Communities and Local Government Building Regulations Division Under the Building Operational Performance Framework

AIRTIGHTNESS OF BUILDINGS — TOWARDS HIGHER PERFORMANCE

Interim Report D1 — Literature Review and Built Examples

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Reference Number: CI 61/6/16 (BD2429)

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Interim Report D1 — Literature Review and Built Examples

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Executive Summary

1 Airtightness is crucial to improving the energy performance of buildings. This is recognised in Approved Document Part L of the 2002 Building Regulations, which, for the first time, includes a maximum air leakage target for both domestic and non-domestic buildings. The overall aim of this project is to investigate means of achieving higher airtightness than the current requirements. This report comprises a literature review of airtightness of building in the domestic sector, and identifies airtightness standards for dwellings, compares airtightness measurements of housing in the UK and overseas, and identifies the causes of poor airtightness and design guidance available. Airtightness measurements were also conducted on seven previously untested UK dwellings, expected to be airtight by UK standards due to their design.

2 The data show that a very wide range of air leakage exists within the UK housing stock, with the least airtight dwellings being over 10 times as leaky as the most airtight. A significant proportion of these dwellings would fail to meet the Approved Document L1 air leakage target. UK dwellings tend to be very leaky in comparison with their international counterparts in Europe and North America. For example, UK dwellings tend to be only as airtight as those constructed in Canada, Sweden and Switzerland some 60 years ago. Dwellings classed as very airtight in the UK, would be classed as normal practice in these countries. The design approach and construction techniques for dwellings must therefore be improved significantly if the UK is to match the airtightness performance of the best buildings overseas.

3 In the UK, one of the most important determinants of airtightness is construction type. Other factors that are known to influence airtightness include age of the dwelling, number of storeys, size and complexity of the building, and site supervision and workmanship. The most common form of dwelling construction in the UK is cavity masonry, and the data show that these tend to be very leaky. The reasons for this can be mostly attributed to the common UK construction practices of plasterboard dry-lining and timber intermediate floors. In comparison, masonry dwellings on the continent are typically wet plastered, and have concrete floors, and are consequently more airtight than their equivalents in the UK.

4 The main air leakage paths within UK dwellings have been identified. The majority of this leakage is attributable to a range of cracks, gaps and joints throughout the building, rather than a single component.

5 A considerable amount of guidance on airtightness has been identified. The majority of this is from overseas, especially from those countries such as Canada and Sweden where air leakage standards have been in place for many years. General guidance on designing dwellings for airtightness gives the following advice: the airtightness layer should be continuous around the building envelope; it should be in the same plane throughout the structure; it should be easily installed, and be durable and accessible for maintenance; designs should avoid, or at least minimise, penetrations through the sealing layer; and designs should avoid complex detailing. Specific issues associated with UK construction practice are highlighted in several documents. In the case of plasterboard dry-lining, design advice is to seal around the perimeter of boards. However, it must be acknowledged that this is very difficult to achieve and despite this advice appearing in the Building Regulations Approved Documents since 1995, it does not appear to have had a significant impact on the airtightness of masonry dwellings in the UK. The alternative approach is to use a wet plastered finish, a method that is generally more robust.

6 The main source of detailed design guidance on airtightness in the UK is the Robust Construction Details document. The guidance given here is restricted in its scope in that it does not give enough information on the principles of airtightness, as applicable to each of the detailed designs. There is also little information on tolerances and potential variability within each of the designs. This would allow for a wide interpretation of the design details and is likely to give rise to variability in the way details are applied, with a reduced impact on airtightness. The impact of Robust Details on the airtightness of new UK dwellings is not yet known, as no significant data are available on buildings constructed since its introduction in 2001. The next stage of this project will address this issue.

7 The results of the airtightness measurements on the seven UK dwellings showed them to be airtight by UK standards, with airtightness ranging from 1.1 to 7.7 ac/h @ 50Pa. Of these, the three earth-sheltered dwellings at Hockerton were found to be amongst the most airtight dwellings ever recorded in the UK, although they still fall short of best practice overseas (less than 0.3 ac/h @ 50Pa). These buildings, all constructed with a wet plastered internal finish, demonstrate that this form of construction can default to a reasonable level of airtightness by UK standards and that it is

possible to build very airtight housing in the UK, given a reasonable level of attention in design and construction.

Introduction

Description of the project

8 This report is milestone D1 of the Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of buildings — towards higher performance*.

9 Airtightness is crucial to improving the energy performance of buildings. This was recognised in the June 2000 consultation paper on Part L of the Approved Document (DETR, 2000) which, for the first time, proposed a maximum air leakage target of 10 $m^3/(h.m^2)$ @ 50Pa for both domestic and non-domestic buildings. In April 2002, the amended editions of the Approved Document came into effect; L1 for dwellings (ODPM, 2003) and L2 for buildings other than dwellings (DTLR, 2001). These amendments are intended to be the first of a series of changes that are proposed to take place to the Building Regulations over this decade, with the next major review scheduled for 2005 (DTI, 2003). The amended editions of the Approved Documents L1 and L2 incorporate an explicit air leakage target of 10 $m^3/(h.m^2)$ @ 50Pa, and compliance can be demonstrated by pressure testing using the method contained within CIBSE TM23 (CIBSE, 2000). In the case of domestic buildings, it is anticipated that house builders will demonstrate compliance by adopting the Robust Details approach, whilst for non-domestic buildings, pressure testing is expected to become more common, particularly for those buildings that have a gross floor area in excess of 1000 m^2.

10 The overall aim of this project is to investigate means of achieving airtightness higher than the current requirements of Approved Documents L1 and L2. In particular, this report addresses those issues relating to the domestic sector, and investigates airtightness standards for dwellings, comparisons of real measurement of airtightness of dwellings, the causes of poor airtightness, and guidance available to improve airtightness in terms of design and workmanship. A separate report is being prepared on the airtightness of buildings in the non-domestic sector. It is intended that the findings of this work will be used to inform the next revision of the Building Regulations.

11 This report presents the results of a literature review, which is supplemented by a small number of field tests of airtight dwellings, together with open-ended questionnaires completed by the current occupiers and those responsible for their design and construction. The purpose of these questionnaires was to assess the occupant experience of airtightness within their dwelling and to assess the experience gained from those involved in the design and construction of airtight dwellings.

Airtightness of UK dwellings

12 The largest and most comprehensive source of information on the airtightness of UK dwellings is BRE's database of air leakage (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. The information contained within the database indicates that a very wide range of air leakage and air permeability exists within the UK housing stock, with the least airtight dwellings being over 10 times as leaky as the most airtight dwellings (see Figures 1 and 2).

13 There is a commonly held perception that new dwellings are built to a high standard of airtightness (Olivier, 1999). This is not generally found to be the case. Cohort data contained within the BRE database suggest that dwellings built between 1980 and 1994 are, on average, as airtight as those built at the beginning of the 20^{th} century (see Figure 3). Whilst the air leakage data for the older dwellings are not likely to be representative of the airtightness of these dwellings when they were first built, the data suggest that the airtightness of new dwellings has not improved significantly over the last century.

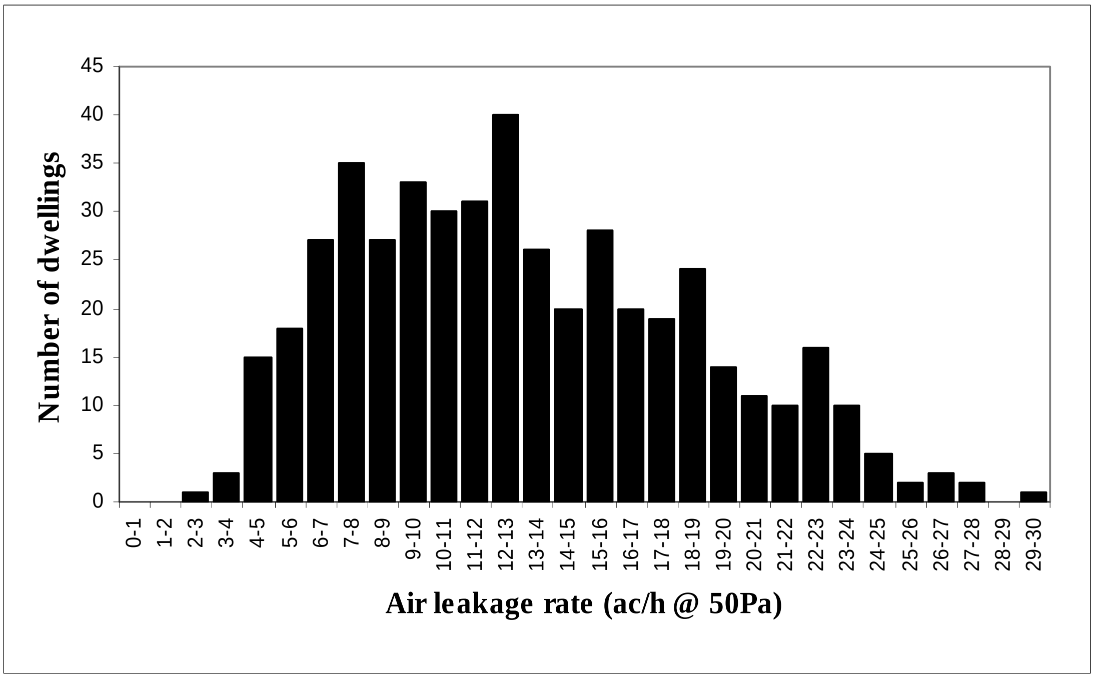


Figure 1 Distribution of air leakage rates in UK dwellings. After Stephen (2000).

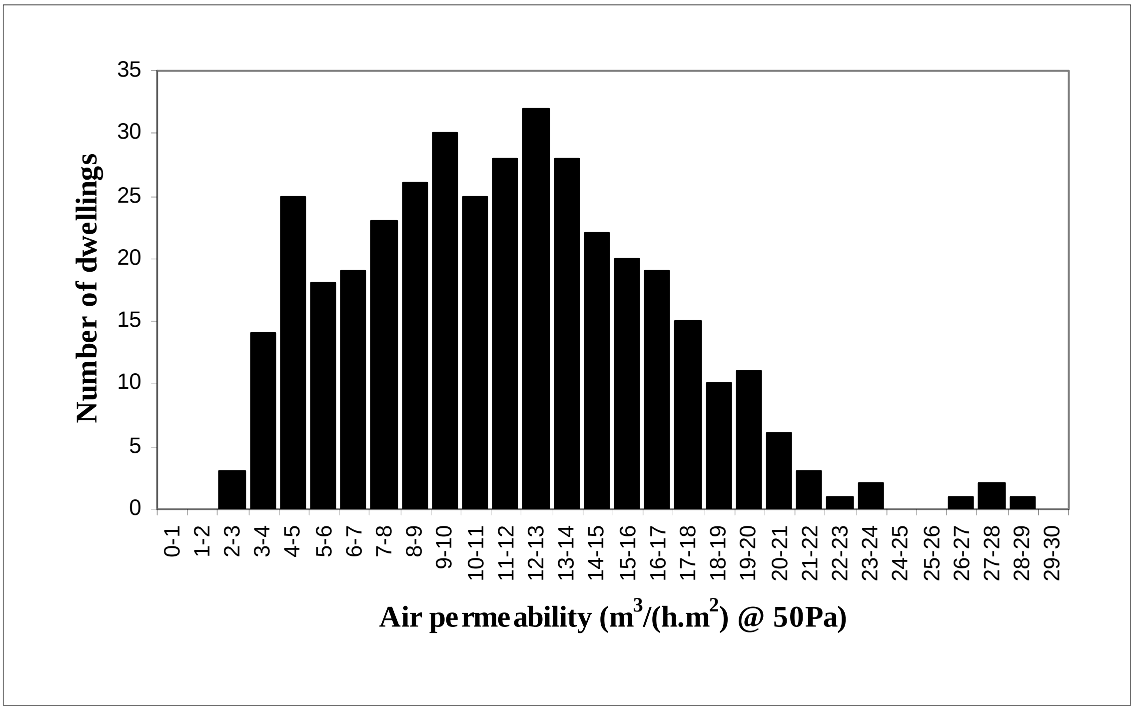


Figure 2 Distribution of air permeability of UK dwellings. After Stephen (2000).

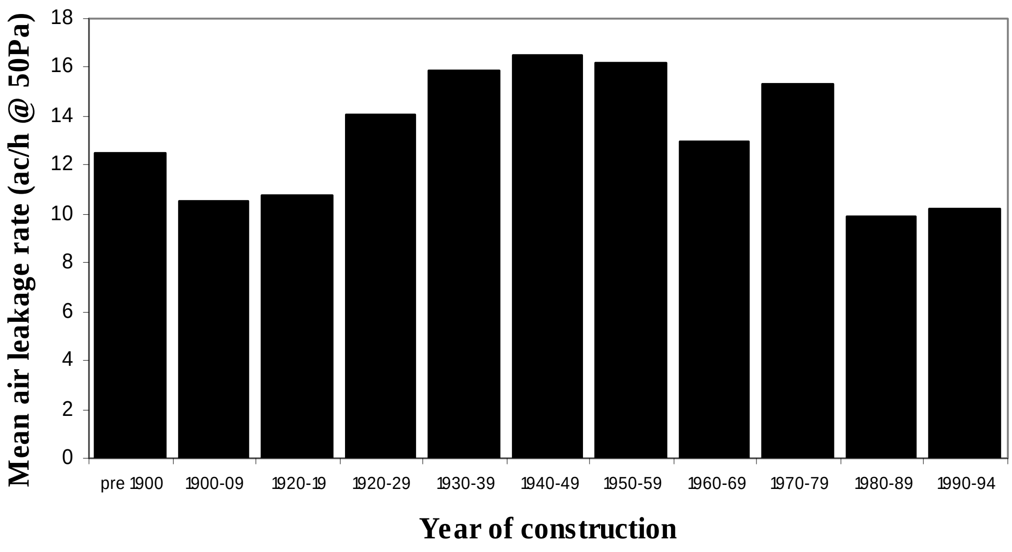


Figure 3 Relationship between dwelling age and air leakage. After Stephen (2000).

14 Air leakage data on dwellings built from 1995 onwards are limited. Recent measurements undertaken by the BRE (see Stephen, 2000) on 32 post 1995 dwellings show that there is still a very wide range of airtightness observed within the sample (6.0 to 19.3 $m^3/(h.m^2)$ @ 50Pa), and that the average value is only marginally more airtight than the average for the stock as a whole (air permeability of 11.3 $m^3/(h.m^2)$ @ 50Pa, as opposed to 11.48 $m^3/(h.m^2)$ @ 50Pa). This small difference indicates that there is no real improvement in the airtightness of buildings built post-1995. These results also suggest that a significant proportion of the post 1995 dwellings would fail to meet the Approved Document L1 air leakage target of 10 $m^3/(h.m^2)$ @ 50Pa (ODPM, 2001). However, the size, structure and non-random nature of the post 1995 sample preclude certainty. It should also be pointed out that the data do not include airtightness measurements on any buildings constructed since the 2002 revision of the building regulations.

Comparison with other countries

15 The UK is not the only country to have whole building airtightness requirements. Currently, Belgium, France, the Netherlands, Norway, Sweden, Switzerland and the USA have criteria to limit whole building air leakage from dwellings (Limb, 2001). However, different countries express the air leakage criteria in a variety of different ways, making any cross-country comparisons difficult. For instance: Belgium, the Netherlands, Norway and the USA express the criteria in terms of ac/h at a specific reference pressure (4, 10 or 50Pa); France, Switzerland and the UK express the criteria in terms of $m^3/(h.m^2)$ at a given pressure difference (4 or 50Pa); whilst Sweden uses $l/s/m^2$. Nevertheless, a simple and relatively crude comparison can be undertaken if assumptions are made about the volume and surface area of a typical building, and by normalising the air leakage criteria to a standard pressure differential. Such an approach was adopted by Limb (2001), who assumed an internal building volume of 300 m^3, a surface area of 250 m^2 and normalised the figures to a pressure differential of 50Pa. Table 1 and Figure 4 illustrate the results of such a comparison, for all of the countries that have air leakage criteria for dwellings.

Country	Whole building requirement	Normalised ac/h @ 50Pa
Belgium	<3 ac/h @ 50Pa for dwellings with balanced mechanical ventilation. <1 ac/h @ 50Pa when heat recovery devices are used.	3.00
France	0.8 to 2.5m^3/h/m^2 @ 4Pa.	11.0
Netherlands	Class 1 ventilation system – Min 0.4 to 0.72 ac/h @10Pa and max of 1.4 to 2.24 ac/h @ 10Pa. Class 2 ventilation system – Max 0.72 to 1.15 ac/h @ 10Pa.	6.50
Norway	Detached and undetached houses – 4 ac/h @: 50Pa. Other buildings two storeys high or less – 3 ac/h @ 50Pa. Other buildings more than two storeys high – 1.5 ac/h @ 50Pa.	4.00
Sweden	Envelope should be so airtight that the average air leakage rate at 50Pa does not exceed 0.8 l/s/m^2.	2.88
Switzerland	New buildings – 0.75 m^3/h/m^2 @ 4Pa upper limit, 0.5 m^3/h/m^2 @ 4 Pa recommended. Refurbished or modified buildings – 1.5 m^3/h/m^2 @ 4Pa upper limit, 1 m^3/h/m^2 @ 4Pa recommended.	3.30
UK	Does not exceed 10m^3/h/m^2 @ 50Pa.	8.30
USA	Max 1.6 ac/h @ 4Pa. Requires no part of the US to be tighter than 0.28 ac/h @ 4Pa.	8.50

Table 1 Maximum whole building airtightness requirements for dwellings. Adapted from Limb (2001).

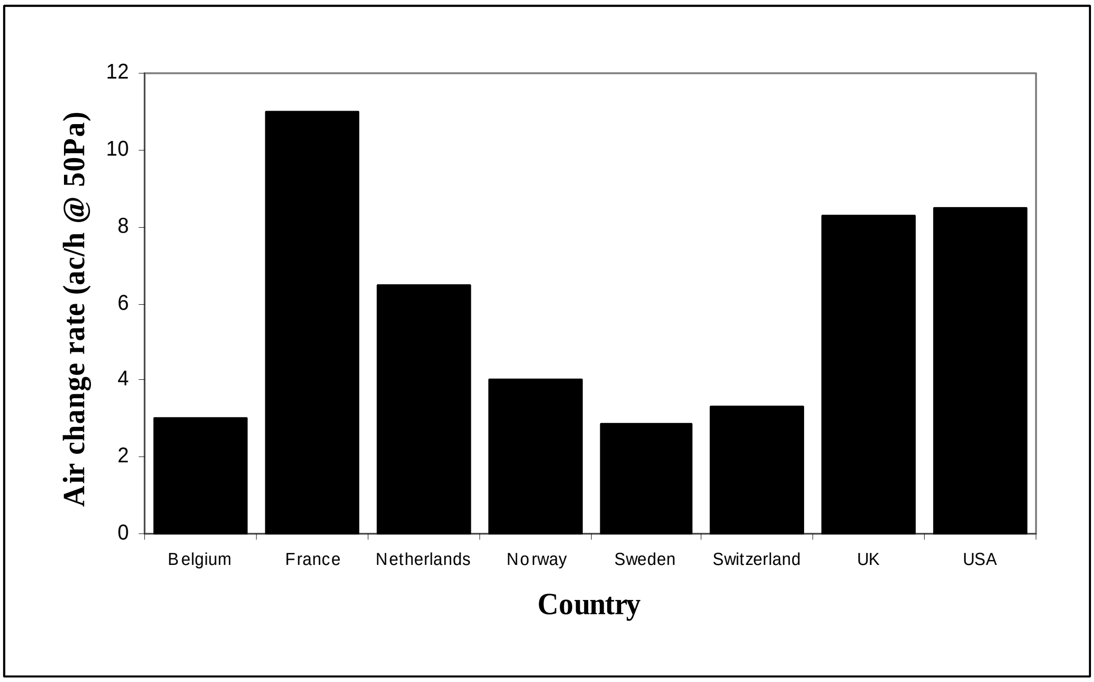


Figure 4 Comparison of maximum normalised air leakage criteria for dwellings.

16 The comparison highlights the wide range of normalised air leakage criteria that exists between the various countries. The most stringent air leakage criteria tend to be found in countries with severe climatic conditions, such as Sweden (2.88 ac/h @ 50Pa), whilst countries with more temperate

climates tend to have less stringent criteria, for instance France (11 ac/h @ 50Pa). Part of the reason for this is likely to be attributable to the fact that in countries that experience severe climatic conditions, leaky buildings can result in extreme user discomfort. Figure 4 also illustrates the considerable gap in air leakage criteria that exists between the UK and countries such as Norway, Switzerland, Belgium and Sweden. In fact, the data would suggest that there are very few tested dwellings in the UK that would satisfy the air leakage requirements of these countries.

17 A number of studies have also compared the airtightness of existing UK dwellings with those in other countries, for instance Olivier (1999) and Orme, Liddament and Wilson (1998). Although the size, structure and non-random nature of the dwellings included within these studies may preclude certainty, the results suggest that existing UK dwellings tend to be very leaky in comparison with a number of their international counterparts, and new UK dwellings tend to be as airtight as dwellings constructed in Canada, Sweden and Switzerland some 60 years ago. Recent work also suggests that new French dwellings are considerably more airtight than new dwellings constructed in the UK (see Litvak, Guillot, Kilberger and Boze, 2000). In addition, dwellings that are classed as very airtight by UK standards, such as the Lower Watts House (3.6 ac/h @ 50Pa) and the Longwood House (3 ac/h @ 50Pa), tend to be normal practice in countries such as Canada, Sweden, Switzerland and Norway.

Factors influencing the airtightness of dwellings

18 A number of factors are known to influence the airtightness of dwellings. These are as follows:

Age of the dwelling

19 One would expect that the airtightness of a dwelling would be influenced, to a certain degree, by the age of the dwelling, with newer dwellings being more airtight than older dwellings. In countries that have well established whole building airtightness requirements, such as Canada, Sweden and Switzerland, this tends to be the case (see Figure 5). Such a distinction in the airtightness of new and existing dwellings has also been observed in the USA (Sherman, 2001). However, it is important that these findings do not lead to complacency. For instance, in the USA, Sherman (2001) found that the airtightness of new construction is no longer improving. In countries with less well established requirements, such as the UK, this trend is almost non-existent (see Figure 3). In fact, as has already been shown in the section on Airtightness of UK dwellings, the work undertaken by the BRE (Stephen, 1998 and 2000) suggests that dwellings constructed at the beginning of the 20th century are as airtight as those that have been constructed since the 1980s.

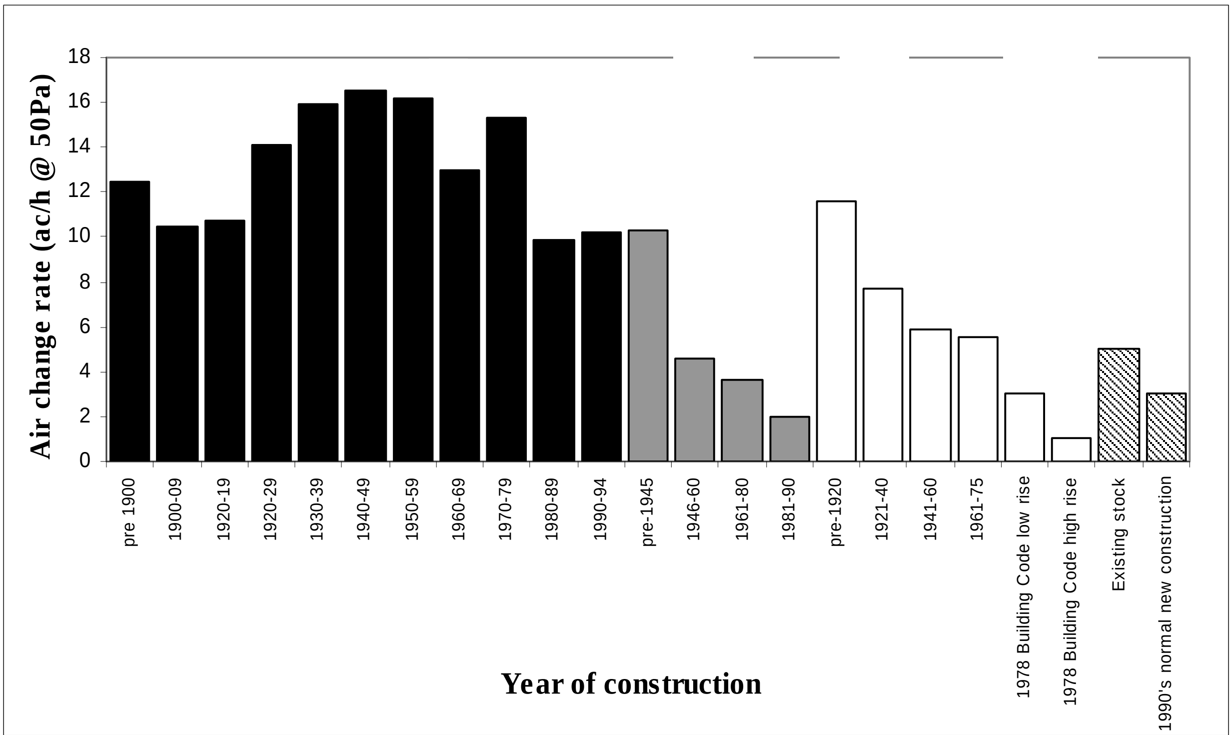


Figure 5 Effect of age on airtightness. Adapted from Stephen (2000) and Olivier (1999).

Construction type

20 Airtightness is strongly influenced by the type of construction. Theoretically, certain types of construction are intrinsically more airtight than other methods of construction. For instance, wet plastered masonry and concrete overseas dwellings tend to be more airtight than comparable timber or steel frame dwellings (Olivier, 1999). Evidence of this has been gained from pressurisation tests undertaken on a large sample of dwellings in Norway and Sweden (Olivier, 1999). These tests indicated that the dwellings constructed from concrete were tighter than plastered brick masonry dwellings, which in turn were tighter than the timber frame dwellings.

21 Conversely, in the UK, cavity masonry construction tends to be inherently leaky. Recent work undertaken by the BRE (Stephen, 2000) on different types of wall construction found that cavity masonry walls were considerably leakier than solid masonry, timber framed and large panel system (LPS) walls (see Figure 6). There appear to be two main reasons for the poor performance of masonry cavity construction in the UK. First of all, wet plastered walls have almost entirely been replaced by plasterboard dry-lined walls, particularly in new housing. This compares with the rest of Europe which still uses wet plaster as an internal finish to masonry walls (Olivier, 1999). Wet plaster has the advantage of sealing any badly pointed joints or shrinkage cracks in the inner leaf, thereby closing air pathways between the wall cavity and the interior of the house. Plasterboard dry-lining, on the other hand, can be a significant source of air leakage if it is not properly edge sealed (see Stephen, 1998 and 2000 and Lowe, Johnston and Bell, 1997), as the air gap behind the plasterboard effectively interconnects all of the air leakage paths within the dwelling, producing a complex network of inter-penetrating voids. Secondly, the majority of upper floors in UK dwellings are constructed using timber joists or I-beams that are either built into the inner leaf of the cavity wall or are supported on joist hangers. Built-in joists are also known to be a significant source of air leakage (Stephen, 1998 and 2000). This compares with the rest of Europe, where *in-situ* concrete upper floors were adopted many decades ago (Olivier, 1999).

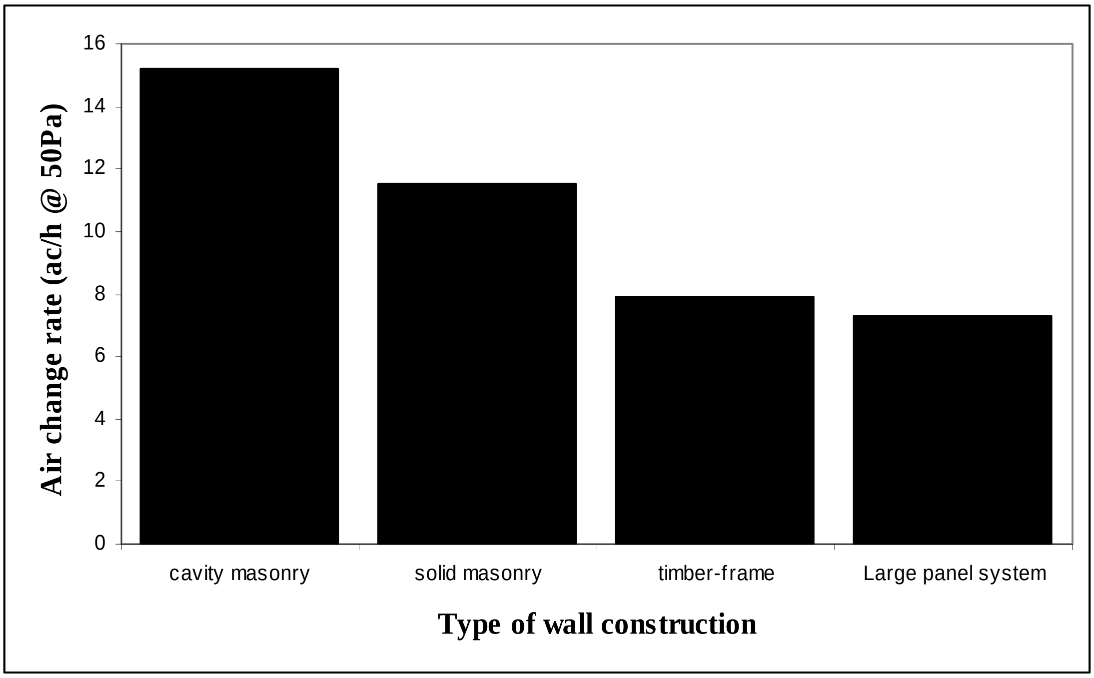


Figure 6 Influence of wall type on mean air leakage rate. After Stephen (2000).

Number of storeys

22 There is some evidence to suggest that the number of storeys has an influence on the air leakage of dwellings. Work undertaken in the United States by Sherman and Dickerhoff (undated) on a database of almost 13,000 air leakage measurements suggests that multi-storey dwellings are

leakier than single-storey dwellings. Similar findings have also been found in Canada (see Allen, 1985 after Sulatisky, 1984).

Size and complexity of the building

23 All things being equal, the larger and more complex the floor plan and the construction techniques used to construct a building, the greater the number of junctions between the elements of the thermal envelope. This increases the potential for air leakage.

Longevity

24 The air leakage of a dwelling tends to increase over time. Work undertaken by Elmroth and Logdeberg (1980) and Warren and Webb (1980) on a small number of Swedish and UK dwellings found that the majority of the increase in air leakage occurred during the first year of occupation, where it was observed to increase by 70% and 83%, respectively. This appears to suggest that the majority of the increase in the air leakage of these dwellings was attributable to shrinkage cracks caused by drying out and settlement of the foundations. A number of other factors are also known to contribute to increased air leakage over time. These include: wear-and-tear of construction materials, particularly window and door seals; and changes carried out by the occupants. For instance, poor sealing of penetrations through the air barrier that have been made once the dwelling is occupied. However, it is unclear how much additional air leakage is likely to be attributable to these different factors.

Seasonal variation

25 There is some evidence to suggest that air leakage is seasonal. Work undertaken on an unoccupied heated test house by Warren and Webb (1980) found a substantial seasonal change in total air leakage (about 25%), with the maximum occurring in winter and the minimum occurring during the summer. The reason assigned for this difference was seasonal changes in the moisture content of the timber. It could also be argued that the differences observed by the authors might also be due to thermal expansion and contraction effects.

Site supervision and workmanship

26 The level and quality of site supervision and workmanship during the construction of a dwelling can influence its overall air leakage. Experience has shown that nominally identical dwellings on the same site can have very different air leakage rates and leakage distributions (BRECSU, 2000 and Allen, 1985).

Location of the main air leakage paths

27 The main air leakage paths in UK dwellings have been well documented by the BRE (see Stephen, 1998 and 2000) and are illustrated in Figure 7. They are as follows (in no particular order of importance):

a) Cracks, gaps and joints in the structure.

b) Plasterboard dry-lining.

c) Areas of unplastered masonry wall.

d) Timber floors.

e) Joist penetrations of external walls.

f) Internal stud walls.

g) Windows and doors and their surrounds.

h) Loft hatches.

i) Skirting boards.

j) Permanent ventilators.

k) Chimneys and flues.

l) Service entries, ducts and electrical components.

28 The BRE have also attempted to quantify the average component air leakage attributable to the main air leakage paths in UK dwellings using reductive sealing techniques[1] (see Stephen, 1998 and 2000). The results of this work are illustrated in Figure 8. Figure 8 suggests that the vast majority of component air leakage cannot be attributed to a single component. Instead, it can be attributed to the numerous cracks and gaps that exist throughout the building. However, it should be noted that these results are based upon a very small sample of dwellings (35) from the BRE's database of air leakage, and so may not necessarily be representative of the leakage of the UK housing stock.

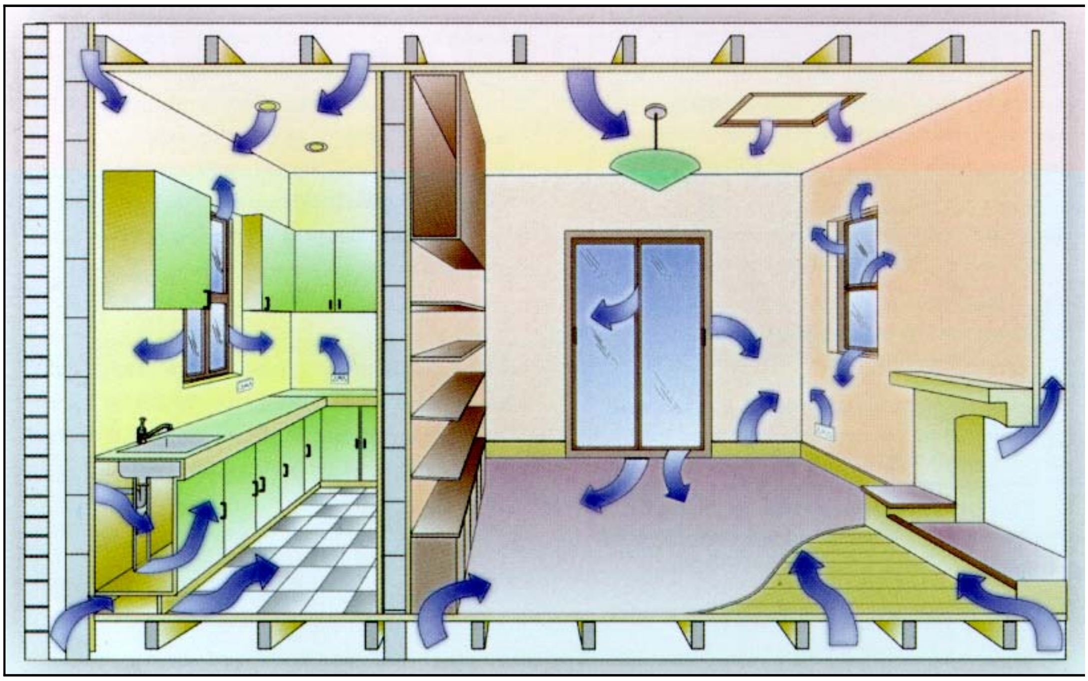


Figure 7 Typical air leakage paths in UK dwellings. After BRECSU (1997).

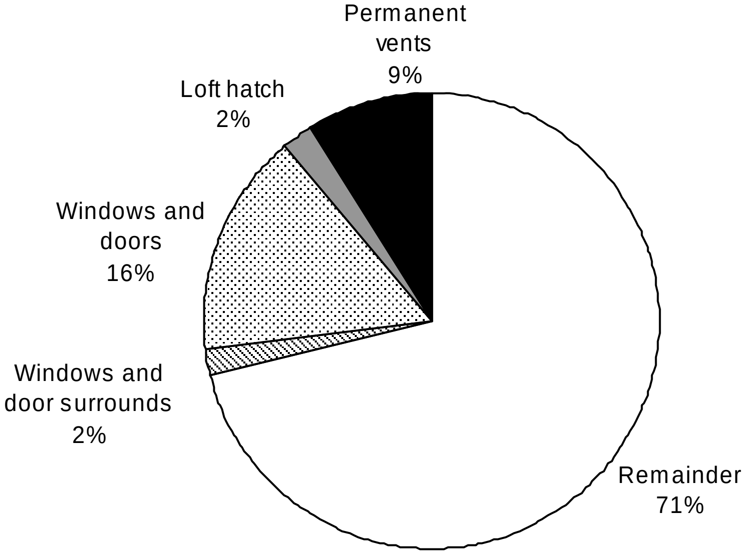


Figure 8 Component air leakage in UK dwellings. After Stephen (2000).

[1] This is where the dwelling is first of all pressure tested as found. Various components are then sealed and the pressure test is repeated. The difference in air leakage between the two tests can then be attributed to the components that were sealed.

Review of Guidance on Airtight Construction

Introduction

29 Guidance and recommendations for techniques to achieving airtightness in dwellings can take the form of either general guidance, applicable to the general construction and design process, and more specific guidance which relates to the use of particular materials, components or construction methods.

General guidance

Basic principles

30 Work carried out by the Swedish Council for Building Research (Elmroth and Levin, 1983) suggests that there are five main alternative construction solutions to achieve an airtight building envelope. These are listed in Table 2 along with the advantages and disadvantages of each. It should be noted that for these solutions to be effective, then the air sealing method selected should be as continuous as possible over the whole external structure of the building taking account of joints, connections and penetrations.

31 General advice given by the BRE (Webb and Barton, 2002) for the design of an airtight envelope for commercial buildings is equally applicable for dwellings. The airtightness layer must be:

a) Comprised of suitably airtight materials.

b) Continuous around the envelope.

c) Able to withstand wind pressure and stack effects.

d) Easily installed.

e) Durable and accessible for maintenance.

32 The following general points on achieving an airtight dwelling are made by the Swedish Council for Building Research Report (Elmroth and Levin, 1983):

a) Carefully plan the airtightness system and show on the drawings how this will be achieved.

b) Where possible, the air sealing layers should be in the same plane throughout the structure. Air barriers that cross from inside to outside the construction envelope can be difficult to detail, problematic to construct, difficult to maintain and are prone to failure in service (TRADA, 2001).

c) Designed penetrations in the sealing layer should be avoided or at least minimised.

d) Any sealing work should be easy to carry out.

e) Materials should have well documented durability and where components or materials have a limited service life they should be easy to replace.

33 Stephen (1998) suggests that a useful approach for a designer to take when designing any new dwelling is to identify on the drawings where the continuous airtight envelope will be positioned and identify those areas where attention to detail is needed to ensure airtightness. The approach should be to make the shape of the envelope as simple as possible and Stephen suggests that where a building has a complicated structure, as in the case of a room over a garage or a ground floor room with cathedral ceiling abutting a two storey part of the same dwelling, then they can be treated as separate envelopes.

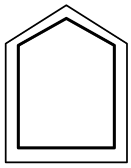
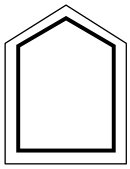
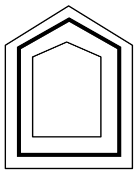
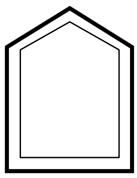
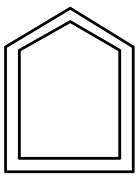
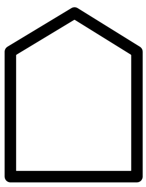
Construction principle	Advantages	Disadvantages
Internal airtight cladding (e.g. plasterboard) 	Uses common sheet lining materials.	Risk of puncture damage. Joints and connection details must be sealed. Sensitive to movement and settlement.
Internal airtight vapour barrier (e.g. plastic film, paper, metal foil) 	Combines functions of air and vapour barrier. Use of large sheets minimises joints.	Construction difficulties. Requires accurate joints. Risk of puncture damage.
Drawn-in airtight vapour barrier (e.g. plastic film, paper, metal foil) 	Sealing layer protected against damage. Services can be installed along walls without damaging sealing layer.	Requires double frame.
External airtight wind barrier (e.g. sheet material) 	Combines function of wind barrier and air sealing. Easy to apply.	Risk of moisture condensation problems. Requires good weather resistance. Risk of damage during construction.
Combined internal and external barrier 	Double Protection.	Cost of additional layer. Possible moisture problems
Homogeneous airtight structure (e.g. cellular concrete, concrete, brick) 	Simple design. Cables and pipework can be positioned within the material without affecting airtightness.	Requires careful sealing of joints between building elements and service penetrations.

Table 2 Basic construction principles for airtightness. Adapted from Elmroth and Levin (1983) and Carlsson, Elmroth, and Engvall (1980).

Building regulations

34 The Building Regulations Approved Document Part L1 (ODPM, 2003) requires that measures are taken that “limit unnecessary ventilation heat loss by providing a building fabric that is reasonably airtight”(p.9) and that “reasonable provision should be made to reduce unwanted air leakage” (p.9). They also give a suggested target for a maximum value for dwelling air permeability as 10 m^3/h per m^2 of external surface area at an applied pressure difference of 50Pa. The only guidance given in the regulation as to how to achieve the recommended levels of airtightness is to provide a continuous barrier to air movement around the habitable space that is in contact with the thermal insulation layer, but no specific techniques are mentioned as to how to do this. The building regulations suggest that further guidance be sought from the Robust Construction Details manual (DEFRA, 2001).

35 The general guidance in the Robust Details manual (DEFRA, 2001) states that the main objective of air tightening is to form a definable and continuous air leakage barrier around the building and that measures should be considered at any penetration of the barrier. Attention is drawn in the manual to the following general areas:

a) Care to be taken at joints between structural components (e.g. walls to floors).

b) Care to be taken around components and openings within walls.

c) Care to be taken at barrier penetrations for plumbing, electrical and ventilation services with careful sealing.

d) Closing of any vertical ducts at top and bottom.

36 Our main concern with the guidance given within the Robust Details document is that it does not give enough information on the principles of airtightness, as applicable to each of the detailed designs. There is also little information on tolerances and potential variability within each of the designs. This would allow for a wide interpretation of the design details and give rise to variability in airtightness. The repeated use of tightly packed mineral wool in many of the designs would give the impression that this material is a good air barrier, whereas it will in fact only limit air leakage. Our opinion, echoed by Olivier (1999), is that any guidance given should be very carefully set out, as different approaches to the construction process can be taken. For example, a careful custom builder constructing to a very high standard would approach the advice given within the Robust Details document differently from the approach taken by a high volume contractor building to the lowest permissible standard, in the fastest possible time and to a tight budget.

Design for airtightness

37 BRE’s general advice on designing for airtightness (Stephen, 1998) is that where possible designers should:

a) Try to ensure an airtight barrier without complex detailing.

b) Consider the effect of components in the external envelope.

c) Recognise potential leakage paths between structural elements, at joints between components and around service entries.

d) Avoid designs that may cause practical construction problems.

e) Provide explicit details and guidance at any potential point of air leakage and at complex junctions, corners and joints.

38 Work by the Air Infiltration and Ventilation Centre (Orme, Liddament and Wilson, 1998) has shown using real building measurements that generic forms of construction have characteristic airtightness performance, and that certain methods are intrinsically more airtight than others. Therefore, when designing for airtightness one should consider selecting a construction technique that is more likely to be airtight. For example, their data show that timber frame constructions in the UK are generally more airtight than brick and block constructions (1998). Dwellings with solid ground floor slabs are twice as airtight as those with suspended timber floors (DETR, 2000). Olivier (2001) suggests that in-situ cast concrete floors and wet plastered walls are inherently airtight. Standard buildings of simple box shapes will generally perform better for airtightness than complex bespoke angular constructions with multiple joints, interfaces and junctions (BRAC, 2001). However, it is noted that it would be impossible to design out all construction joints and details, and there will be always be junctions that need to be sealed. It is advised that any designed gap should

be of sufficient size for the sealing process to be effective, and a gap of around 15±5 mm is suggested as appropriate for most situations (Elmroth and Levin, 1983).

Site supervision and workmanship

39 No matter which construction methods are employed, the production of a well-sealed and airtight structure relies to a great extent upon careful planning of the work sequence, good site supervision and good workmanship (Elmroth and Levin, 1983). Prefabricated system buildings, such as volumetric and panellised modular construction, offer the benefit of a large proportion of the construction process being carried out off-site in a factory environment. This has the potential for better airtightness due to improved workmanship and more controlled work conditions (BRAC, 2001). Murray (2002 and 2003), argues that timber frame construction, with its high level of prefabrication, has a quality control advantage over site-based construction techniques. Even regional variations in construction methods and practices can influence levels of airtightness (Allen, 1985).

Other general guidance

40 The Energy Efficiency Good Practice Guide 224 (BRECSU, 1997) lists a range of general sealing and draughtproofing opportunities to improve airtightness that are applicable to both new construction and to refurbishment work. These are listed as follows:

a) Draughtstrip loft hatch and fit securing bolts.

b) Draughtstrip opening lights and external doors.

c) Seal around windows and door frames.

d) Seal service holes through timber floors.

e) Seal service penetrations through ceilings.

f) Seal plumbing services.

g) Seal joints in heating ductwork.

h) Seal electrical services including faceplates.

i) Hardboard across timber floors and seal to skirting.

j) Seal airspace behind plasterboard dry-lining.

k) Seal top and bottom of stud partitions.

l) Add a draught lobby to exterior doors.

41 Consideration should be given to sealing potential gaps in the air barrier that are normally hidden by other fittings and components. For example, Olivier (1999) and Stephen (1998) highlight often forgotten areas such as gaps above suspended ceilings, behind baths, behind fitted cupboards and appliances, and behind risers. They suggest that walls and ceilings in these and similar areas should be wet plastered or carefully sealed if dry-lined.

Component specific guidance

Plasterboard dry-lining

42 Several reports, including the Robust Details document (DEFRA, 2001) identify that the use of dry-lining fixed to walls by adhesive dabs (and to a lesser extend on battens) is an important factor in excessive air leakage, especially in masonry cavity wall constructions. To mitigate this problem, it is recommended in Robust Details (DEFRA, 2001), and previously in the 1995 Building Regulations Approved Document Part L (DoE and Welsh Office, 1994), that ribbons of adhesive be used to seal the lining perimeter and openings during installation. This is illustrated in Figures 9 and 10. In our opinion, the process of applying plaster ribbons in such a way as to seal all potential leakage sites would be difficult to carry out. The practical difficulties would mean that, without careful site supervision, the process could be missed out entirely, and it would be difficult to check compliance after the boards were in position. Also, none of the documents describes the process in any detail and does not say, for example, how wide or thick the adhesive ribbons should be, or how far they should be from the perimeter.

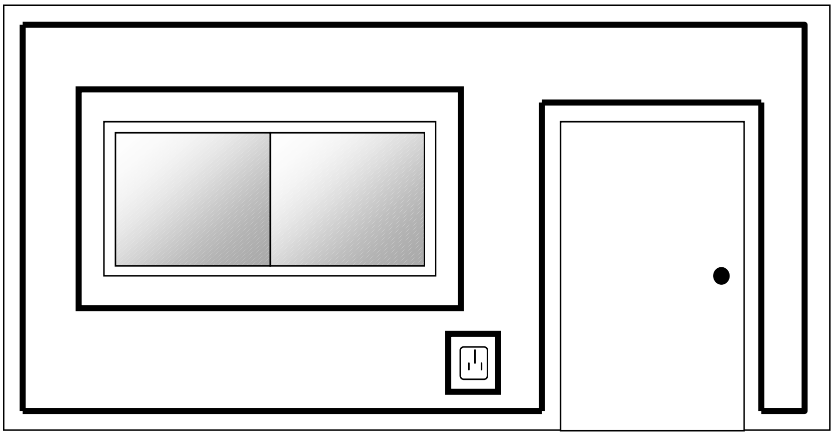


Figure 9 Schematic of sealing of perimeters of dry-lined wall**.**

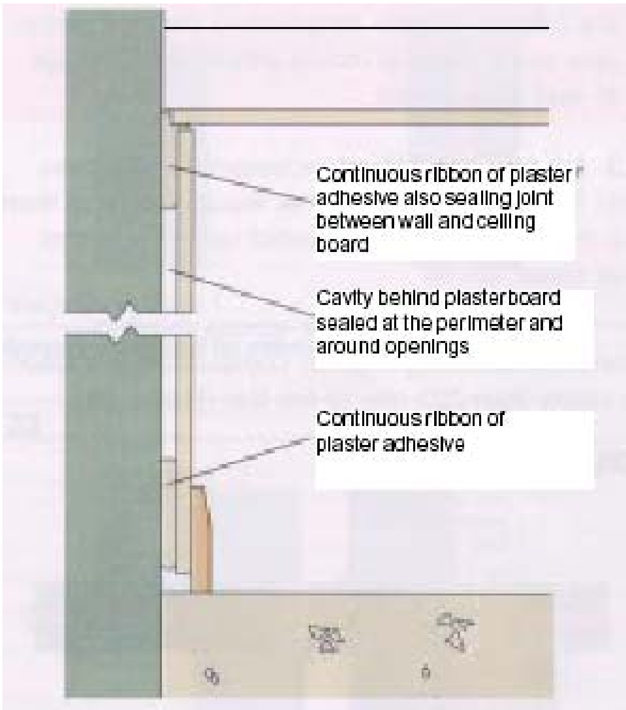


Figure 10 Sealing at the perimeter of dry-lining. After Stirling (2002).

43 Stephen (2000) and other authors (see for instance, Lowe, Curwell, Bell and Ahmad, 1994) suggest that to achieve a high level of airtightness a wet plaster internal finish should be used in preference to dry-lining on external walls. This recommendation is also made by Olivier (1999), who makes the point that the plastering should continue past the junction of the external wall with hollow internal partition walls.

44 The NHBC Standards Manual (1999) reiterate the point that, when using plasterboard dry-lining, a continuous ribbon of adhesive should be applied to the perimeter of external walls, openings and services to prevent air infiltration. The manual also states that dry-linings should be completely taped and filled at board joints and abutments to ceilings and internal walls, that dry wall lining at door and window openings should be securely fixed and filled at external and internal corners and that gaps around service points, electric sockets and light switches should be filled with jointing compound.

45 Olivier (1999) notes that acceptable results with dry-lining on dabs are dependent upon a combination of good design, workmanship and supervision. He suggests that, if dry-lined walls are still preferred to wet plastering techniques, then alternative construction methods should be

considered such as the North American practice of dry-lined masonry walls used as infill to steel or concrete frames and with an air barrier membrane attached to the outside of the inner leaf. Olivier (2001) points out that, due to the problems of excessive air leakage, the use of dry-lining is in fact prohibited in some northern countries and its use in dwellings on the continent is very rare.

46 An alternative approach that has been shown to be effective in reducing air leakage when using dry-lined masonry dwellings is the use of thin layer of parging on the inner blockwork leaf of external walls prior to installation of the plasterboard (Roberts, Johnston and Isle, 2005). Parging is a thin (2–4mm) plaster-based coating traditionally used as a chimney lining. It should be noted that this work is only at the preliminary stage and the results would need to be confirmed with further trials. However, they do indicate the effectiveness of a secondary air barrier layer in conjunction with dry-lined construction.

Service ducts

47 Stephen (2000) and others (Olivier, 1999) recommend that where ducts constructed of plasterboard or plywood fixed to a wooden frame or similar techniques are used to conceal services such as soil waste pipes, that these be sealed, especially where the duct enters the roof space. Stephen (1998) suggests that the service duct should be blocked completely near top floor ceiling level and that in dwellings with suspended ground floors the duct is blocked near floor level.

Service penetrations

48 All service penetrations should be sealed with expanding foam or other suitable sealant, whether in the wall, ground floor, intermediate floor or ceiling (DEFRA, 2001). For large voids, mineral wool or some other backing material should be used to support the sealant.

Loft hatches

49 The Robust Details guide (DEFRA, 2001), Stephen (2000) and others advise that draughtstrips are fitted to loft hatches to reduce air movement to the roof space. The hatch should also be fitted with bolts or catches that fully compress the seals (Stirling, 2002).

Window openings in walls or roof

50 Windows, doors and rooflights should be sealed to the wall or roof (Olivier, 1999). Conventional window and door reveal details are reasonably airtight as long as attention is paid to the sealing (Stephen, 1998).

51 The joint between any window frame and wall should be sealed with both an outer primary seal and an inner secondary seal (Stirling, 2002). Examples of possible seal options are listed below and illustrated in Figure 11.

a) Sealant pointing on the outside and expanding foam on the inside.

b) Expanding foam strip on the outside and sealant pointing on the inside.

c) Sealant bedding on the outside and plaster adhesive on the inside.

Hollow partition walls

52 When constructing hollow partition walls, the ceiling plasterboard or polyethylene air barrier should continue over the top of the partition wall or some other form of seal should be used at the junction of the wall and ceiling (Olivier, 1999).

Electrical outlets, sockets and fitting

53 Sockets and outlets should be grouted and any gaps around the fittings sealed at the junction with the wall or ceiling, with particular attention paid to fittings in dry-lined walls (BRECSU, 1997). Electrical backplates and any holes in the plates should be sealed before fixing. In countries such as Canada (Murray, 2002 and 2003), socket boxes are available that come pre-fitted with gaskets and foam seals.

Draughtstrips/weather stripping

54 Draughtstrips are used to block air leakage around doors and opening windows (Natural Resources Canada, 2002). They come in a variety of shapes such as flat strips, tubes, 'V', 'D' or other more complicated forms. According to Elmroth and Levin (1983), the forms with the least air leakage are tubular and angular strips. The report also gives advice on the performance and

durability of the materials the strips can made from, e.g. closed cell foam, rubber, PVC or metal. Examples of different types of draught seals are shown in Figure 12.

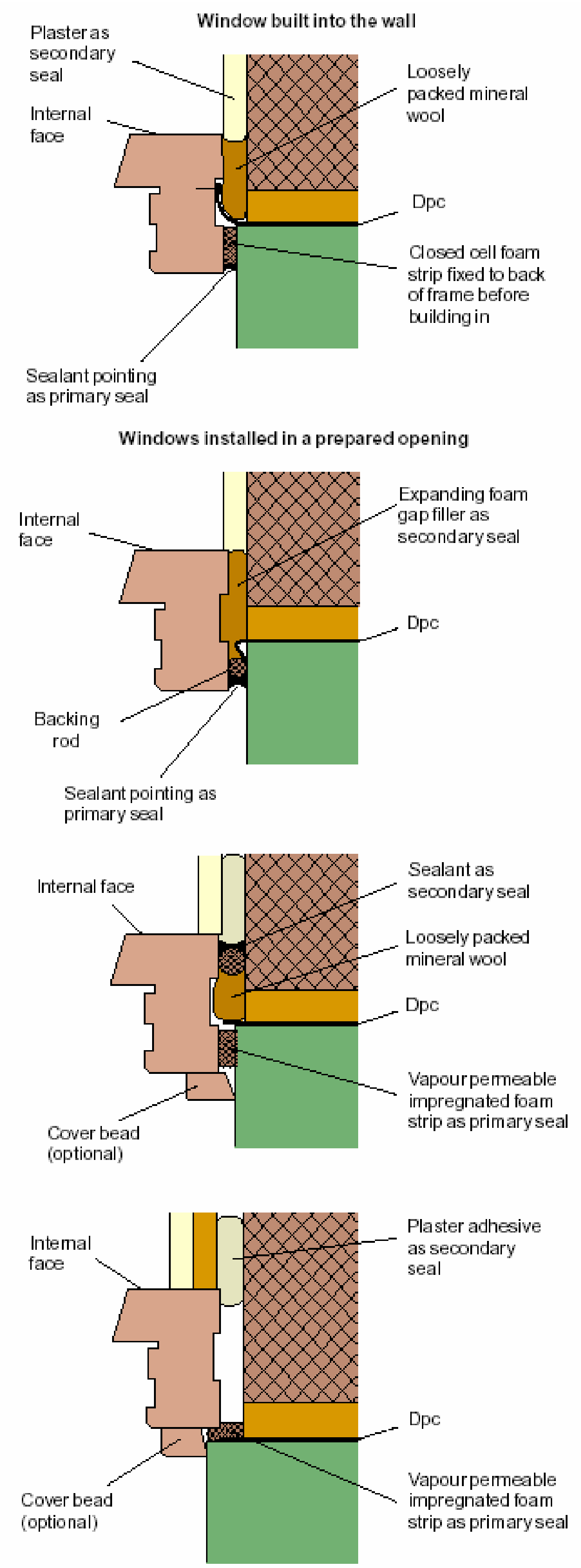


Figure 11 Examples of sealing at window to wall junctions. After Stirling (2002)

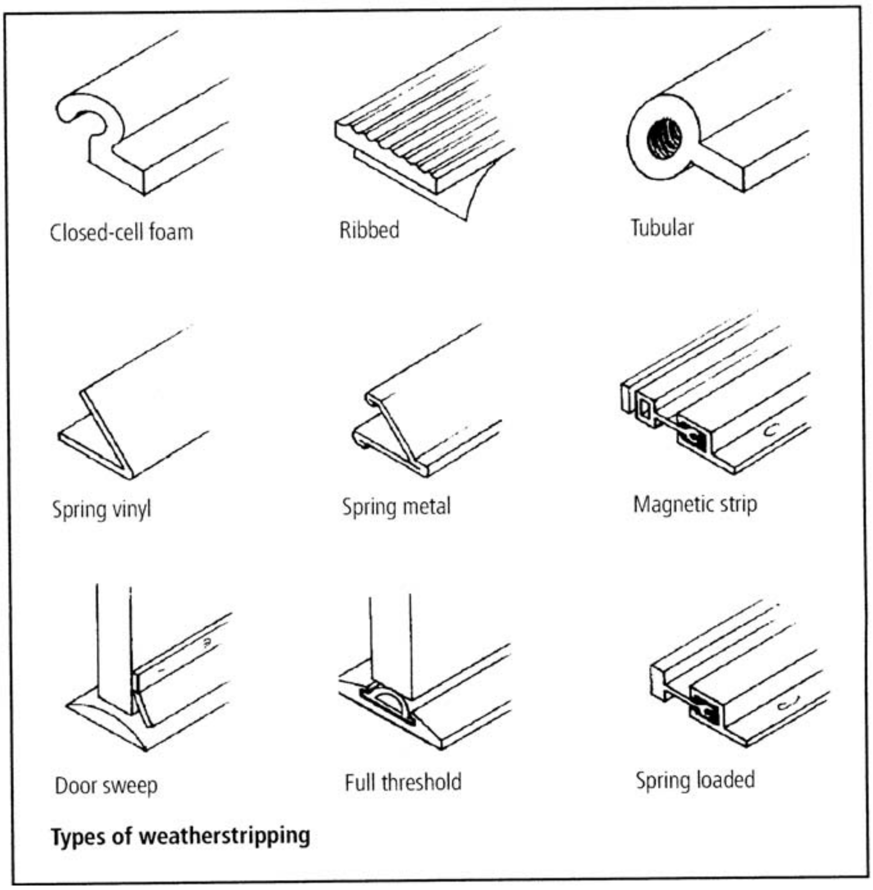


Figure 12 Examples of types of draughtstrip. After Natural Resources Canada (2002).

Material specific guidance

55 In order for it to be effective, the materials that form the airtight barrier must be resistant to air movement and be strong and durable. Barrier materials can take the form of flexible sheets, rigid boards, structural elements, sealants, foams, seals or gaskets.

Sealing materials

56 Small gaps and cracks should be filled with a construction sealant suitable for the materials to be sealed, taking account of joint movement and durability, and using a support backing where appropriate (BRECSU, 1997). A wide range of sealants are available, including silicone, polysulphide, butyl rubber, and acrylic. BSI document 6213 (BSI, 2000) gives advice on the selection of construction sealants appropriate to different situations. Large cracks and gaps can be filled using an expanding polyurethane foam (BSI, 2000). Very large gaps can be packed with bagged mineral wool or alternatively polythene sheet can be taped over openings and then covered with plywood or plasterboard (BSI, 2000). Unbagged mineral wool is not an effective air sealing material (Elmroth and Levin, 1983).

57 The robust details guide (DEFRA, 2001) requires that the appropriate sealant or gap filler be selected that is appropriate for the size of the gap and the degree of joint movement anticipated.

Plastic films

58 Any plastic film material used as an airtight barrier should be stabilised, especially against oxidation and UV degradation, and have sufficient mechanical stress to withstand stresses during construction and use (Elmroth and Levin, 1983). Degradation is faster at higher temperatures and the Swedish Verksnorm 2000 standard suggests heat-reflecting foil be placed behind radiators to reduce the temperature in any wall where plastic film is fitted. Polyethylene is probably the most widely used plastic sheet, typically with a thickness 15 mil (0.38 mm) (Natural Resources Canada, 2002). Copper or non-rust protected staples should not be used with polyethylene film as they

accelerate degradation (Elmroth and Levin, 1983). Any plastic film should also be suitably structurally supported.

Paper

59 Where asphalt impregnated paper is used as an airtightness barrier, then joints should be sealed using the adhesive strips specified by the paper manufacturer (Elmroth and Levin, 1983).

Metal foils

60 Metal foils of aluminium or copper have good air sealing properties. They are generally supplied adhered to insulating boards or other board products and the seal obtained is therefore highly dependent upon the seal at board joints (Elmroth and Levin, 1983).

Board materials

61 Many board materials, such as plasterboard and wood fibreboard, are inherently airtight. Others can be made airtight by adhering sheets of foil or plastic film to one face. The main problem when using board materials to form an airtight layer is in ensuring airtightness at the joints using some form of sealing material (Elmroth and Levin, 1983). There is also the risk that the airtight layer will be punctured when holes are made to fix things to the wall.

Insulation materials

62 Rigid closed cell foam insulation materials, such as polyurethane or phenolic foam and expanded polystyrene blocks, are intrinsically airtight, as long as attention in paid to sealing any joints in blocks or panels. The only loose-fill blown-in insulation material that can significantly restrict air flow is cellulose fibre, if it is blown to densities of greater than 56 kg/m^2 (Natural Resources Canada, 2002). Use of cellulose insulation can give rise to very airtight dwellings (Allen, 1985). Mineral and glass fibre will only partially restrict the flow of air and should be supplemented by a plastic strip or jointing compound to achieve good airtightness (Carlsson, Elmroth and Engvall, 1980). Tightly packed mineral wool is suggested as a method to 'limit air leakage' in some of the Robust Details (DEFRA, 2001), such as in the case of gaps between wall insulation and roof insulation, though it is not clear how effective this will be and, in common with other solutions, would be highly dependent upon good workmanship.

Construction method specific guidance

63 The main source of official UK guidance on steps to achieving airtightness using specific construction techniques is given in the Robust Details guide (DEFRA, 2001), but its scope is limited in relation to airtightness. A comparison of international practice in controlling airtightness is given in a Swedish Council for Building Research Report (Elmroth and Levin, 1983). Countries such as Canada (Energy Mines and Resources, 1984), have issued much more comprehensive guidelines on air sealing of homes.

Pitched roofs with insulation

64 In constructions where insulation is placed in between the roof rafters creating a warm loft space, then consideration should to be given to the details at the gable ends, ridges, eaves and abutments to ensure that all gaps and penetrations are sealed with an expanding polyurethane foam or flexible sealant (Stirling, 2002). There should be a tight fit between the insulation boards and the rafters, which can be achieved using suitably sized rebated insulation boards. All board joints should be taped according to the manufacturer's instructions.

Masonry walls with cavity wall insulation

65 In general, masonry walls with wet plastered lining are relatively impermeable so attention to airtightness should focus mainly on the top floor ceiling, on junctions between walls and other components and on any unplastered areas of wall (Stephen, 1998). Particular attention needs to be given to joist penetrations though the inner blockwork, as these are a known as a major potential air leakage location. It is also important there should be no cracks and gaps in the mortar (Webb and Barton, 2002).

66 The Robust Details guide (DEFRA, 2001) identifies the following general airtightness advice for masonry construction:

a) Ensure continuous ribbons of adhesive are use to fix dry-lining at perimeters of external walls.

b) Use joist hangers to support floor joists.

c) Seal under skirting boards on suspended floors or with dry-lining.

67 In the case of partial fill cavity insulation, there is the risk of air movement behind the insulation or through service holes (Stirling, 2002). It should therefore be ensured that the partial insulation is held tightly against the inner leaf and that joints between boards abut tightly and are preferably sealed. The effects of air circulation around poorly fitted insulation have been reported since the 1960s (Ball, 1961)

68 There is evidence that cavity walls in-situ filled with polyurethane foam have good airtightness, presumably because the foam covers joist penetrations and surrounds window reveals (Lowe, Curwell, Bell and Ahmad, 1994).

69 The perimeter of the air space behind dry-lining on external masonry walls should be sealed using a continuous ribbon of plaster adhesive at the ceiling, skirting, adjoining walls, window reveals and around holes made in the lining for service penetrations (Stirling, 2002). In addition, consideration should be given to the installation of a vapour permeable membrane.

Masonry walls with internal insulation

70 As for uninsulated plasterboard, the perimeter of any dab bonded insulated board should be sealed using a continuous ribbon of plaster adhesive and any service holes in the board should be sealed using an appropriate sealant (DEFRA, 2001 and Stirling, 2002).

Timber frame

71 In timber framed construction the usual approach is to use the vapour barrier, such as polyethylene sheet as the air barrier over most of the envelope, ensuring that the barrier is continuous over the envelope (Olivier, 1999 and Stephen, 1998).

72 The Robust Details guide identifies the following general airtightness advice for timber frame construction (DEFRA, 2001):

a) Ensure damp proof course membranes are turned up behind sole plates and lap with vapour control layer or seal between the DPC and sole plate.

b) Lay bead of mastic on timber floor deck before positioning wall panels.

c) Ensure sheet vapour control layers are properly lapped at joints and that vapour control plasterboard is jointed in accordance with manufacturer’s instructions.

d) Return vapour control layers into door and window reveals, heads and sills.

e) Cut vapour control layer tight to penetrations such as electrical outlets and seal at service penetrations.

f) Ensure breather membranes overlap and are stapled in place.

73 Olivier (1999) suggests that an alternative approach for timber frame would be to use plasterboard with gasketed joints as the air barrier.

74 TRADA (2001) give some advice on site control actions that relate to vapour control layers. They state that the minimum overlap for polyethylene sheets should be 100 mm, that the sheet should be returned into reveals, openings and sills and that any penetrations should be sealed.

Light steel frame

75 The Robust Details guide identifies the following general airtightness advice for light steel frame construction (DEFRA, 2001):

a) For both warm frame and hybrid constructions, all joints between insulation boards should be either lapped or sealed with tape approved by the insulation manufacturer.

b) Ensure sheet vapour control layers are properly lapped at joints and that vapour control plasterboard is jointed in accordance with manufacturer’s instructions.

c) Return vapour control layers into door and window reveals, heads and sills.

d) Cut vapour control layers tight to electrical and other outlets and seal any piped service penetrations.

e) Good seals should be ensured at junctions, particularly with the ground floor.

f) A vapour control layer, if specified, can act as an additional air barrier.

Suspended timber floor

76 Suspended timber floors can be difficult to make airtight in either timber framed or masonry construction and as a general rule concrete floors or gasket-jointed floor panels are easier to make airtight (Stephen, 1998).

77 Where timber intermediate floors are used in masonry construction, they should be supported using joist hangers with well pointed blockwork joints and a skim of plaster in preference to penetrating the internal wall (Stephen, 1998 and Olivier, 1999). In situations where joist penetrations are used, then one potential solution used by Lowe and Curwell (1996) is to install noggins between the joists and inject foam sealant between the joists, noggin and wall.

78 A range of actions have been suggested by Stirling (2002) to minimise air movement through suspended timber ground floors (see Figure 13), including:

a) Use full depth strutting between the joists at the perimeter of the floor to provide a fixing point and limit to size of gaps.

b) Seal the skirting to the wall with a sealant and to the floor with a flexible sealant and extruded draughtproof section.

c) Seal any gaps at service penetrations or access panels in the floor.

d) Where dry-lining in used, ensure that the space between board and wall is sealed with a continuous ribbon of plaster adhesive.

e) Position insulation level with top of joists to avoid air movement between insulation and flooring.

f) Where quilt insulation is used, it should be supported, either on a board fixed to battens nailed to the side of the joist (see Figure 14) or on plastic netting or strips of vapour permeable membrane. These may be draped over the joists and held against the sides with staples or battens (see Figure 15).

g) The laying of a vapour permeable membrane below the flooring should be considered.

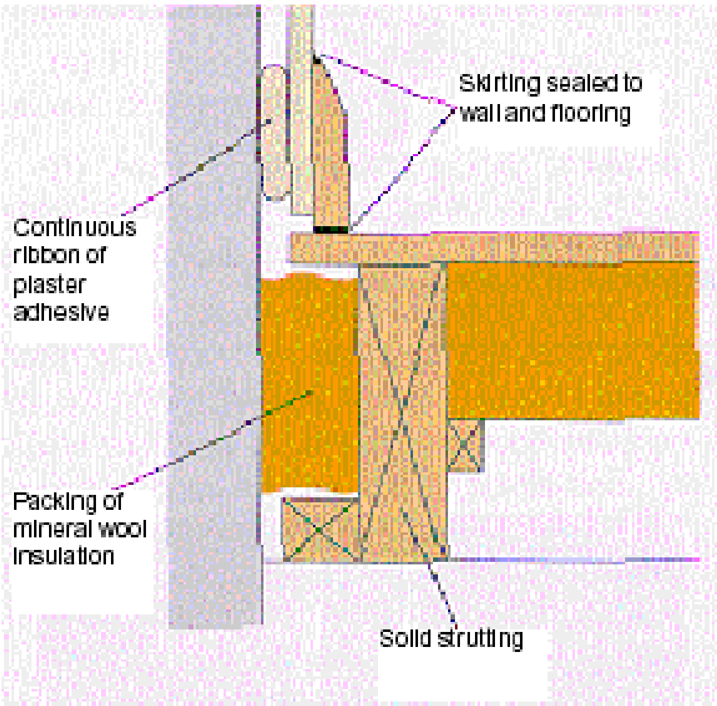


Figure 13 Insulating and sealing the floor perimeter. After Stirling (2002).

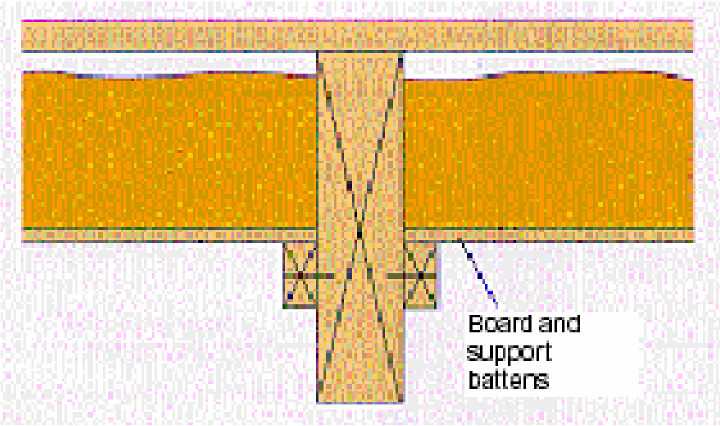


Figure 14 Quilt insulation supported on a board. After Stirling (2002).

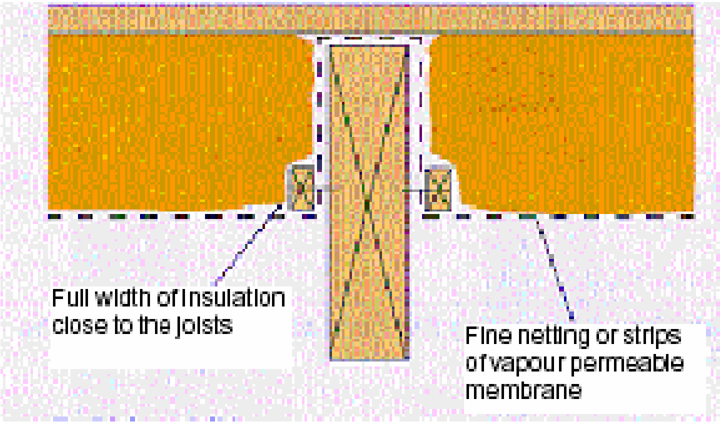


Figure 15 Quilt insulation supported on netting or vapour membrane. After Stirling (2002).

79 For all forms of wall construction, the Robust Details guide (DEFRA, 2001) recommends that to limit air leakage, attention should be given to sealing around the perimeter of a suspended timber floor. Any gaps between wall panels and floor should be sealed. Expanding foam tape should be applied under the skirting and a continuous bead of sealant applied to the back of skirting prior to fixing.

80 An example of a method to seal potential air leakage paths where timber floor joists do penetrate the internal wall was demonstrated at the Future World housing exhibition in Milton Keynes in 1994 (ANON, 1994) where a bitumen seal was applied to the internal brickwork at the level of the first floor joists.

In-situ concrete floor/beam-and-block floor

81 Significant leakage can occur at junctions between the floor and walls. Stephen (1998) recommends that these are sealed before the skirting boards are fixed.

82 Ensure gaps between wall and floor are sealed with split course infill blocks, full depth edge blocks or with a dry non-compressible mix (DEFRA, 2001).

Field Measurements

Introduction

83 In order to supplement the literature review with on-the-ground experience, spot pressurisation tests were undertaken on a small number of UK case study dwellings that had been identified as being potentially very airtight, but had not been pressure tested. The dwellings chosen for the tests varied in terms of size, built form and construction technique, and were as follows:

a) The Hockerton Housing Project, Southwell, Nottinghamshire.

b) The Autonomous Urban House, Southwell, Nottinghamshire.

c) Three Gusto Homes dwellings — two from the Bee Field site in Lincoln and one from the Millennium Green site, Collingham near Newark.

Description of the case studies

The Hockerton Housing Project

Figure 16 The Hockerton Housing Project.

84 The Hockerton Housing Project is the UK's first earth-sheltered, self-sufficient ecological housing development and the dwellings are amongst the most energy efficient in Europe. The development was designed by Robert and Brenda Vale and was completed in 1998. It comprises a terrace of five single storey earth-sheltered dwellings, four of which have 3 bedrooms and one that has 4 bedrooms. The 3 bedroom dwellings have an internal floor area of 122 m^2, whilst the 4 bedroom dwelling has an internal floor area of 140 m^2. In addition, a south-facing conservatory runs the full width of each dwelling.

85 The dwellings have been constructed using masonry cavity and reinforced concrete rear and side walls, a reinforced concrete ground floor slab and a pre-cast concrete beam-and-block roof. All of these elements are insulated externally using 300 mm of expanded polystyrene. The south-facing wall of the dwellings is of brick-block construction, with a 150 mm fully filled cavity. Internal walls are constructed from 200 mm dense concrete blocks, and all of the internal walls are wet plastered. Considerable attention was given to airtightness during the design and construction of the building.

The Autonomous Urban House

Figure 17 The Autonomous Urban House.

86 The Autonomous Urban House is the UK's first 'autonomous' house, which is intended to have net zero CO_2 emissions, low embodied energy, and derive its power from passive solar heating and a photovoltaic array. It was completed in 1993 and was designed by Robert and Brenda Vale, the architects responsible for designing the Hockerton Housing Project. The dwelling consists of a 2½-storey, four bedroom detached house, which has an internal floor area of 169 m^2 (excluding the unheated basement). A 2-storey lean-to conservatory is attached to the west-facing garden elevation of the dwelling.

87 The dwelling has been constructed using masonry cavity walls, which are fully filled with 250 mm of mineral fibre insulation. The ground and first floor are of pre-cast concrete beam and block construction. The roof has been constructed using timber I-beams, and is insulated with 500 mm of cellulose fibre insulation. All of the internal walls are wet plastered. Considerable attention was given to airtightness during the design and construction of the building.

Gusto Homes

Figure 18 Gusto Homes Plots 8 and 23.

88 Gusto Homes is a small commercial house building company based in Nottinghamshire, which has been designing and constructing energy efficient new dwellings that incorporate high levels of insulation, utilise solar water heating, maximise the use of passive solar gains and recycle rainwater from the roofs. In total, three Gusto Homes dwellings were pressure tested, two at the Bee Field site (Plots A and B) and one at the Millennium Green site (Plot C). The dwellings at the Bee Field site were built in 2003 and consist of 2-storey, 4/5 bedroom detached properties with an internal floor area of 178 m^2 (Plot A Saturn house type) and 185 m^2 (Plot B Atlas house type). The Millennium Green dwelling was built in 2001 and comprises a 2-storey, 2 bedroom terraced property with an internal floor area of 67 m^2.

89 All of the dwellings have been constructed using masonry cavity external walls, which are fully filled with 150 mm of DriTherm insulation and are wet plastered. The ground floors are of pre-cast beam and block construction, whilst the upper floors have been constructed using timber I-beams. The roof of Plot B has been constructed using trussed rafters, whilst timber I-beams have been used to construct the room-in-the-roof in Plots A and C. All of the roofs are insulated with 300 mm of cellulose fibre. The majority of the airtightness in these dwellings is expected to be provided by the wet plaster, and by specifying high performance doors and windows.

Results of the pressurisation tests

90 Pressurisation tests were undertaken on seven dwellings (two more than was originally planned). All of the tests were carried out by Building Sciences Limited using an Infiltec Blower Door (Model E3). Details of the dwellings that were tested are contained within Table 3.

Dwelling	Volume (m^3)	Internal surface area (m^2)
Hockerton Housing Project dwelling 1*	324	372
Hockerton Housing Project dwelling 2*	324	372
Hockerton Housing Project dwelling 5*	324	372
Autonomous Urban House*	429	377
Gusto Homes Plot A	433	362
Gusto Homes Plot B	476	399
Gusto Homes Plot C	159	192

*****Excludes the conservatory

Table 3 Dwellings that underwent the spot pressurisation tests.

91 In addition to the pressurisation tests, the main air leakage paths within all seven dwellings were also identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. Although this technique enabled identification of all of the main air leakage paths within each dwelling, it was not possible to quantify the contribution that these leakage paths made to the dwellings overall air leakage.

92 Detailed pressurisation reports on the dwellings can be found within Appendix 1.

Air permeability

93 The results of the air permeability tests are set out in Table 4 and Figure 19.

Dwelling	Mean air permeability @ 50Pa ($m^3/(h.m^2)$)
Hockerton Housing Project dwelling 1	0.95
Hockerton Housing Project dwelling 2	1.11
Hockerton Housing Project dwelling 5	1.23
Autonomous Urban House	4.43
Gusto Homes Plot A	7.06
Gusto Homes Plot B	4.72
Gusto Homes Plot C	6.40

Table 4 Mean air permeability of the case studies.

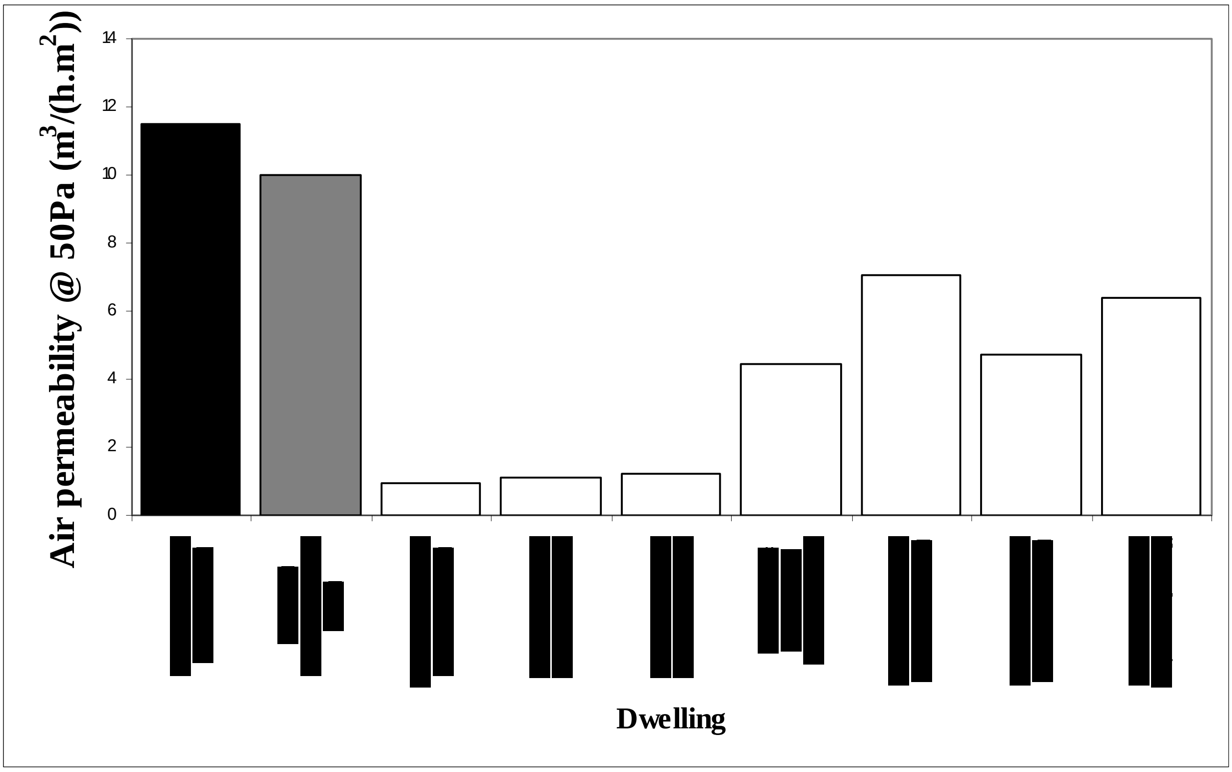


Figure 19 Mean air permeability of the case studies.

94 Although the small number of pressurisation tests makes it impossible to be able to draw any definitive conclusions, a number of interesting observations have been obtained from Figure 19. These are as follows:

a) All of the dwellings tested are relatively airtight by UK standards, being significantly lower than the UK mean of 11.48 $m^3/(h.m^2)$ @ 50Pa (Stephen, 2000), and the maximum specified level of 10 $m^3/(h.m^2)$ @ 50Pa that is contained within the Building Regulations Approved Document Part L1 (ODPM¸2003).

b) The results suggest that wet plastered masonry cavity construction can default to being relatively airtight, without much attention being given to airtightness. This was observed in the Gusto Homes dwellings, which achieved an air permeability of between 4.7 and 7.1 $m^3/(h.m^2)$ @ 50Pa. However, if considerable attention is given to airtightness during the design and construction phase, as was the case with the Autonomous Urban House, the air permeability can be reduced even further (in this case to 4.43 $m^3/(h.m^2)$ @ 50Pa, for a dwelling that was completed over 10 years ago).

c) As expected, the highest levels of airtightness were observed in the Hockerton Housing Project. The dwellings that were tested achieved an air permeability of between 0.95 and 1.23 $m^3/(h.m^2)$ @ 50Pa, putting them amongst the most airtight dwellings ever recorded in the UK. The reason why these dwellings achieved such a high level of airtightness can be attributed to the method of construction — earth-sheltering is intrinsically airtight. However, it is also a very unusual form of construction in the UK.

d) One of the main air leakage paths identified within the existing dwellings (the Hockerton houses, the Autonomous Urban House and Gusto Homes Plot C), was the opening casements of the windows and the French doors. This was attributed to worn or damaged seals, warped casements and doors, and ‘dropped’ casements and doors. In addition, in dwelling 2 of the Hockerton Housing Project, a number of poorly sealed service penetrations had also been made through the building fabric, after the dwelling had been occupied. Both of these observations suggest that the existing dwellings are likely to be leakier than they were when they were first built.

e) The opening casements of the windows and the French doors were also identified as a significant source of air leakage in the newly built dwellings (Gusto Homes Plots A and B). This was attributed to some poorly fitted casements and doors, as well as a number of incorrectly adjusted cams on the opening portion of the casements and the French doors.[2] Other significant areas of air leakage within these dwellings included: the junction between the upper floor and the external wall; service penetrations in the kitchen and through the first floor of Plot 5; the trickle ventilators; and the loft hatch.

f) It is clear that the air leakage of all of the dwellings could be improved by undertaking a number of relatively simple measures. For instance, replacing worn or damaged window and door seals, adjusting the cams on the window casements and sealing service penetrations.

Pressure equalisation test

95 In addition to the pressurisation tests identified within Table 3, a progressive equalisation test was also undertaken on one of the Hockerton houses (dwelling 2) to establish whether there was any inter-dwelling air leakage between this dwelling and dwelling 1. This test revealed that there was no significant inter-dwelling leakage between these two dwellings.

Air change rate

96 In order to put the spot pressurisation test results into context, the air leakage of the case study dwellings has been compared against the air leakage of some of the most airtight dwellings constructed in the UK and abroad. The dwellings incorporated within this comparison are as follows:

a) Lower Watts House, Charlbury, Oxfordshire – A 2-storey 290 m^2 wet plastered masonry cavity detached house with an air leakage rate of 3.6 ac/h @ 50Pa (Olivier and Willoughby, 1996b).

b) Low Energy Housing, Stenness, Orkney – A pair of timber-frame semi-detached houses with a mean air leakage rate of 1 ac/h @ 50Pa (Scivyer, Perera and Webb, 1994).

c) Two Mile Ash, Milton Keynes – A 2-storey timber frame detached house with an air leakage rate of 1.47 ac/h @ 50Pa (Olivier and Willoughby, 1996a).

d) The Longwood House, Huddersfield, West Yorkshire – A 2-storey 107 m^2 wet plastered masonry cavity detached house. Air leakage of 3 ac/h @ 50Pa (Lowe and Curwell, 1996).

e) Zero-Energy Timber-frame House, Brunnadern, Switzerland – A 2-storey 318 m^2 timber frame detached house. Air leakage of 0.17 ac/h @ 50Pa (Olivier and Willoughby, 1996a).

f) The Passive Houses, Kranichstein, Darmstadt, Germany – A row of four 2½-storey 156 m^2 externally insulated masonry terraced houses plus uninsulated cellars. Air leakage of 0.4 ac/h @ 50Pa for the first house, falling to 0.2 ac/h @ 50Pa by the third and fourth house (Feist, 1997).

g) The Self-sufficient Solar House, Freiburg, Germany – A 2-storey 145 m^2 externally insulated masonry detached house with an unheated cellar. Air leakage of 0.3 ac/h @ 50Pa (Voss, Stahl and Goetzberger, 1993 and Fraunhofer Institute for Solar Energy Systems, 2000).

97 Due to data availability, it has only been possible to undertake a relatively crude comparison, using ac/h @ 50Pa, rather than $m^3/(h.m^2)$ @ 50Pa. The use of ac/h means that it is not possible to be able to take into consideration the effects of shape and size, and the results will favour those dwellings that have a low ratio of envelope surface area to volume.

98 The results of this comparison are illustrated in Table 5 and Figure 20.

[2] Interestingly, this only came to light following a discussion with the window and door manufacturer during a subsequent test at a Gusto Homes site that also had these windows and doors fitted. This raises the issue that it is possible for components to be installed in a building without proper attention to the correct installation procedure and necessary adjustments, with the potential that the components will consequently not perform as expected. This risk could be minimised by more comprehensive and more visible information from the component supplier. Also, this is the kind of information that should be provided and highlighted on designs and drawings. It also raises the question whether components are too complicated and if they should be simplified in design to eliminate the possibility of incorrect installation.

Dwelling	Mean air change rate @ 50Pa (ac/h)
Hockerton Housing Project dwelling 1	1.09
Hockerton Housing Project dwelling 2	1.29
Hockerton Housing Project dwelling 5	1.40
Autonomous Urban House	3.89
Gusto Homes Plot A	5.91
Gusto Homes Plot B	3.95
Gusto Homes Plot C	7.72
Lower Watts House, Charlbury, Oxfordshire	3.60
Low Energy Housing, Stenness	1.00
Two Mile Ash, Milton Keynes	1.47
The Longwood House, Huddersfield	3.00
Zero-Energy Timber frame House, Brunnadern	0.17
The Passive Houses, Kranichstein	0.20
The Self-sufficient Solar House, Freiburg	0.30

Table 5 Comparison of air leakage rates.

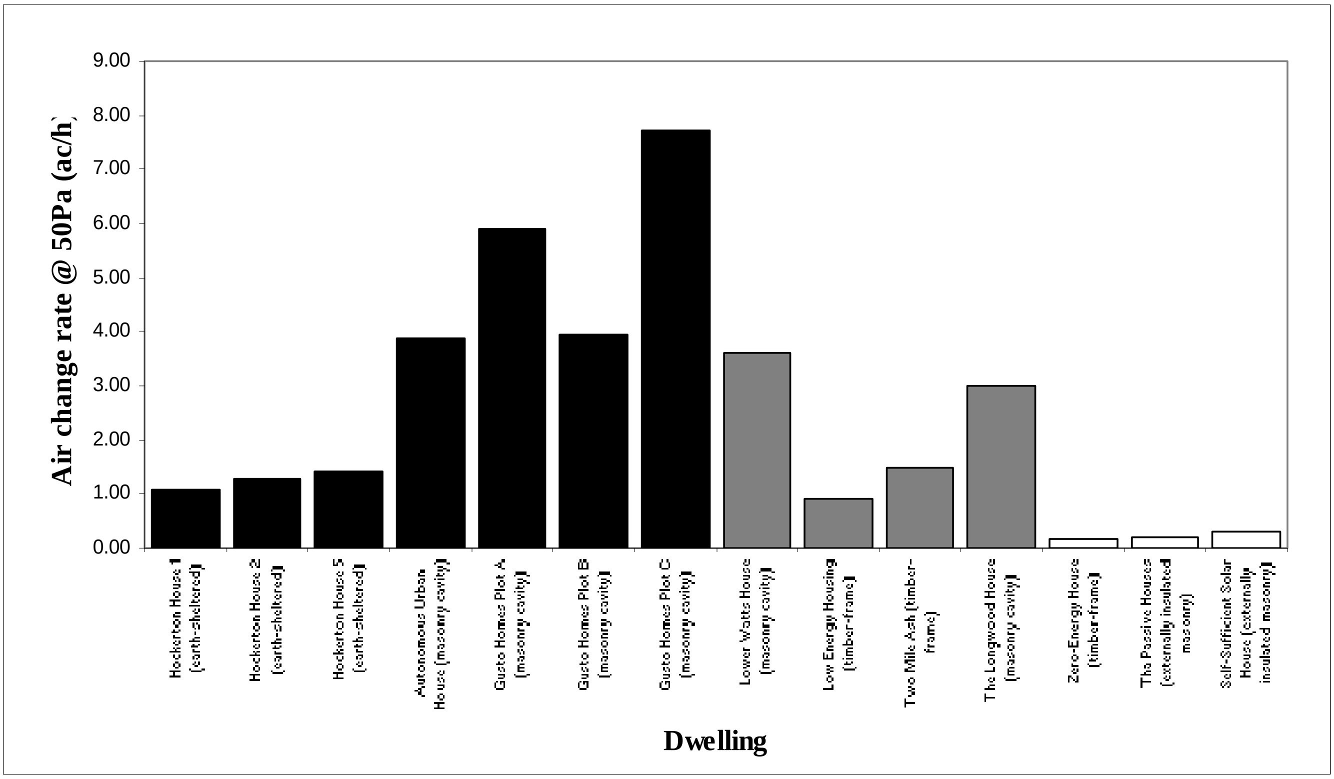


Figure 20 Comparison of air leakage rates.

99 The main points that can be obtained from this comparison are as follows:

a) The majority of the case study dwellings are very airtight by UK standards.

b) The Autonomous Urban House and Gusto Homes Plot B have levels of air leakage that are comparable with Lower Watts and the Longwood House (3.89 and 3.95 ac/h @ 50Pa, compared with 3.60 and 3.00 ac/h @ 50Pa). This puts these two dwellings amongst the tightest masonry dwellings yet recorded in the UK.

c) The Hockerton Houses are amongst the most airtight dwellings yet recorded in the UK, with an air leakage of between 1.09 and 1.4 ac/h @ 50Pa. This is remarkable, given that these dwellings have been occupied since 1998. Only one other UK scheme has recorded an air leakage rate lower than Hockerton. This scheme is the Low Energy Housing at Stenness in Orkney, which achieved an air leakage of 1 ac/h @ 50Pa. This is interesting, given that earth-sheltered construction is intrinsically more airtight than timber frame construction. However, it is almost certain that the Hockerton Houses would have achieved a lower air leakage rate when they were first built.

d) The results suggest that, in the UK, relatively airtight dwellings can be built using both timber frame and wet plastered masonry.

e) The overseas dwellings are all very airtight, achieving an air leakage rate of less than 0.3 ac/h @ 50Pa. The lowest level of air leakage recorded was 0.17 ac/h @ 50Pa for a timber frame house at Brunnadern, Switzerland.

f) There is a still considerable gap in airtightness between the best performing dwellings constructed in the UK and those constructed abroad. The lowest recorded airtightness readings for UK dwellings are from the Low Energy Dwellings at Stenness and the Hockerton Houses, but these fall short of the best performing houses overseas, such as the Brunnadern house. This indicates that the design approach and construction techniques must be improved further if the UK is to match the airtightness performance of the best overseas dwellings.

Questionnaires

100 The spot pressurisation tests were also complemented by open-ended questionnaires with the current occupiers and those responsible for the design and construction of the dwellings in question. The general aim of the questionnaires was to assess the occupant's experience of airtightness within their dwelling and the experience gained from those involved in the design and construction of these dwellings. In the project proposal, the original intention had been to undertake open-ended interviews rather than a questionnaire. However, the occupants of one of the case study dwellings (who also designed the Hockerton Housing Project and the Autonomous Urban House), no longer resides in the UK. It was therefore felt that an open-ended questionnaire, which could be completed and returned by e-mail, would be more appropriate.

101 In total, two separate questionnaires were devised, one for the current occupiers and one for the designer and builder of the dwellings. Copies of these questionnaires are contained within Appendix 2. The questionnaires were qualitative and explorative in nature and sought to gain insights into the following:

a) Occupant questionnaire

Experience of living in an airtight dwelling.

Experience of the ventilation system.

b) Designer and builder questionnaire

Experience of designing the dwellings.

Experience of constructing the dwellings.

How they envisaged the operation of the ventilation system.

102 The current occupants, designers and builders of the case study dwellings were sent a copy of the questionnaire in December 2003. Currently, five questionnaires have been returned[3]; two from the dwelling occupants and three from the designers and builders.

Comments on questionnaire findings

103 This section summarises the preliminary findings from the returned questionnaires. As the study involved small numbers of respondents, these findings do little more than provide insights into some of the issues involved.

104 One of the concerns with airtight dwellings is that they require careful control of ventilation to maintain adequate air quality, and consequently buildings designed for high airtightness often require a mechanical ventilation system. All seven houses measured in the spot tests were fitted with a mechanical ventilation heat recovery (MVHR) system. The occupant questionnaire therefore specifically asked questions about air quality and control of ventilation. The two respondents to the occupant questionnaire resided in the Hockerton Housing Project (dwellings 1 and 2). From their comments, it can be concluded that the high levels of airtightness observed for these dwellings did not appear to have had any adverse effect on the internal environmental conditions within the dwellings and that the ventilation systems provided were suitable for the conditions. The occupants reported that the dwellings were comfortable[4], not stuffy, smells dissipated quickly and they did not experience any draughts, apart from when doors were left open. The only instances when this was not the case were when the ventilation system had either been switched off, or on one occasion when it had failed due to an electrical fault. Very few problems were encountered with condensation. Both occupants felt that they had good control of the ventilation system and that it was effective in maintaining air quality. The only problems experienced with the ventilation system were due to maintenance issues with the MVHR. Summer conditions required the opening of windows, doors and skylights to reduce any overheating.

105 There was only one response on designing for airtightness (Gusto Homes). This response indicated that the level of difficulty in designing for airtightness could be high. The approach taken in this case to achieve airtightness was to have a detailed design; a wet plastered internal finish and high performance doors and windows. Suggested improvements for the next house design were better detailing on stud partitions and floor joists.

106 The experience of the two respondents in terms of the construction process was that they found it relatively easy to achieve high levels of airtightness, as long as the specification was followed carefully and that there was good on-site supervision. Opportunities for improvement to the construction process include improved seals at frame junctions, attention to sealing between basement and ground floor and better education of the workforce. Issues of concern were the availability of high specification components such as windows and the lack of trained plasterers able to produce a high quality wet plastered finish.

107 All three designers specified a MVHR system to ventilate the houses. Additional ventilation to the dwellings was intended to be through the opening of windows and trickle ventilators as required, such as during the summer period. All three respondents felt that this method of ventilation was the best available, giving a good degree of comfort and allowing the occupants good control over the amount of ventilation.

Conclusions

108 This report presents the results of a literature review, which was supplemented by a small number of field tests of airtight dwellings, together with open-ended questionnaires with the current occupiers and those responsible for their design and construction. The purpose of these questionnaires was to assess occupant experience of airtightness within their dwelling and to

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[3] In total, nine questionnaires were sent, four occupant and five designer and builder. Unfortunately, one of the consequences of the choice of case studies is that it will not be possible to obtain a completed occupant questionnaire for all of the dwellings tested. The reason for this is that two of the dwellings (Gusto Homes Plots A and B) have just recently been completed, and it has not been possible to contact the previous occupant of another dwelling (Gusto Homes Plot C).

[4] The conservatory occasionally gets too hot on very warm sunny days and can get too cold during the heating season. However, it is not part of the heated envelope.

assess the experience gained from those involved in the design and construction of airtight dwellings.

109 A very wide range of air leakage exists within the UK housing stock, with the least airtight dwellings being over 10 times as leaky as the most airtight. Recent measurements also suggest that post-1995 dwellings may only be marginally more airtight than the stock as a whole, and a significant proportion of these dwellings would fail to meet the Approved Document L1 air leakage target of 10 $m^3/(h.m^2)$ @ 50Pa.

110 A number of countries have criteria to limit whole building air leakage from dwellings. The most stringent air leakage criteria tend to be found in countries with severe climatic conditions, such as Sweden, whilst countries with temperate climates tend to have less onerous criteria.

111 In general, existing UK dwellings tend to be very leaky in comparison to their international counterparts, whilst new UK dwellings only tend to be as airtight as those constructed in Canada, Sweden and Switzerland some 60 years ago. In addition, dwellings classed as very airtight in the UK, would be classed as normal practice in these countries.

112 In the UK, one of the most important determinants of airtightness is construction type. Other factors that are known to influence the airtightness of dwellings are: age of the dwelling; number of stories; size and complexity of the building; longevity; seasonal variation; and site supervision and workmanship.

113 The most common form of dwelling construction in the UK is cavity masonry. The UK data show that this tends to be very leaky. The reasons for this can be attributed to the use of plasterboard dry-lining as an internal finish to masonry walls, as opposed to wet plaster, and the use of timber intermediate floors, as opposed to concrete floors. On the continent, masonry dwellings are nearly always wet plastered, and have concrete floors, which explains why masonry dwellings on the continent are typically more airtight than their equivalents in the UK.

114 The main air leakage paths within UK dwellings have been identified. The majority of this leakage is attributable to a range of cracks, gaps and joints throughout the building, rather than a single component.

115 A considerable amount of guidance on airtightness has been identified. The majority of this is from overseas. This guidance can be split into two distinct areas: general guidance and detailed guidance. General guidance highlights design issues associated with the entire dwelling envelope that are important for airtightness. Detailed guidance highlights specific issues for components, materials and construction methods.

116 General guidance on designing dwellings for airtightness gives the following advice: the airtightness layer should be continuous around the building envelope; it should be in the same plane throughout the structure; it should be easily installed, and be durable and accessible for maintenance; designs should avoid, or at least minimise, penetrations through the sealing layer; and designs should avoid complex detailing.

117 The main source of guidance on airtightness in the UK is the Report on Robust Construction Details. The guidance given within the Robust Details document is restricted in its scope in that it does not give enough information on the principles of airtightness, as applicable to each of the detailed designs. There is also little information on tolerances and potential variability within each of the designs. This would allow for a wide interpretation of the design details and give rise to variability in airtightness.

118 The impact of the Robust Construction Detail document on the airtightness of new UK dwellings is not yet known, as no significant data are available on buildings constructed since its introduction in 2001. The next stage of this project will address this issue.

119 Detailed guidance in the UK does highlight specific issues associated with UK construction practice. For example, the difficulties associated with air leakage around plasterboard dry-lining are identified in several sources and recommendations are made to seal around the perimeter of boards, or preferably use wet plastered finishes in preference to dry-lining.

120 Spot measurements have been undertaken on seven UK dwellings that had been identified as being potentially very airtight, but had not been tested. The results suggest that:

a) All of the dwellings tested were relatively airtight by UK standards. The three earth-sheltered dwellings at Hockerton were found to be amongst the most airtight dwellings ever recorded in the UK, with an air permeability of between 0.95 and 1.23 $m^3/h/m^2$ @ 50Pa. The very high level of airtightness was felt to be attributable to the method of construction.

b) Wet plastered masonry cavity construction can default to being airtight by UK standards (<7.1 $m^3/(h.m^2)$ @ 50Pa), without much attention being given to airtightness.

c) One of the most significant sources of air leakage within all of the tested dwelling was the opening casements of the windows and the French doors. Leakage through these components was caused by wear-and-tear and poorly fitting casements.

d) The air leakage of all of the tested dwellings could be improved by undertaking a number of relatively simple measures. For instance, sealing service penetrations, adjusting window and door casements, and replacing seals.

e) The data suggest that there is a significant gap in airtightness performance between the most airtight dwellings constructed in the UK and those constructed abroad, where values have been measured as low as 0.17 ac/h @ 50Pa.

121 The spot measurement tests were complemented with questionnaires to the designers, constructors and occupiers of the dwellings. These were intended to assess the occupant's experience of an airtight dwelling and identify any conclusions from the design and construction process. The occupants reported that the dwellings were comfortable to live in, and there was no indication of any major problems with air quality, condensation, smells or draughts. The one designer that submitted a response indicated that the difficulty of designing for high airtightness was high. In terms of the construction process, the responses suggest that it is relatively easy to construct an airtight house, as long as the specification is followed carefully and that there is good on-site supervision.

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