No change	No change	No change	No change
Roof	u-value: 1.63 W/m²k Uninsulated pitched rafter & purlin roof with breathable membrane	u-value: 0.15W/m²k Insulated with 300m glass mineral wool	No change	No change	No change	No change
Ground Floor	u-value: 0.720 W/m²k Uninsulated suspended timber floor with 920mm undercroft beneath Exception – kitchen floor comprised uninsulated concrete slab- u-value: 0.99 W/m²k	Carpets & underlay fitted	No change	No change	Breathable membrane fitted under carpets sealed with tape. Overcladding of existing skirting boards	No change
Upper Floor	Uninsulated suspended timber floor	No change	No change	No change	Carpets fitted with breathable membrane beneath sealed with tape. Overcladding of existing skirting boards	No change
Windows	u-value: 4.8 W/m²k Timber framed single glazed	u-value: 1.2-1.7 W/m²k Timber framed double glazing.	No change	No change	No change	No change
Doors	u-value: 3.6-4.0 W/m²k Timber framed single glazed	u-value: 1.7 W/m²k Timber framed double glazed	Covers fixed to external door locks	No change	No change	No change
Draught Proofing & Air Tightness Work	N/A	Installed to clear glass windows & doors	Installed to obscure glass windows & doors. Silicone sealant to frames	Service risers and penetrations sealed with expanding foam. Kitchen extract fan removed and hole sealed	Floor sealing work (detailed above)	Tape and coving fixed to wall/ ceiling junction. Silicone ceiling to light fittings & power sockets
Heating System	Open fires to two ground floor and two upper floors rooms. Electric heating. Low efficiency boiler.	Radiators & A-Rated Gas Condensing Boiler with fully programmable thermostat	No change	No change	No change	No change
Ventilation Strategy	Background infiltration & natural ventilation	MVHR System installed	No change	No change	No change	No change

Table 1 - Summary of Fabric and Ventilation Characteristics of the E.On Research House at each Improvement Phase

It can be seen that the programme of work was extensive, with the intention that all efforts would be made to eliminate as many air leakage pathways as possible. The focus was, therefore, to achieve an 'airtight' building envelope. However, whilst creating such an environment may have a beneficial effect in lowering energy demands and carbon emissions, the reduction in inherent background infiltration within the building fabric can cause moisture build up and elevated relative humidity levels. This can result in stale air accumulating and poor indoor air quality, which may affect the health of the occupants [20].

In any building, it is vital that combustion appliances receive the appropriate ventilation requirement to prevent carbon monoxide poisoning and potential loss of life. It is also important, in any building, that the ventilation strategy is designed and installed to allow the correct throughput of fresh air and removal of stale air. This can sometimes be achieved through natural means, via vents and window openings. As the retrofit project progressed and the building became progressively more airtight, it became necessary to install a Mechanically Ventilated Heat Recovery (MVHR) system in the test dwelling in order to maintain sufficient levels of air change. This was installed in the unheated loft space of the dwelling, with supply vent to the living room, dining room and bedrooms, and extract vents to the kitchen and bathroom. The predicted efficiency was in the region of 90%, with a specific fan power of 0.56 w/l/s and a specified system flow rate of 33 l/s (manufacturer data).

MVHR systems can be efficient in recovering heat through heat exchange between exhaust stale air and incoming fresh air. This recovery of heat from the exhaust air theoretically provides energy savings when compared to the alternative of naturally ventilating the property i.e. opening windows etc. However, if the property is not sufficiently air-tight, or if the MVHR system is not correctly installed or commissioned, heating and auxiliary energy demand can be increased. This work provides an evaluation of the retrofit measures applied to the test house. Note that a detailed evaluation of the MVHR system has been conducted, and is reported elsewhere [21].

4. Evaluation of Retrofit Measures – In-situ Measurement

The technique most commonly used to evaluate building air-tightness is the fan pressurisation method ('blower door test'), with procedures prescribed by legislation and best practice [22-24]. Whilst other techniques, such as tracer gas, are also utilised, UK Building Regulations require that air tightness is measured using the blower door test. This method has been developed over a number of decades, being analysed in detail in the US by Sherman in the 1970's and 1980's [25]. The basic principle of the test is to temporarily seal all ventilation ducts and vents within a property and then to replace an exterior doorway of the house with a temporary door that incorporates a fan.

Air pressurisation tests using the standard blower door methodology were undertaken at key stages throughout the retrofit project in order to assess the impact of various retrofit measures on air tightness of the test dwelling. The same company was used to conduct all of the tests to meet the requirement of the ATTMA TS-1 standard.

Depending on whether the fan is operating in pressurisation or depressurisation mode, it is used to create a slight positive or negative difference between internal and external air pressures, from a baseline difference of 50Pa. The air flow through the fan is continuously measured, and the relationship between the pressure difference across the building envelope and rate of air flow required to maintain a specified pressure is a metric of the air leakage rate of the property. There are two main terms used to describe the normalised air tightness parameters that can be calculated as outputs from the air pressure test, as defined below [26]:

> Air Permeability (q50) – the volume of air passing through each m^2 of building envelope, including ground floor area, expressed in $m^3/(h.m^2)$ @ 50Pa
>
> Air Leakage Rate (n50) – airflow at a controlled pressure differential divided by gross internal volume of the dwelling, expressed in air changes per hour (ach)

The air pressure test result can be used to calculate both of the above terms [27], but throughout this study evaluation will be limited to relative q50 values. It is standard practice for both a pressurisation and depressurisation test to be undertaken, and an average of the two values taken as the dwelling air permeability value. This enables account to be taken both of additional infiltration due to pressurisation, with air being pushed from indoors to outdoors through the fabric (through potentially widened gaps and cracks), and the sealing effect of depressurisation (through potentially narrowed gaps and cracks) [28].

Thermographic surveys, using a FLIR T400 handheld thermal camera, were scheduled before and after every stage of improvement works, as well as during the air pressure tests. This helped to assess the effectiveness of the retrofit measures in order to identify areas of weakness to be targeted for future improvement. In addition, a hand-held smoke pen was used to isolate localised areas of air leakage within the dwelling.

5. Identification of Air Leakage Pathways

As previously stated, infrared (IR) thermal imaging was carried out during the various stages of this study to provide visual evidence of air ingress and air leakage paths. Thermography was not used to quantify the impact of air leakage but was used to identify air leakage pathways by observation of temperature differences due to air flow, whilst the building was in a pressurised or depressurised state. Figure 5 (a-f) includes a number of thermal images taken outside and inside the test dwelling, in both a pressurised (Figure 5 a & b) and depressurised (Figure 5 c-f) state. Within the grey scale images, yellow and orange indicates areas with higher temperatures, while darker blue and purple regions represent lower temperatures. Figure 5 a and d are standard infrared thermographs, whilst Figure 5 b,c,e and f are picture-in-picture images - a thermal picture within a visual spectrum (standard) photograph.

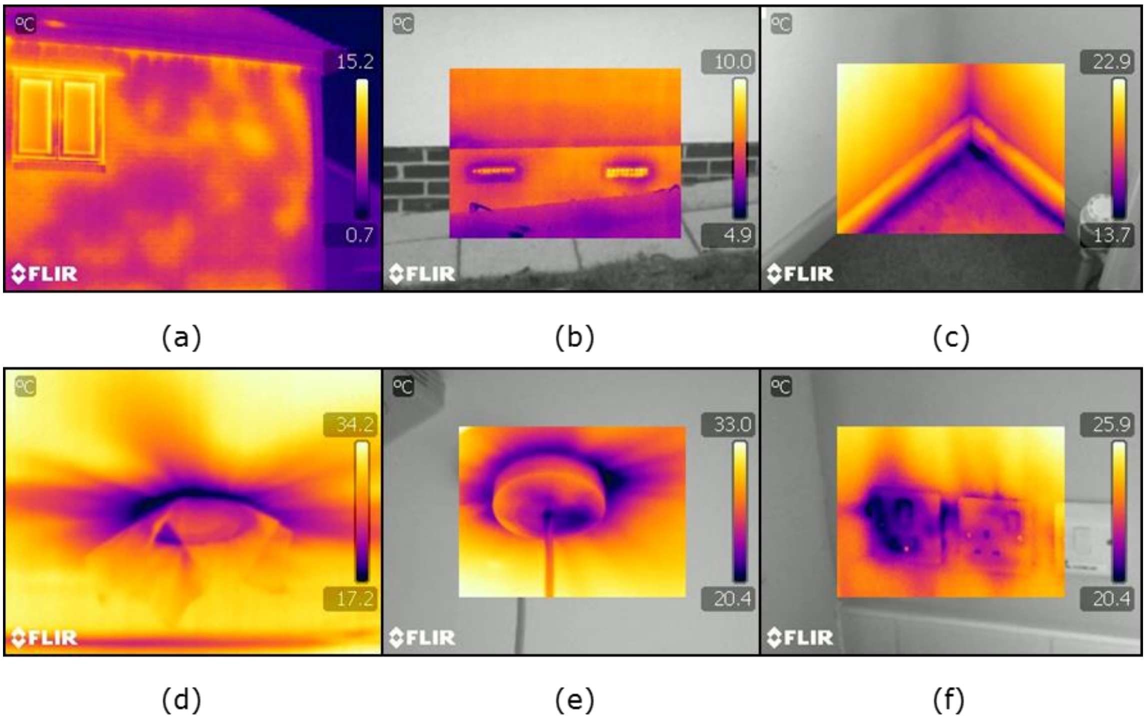

Figure 5 - Thermal Images Showing Air Leakage Paths

The thermal image shown in Figure 5a was taken whilst the house was being heated (internal air temperature up to 35°C and ambient external below 10°C) and pressurised. It shows warm air leaking from beneath the eaves, as well as patchy fabric heat loss through the wall which is likely to be caused by uneven distribution of the blown mineral wool insulation within the narrow 50mm cavity. Note also the thermal bridge and air leakage in the area surrounding the lintel above the window and the heat loss from the perimeter of the glazing due to edge effects. These leakage pathways highlighted in these areas became clearly evident once the building was pressurised.

Between work undertaken in Phases 3 and 4, several thermal images revealed that the suspended timber floors were acting as a major air leakage pathway. Figure 5b shows warm air escaping from the pressurised house through the air bricks which ventilate the undercroft, however this would also be partly due to passive heating of the air space. Cold air ingress around the edge of the carpet in the living room is apparent in Figure 5c, which was taken whilst the house was depressurised.

Figure 5d shows air entering the house via a gap at an MVHR outlet diffuser. Note that the diffuser outlet was sealed for the test and infiltration was occurring through the hole in the ceiling for the duct to pass through. It is concerning to observe that the installation of the MVHR system, which requires an airtight dwelling for high operational efficiently, has actually created additional air leakage paths.

Figure 5 (e and f) illustrate air infiltration occurring around ceiling electric light fitting roses and electrical plug sockets. The air infiltration issues identified in Figure 5 (d-f) were addressed by the measures undertaken in Phase 5 improvements.

6. Effectiveness of Retrofit Measures on Fabric Air Tightness

Following each of the five main phases of retrofit work (see Table 1), an air pressurisation test was conducted in order to assess the magnitude of improvement in airtightness associated with each intervention. The results from this process are shown in Table 2.

Improvements to House	Test Date	Result from Air Test (m^3/hm^2)
Baseline Condition	18/03/2009	15.57
Phase 1	09/09/2010	14.31
Phase 2	01/10/2010	9.84
Phase 3	19/11/2010	8.6
Phase 4	20/12/2010	5
Phase 5	14/02/2011	4.74

Table 2 - Air Tightness Test Results for Each Phase of Improvement

The baseline condition of the test house, prior to any retrofit work, produced an air pressure test result of 15.57 $m^3/(h.m^2)$ @ 50Pa. To put this into context, this considerably exceeds the current maximum air leakage compliance level of 10 $m^3/(h.m^2)$ @ 50Pa, as specified by Part L of the 2010 UK Building Regulations. After completion of Phase 1, the air leakage rate was reduced to 14.31 $m^3/(h.m^2)$ @ 50Pa. There was a minimal decrease of 1.26 $m^3/(h.m^2)$ @ 50Pa observed between the baseline condition and Phase 1, which resulted from the integration of wall and roof insulation together with replacement of single glazing with double glazed units.

A possible explanation for this apparent lack of effectiveness from the baseline to the phase 1 condition could relate to the fact that the test house had been recently built and, albeit constructed to a 1930s design, the single pane glazed units were constructed as new and were installed to a high standard. The building had therefore suffered little actual ageing and it is reasonable to consider that the sealing around the glass and frames would potentially be more effective than that associated with existing actually aged housing stock. It is likely that when windows, which could be many decades old, are replaced, the impact on the reduction in air leakage could be more pronounced.

The quality of the workmanship with respect to the installation also has a significant impact on the scale of improvement observed. A commercial company had been employed to carry out draught proofing and sealing measures, as part of the investigation. As shown in Figure 6, visual observations and thermal imaging revealed that the Phase 1 draught proofing measures and sealing to the windows and doors had not been completed to a satisfactory level.

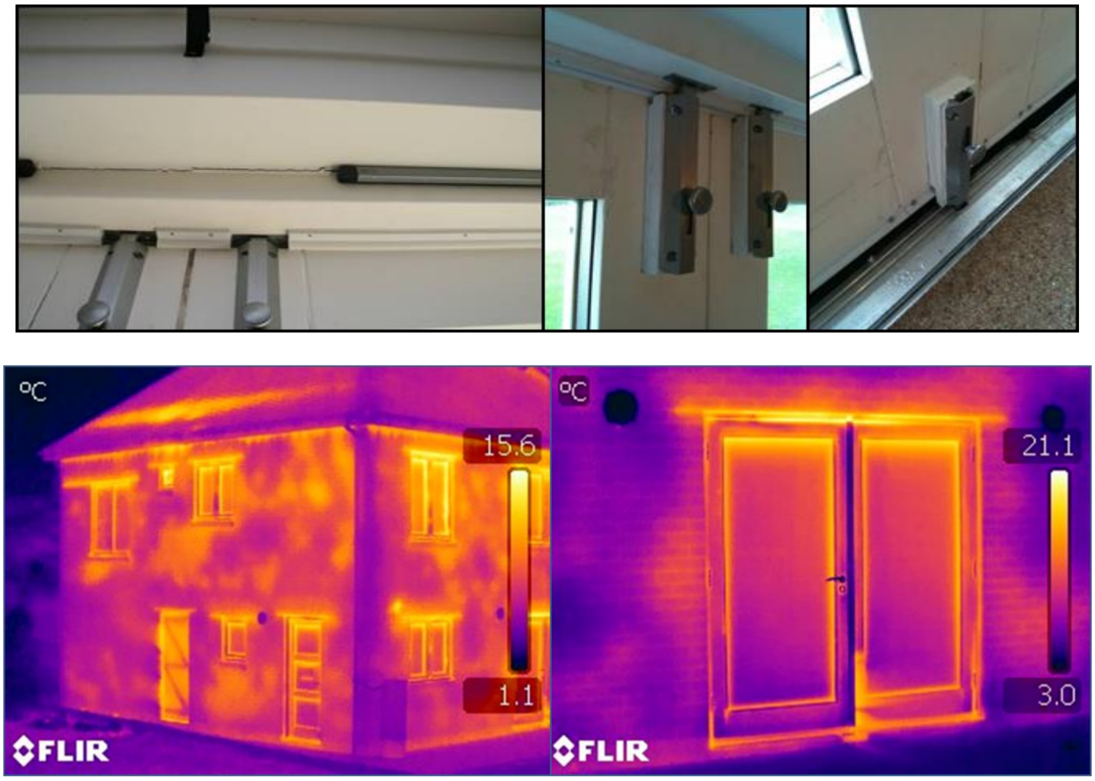

Figure 6 – Observational evidence of poor quality installation and of uneven cavity wall insulation.

The images in Figure 6 clearly indicate the presence of heat losses through these elements, as well as uneven distribution of the insulation applied to the external wall cavity. It was also observed that the installation of the MVHR system had created newly exposed gaps within the building envelope and in the ductwork connections running between the control unit in the loft space and supply/extract vents in individual rooms. This resulted in a higher level of airflow occurring between the internal and external environments [29].

Discussions took place with the commercial company regarding the shortcomings in application of the sealing and draught proofing measures. Improvements were readily accommodated, and Phase 2 works then included the reapplication of draught-proofing measures to transparent glass windows and doors, in order to remedy the poor workmanship of Phase 1, that had been identified through the thermal imaging surveys. Additional work involved the application of the same draught-proofing system to translucent glazed units, alongside the sealing of trickle vents and joints in timber frames, and the fitting of covers to key locks on external doors. Following these improvements, the airtightness level of the house improved substantially (by 4.47 $m^3/(h.m^2)$ @ 50Pa to 9.84 $m^3/(h.m^2)$ @ 50Pa.

The airtightness value recorded at this point now aligned more readily with expectations relating to the level of reduction that could potentially be achieved through the three main fabric interventions – double glazing, external cavity wall insulation and roof insulation. This has demonstrated the importance of the close attention to detail that is required when applying draught-proof measures. It also shows that the correct application of these key measures could be sufficient to improve the airtightness performance of a 1930s house to meet the 2010 building regulations requirements of 10 $m^3/(h.m^2)$ @ 50Pa or lower.

Another significant area of work in terms of reduction of the air leakage rate can be attributed to the sealing of the ground and upper floors as conducted at Phase 4. This resulted in a value of 5 $m^3/(h.m^2)$ @ 50Pa, against a Phase 3 value of 8.6 $m^3/(h.m^2)$ @ 50Pa. When it is considered that the wall/roof insulation and glazing improvements combined (Phases 1 and 2) achieved a reduction of 5.73 $m^3/(h.m^2)$ @ 50Pa, the further 3.6 $m^3/(h.m^2)$ @ 50Pa accredited to the floor sealing works alone is quite considerable. This demonstrates that it is extremely important to ensure that an air tight seal is present at the junction between the floor and wall elements to restrict heat losses via this pathway.

7. Air Tightness and Energy Performance – Model-Based Evaluation

In order to assess theoretical energy and carbon reductions that may be associated with the staged improvement programme, the UK Government approved Standard Assessment Procedure (SAP) 2009 was utilised [30]. This steady state energy assessment model was selected as the reduced data input version of the model (RdSAP) is widely used in the UK in the context of domestic retrofit analysis, and also forms the basis for the generation of dwelling Energy Performance Certificates (EPCs).

Within the context of dwelling energy efficiency, theoretical energy performance assessment can be undertaken with the aid of data modelling tools. The Standard Assessment Procedure (SAP) 2009 is the main tool utilised in the UK for such purposes, and is endorsed by the UK Government for use in design-stage evaluation exercises, and the production of mandatory building Energy Performance Certificates (EPC's) (RdSAP). The final outputs are reliant upon completion of a series of sections, requiring accurate data input and correct use of standard calculations. The first part of the worksheet concentrates on key details relating to the fabric of the property, location and environment, basic design matters (dimensions and type of dwelling) and ventilation. From this information, heat losses from the building can be calculated, which then affect much of the data in the remainder of the model. Other areas considered include energy required for water and space heating, solar gains, internal gains, and energy from renewable sources. When combined, the final outputs of the model are the SAP and EI ratings and the calculation of primary energy requirements (measured in kWh/year).

The SAP 2009 methodology is based upon several assumptions, including:

- The main living areas assume an internal temperature of 21°C
- Other areas assume an internal temperature of 18°C
- Weather data is calculated monthly based on a weather file for the East Pennines Region of the UK (Sheffield)
- Occupancy is calculated as a function of floor area

Key benchmark outputs from the model are:

- SAP Rating – energy costs associated with space heating, water heating, ventilation and lighting, adjusted for floor area (Rating of 1 – 100, with 100 being lowest running costs – average SAP Rating for UK in 2013 was 56.7 compared to 17.6 in 1970 [31])

- Environmental Impact (EI) Rating – annual CO_2 emissions associated with space heating, water heating, ventilation and lighting, adjusted for floor area (Rating of 1 – 100, with 100 being highest standard)

- Supply Energy for Space Heating – the number of kWh required to heat a dwelling, adjusted to account for efficiency levels of integrated systems and boilers. The parameter therefore provides an indication of the supplied energy consumed, rather than building energy demand. It provides a metric that can be understood in the UK and international context.

A baseline model (set of input parameters) for the test dwelling was constructed in SAP 2009 using the SAPPER 9 (RUSFA) software package. SAP 2009 methodology was then utilised in order to develop separate models for each phase of the UK improvement works, with each case adjusted to contain the relevant details of airtightness data and materials/systems utilised within the property as applicable to each stage. This extended to inclusion of the MVHR system as the main ventilation strategy from Phase 1 onwards.

Table 3 contains data relating to the SAP and EI Ratings, and space heating supply energy, for each phase of the retrofit improvement programme. The Phase 1 improvements were threefold, and involved fabric (insulation and glazing works), systems (installation of new boiler, radiators and thermostat together with an MVHR unit), and airtightness (draught-proofing and sealing) works. It is therefore necessary to isolate the impact of each of these intervention types in the model, in order to obtain an estimate of the space heating savings related to each element of the retrofit improvements.

Within Table 3, Phase 1a refers to a model constructed to reflect the improved fabric characteristics, and utilises the baseline airtightness value of 15.57 $m^3/(h.m^2)$ @ 50Pa in conjunction with updated materials and U-values. Subsequently, a second model (Phase 1b) was developed, which comprised of the Phase 1a model and information relating to the new heating and ventilation systems. Finally, the Phase 1c model incorporated all of the Phase 1 fabric and systems information, together with the new measured airtightness test value of 14.31 $m^3/(h.m^2)$ @ 50Pa. The staged development of the model allowed the impact of fabric, systems and airtightness improvements to be individually estimated.

Improvements to House	Test Date	Result from Air Test Q50 (m^3/hm^2)	Infiltration Rate (ACH/h^{-1})	Normal Infiltration Rate (ACH/h^{-1})*	Information from SAP 2009					
					SAP Rating		EI Rating		Space Heating Supply (kWh)	
					Rounded Value	Band	Rounded Value	Band	Total	% Reduction **
Baseline Pre-Retrofit Condition	18/03/2009	15.57	14.85	0.74	36	F	33	F	32373	0.0%
Phase 1a - with baseline Q50 test value (fabric improvements)	09/09/2010	15.57	14.85	0.74	42	E	43	E	19282	40.4%
Phase 1b - with baseline Q50 test value (fabric, heating & MVHR improvements)	09/09/2010	15.57	14.85	0.74	72	C	71	D	11617	23.7%
Phase 1c - all completed work and improved Q50 test value	09/09/2010	14.31	13.65	0.68	72	C	71	D	11342	0.9%
Phase 2	01/10/2010	9.84	9.39	0.47	73	C	73	C	10348	3.1%
Phase 3	19/11/2010	8.60	8.21	0.41	74	C	73	C	10067	0.9%
Phase 4	20/12/2010	5.00	4.77	0.24	75	C	75	C	9237	2.6%
Phase 5	14/02/2011	4.74	4.52	0.23	75	C	75	C	9177	0.2%

*Normal Infiltration Rate is equal to the infiltration rate divided by the value of 20, to convert the test result from Q50 to 'normal' indoor environment conditions

**% reduction is the % reduction between each subsequent stage as a proportion of the baseline space heating value of 32,373.44 kWh

Table 3 - Relevant SAP 2009 Data for Each Phase of Improvement Work

The column in Table 3 headed '% reduction' under 'space heating supply (kWh)' is the reduction between subsequent phases as a proportion of the baseline space heating consumption. For example, the improvements made at Phase 1a resulted in a 40% (19,282 kWh) reduction in space heating consumption when compared against the original value derived from the SAP methodology. The relative metrics highlight the impact of each retrofit measure.

It can be seen that the most significant reductions in supply energy for space heating relate to the glazing works, fabric insulation and the improvements to the integrated heating and ventilation systems. It is interesting to note that, while these elements of the intervention works collectively result in a reduction in space heating supply energy of over 60%, it is actually the fabric improvements rather than systems enhancements (installation of the MVHR system) that have the greater individual effect in reducing space heating requirements.

In terms of the fabric interventions, the impact on the SAP and EI ratings is not major, being 6 and 10 index points, respectively, and a change from Band F to E for both parameters. The systems improvements have a far greater effect on SAP and EI performance indicators, with an increase of 30 and 28 for SAP and EI ratings respectively, and a change from Band E to Band C or D, depending on the parameter being considered. A reduction in space heating supply energy of 13,091 kWh can be observed with respect to the fabric thermal improvements of Phase 1a, whilst Phase 1b, which additionally includes the condensing boiler installation, results in a further decrease of 7,665 kWh. Therefore, it can be concluded that, in the context of space heating, the fabric enhancements are predicted by SAP to have the greatest effect on space heating energy within the case study under consideration, as shown in Table 4.

Improvements to House	Decrease in Pressure Test Result (m^3/hm^2)	Increase in SAP Rating	Increase in EI Rating	Decrease in Space Heating Supply Energy (kWh)
Phase 1a - with baseline Q50 test value (fabric improvements)*	0 (0%)	12.0 (31%)	10.6 (25%)	13,091 (56%)
Phase 1b - with baseline Q50 test value (fabric, heating & MVHR improvements)**	0 (0%)	23.2 (60%)	27.1 (64%)	7,666 (33%)
Phase 1c - all completed work and improved Q50 test value***	1.3 (12%)	0.4 (1%)	0.5 (1%)	274.8 (1%)
Phase 2	4.5 (41%)	1.3 (3%)	1.7 (4%)	994 (4%)
Phase 3	1.2 (11%)	0.4 (1%)	0.5 (1%)	281 (1%)
Phase 4	3.6 (33%)	1.1 (3%)	1.4 (3%)	830 (4%)
Phase 5	0.3 (2%)	0.1 (1%)	0.1 (1%)	61 (0.3%)
Total Change	10.8 (100%)	38.5 (100%)	41.9 (100%)	23,197 (100%)

Notes

* Phase 1a does not include any impact of systems improvements or increased airtightness levels

** Phase 1b accounts for the impact of MVHR/heating systems over solely fabric improvements, excluding any impact of increased airtightness levels

*** Phase 1c accounts for the impact of the work undertaken during Phases 1a and 1b, including the associated increase in airtightness levels

Table 4 - Change in SAP 2009 Parameters Associated With Each Phase of Work

The changes to building fabric and systems account for approximately 90% of the total improvement in SAP Rating, EI Rating and space heating supply energy. However, these measures had only a limited measured effect on the airtightness test result, and it was not until Phase 2 that a considerable reduction in measured air leakage was observed. This was the point at which the draught-proofing and resealing of windows and doors was undertaken, to resolve observed areas of poor workmanship that were evident following the completion of Phase 1.

The total airtightness improvement observed between the Phase 1 condition and Phase 5 amounted to a reduction of almost 10 $m^3/(h.m^2)$ @ 50Pa. It is interesting to note that the SAP output parameters do not appear to be particularly sensitive to variations in air permeability input data, as the large change in airtightness level results in only a 10% change in SAP and EI Rating and space heating supply energy. Therefore, some caution should be used when using the SAP methodology to evaluate airtightness works. In the case of the test dwelling, and the order in which the improvement work was undertaken, the upgrading of the heating and ventilation systems resulted in the greatest shift in the SAP Rating and EI Rating data, an approximately 60% improvement. The exception to this is apparent in relation to comparison of space heating requirements, where fabric upgrades cause the largest change in the data.

Figure 7 shows the relationship between the measured decreasing air permeability (i.e. improving airtightness) and the reduction in space heating supply energy as predicted by SAP. This graph relates solely to the improvement works associated with airtightness from Phase 1c through to Phase 5 in order to illustrate the relationship between the two parameters (measured air permeability, and SAP predicted space heating energy supply). Reducing air permeability from 15.57 to 4.74m^3 hr m^{-2} @ 50Pa results in a SAP predicted energy saving of (11,617– 9,177) = 2440 kWh per annum. The initial state is taken as Phase 1b, to remove the effect of the fabric and systems upgrades undertaken.

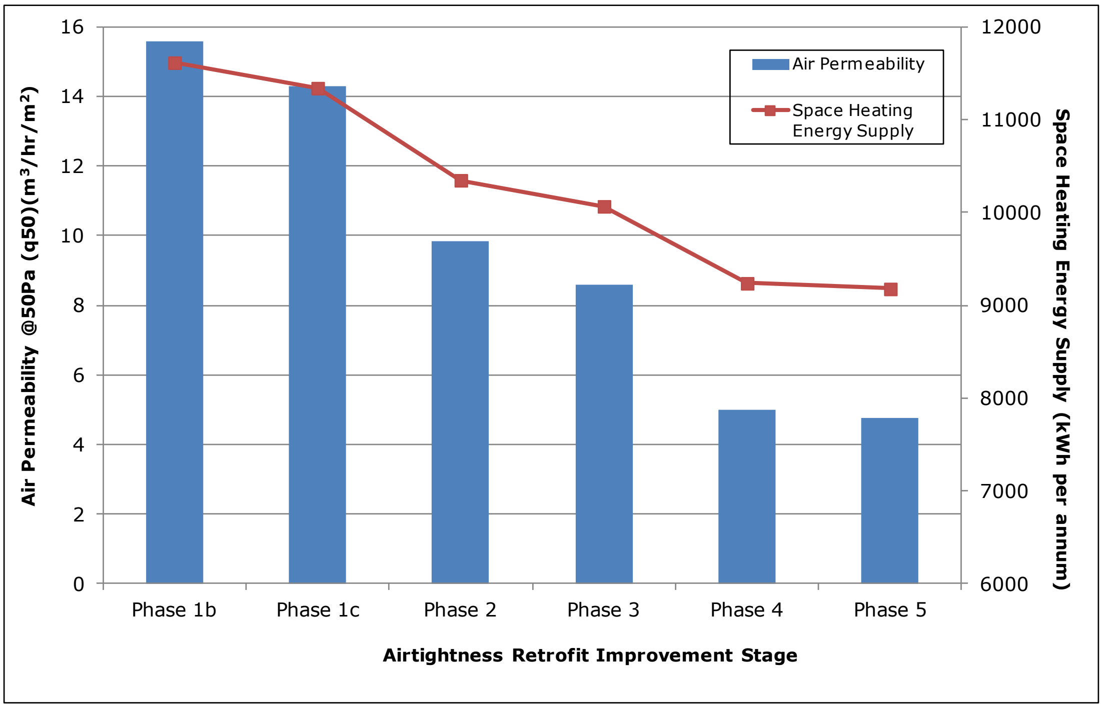

Figure 7 – Airtightness Measures Only – Pressure Test and Space Heating Supply Energy Data

The order of retrofit has an impact upon the energy savings attributable to a particular retrofit intervention. It is interesting to note that, theoretically had the same airtightness improvements been undertaken before any alterations were made to the building fabric and heating systems, the amount of energy savings attributable to the air tightness measures would have been greater. This being due to the fact that utilising a higher efficiency boiler in the earlier stages proportionately impacts upon the supply energy requirement in subsequent stages. Findings by Simpson and Banfill [32] suggest that in improvements to glazing and building fabric U-values consistently result in the largest savings, regardless of the stage in the retrofit programme at which they are undertaken. Heating system upgrades are more difficult to analyse, due to the issues of correct sizing to deliver peak load demands and related performance efficiency, which may increase energy use depending on the appropriateness of the boiler installed and the timing of the upgrading work.

8. Cost Effectiveness Aspects and Discussion

In this final section, the energy savings and cost effectiveness associated with the air tightness measures undertaken will be considered and discussed in relation to the other works carried out on the test house. The process of estimating the cost-effectiveness of the measures undertaken is complicated by several factors, and it is necessary to put these in perspective, as follows.

Firstly, figures for energy consumptions are estimated through use of the SAP modelling procedure, and thus can only be approximations. It is also questionable whether the use of data from the SAP 2009 methodology is suitable, when taken in isolation, for assessing the effectiveness of purely air tightness improvement measures. Within the SAP methodology, the formula used to estimate background infiltration rates is based upon a standardized rule of thumb, where the q50 air pressurization test result is divided by a factor of 20. The methodology applied has been simplified in the model, as originally a series of additional factors were developed to adjust for dwelling height, shelter/exposure, type and size of air leakage pathways, and environmental concerns, which led to subsequent modification of the default division factor [11, 25]. The ability of the simplified equation to accurately reflect background infiltration rates in energy models has been questioned, although research in this area is currently limited [12]. The limitations of the SAP model in this respect may be leading to underestimation of the effect of airtightness measures on energy demands.

Secondly, figures for financial expenditure relate to refurbishments made to an experimental test house, and in some cases have involved specialised approaches. This is particularly the case with the floor to wall sealing process for reducing air leakiness via the floor. In this study, bespoke over-cloaking skirting boards were used to lessen the disruption to occupants, which is an expensive solution. In future, it may be possible that floor sealing could become a process carried out as part of normal carpet laying, utilising a suitable edge-sealing method to the underside of the skirting board, which may be a much less expensive approach.

Thirdly, factors related to improvement of indoor environmental quality and occupant 'comfort' in the broader sense, as well as the 'inconvenience' associated with certain domestic refurbishment activities, are difficult to quantify, yet nevertheless are important considerations.

Table 5 shows preliminary estimates of energy and costs associated with each phase of improvement works for the test house. SAP-predicted space heating energy supply has been used to estimate the energy savings realised for each intervention. A standard gas price of £0.0421 / kWh has been applied to obtain a monetary value for the level of reduction in household energy consumption [33]. The costs of each retrofit measure have been estimated in accordance with prices and tax rates applicable at the time when the work was undertaken (between 2009 and 2011).

It is important to note that these costs relate to the actual costs incurred for this experimental work, and thus includes the cost of remedial work to the draught-proofing intervention (giving a total cost of about £300). A more realistic figure for draught-proofing by well-trained installers might only be half of this figure, say £150, and so the latter figure is also shown. Furthermore, the cost of £9000 for floor-sealing relates to a bespoke measure; were this to become part of normal future carpet-fitting practice, then a figure of perhaps £2000 (also shown in Table 5) or less might be more reasonably expected.

The costs of this intervention are high due to the use of bespoke joinery and the experimental nature of the work. The focus was to prove the concept of using the floor membrane to create an airtight element, rather than financial concerns. In a real retrofit situation, it may be more appropriate to remove and replace skirting boards, allowing the membrane to be glued or taped to the wall behind the boarding. This would achieve the same end result at a lower cost of around £2000 (£1000 for materials and 3 days of labour at approximately £300/day).

Essentially, it is important to note that the findings presented in this study should not be used as a basis for financial or price-based decisions, as true costs may be significantly less for some of the intervention work.

Stage of Project	Pressure Test Result (m^3/hm^2)	Space Heating Supply Energy (kWh/annum)	Saving in Space Heating (kWh/annum)	Saving in Space Heating (£/annum)	Cost of Retrofit Measures
Baseline Pre-Retrofit Condition	15.57	32,373	n/a	n/a	n/a
Phase 1a - fabric improvements only*	15.57	19,282	13,091	551	3,350
Phase 1b - fabric and systems improvements only (heating & MVHR)**	15.57	11,617	7,665	323	10,000
Phase 1c - all improvements with relevant Q50 test value***	14.31	11,342	275	12	300
Phase 2	9.84	10,348	994	42	included
Phase 3	8.6	10,067	281	12	200
Phase 4	5	9,237	830	35	9,000
Phase 5	4.74	9,177	61	3	2,800
Change in Parameter/Total	10.83 (100%)	23,197 (100%)	23,197 (100%	£977 (100%)	25,650 (100%

Notes
* Phase 1a does not include any impact of systems improvements or increased airtightness levels
** Phase 1b accounts for the impact of MVHR/heating systems over solely fabric improvements, excluding any impact of increased airtightness
*** Phase 1c accounts for the impact of the work undertaken during Phases 1a and 1b, including the associated increase in airtightness levels

Table 5 - Costs and Savings Associated with Retrofit Measures

In Table 5, Phase 1a relates to fabric insulation and double glazing expenditure; Phase 1b relates to heating system (boiler) and MVHR system expenditure. Note that any space heating savings associated with MVHR would probably not be realised until later in the retrofit programme, once the building envelope is sufficiently airtight; Phase 1c relates to draught-proofing measures applied to transparent glazing and doors; Phase 2 relates to draught-proofing measures applied to translucent glazing and doors, and to fitting of covers to external door locks; Phase 3 relates to sealing of pipe penetrations and removal of kitchen extract fan; Phase 4 relates to sealing of floor boards and sealing of floor / wall junctions at skirting boards; Phase 5 relates to sealing of junctions between walls and ceilings.

Using the data in Table 5, together with the adjusted figures of £150 and £2000 for detailed draught-proofing and skirting sealing, respectively, Table 6 presents a summary of expenditure per kWh saved for each phase of improvement. Also shown is a subjective assessment of potential 'inconvenience' for the occupants associated with each measure, classified as 'high', 'medium' or 'low'. For example, the installation of a boiler and MVHR system might have an 'inconvenience' level judged as 'high', due to invasiveness within the home and time taken to complete the work; sealing of ground floors at the skirting board when conducted as part of a future normal carpet refitting might be considered as 'medium' in terms of inconvenience; and draught-proofing around doors and windows might be considered as 'low' in inconvenience (completed fairly rapidly with little disturbance to household routines).

Phase of improvement	Saving in space heating (kWh/annum)	Cost of retrofit measure (adjusted)(£)	Cost per kWh saved (£/kWh)	Simple payback (years)	Subjective level of 'inconvenience' to occupants
Phase 1a: fabric (cavity wall) insulation, double glazing	**13,091**	**£3,350**	**£0.26**	**6**	**medium**
Phase 1b: boiler and MVHR	**7,665**	**£10,000**	**£1.31**	**31**	**high**
Phases 1c and 2: all draught-proofing, external lock covers	**1,269**	**£150 (adjusted figure)**	**£0.12**	**3**	**low**
Phase 3: sealing of pipe penetrations	**281**	**£200**	**£0.71**	**17**	**medium**
Phase 4: floor sealing at skirting boards	**830**	**£2,000 (adjusted figure)**	**£2.41**	**57**	**medium**
Phase 5: sealing at junction of walls and ceilings	**61**	**£2,800**	**£45.90**	**933**	**medium**

Table 6: Cost-effectiveness and subjective 'inconvenience' associated with each measure

Of all the air-tightness improvements undertaken in this retrofit context (Phases 1c-5), the draughtproofing measures are the most effective in terms of energy-saving, cost, and reduction in air permeability. Sealing of the suspended timber floors also significantly reduced air leakage, and its cost-effectiveness could be improved if developed to become part of normal carpet-fitting practice in future. There could also be beneficial effects on occupant thermal comfort and behaviour. For instance, this may lead to fewer situations where thermostat settings are increased to offset local thermal discomfort caused by draughts. Consequent potential energy savings via these mechanisms are not accounted for in this analysis.

Taking the perspective of air tightness improvements in comparison with fabric insulation and boiler improvements, it is clear that the fabric and boiler improvements, taken together, yield by far the greater energy savings (approximately 64% of the total savings of 23,197kWh achieved across all phases, in comparison to less than 9% for the air-tightness measures). However, these figures relate to the case of a house being improved from an initially-uninsulated condition. For initially better-insulated dwellings, improvements to air tightness can have a correspondingly better impact on energy savings in percentage terms. Furthermore, reduced carbon emissions, improvements to occupant thermal comfort and to indoor environmental quality (reduction in unwanted sound transmission, for example) [34] should not be overlooked. The relatively low inconvenience associated with applying some of the air-tightness measures is also worthy of note.

Taken together, improving the air tightness – perhaps better described to householders in terms of reduction of unnecessary air leakage – of a home is an important and worthwhile refurbishment practice. Where the retrofit installation of an MVHR system is contemplated, having a sufficiently airtight building envelope becomes essential [35].

9. Conclusions

When evaluating the effectiveness of the retrofit measures, a number of criteria should be considered, including impact on the air pressurisation test result, reduction in energy demand and energy costs, and the capital cost of the intervention. In this case, a test house was utilised in order to complete a phased programme of fabric and ventilation interventions and improvements. For the case in question, it was possible to improve the measured air permeability from 15.57 to 4.74 $m^3/(h.m^2)$ @ 50Pa in a retrofit context. It should be noted that, at the latter level of airtightness, it is necessary to ensure that adequate ventilation is provided for all combustion appliances and also because of other aspects of air quality such as internal humidity and airborne pollutants. The negative aspects of not addressing these unintended consequences could result in health implications for the occupants of the dwelling.

In order to achieve this significant improvement in air tightness, a high level of attention to detail was required, which may mean that an increased level of rigour should be emphasised during training programmes for installers. This study has shown that poor workmanship could easily compromise the benefits realised and therefore attention to detail is critical. Of the airtightness improvement measures used in this project, draughtproofing and sealing of the floor/wall joint at the skirting board interface were found to be the most effective, providing reductions in measured air permeability of 5.73 $m^3/(h.m^2)$ @ 50Pa) and 3.6 $m^3/(h.m^2)$ @ 50Pa respectively. The installation of double glazed units showed very minimal improvement of air tightness circa 1.26 $m^3/(h.m^2)$ (when coupled with the installation of wall and roof insulation). It was considered that this was perhaps unrepresentative of the air tightness increase that could be observed in aged properties as the test house was a newly built replica with well-engineered fabricated wooden frames.

The effects on building energy consumption attributable to each intervention (both fabric and ventilation) have been estimated using the SAP 2009 methodology. The modelling work clearly shows the effectiveness of fabric measures (64% reduction) in relation to air tightness measures (9% reduction), when considering the case of the initial uninsulated house. These values may change when better-insulated properties are considered, and it should also be noted that SAP may underestimate the effects of ventilation measures. It must also be noted that this study has presented one retrofitting case for a certain set of parameters and therefore the findings are limited as they are informative. Further studies are required to provide greater evidence to support the efficient deployment of retrofit processes.

In terms of cost effectiveness, this was difficult to assess due to the nature of the project being an experimental case study. However, draught-proofing measures to the external building envelope are comparatively cost effective, with a payback period of less than 6 years. The floor sealing works incurred a considerable expense for a minor reduction in space heating supply energy. The work is also quite complex and time-consuming, with some inconvenience to residents whilst it is being undertaken. It is considered, however, that alternative methods of floor sealing could be performed as a process prior to laying of new carpets, which could reduce the expense of this airtightness measure.

When selecting improvement methods, the practicality of actually implementing them within the context of an existing home must be given full consideration. Factors such as appeal to and acceptance by the householder, alongside potential levels of inconvenience and disruption, should be assessed. Improved comfort and indoor environmental quality are also key issues that should not be overlooked when evaluating refurbishment measures. It is also fundamental to ensure that a high level of workmanship is employed when carrying out the associated construction, installation and snagging workstreams, in order to realise the maximum benefit for the effort involved.

The order in which retrofit measures are applied can affect the impact of interventions, and the difficulties experienced throughout the research programme suggest that the challenge of achieving low levels of air permeability should not be under-estimated. However, taken together, improving the air tightness and reducing unnecessary air leakage is a worthwhile course of refurbishment. It is also an essential part of any programme that includes the retrofitting of an MVHR system in order to ensure optimum ventilation system performance.

Air tightness testing is a highly informative tool and this study has shown that there varying degrees of air leakage reduction exist for different interventions. Currently in the UK such testing is not routinely performed in retrofit projects, but it is apparent that the inclusion of this testing could assist in delivering optimised retrofit processes particularly for owners of large housing stock such as social landlords. When used alongside air leakage diagnostic methods such as thermography, air tightness testing would ensure that retrofit work undertaken is performed to the highest standards delivering the required improvements.

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