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Airtightness of UK Buildings: Status and Future Possibilities

Earle Perera and Lynn Parkins

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1. INTRODUCTION

A major factor in the ventilation of buildings and their energy performance is the airtightness (or leakiness) of the building envelope. While adequate ventilation is essential for the health, safety and comfort of the occupants, the adventitious ingress (infiltration) of air through the building envelope is not ventilation that is designed for. It can, therefore, be a source of excessive ventilation leading to energy waste and, sometimes, to discomfort.

Buildings are profligate in their use of energy. At a cost of about £17 billion per year, building services consume 2900 PJ of delivered energy,[1] ie, almost half of the total UK consumption. Similarly, this consumption in buildings is also responsible for the emission of about 294 million tonnes of carbon dioxide every year. This is almost half of the UK's annual production and, therefore, generates more external air pollution than any other activity.

Space heating of buildings accounts for most of this energy consumption, eg 60% in dwellings.[1] Of this, the heat loss through ventilation is significant and becomes increasingly important as fabric heat losses are reduced through better insulation. Infiltration could, therefore, be justifiably considered an overhead or a penalty.

It should be the basis of good design to make the building envelope airtight and then to provide controlled ventilation. This may be natural, through openable areas (windows and doors) and controlled background (trickle) or mechanical ventilation. The aim is to satisfy the ventilation requirements[3,4] and regulations[5,6] concerning occupant health, comfort and safety, ie, the idea of 'build tight – ventilate right' advocated over a decade ago.[7]

This paper describes briefly the accepted procedure used to measure the airtightness of building envelopes. Results from field measurements on various types of UK buildings, mostly carried out by the Building Research Establishment (BRE) or its contractors, are given and the implications of these measurements discussed. Guidelines are proposed that could be used to categorise the airtightness (or alternatively, the leakiness) of a UK building, ie, whether it is 'tight', 'average' or 'leaky'. This could be used as the basis for a quality assurance assessment of an individual building, whether new-build or refurbished. The potential for improvement is identified by comparing the tightness of UK buildings with those from North America and Sweden.

A building cannot be too tight – but it can be underventilated. This paper concludes by summarising current guidance on ventilation requirements, possible design procedures to implement these and measurement procedures to ensure that requirements have been met.

2. MEASURING AIRTIGHTNESS

The 'fan pressurisation' method[8] gives the most direct way of measuring and characterising the airtightness of the building envelope. This involves sealing a portable fan into an outside doorway and measuring the air flow rates Q (m^3/s) required to maintain a series of pressure differences Δp (Pa) across the building envelope. A full description of the technique, including the necessary protocol to carry out the measurements, is given in a BRE report[8] and in an International Standards Organisation (ISO) draft.[9] Other countries have similar procedures[10] to ensure that interpretation and comparison of results are meaningful.

Over the last decade, use of this technique for dwellings has increased and the equipment necessary to carry out these tests is now available commercially. However, it is only recently that similar hardware has been developed for testing larger, non-domestic buildings and its commercial availability is still limited.

One such system, designed for large non-domestic buildings, is the BREFAN rig built by BRE (Fig 1). It consists of separate fan pressurisation units powered from conventional 13 amp sockets and operated by single to three-phase speed controls. On any particular building, the number of fan units used is dictated by that necessary to get a target envelope pressure difference. Airflow through each fan is measured using a conical inlet. Reference 11 describes the system in greater detail.

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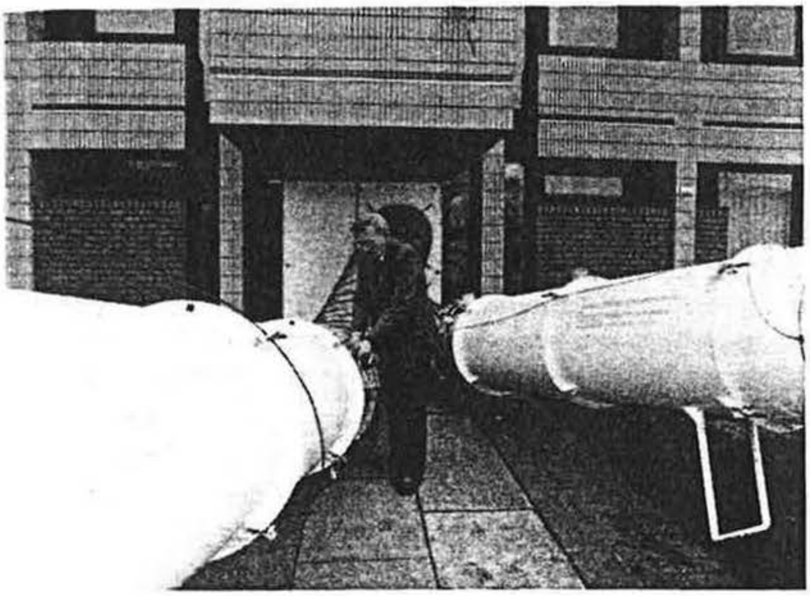

Figure 1. Two of the BREFAN fan pressurisation units

The airtightness characteristics of a building can be quantified by plotting graphically the measured data as Q versus Δp. If there are no irregularities, the relationship between the two variables follows a smooth curve[12] and a simple power-law function of the form

$$Q = k (\Delta p)^n$$

can be fitted to the data. In this equation, k is a constant (whose value depends on envelope size and tightness and the system of units used) and n is an exponent lying between 0.5 and 1. Although this form of presentation can explicitly identify the airtightness characteristics of any building, it is a difficult form to use for comparison between buildings since 'k' and 'n' cannot be considered separately.

In dwellings, it is useful for purposes of comparison[12] to calculate the air change rate (leakage air flow rate Q m^3/h divided by building volume V m^3) at an applied pressure differential. It is usual to have this pressure set at a value well in excess of the pressure differences that drive natural ventilation. By convention, the flow rate Q_{50} measured at a pressure difference of 50 Pa is used. For larger non-domestic buildings, eg offices and factories, this is a difficult pressure to achieve. Consequently the flow rate Q_{25} at a lower pressure (but still larger than pressures usually induced by natural mechanisms like wind and temperature) can be used.[13,14] Note that although the air leakage rates in this form are expressed as air changes per hour (ach), they have completely *separate meanings from ventilation rates* (also usually expressed in the same units).

Comparing the air change rates of buildings with substantially different form and volume is, for most purposes, meaningless. A more suitable measure is the leakage index, Q_{25}/S (where S is the total permeable external surface area). This can be considered[15] as the permeability of the building envelope to air flow (at 25 Pa) and, thus, a measure of the construction quality of the external fabric of the building.

3. FIELD MEASUREMENTS

3.1. Dwellings

There is a considerable amount of information available on UK stock. BRE holds the largest database with 385 dwellings including buildings of different types, wall construction, age of building and whether or not the buildings are draughtstripped. Figure 2 illustrates the measured 50 Pa leakage rate of these dwellings. This shows a skewed distribution and a wide span of rates ranging from 4 to 30 ach. The median *leakage* rate is evaluated as 13 ach.

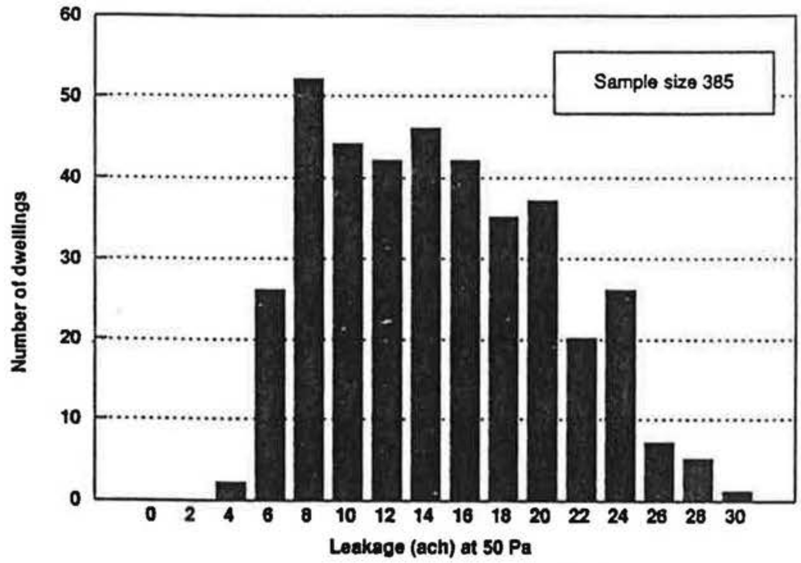

Figure 2. Distribution of air leakage for dwellings

3.1.1. Categorising airtightness

It is possible to provide some guidance on what constitutes a 'tight' or a 'leaky' dwelling in the UK by using as a marker the ventilation necessary to minimise risk of condensation and mould growth – a major and widespread problem in the UK. It should be noted, however, that ventilation is just one of the many remedial measures that can be taken to solve a condensation problem.

Guidelines[16] indicate that a whole-building *ventilation* air change rate of about 0.5 ach is generally adequate to keep the relative humidity below levels at which condensation may occur. Above 1.0 ach, however, further provision of ventilation is not likely to help a dwelling with condensation problems. Making the broad assumptions that:

(a) this ventilation is provided wholly through infiltration rather than by controlled ventilation; and

(b) the infiltration rate can be linked to the leakage rate by the general 1/20th rule-of-thumb.[17] This rule states that at an inland site, the average infiltration rate of a dwelling is approximately equal to 1/20th of the leakage rate (at 50 Pa),

it is then possible to specify that an airtight dwelling may be taken as one that has a 50 Pa leakage rate of 10 ach or less. Similarly, a leaky building will have a rate of 20 ach or greater.

On this basis, approximately 30% of dwellings in the BRE database are 'tight' and 15% are 'leaky'. As a corollary, the 1/20th rule indicates that the median infiltration rate of the BRE sample is about 0.7 ach.

3.1.2. Leakage index

The BRE database contains Q_{50} values and, for 343 dwellings in the sample, the coefficient k and exponent n (of the power-law function given earlier) were known. For these, it was a straightforward matter to obtain Q_{25}. For the remainder, Q_{25} was

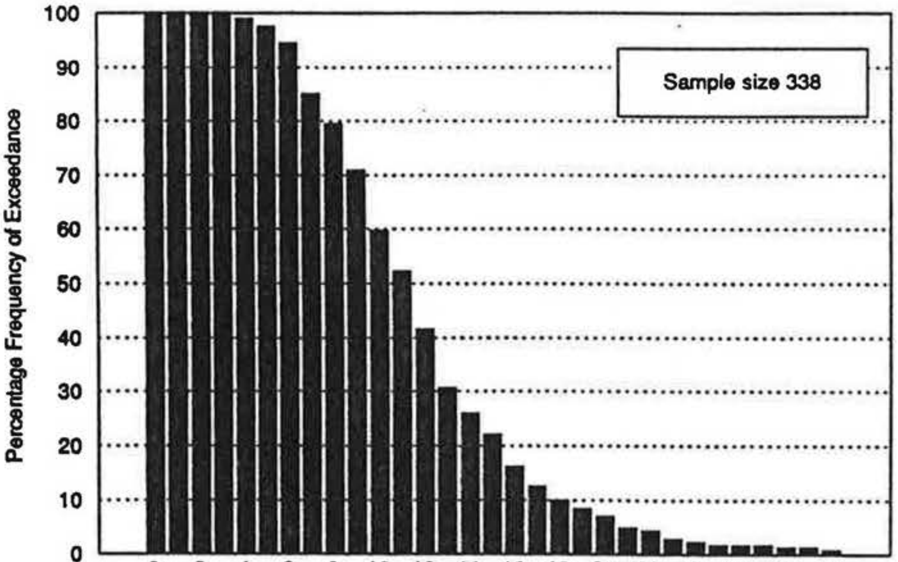

Figure 3. Distribution of 'leakage index' for dwellings

evaluated from the Q_{50} value by using information derived from the data sets where this information was known. This was done by carrying out a linear regression (with $r^2 = 0.97$) on the 'known' data. As a by-product of the regression analysis, the average exponent n was evaluated as 0.68 (± 0.01 at 95% confidence level) from the sample of 343 dwellings.

The leakage index, Q_{25}/S, was calculated for 338 dwellings for which the permeable area S was known. Figure 3 shows the percentage frequencies with which various values of the leakage index are exceeded. The median value was estimated as 11 m^3/h per m^2. The mean values (and the associated confidence intervals) of the index for all dwellings and for those identified earlier as 'tight' or 'leaky' were evaluated as follows:

all dwellings	– 11.8 (± 0.5) m^3/h per m^2
tight dwellings ($Q_{50} < 10$ ach)	– 9.2 (± 0.9) m^3/h per m^2
leaky dwellings ($Q_{50} > 20$ ach)	– 15.8 (± 1.2) m^3/h per m^2
remainder ($10 < Q_{50} < 20$ ach)	– 12.6 (± 0.6) m^3/h per m^2

3.1.3. Construction date

To determine whether the airtightness of dwellings improved with better insulation levels over the years, the dwellings in the database were subdivided by their decade of construction and the data analysed. For each of these subgroups, the mean leakage index (with the associated 95% confidence levels) was evaluated and plotted in

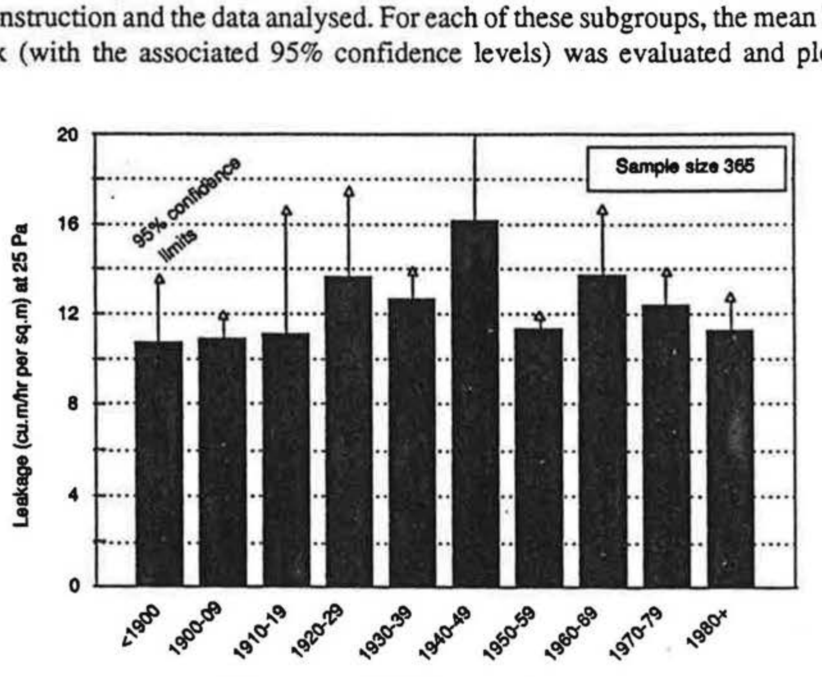

Figure 4. Effect of age of dwelling

Figure 4. This shows no identifiable change in airtightness of the envelopes during the past century of house-building, ie, buildings are as leaky now as they were at the turn of this century. This has important implications for newer buildings. Without tighter envelopes, ventilation heat losses will dominate total space heating requirements as dwellings become better insulated.

3.1.4. Distribution of air leakage between components

If the distribution of leakage between various components is considered, it is possible to understand why better insulation does not necessarily mean tighter buildings. Figure 5 shows the mean distribution of air leakage (at 50 Pa) between components in 35 dwellings (within the BRE database) obtained by carrying out selective sealing during whole house tests.

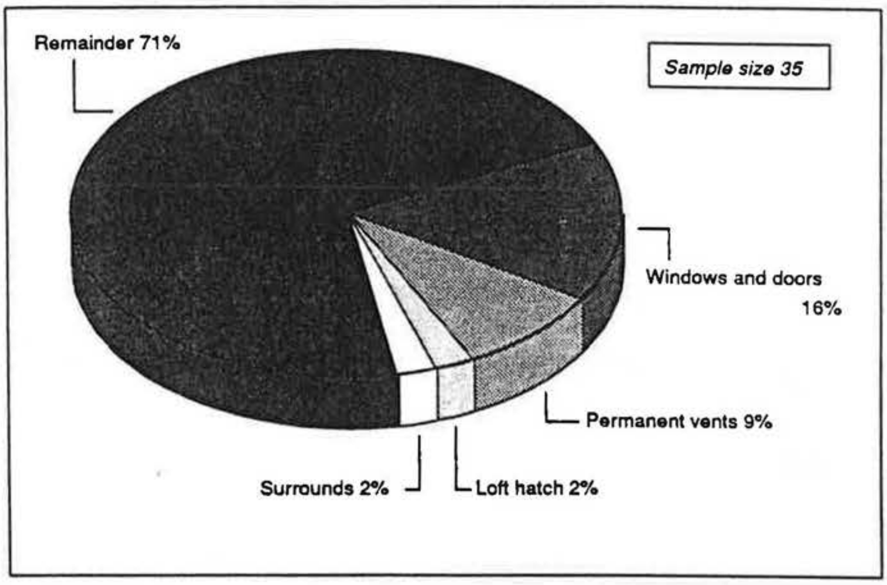

Figure 5. Component leakage in dwellings

Most of the leakage, ie, 71%, is ascribed to 'background', ie, through unidentifiable gaps rather than through cracks such as around door and window surrounds. This shows that even though the building may be better insulated, or draughtstripped or have tighter windows, the building will still be leaky if the envelope has not been constructed to reduce infiltration.

This average value of 71% for the background leakage of this particular sample was obtained at 50 Pa. This value would be reduced somewhat if the measurements were carried out at a lower applied pressure. Rough calculations indicate 53% at 10 Pa. This is because the total air leakage is an aggregate of many individual leakage paths; each with (possibly) a different value for the leakage exponent, n.

Components with higher values of n (ie smaller gaps) are more dominant at the higher end of the pressure difference range and thus contribute more to the overall background leakage.

3.1.5. Effect of draughtstripping

Figure 5 also shows that air leakage through windows and doors contributes to only about 16% of the total. Measurements in 79 other dwellings in the database, made before and after routine draughtproofing treatment showed[18] reductions in Q_{50} from 0 to 35% with a mean of 8%. This indicated that draughtstripping was effective in reducing by at least half the losses through doors and windows. However, dwellings should not be draughtstripped without proper provision and checks relating to combustion appliances and the presence of condensation.[18]

3.1.6. Large panel system (LPS) flats

BRE has carried out[12] airtightness measurements in 87 LPS flats of differing systems. The mean leakage rate at 50 Pa was 7.3 ach, ie, about half that for the typically low-rise dwellings contained within the BRE database. The BRE study concluded, however, that this low leakage rate did not necessarily imply that the flats were underventilated.

Using a method of balanced pressures, cross-leakage measurements were also carried out. Significant leakage, amounting to 10% of the 'whole flat' leakage rate was found across compartment floors, ie, to floors above and below. Generally, however, no significant leakage was found across compartment walls, ie, between adjacent flats on the same floor.

3.2. Office buildings

Unlike those for dwellings, airtightness information on UK non-domestic buildings is rather scarce, especially for office buildings, as a result of a lack of suitable test equipment. At present, BRE has the only published (and rather sparse) information regarding these buildings. Work is continuing at BRE to increase this database.

3.2.1. Leakage index

Tests[11] were carried out in a conventional naturally ventilated 6,000 m^3 office block. The outer face of the building consists mainly of single-glazed, steel-framed windows and 13 mm thick insulated infill panels. Behind each panel there is a 114 mm air gap followed by a 114 mm thick brick wall lined with 16 mm of plaster on the inside. Measurements gave a leakage index of about 12 m^3/h per m^2 (at 25 Pa), similar to the average airtightness found for the UK dwellings.

This value is about twice that found[11] for a 'tight' building built specifically as a low energy office (LEO). All windows of the 5,315 m^3 LEO building were double glazed (with aluminium frames). The walls were constructed to a high standard and consist mainly of 9 mm thick clay tiles on the outside face. This was followed in succession by 125 mm thick precast concrete panels, a 300 mm void filled with blown polystyrene beads and a 12.5 mm thick plasterboard with an aluminium foil vapour barrier. In both buildings, the occupants appeared to be satisfied with the internal environment.

In contrast, BRE recently investigated[19] an office building considered 'leaky' where staff dissatisfaction had been expressed. In this building, and depending on the outside air temperature, some areas were usually either too hot or too cold. Using BREFAN, the leakage index of this 18,000 m^3 building was evaluated as 21 m^3/h per m^2 (at 25 Pa). This was nearly twice that obtained for a 'conventional' building and four times greater than that of the LEO and confirmed that the building was indeed leaky. Using hand-held smoke-tubes and with BREFAN depressurising the building, it was found that most leakage of external air occurred through specific portions of the roof void. Some secondary leakage occurred through cracks along the top edge of most openable windows.

3.2.2. Leakage through duct openings

As for dwellings, sealing identifiable leakage paths does not reduce the air leakage significantly. When buildings have provision for mechanical ventilation, duct openings (to the outside) in air handling units can contribute to the general leakiness of the building.

Although the occupants in the LEO are free to open the windows whenever they choose, the building has a mechanical ventilation system. This allows a varying amount of fresh air to be taken into the building depending upon the setting of mechanical dampers at the air-handling unit (AHU). By carrying out selective sealing, it was found that duct openings in the AHU contribute about 15% to the total leakiness of the building.

3.2.3. Tighter windows

As part of a program to improve thermal insulation levels, the older double-glazed windows (with 6 mm air gaps) of the LEO building were replaced with tighter units incorporating Argon fill. Measurements[20] before and after installation showed a 9% reduction in the leakage rate at 25 Pa. However, because of the time gap of about one year between the measurements, it is difficult to state categorically that this reduction is due to the newer and tighter windows. For instance, it is known that in dwellings, seasonal variations do occur[15] in the leakage rates. Further work is, therefore, still necessary.

3.3. Industrial single-celled buildings

Preliminary studies[20] have shown that an indication of the airtightness of industrial buildings can be obtained by considering when they were constructed. This reflects different levels of fabric insulation imposed by changes in the Building Regulations over the years, namely:

(a) those built before the 1979 amendments[21] to the Building Regulations;

(b) those built according to the 1979 amendment (Part FF) to the Regulations (requiring U-values of 0.7 $Wm^{-2}K^{-1}$ in roofs and walls);

(c) those built that satisfy the current 1990 amendments to the Regulations through Approved Document Part L (by raising the levels of insulation to produce U-values of 0.45 $Wm^{-2}K^{-1}$).

3.3.1. Leakage index

Tests were carried out[20] in two of the older buildings. One of these was a 25-year-old hangar-type building known in the UK as a 'Marston' shed. The walls and roofs comprised corrugated asbestos cement sheeting fixed to a steel frame and lined internally with plasterboard) gave a leakage index of 44 m^3/h per m^2 at 25 Pa. A similar value was obtained from measurements in a 35-year-old 5,000 m^3 poorly insulated factory unit of a masonry construction.

Tests on two buildings (with a cladding construction) and built according to the 1979 amendments gave[20] a leakage index of about 21 m^3/h per m^2. This is about half the leakiness of the two older (and poorly insulated) buildings. However, measurements (yet unpublished) in a factory unit satisfying the 1990 amendments gave a leakage index of about 16 m^3/h. Although there is some reduction, it is not as significant as that obtained previously. These are only preliminary results and further work is necessary to firm up these conclusions.

3.3.2. Sealing loading doors

In older buildings that are poorly constructed, the amount of air leaking through a (closed) loading door is only a little of the total through the whole envelope. Measurements[20] in the 25-year-old Marston shed showed that sealing a partition door only reduced the total leakage (at 25 Pa) by 7%.

As the walls and roofs of the building are constructed and insulated better, this proportion increases. Measurements[22] before and after sealing an uninsulated loading door of a factory unit built to 1979 Part FF standards showed a reduction of 14% in the leakage rate. A prediction procedure was used to make the link between leakage measurements and ventilation characteristics. The effect of this reduction was evaluated[22] as decreasing the average infiltration rate by 24% and the total space heating requirements over the heating season by 14%.

Similar reductions in the infiltration rate have been found elsewhere.[23] Measurements in a low-energy factory unit (satisfying 1990 Part L standards and with insulated and sealed loading doors) were compared with another built to Part FF

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standards. Results showed a marked reduction (about 60%) in the infiltration rate of the low energy factory. It was estimated that the installation of the insulated loading doors, with good sealing characteristics, had the most significant impact and accounted for about three-quarters of this reduction.

3.3.3. Cross-leakage

There is evidence, from as yet unpublished measurements, that cross-leakage of air occurs across common party walls into adjacent factory units. Measurements were carried out using a system of balanced pressurisation on a well insulated end-of-terrace factory unit. This showed that approximately 15% of the total leakage (at 25 Pa) was through the party wall to the adjacent unit.

4. POTENTIAL FOR TIGHTER BUILDINGS

Figure 6 shows the measured leakage index (at 25 Pa) of different building types in the UK, North America (USA and Canada) and Sweden. For the North American buildings, data obtained for dwellings were derived from Reference 15 while those for non-domestic buildings had been obtained previously.[19] Values for Swedish buildings conform to their current Standards. Since this Standard quotes the values required at 50 Pa, we have carried out an appropriate revision to specify it at the lower 25 Pa pressure. Figure 6 then shows that the average UK dwelling is twice as leaky as one in North America and six times more leaky than one in Sweden.

In the office sector, Figure 6 also shows that the purpose-built LEO is as tight as a representative North American building. This shows that it is possible to construct a

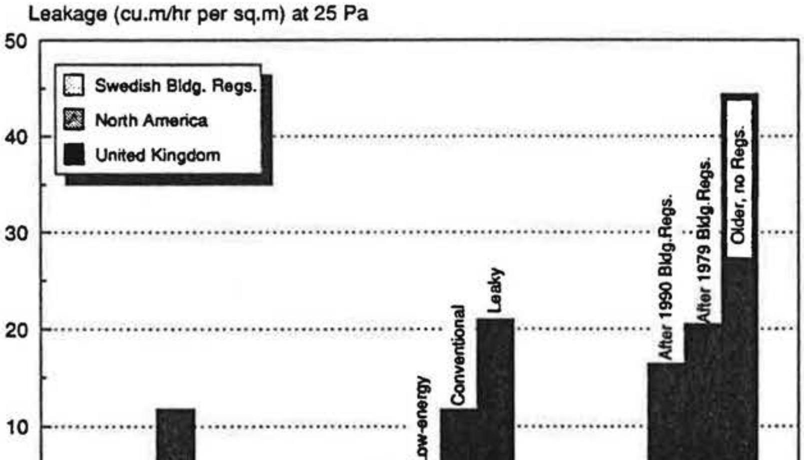

Figure 6. Comparing leakage of different building in different countries

building in the UK with a tight envelope provided attention is given to good practice. In contrast, the more conventional building is twice as leaky while the building with problems was four times as leaky.

However, some of the leakiest buildings were industrial single-cell buildings. Even the tightest UK industrial building (satisfying current Building Regulations) was five times more leaky than a similar Swedish building while the older buildings were ten times as leaky.

Using the 25 Pa leakage index, preliminary analysis indicates that it is possible to categorise the tightness of UK buildings. The following Table does this and includes target values (following those obtained elsewhere) that could potentially be achieved in new-builds using:

(a) better building practice; and

(b) better attention to details affecting the envelope.

Building Type	Leakage Index (m^3/h per m^2) at 25 Pa			
	Tight	Median value	Leaky	Achievable
Dwellings	⩽ 9	12	16	⩾ 3
Offices	⩽ 5	10	20	⩾ 5
Industrial (single-cell)	⩽ 15	20	30	⩾ 5

5. DESIGNING FOR TIGHTER BUILDINGS

The UK has neither mandatory nor recommended standards for the airtightness characteristics of complete buildings. However, two ISO standards;

ISO 6613:1980 Air permeability tests on windows and doors

ISO 6589:1981 Air permeability of joints in buildings

and a European standard

EN42 Methods of testing windows: Air permeability

dealing with components are used in the UK. For pressurisation testing guidelines, there is an ISO draft (in its final stages), ISO/DIS/9972 'Determination of building airtightness – Fan pressurisation method'.

There is also no central planning directive but there are various *ad hoc* initiatives to design for tighter buildings while providing controlled ventilation. In new housing, there are several schemes including low-cost low-energy housing by local authorities and by developers such as Wimpey.[24] Information regarding design aspects for tighter buildings exists in various forms, eg in the architectural press[24] or as guidance documents to international practice.[25]

Guidance relating to office-type buildings is somewhat lacking. BRE is addressing this issue now and work is being carried out to produce a guide book on minimising air infiltration and providing adequate ventilation in office buildings. Meanwhile, some pointers regarding the construction aspects of tight buildings can be obtained by examining some current and ongoing projects, eg the new low-energy hospital in Ashington.[26]

The Welsh Development Agency is building low-energy factory units incorporating higher levels of insulation and tighter envelopes. The integrity of the external envelope is then confirmed by pressure testing and thermal imaging. These designs have considered[27] details such as; the routes by which air infiltrates industrial buildings, the construction details that need to be addressed to minimise this unwanted ingress of air and the methods by which controlled ventilation can be introduced.

6. PROVIDING CONTROLLED VENTILATION

6.1. Requirements

Greater attention has to be paid to provide adequate ventilation through controlled means if tighter buildings minimising infiltration are to be achieved. While ventilation is needed for good indoor air quality, it is also needed in dwellings to control condensation and to ensure the safe and efficient operation of combustion appliances. For dwellings, Building Regulations Approved Document F (1990) gives guidance on meeting these requirements by *controlled* ventilation.

The present Building Regulations do not deal with provision for ventilation requirements in non-domestic buildings except for rooms containing sanitary conveniences, although the position is currently under review. The UK Government is currently consulting on proposals for regulations to implement the provision of the EC Workplace Directive which includes requirements relating to ventilation.

In office buildings, ventilation requirements are mainly governed by comfort criteria which are usually set by aspects relating to body odour, smoking and, in the summer, to overheating. CIBSE[4] gives guidance on fresh air requirements relating to metabolic needs and controlling body odour (8 l/s fresh air per person) as well as on tobacco smoke (from 16 to 32 l/s per person depending on proportion of occupants smoking). The recently published Government code of practice on smoking in public places[28] also contains suggestions on ventilating smoking areas and rooms.

Some industrial processes may generate large amounts of pollutants. Recommended measures[29] to deal with the pollutant sources and to control indoor levels to safe and acceptable limits are available. It should be noted that, although general dilution ventilation of the workplace is usually perceived to be the only remedial measure, it ranks very low in the list of recommended measures. Other strategies, eg local extract ventilation, may be better and more economical. Guidance is given by the Health and Safety Executive.[6]

6.2. Design

A building is taken to consist of a number of interconnected zones, each at a specific pressure, with air moving from regions of high to low pressure. The pressure differentials are set up both by the action of wind on the external surface of the building and by the temperature difference between the inside air and the outside. The amount of air flowing between the outside and the various zones, or between the zones themselves, is governed by the magnitude of pressure differentials and also by the type of flow path (such as open doors and windows). Design guidance[30,31] is available for simple building forms, such as for housing, when the building can be approximated to a single-cell structure.

For more complex buildings like offices, multicell computer prediction procedures are available.[32] These programmes can be used to obtain detailed information about air movement within buildings as well as a global value for the overall ventilation. This information can then also be used to identify not only the movement of air but also of contaminants or heat from one zone to another; and to determine the effectiveness of remedial measures (such as draughtstripping) or indicate zones where selected remedial measures will be cost effective.

When designing for natural ventilation, calculations should also take into account the expected ventilation performance of the building; ie by combining the influence of expected local weather with the ventilation characteristics of the building.[33] Guidance[34] is also available on ventilation and shading necessary to minimise summer overheating.

6.3. Monitoring performance

Tracer gases are often used[35] to measure ventilation airflows. In housing, the most widely used conventional procedure is the tracer 'decay' technique. The gas is first evenly distributed throughout the dwelling and the rate at which the tracer concentration decays is then measured as the gas becomes diluted by incoming outside air. The 'decay' rate can then be related directly to the ventilation rate.

For large and complex buildings, like offices, it is often difficult to disperse and maintain uniform gas concentrations before and during measurement. Other techniques then have to be used. One method[36] is to use several gases simultaneously to trace the exchange of air between zones within a building as well as the exchange between the outside air and relevant zones.

However, multiple tracer techniques are labour intensive and require specialist equipment and personnel. For (large and complex) buildings where such detailed information is not necessary, BRE has developed a simplified technique BRESIM [37] for determining approximately the overall air change rate using a single tracer gas. It comprises equipment and an easily implemented procedure designed to help non-specialists carry out assessments of the ventilation performance of buildings.

Finally, in offices where there is no smoking, the internal CO_2 level may in certain instances be used as a surrogate measure of the adequacy of the indoor air. With an ambient outdoor level of 350 parts per million (ppm), simplified calculations indicate that a monitored CO_2 level below 1,000 parts per million (ppm), should (in general) ensure that the requirement of 8 l/s per person is being met.

7. GENERAL DISCUSSION AND CONCLUSIONS

Infiltration through the building fabric is not ventilation that is designed for and can, therefore, be a source of excessive ventilation leading to energy waste and, sometimes, to discomfort. The basis of good design should be to make the building airtight and then to provide controlled ventilation to satisfy requirements and regulations concerning occupant health, comfort and safety.

Either the airtightness or the leakiness of the building envelope can be measured using the fan-pressurisation method. To compare different envelopes, a leakage index, ie, the leakage rate per unit external permeable area at a stated applied pressure difference (25 Pa in this paper) was derived from the measurements carried out by BRE or its contractors. Dwellings, office buildings and single-celled industrial buildings were considered. Using their leakage index values, criteria were derived that could be used to classify whether a building is 'tight', 'leaky' or 'average'.

Measurements from 385 dwellings of various types and ages showed no identifiable change in airtightness of the building envelope during the past century of house-building, ie, buildings appear to be as leaky now as they were at the turn of the century. Detailed examination, through progressive reductive sealing on 35 of the buildings, showed that (at 50 Pa pressure difference between inside and out) 71% of the total leakage could be ascribed to 'background', ie, directly through the fabric rather than through known gaps. This showed that 'newer' buildings, eg those built with better insulation and tighter windows, may not be more airtight unless careful attention has been paid during design and construction.

Analysis showed that existing UK dwellings could be categorised 'tight' if they had a leakage index less than 9 m^3/h per m^2 (at 25 Pa) and 'leaky' if this index is greater than 16. Of the dwellings within the BRE database, approximately 30% were tight and 15% were leaky with a median index of 12.5 m^3/h per m^2.

Unlike dwellings, airtightness information on UK non-domestic buildings is scarce. However, even with this limited information it was possible to categorise their tightness. For existing offices, leakage index values of 5, 10 and 20 m^3/h per m^2 (at 25 Pa) would imply a tight, an average and a leaky building respectively; while values of 15, 20 and 40 would provide similar markers for industrial buildings.

It was also shown that sealing identifiable leakage paths as a retrofit measure does not significantly improve the airtightness of non-domestic buildings – similar to the findings for dwellings. Some benefits can, however, be obtained by remedial measures (such as tighter windows in offices or better sealed loading doors in factories) if the building is already tight.

Comparison with buildings built in North America and Sweden shows that UK buildings are leaky and that there is considerable scope for improvement. The average UK dwelling or office is twice as leaky as one of similar type in North America. Comparisons with Swedish buildings show greater differences, eg dwellings six times as leaky and industrial buildings five times as leaky.

Tighter buildings imply better building practice and better attention to details affecting the envelope. Through the design of the BRE low-energy office and other *ad hoc* activities, it is shown that tight buildings can be built in the UK without compromising ventilation requirements. Guidance on both these aspects is available or will be shortly available and, for all new-builds or major refurbishments, the idea of 'build tight – ventilate right' needs to be encouraged.

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