

Airtightness of buildings — towards higher performance

Final Report — Domestic Sector Airtightness

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Dr David Johnston, Dominic Miles-Shenton, Prof. Malcolm Bell, Dr Jez
Wingfield,

Centre for the Built Environment, Leeds Metropolitan University

Department for Communities and Local Government

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Department for Communities and Local Government
Eland House
Bressenden Place
London
SW1E 5DU
Telephone: 030 3444 0000
Website: www.communities.gov.uk

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Executive Summary

- 1 This report constitutes milestone D11 — Final Report — Domestic Sector Airtightness of the Communities and Local Government/ODPM Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). This report presents the overall conclusions and key messages obtained from the project through design assessments, construction observations, discussions with developers and pressurisation test results. It also summarises discussion on the airtight performance of current UK housing, the implementation and impact of current and future legislation, and identifies potential areas for future work.
- 2 Following an initial literature review, the project adopted an action research methodology that involved the research team working very closely with five developers to investigate the practical design and construction issues that arise in making improvements to the airtightness of speculatively built mainstream housing. Two construction types were represented in the project: masonry cavity and steel frame. The action research was carried out in three phases. Phase 1 sought to track in detail the design and construction of 25 dwellings (five per developer) built to the regulatory requirements of the 2002 revision to Part L of the Building Regulations and then to measure air leakage in the completed dwellings. During this phase no attempts were made to influence the nature of the design or construction. Phase 2 involved extensive feedback to each developer on the results of Phase 1, including the analysis of detailed design drawings and observations of dwelling construction. This was used to improve the understanding of the airtightness issues and to prompt the developers into making improvements to the processes they were adopting. The feedback phase was followed by a further construction phase (Phase 3) in which the design and construction of 25 dwellings were observed and detailed feedback provided to each developer at every opportunity. Upon completion of the second cohort of dwellings airtightness was measured and the results compared with the first phase results. The data were then used to assess the impact of the different methods adopted and the implications for future regulatory policy.

Airtightness design and construction

- 3 The key conclusions that have emerged from the pressurisation test results obtained during the course of this project are as follows:
 - a) Although the size, structure and non-random nature of the samples preclude it being taken as fully representative of UK house production, the results obtained from Phase 1 suggest that the dwellings tested were broadly in line with the existing data on the stock as a whole and that, at least in these cases, the impact of the 2002 edition of Approved Document Part L1 on airtightness has been minimal.
 - b) Given the qualitative nature of the project, it was not possible to extrapolate the Phase 1 results to the post 2002 new build stock with any degree of confidence. However, the results were broadly in line with the results from pressurisation tests on 99 post 2002 dwellings (also not a random sample) reported by Grigg (2004). The Phase 1 observations and test results were discussed with the individual developers in a series of feedback sessions. The outcome of these discussions suggested that there was nothing particularly anomalous or atypical in the results of Phase 1 of the project or the conclusions that had been drawn.
 - c) The failure of the majority of the dry-lined masonry cavity and steel framed dwellings included within Phase 1 to achieve the ADL1 2002 airtightness target also suggests that the adoption of Robust Construction Details, at least in their current form, provides no guarantee that the current regulatory standard will be achieved with any degree of consistency. As to whether the revised versions (now available as Accredited Construction Details – Communities and Local Government, 2006) together with the increased awareness following the 2006 revision of Part L will achieve this remains to be seen.
 - d) The results from Phase 3 of the project suggest that an air permeability of less than $6 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa is genuinely achievable within mass-produced housing in the UK using existing techniques, materials and practices, and without incurring significant cost. A caveat to this may exist in the form of light steel frame construction, where a re-examination of how to achieve a continuous and durable primary air barrier may be necessary at design level. However, to achieve such a standard in a consistent and robust way is likely to require a mix of design modifications and a committed and targeted approach to quality control.
- 4 The project highlighted a number of issues that need to be considered when constructing dwellings to meet a particular airtightness target. These issues were as follows:

- a) The overall results from the project suggest that certain construction types appear to be intrinsically more airtight than others. Wet plastering and quasi-wet plastering (parging) of masonry cavity construction can default to a reasonable level of airtightness by UK standards since it creates a robust and easily distinguishable air barrier on external walls. However, a continuous air barrier at the loft boundary would appear more difficult to accomplish using current construction techniques. If successfully achieved, this would be expected to increase the level of airtightness further. Dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to reliably achieve an air permeability much below $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$. Air permeability values of below $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$ are possible with these types of construction, but are likely to require considerable additional attention to detail on site and changes to the design to ensure that continuity of the primary air barrier is maintained.
- b) The complexity of the design can have a significant effect on airtightness. Results illustrate that significant variations in air permeability can be observed in dwellings of the same form, constructed by the same site team, where the only observed difference was the number of complex details associated with these dwellings. These disparities were most common where certain design features required the primary air barrier to cope with complex changes in plane, negotiate structural members and accommodate changes in material. Such details included ground floor projections, rooms adjacent to semi-exposed areas, timber bays in masonry construction and complex junctions with ventilated cold roof loft-spaces. Conceptual and detail design approaches that recognise the importance of buildability, simplify the construction process and give priority to good communication at all levels are less likely to result in discontinuities in the primary air barrier and poor airtightness.
- c) The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on secondary sealing measures (such as many of those implied in the current edition of Part L Robust Details — DEFRA, 2001) are likely to be much less robust than those approaches that concentrate on ensuring that there is an effective and continuous primary air barrier. Approaches that are easy to build and are most amenable to simple and effective quality control procedures are also likely to be more robust.
- d) The approach adopted to increase airtightness has been shown to influence the potential level of air permeability achievable. The lowest levels of air permeability were achieved where attention was given to design modifications in which the primary air barrier was designed and made explicit, in conjunction with ensuring that the design was executed successfully on site.
- e) The results suggest that providing only general feedback and guidance on airtightness may have little effect on the air permeability of dwellings constructed. Feedback and guidance should therefore be continuous and targeted. However, providing this sort of feedback and guidance on a site by site, or even dwelling by dwelling basis can be onerous and labour intensive. Although during any learning phase the need for such intensive feedback will be inevitable, in the long term, ensuring that airtight design is built into the routine quality control culture of design and site teams (including an element of testing) will be critical.
- f) Anecdotal observations of non-test dwellings on the sites involved during Phase 3 of this project would suggest that on-site knowledge and experience gained through feedback does not always appear to be utilised more generally. Although the research team were not able to carry out any random tests on non-test dwellings, visual inspections suggest that it is unlikely that the other dwellings on site will achieve around the same levels of airtightness as the dwellings featured in this project. The results also suggest that achieving consistent levels of airtightness in dwellings of the same size, construction type and form may be difficult within existing design and construction cultures.

Implementation of pressure testing

- 5 The policy analysis carried out in the light of the findings from the action research highlighted a number of issues relating to the pressure testing regime incorporated within Part L1A 2006 of the Building Regulations. These issues were as follows:
 - a) The testing regime incorporated within ADL1A 2006 categorises dwellings by generic form. Such a categorisation is unlikely to capture a number of important house type issues that influence airtightness. The results obtained from this project, and supported by parallel research, suggest that the geometry and complexity of the construction may have a much greater influence on the eventual airtightness of a dwelling than generic form. In the light of this

finding it will be important to assess over the next few years the effectiveness of the testing regime incorporated within ADL1A (2006).

- b) No guidance is given within ADL1A 2006 as to when the BCB should notify the developer of the dwellings that require testing. In addition, ADL1A suggests that a significant proportion of the testing be front loaded to enable any lessons to be learnt during construction to be fed back into the construction and design process. Anecdotal evidence from Phase 3 suggests that this is unlikely to be the case. Although the response of developers to Part L1A 2006 is uncertain, the experience obtained from this project would suggest a risk that the airtightness of those dwellings that are selected for testing may not be representative of the performance of other dwellings of the same type on the same development. Further guidance indicating when dwellings should be selected and tested should be incorporated within ADL1A 2006.
- c) It is unclear from ADL1A 2006 who, apart from those registered by the British Institute of Non-destructive Testing (BINDT), can undertake pressure tests and issue certificates. This may lead to issues relating to equity and fairness if Building Control Bodies (BCBs) adopt different practices and developers are treated differently in different parts of the country. Also the question of the independence of testing arises if developers are allowed to test and issue certificates for their own dwellings. Guidance on this issue may be necessary.
- d) In most cases, the sampling frequencies outlined in ADL1A 2006 are likely to result in a statistically insignificant non-random sample of dwellings tested on each development. Therefore it will be very difficult for BCBs to be confident in the performance of those dwellings not tested. In addition, the results obtained from this project suggest that the proportion of dwellings requiring testing is likely to vary considerably between developments, with a greater proportion of apartments requiring to be tested than other dwelling types. This is despite the fact that apartments tend to be intrinsically more airtight than other dwelling forms of equivalent area. Sampling frequencies should be revised such that a randomly selected statistically significant sample of dwellings is tested on each development.
- e) Experience gained from this project suggests that developers currently appear to be unaware of how to prepare a dwelling for a pressure test. This situation is likely to change in the medium to long term as developers become more familiar with pressurisation testing and the associated costs.
- f) The design air permeability target for many dwelling designs is likely to be considerably lower than the maximum recommended level of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ specified within ADL1A 2006, particularly where fuels with a higher carbon intensity than gas are to be used. Assuming a 10% initial failure rate, modelling work on statistical distributions suggests that an average air permeability of around 7, 5 and $3 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ would need to be achieved by a developer to meet a design air permeability target of 10, 7 and $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. Reliably achieving an average air permeability of below $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ in mass UK housing will be technically demanding, and such levels of air permeability are likely to require a fundamental rethink of airtightness design in new dwellings and on-site quality control systems.
- g) The way in which the dwelling is tested can influence the eventual levels of air permeability achieved and bias the results. The approved procedure for pressure testing a dwelling is contained within the Airtightness Testing and Measurement Association (ATTMA) Technical Standard 1 (ATTMA, 2006). This standard states that valid test results can be achieved in a variety of different ways: by pressurising the dwelling; by depressurising the dwelling; or by pressurising and depressurising the dwelling and averaging the results. The results from this project indicate that the difference between pressurisation and depressurisation can be as high as 14%, and the results obtained by depressurising the dwelling only are, in most cases, lower than the corresponding test results for pressurisation. The ATTMA Technical Standard should be amended to remove any possibility of bias.

Logistics of pressure testing

- 6 In addition to the action research element, the project sought to investigate the logistics and other practicalities of the regulatory testing regime proposed in the 2006 revision of Part L. The results of this aspect of the project are set out as follows:
 - a) It is estimated that between 25,000 and 42,000 dwellings will require to be tested per year, based upon construction statistics for 2004 and 2005. Due to re-tests and the trend towards constructing more multi-dwelling buildings, it is likely that the figure will lie towards the higher end of this range or may even extend beyond it. This will place considerable strain on testing capacity and will have a disproportionate effect on small and medium size developers, many of

whom may have to test a high proportion of their production. Although the number of tests would be high, the impact in quality control terms will be statistically inefficient and unbalanced, since sample sizes will be extremely variable and are unlikely to be well constructed.

- b) Assuming a working day from 8am to 6pm, an analysis of the CIBSE/Met Office weather data for a semi-empirical Test Reference Year suggests that the average maximum number of hours available for testing in a year would be reduced by over 7% due to unfavourable wind conditions. The number of hours available for testing is likely to reduce further when tests are undertaken in more exposed locations, increasing the incidence of less reliable test data. Time spent travelling between sites, in order to undertake tests in different locations on the same day, will also affect the number of tests that can be performed.
- c) The average number of pressure tests that are likely to be required to be undertaken on a single day will vary considerably depending on completion rates at different times of year. For instance, it is conceivable that they could exceed 200 in June or December but fall below 80 in January. Assuming that a testing team is capable of undertaking an average of four pressure tests each working day, a minimum of 50 testing teams would be required in June and December reducing to a minimum of 20 testing teams in January.
- d) The commercial charge for undertaking a pressure test on a single dwelling on a single site is currently of the order of £500 excluding VAT plus travel and subsistence. The introduction of compulsory airtightness testing for dwellings may result in increased competition and economies of scale reducing this figure in the medium and long term. However, the dominating factor in estimating the cost per test is how many tests can be performed in a single visit, and in low-rise housing developments it is currently uncommon for more than two or three dwellings to be ready for testing on any given day. The costs associated with undertaking any additional tests once on site are marginal, and are of the order of £100 per dwelling excluding VAT. The current net cost of blower door equipment is around £3,200. This figure does not include delivery, calibration or training and assumes that the purchaser owns certain essential items, such as a computer, to run the necessary software.
- e) Limited data are available on the costs associated with undertaking remedial work in dwellings that have failed a pressure test. However, experience suggests that the costs could vary significantly and will be dependent upon the scale of the reductions in air permeability that will be required, the location of the main air leakage points and the amount and nature of the remedial work that is required to be undertaken. Experience obtained from undertaking remedial airtightness work on a small number of existing dwellings at Derwentside suggests a cost in the region of £1,200 per dwelling (see Johnston and Lowe, 2006). However, the lack of published data on this issue means that this figure is highly speculative. In addition, we believe that this cost is likely to exceed the costs of undertaking remedial airtightness work in newly constructed dwellings.
- f) Little is also known about the additional costs associated with achieving the airtightness standards set out in ADL1A 2006, although they are likely to be dependent upon the method of construction used, the approach taken to make the dwelling airtight and the target air permeability rate. The results obtained from Phase 3 of this project and from parallel studies suggest that an air permeability of less than $10 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa can be achieved at marginal cost. In addition, data obtained from the Stamford Brook project (see Lowe and Bell, 2002) suggest that very high levels of airtightness by UK Standards (mean air permeability of $4.9 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa), can be achieved for moderate costs.

Options for regulatory testing

- 7 In order to address a number of the limitations associated with the pressure testing regime contained within ADL1A 2006, three separate approaches have been identified for further assessment. These are as follows:
 - a) Direct quality control — This approach involves making a number of amendments to the current edition of ADL1A 2006. These amendments would concentrate on providing clearer and more detailed guidance on a range of factors such as dwelling type, dwelling selection, registered testers and dwelling preparation. In addition, it is also suggested that the current sampling frequency should be increased such that a representative sample of dwellings is tested on each development.
 - b) Indirect quality control — This quality control approach would be outside the regulatory loop along the lines of the Robust Details system used by many developers with respect to Part E. It involves putting in place a national airtightness quality control system as an alternative to

compulsory pressure testing or a direct regulatory checking process. Within the context of the scheme, a random sample of visual inspections and pressure tests of completed dwellings would then take place to ensure that the dwellings are built as designed and meet the airtightness requirements of the Approved Document. Care would need to be taken with such an approach to ensure that the sampling protocols ensure statistical validity.

- c) Compulsory testing — This would involve the compulsory pressure testing of all new dwellings. This approach would be the most expensive, and the UK does not currently possess the necessary testing capacity to implement it. Although currently impractical, this is the only approach that would ensure that the air permeability of all new dwellings is as specified in the calculation of the Target Emission Rate.

Further work

8 The following areas of further work have been suggested:

- a) In order to improve our understanding of the airtightness of the new build stock as a whole, the time has come for a representative sample of dwellings to be pressure tested. This should be carried out following the grace period (18 months) set out in the 2006 revision of Part L of the Building Regulations.
- b) In order to assess the impact of the 2006 revision on design and construction, the project should be repeated in revised form and set against the airtightness survey outlined above. The repeat project should focus on studying a range of different design and construction approaches which seek to achieve airtightness levels below $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$.
- c) An analysis of the success of alternative dissemination strategies designed to increase awareness of airtightness issues at all levels within the construction would prove beneficial for future training policy.
- d) A programme of dissemination should be undertaken, targeted towards construction personnel at all levels, including designers, site management, site operatives that increases the awareness of airtightness issues and encapsulates training, site supervision, workmanship and quality control.

Introduction

- 9 This report constitutes milestone D11 — Final Report — Domestic Sector Airtightness of the Communities and Local Government/ODPM Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). This project addresses those issues relating to the domestic sector. Work is being undertaken in parallel on the airtightness of buildings in the non-domestic sector.
- 10 Airtightness is crucial to improving the energy performance of buildings. This was recognised in Approved Document Part L1 of the 2002 Building Regulations, which, for the first time, included a maximum air leakage target for domestic buildings. This document has since been superseded by the publication of two revised versions of Approved Document Part L1: L1A Work in New Dwellings and L1B Work in Existing Buildings. Approved Document L1A (ADL1A) requires that the building fabric should be constructed to a reasonable quality of construction so that the air permeability is within reasonable limits (ODPM, 2006). Guidance on a reasonable limit for the design air permeability¹ is given as $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$.
- 11 The key objectives of this project were as follows:
- a) To investigate ways of achieving higher levels of airtightness performance than the requirements of Approved Document Part L1 2002.
 - b) To produce recommendations for higher airtightness standards with justification for levels and timing.
 - c) To assess the potential costs and benefits of pressure testing new dwellings and propose how this might best be introduced.
- 12 The project was undertaken in two parts:
- a) **Literature review** — A conventional literature review was undertaken, 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.
 - b) **Participatory action research** — This part of the project was undertaken in three distinct phases and involved five developers from the commercial and social housing sectors. Phase 1 involved a detailed assessment of the design and construction of 25 dwellings, together with pressure tests conducted upon completion. In Phase 2, the results from Phase 1 were fed back to each of the developers in a participatory seminar, and ways of improving airtightness were discussed with the developer and their design and construction teams. Phase 3 mirrored Phase 1 in which the design and construction of a further set of dwellings (28 in total) were monitored following the feedback and enhanced understanding gained during Phase 2.

Structure of the Report

- 13 This report takes the form of a summary report that presents the key results and project findings. Detailed results for each stage of the project are based on previously presented interim reports, and these are included in this report as a set of technical appendices. The main report presents, for the first time, the overall conclusions obtained from the project, and identifies areas of future work.
- 14 It is anticipated that this report will form one of the inputs into the Forward Thinking Paper on energy conservation which is due to be updated in 2006. It is also intended that the findings of this work will be used to inform future revisions to Part L of the Building Regulations.

Literature Review

- 15 Prior to the commencement of the action research component of the project, a literature review was undertaken. The aim of the literature review was to identify the airtightness requirements for UK dwellings, compare the airtightness of UK dwellings to those constructed overseas, establish the factors that influence airtightness, and identify the design guidance available. Airtightness measurements were also conducted on seven UK dwellings that had been identified as being potentially very airtight, but had not been tested. The measurements were complemented with

¹ Design air permeability is defined in ADL1A 2006 as the value of air permeability that is selected by the designer for use in the calculation of the DER.

open-ended questionnaires completed by the current occupiers of the dwellings 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. The literature review (see Appendix 1) identified the following key points:

- a) 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. UK dwellings also tend to be very leaky in comparison with their international counterparts in Europe and North America, with dwellings classed as very airtight in the UK, being classed as normal practice in these countries.
- b) In the UK, one of the most important determinants of airtightness is construction type. 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 more airtight than their UK equivalents as they are nearly always wet plastered and have concrete floors. 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.
- c) The majority of the air leakage in UK dwellings is attributable to a range of cracks, gaps and joints throughout the building envelope, rather than any single component.
- d) A considerable amount of guidance is available on airtightness. The majority of this originates from overseas, especially Canada and Sweden, where air leakage standards have been in place for many years. General guidance on designing for airtightness advises that: the air barrier is continuous around the building envelope; it is in the same plane throughout the structure; it is easy to install, durable and accessible for maintenance; penetrations through the air barrier should be avoided or at least minimised; and complex detailing should be avoided. Several documents highlight specific issues associated with UK construction.
- e) The main source of detailed design guidance on airtightness in the UK is the Robust Details – Part L document (DEFRA, 2001). The guidance given within this 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 allows 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.
- f) The results of the field tests indicate that the dwellings tested were all airtight by UK standards, with the air permeability ranging from 1.0 to 7.1 m³/(h.m²) @ 50Pa. The three earth-sheltered dwellings tested at Hockerton were also found to be amongst the most airtight dwellings ever recorded in the UK, although they still fall short of best practice overseas. The results demonstrate that it is possible to build very airtight housing in the UK, given a reasonable level of attention to design and construction. In addition to these tests, 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.

Participatory Action Research — Phase 1

- 16 The objective of this phase of the project was to establish those factors relating to design and construction that are likely to influence airtightness.

Selection of developers, sites and house types

- 17 Following the literature review, 25 dwellings, selected from five developers (one site and five dwellings per developer) were identified for inclusion in the project. The criteria used to select the developers, the sites and the dwellings are contained within Appendix 2. Table 1 details the size, built form and construction type of the dwellings selected to participate in this phase of the project.

Developer	Type of construction	Dwelling	Built form	Internal floor area (m ²)
A	Dry-lined masonry cavity, partial fill.	A09	Mid-terrace	83
		A11	Mid-terrace	117
		A12	End-terrace	117

Developer	Type of construction	Dwelling	Built form	Internal floor area (m ²)
		A13	Detached	118
		A14	Semi-detached	80
B	Dry-lined masonry cavity, full fill ² .	B79	Detached	129
		B80	Detached	164
		B81	Detached	149
		B82	Detached	149
C	Dry-lined masonry cavity, full fill.	C236	Mid-terrace	72
		C237	Mid-terrace	71
		C238	End-terrace	61
		C239	Semi-detached	69
		C240	Semi-detached	68
D	Light steel frame.	D39	Semi-detached	72
		D42	Detached	91
		D43	Detached	84
		D44	Detached	91
		D59	Detached	102
E	Mechanically/ manually wet plastered ³ masonry cavity, partial fill.	ECG01	Ground-floor apartment	57
		ECG02	Ground-floor apartment	43
		EC201	Mid-floor apartment	58
		EC202	Mid-floor apartment	44
		EC301	Top-floor apartment	59
		EC302	Top-floor apartment	44

Table 1 Size, built form and construction type of the dwellings selected for Phase 1.

- 18 Following the selection of the dwellings, the design and construction of each dwelling was monitored in detail. This was achieved by undertaking detailed assessments of the design drawings relating to each dwelling type and extensive site surveys of each dwelling as they were being constructed on site.

Design assessments and site surveys

- 19 The design drawings were analysed in order to identify the methods that were being used to construct the dwellings, and the method used to demonstrate compliance with Part L1 2002. In addition, the analysis also sought to look qualitatively at those aspects of the dwellings design that could have an impact on air leakage. In the main, the design assessments focused on the position of the air barrier, the continuity of the air barrier and whether service penetrations were to be sealed or not.
- 20 In order to assess the design and construction phase of each dwelling, a design assessment and site survey protocol was devised. These protocols were based upon the checklisting approaches developed by Webb and Barton (2001) and Webb, Barton and Scivyer (2001) for the assessment of the airtightness of buildings. Details of these protocols are presented in Appendix 2.
- 21 The completed design assessment for each dwelling was then used as a starting point for the site surveys. The site surveys were designed to capture the dwellings at a number of important stages throughout the build programme where inspections could be made of various elements that were

² It was not possible to test one dwelling from developer B prior to occupation due to the very quick completion date requested by the buyer. In order to maintain the number of selected dwellings, an addition dwelling was selected from developer E (dwelling EC201).

³ All of the plots were originally intended to be mechanically plastered. However, due to delays in the construction and the drying out times associated with the mechanical plastering system, Plots C301 and C302 were manually wet-plastered.

likely to influence the eventual airtightness performance of the dwellings. In total, three separate stages were identified. These stages were as follows:

- a) **Stage 1: During intermediate floor construction** — This enabled inspection of the method of supporting the intermediate floors and enabled any potential leakage problems to be identified.
 - b) **Stage 2: During dry-lining/wet plaster phase** — This enabled inspection of the internal leaf of the external walls, the application of the dry-lining, inspection of window/wall junctions and inspection of service penetrations.
 - c) **Stage 3: Completion** — This enabled identification of any potential leakage areas that had not been picked up during the ‘snagging’ process.
- 22 The site surveys were also designed to be purely observational in nature. Consequently, while undertaking this phase of the project, no attempt was made to influence dwelling construction through direct or indirect feedback following site visits.
- 23 The key issues emerging from the design assessments and the site surveys were as follows (see Appendix 3):
- a) There was a considerable difference in the way in which information on air leakage was presented to those on site, and the level of detail that it contained. The information varied from general arrangement drawings containing general textual material, to sets of detailed 1:10 scaled drawings that indicated explicitly where sealing work had to be undertaken. In some cases, the sealing work would be very difficult to achieve. For instance, applying sealing around the perimeter of plasterboard linings to external walls and openings with continuous ribbons of plaster.
 - b) None of the drawings submitted identified the location of the air barrier or indicated that it should be continuous around the envelope.
 - c) All of the developers were using Part L Robust Details (DEFRA, 2001) as the basis of the application for regulatory approval.
 - d) There was considerable variation in the work that had been undertaken on site to achieve a particular specification. Site observations illustrated that often a mixture of approaches had been undertaken to achieve the same specification. For instance, around built-in joists there was considerable variation in the way in which the mastic sealant had been applied around the bottom flange and the web of the timber I-beams, and in a number of cases, the mastic sealant appeared to have only been applied to areas where the mortar had been missed out. This suggests that the operatives undertaking the work do not always fully understand the importance of the particular detail.
 - e) The site observations also identified areas where there appeared to have been a lack of foresight in the detailed design stage. This resulted in specifications that were practically very difficult to achieve and forms of construction that sought to ‘work round’ any practical problems. Such ‘work-rounds’ were made up on site based on the experience and trade knowledge of operatives and site managers.

Airtightness results

- 24 Upon completion, each of the selected dwellings was pressure tested in accordance with CIBSE Technical Memorandum TM23 (CIBSE, 2000) and the main air leakage paths were investigated using smoke tests.⁴ The pressure test results of the dwellings participating in Phase 1 of the project are detailed within Table 2 and Figure 1.

Dwelling	Pressurisation test		Depressurisation test		Mean permeability (m ³ /(h.m ²)@50Pa)
	Permeability (m ³ /(h.m ²)@50Pa)	r ² coefficient of determination	Permeability (m ³ /(h.m ²)@50Pa)	r ² coefficient of determination	
A9	13.95	0.999	13.86	0.999	13.91
A11	15.46	0.996	14.66	0.997	15.06

⁴ Smoke tests were performed from inside the dwelling using handheld smoke puffers, with the dwellings pressurised to 75–80 Pa. The direction and rate at which smoke flowed into the building structure provided indications of internal points of air leakage and their comparative significance; however, this method alone cannot identify or quantify many of the more complex air leakage paths.

Dwelling	Pressurisation test		Depressurisation test		Mean permeability (m ³ /(h.m ²))@50Pa)
	Permeability (m ³ /(h.m ²))@50Pa)	r ² coefficient of determination	Permeability (m ³ /(h.m ²))@50Pa)	r ² coefficient of determination	
A12	12.12	0.990	12.49	0.999	12.31
A13	14.51	0.999	14.16	0.999	14.33
A14	15.33	0.993	15.71	0.994	15.52
B79	8.96	1.000	9.02	0.983	8.99
B80	11.76	0.992	11.20	0.990	11.48
B81	10.11	0.999	9.66	0.993	9.89
B82	12.04	0.996	11.53	0.999	11.79
C236	16.81	1.000	16.26	1.000	16.53
C237	14.08	1.000	13.98	1.000	14.03
C238	11.17	0.998	11.02	1.000	11.09
C239	12.46	0.997	11.90	0.986	12.18
C240	12.11	0.971	11.40	0.981	11.76
D39	12.82	0.992	12.61	0.984	12.72
D42	15.55	1.000	16.37	0.999	15.96
D43	12.10	0.997	11.44	0.999	11.77
D44	14.58	1.000	14.94	1.000	14.76
D59	12.50	0.990	11.76	0.984	12.13
ECG01	5.13	0.999	4.90	0.996	5.01
ECG02	4.37	0.998	4.32	0.997	4.35
EC201	4.79	1.000	4.43	0.997	4.61
EC202	3.94	0.999	3.96	1.000	3.95
EC301	7.46	0.995	7.38	0.997	7.42
EC302	5.53	0.999	4.98	0.995	5.25

Table 2 Mean air permeability of the dwellings tested during Phase 1.

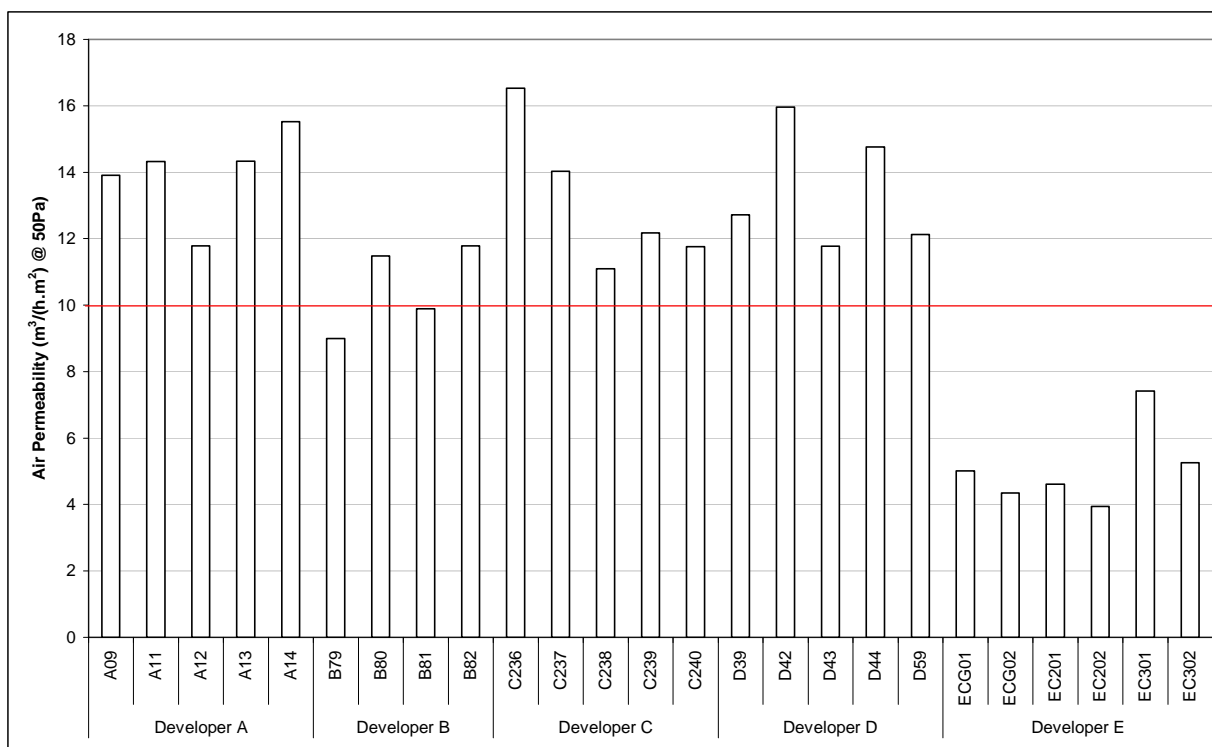


Figure 1 Mean air permeability of the dwellings tested during Phase 1.

- 25 The results show that a relatively wide range of air permeability was measured for the tested dwellings. The air permeability of the dwellings ranged from 4.0 to 16.5 m³/(h.m²) @ 50Pa, with a mean of 11.1 m³/(h.m²) @ 50Pa and standard deviation of 3.9 m³/(h.m²) @ 50Pa. Although the range of air permeability measured within these dwellings was consistent with the recent measurements undertaken by Grigg (2004), the mean for these dwellings was higher (11.1 as opposed to 9.2 m³/(h.m²) @ 50Pa obtained by Grigg). This is probably a result of the larger proportion of apartments⁵ (36%) included in the Grigg sample compared with the dwelling types tested in phase 1 (24%). The data also indicated that only 10 of the 25 dwellings (40%) had an air permeability that was lower than or equal to the UK mean of 11.5 m³/(h.m²) @ 50Pa. The mean of all 25 results (11.1 m³/(h.m²) @ 50Pa) suggests that these dwellings are broadly in line with existing data on the UK stock as a whole and that, at least in these cases, the impact of the 2002 edition of ADL1 has been minimal. Given the qualitative nature of the project it is not possible to extrapolate to the post 2002 new build stock with any confidence, but the Grigg (2004) data would suggest that the results obtained are not atypical.
- 26 The results also suggest that despite all of the developers using Part L Robust Construction Details (DEFRA, 2001) as the basis of the application for regulatory approval, only eight of the tested dwellings (six flats and two houses; 32%) had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa set out in the 2002 edition of the Approved Document Part L1 (DTLR, 2001). The proportion of dwellings achieving a value for air permeability below the specified level varied considerably between houses and apartments. All of the apartments tested had levels of airtightness in excess of the required 10 m³/(h.m²) @ 50Pa. If the six apartments tested are excluded (flats tend to be a more airtight dwelling form), only two out of 19 houses achieved a level below the value given in ADL1 2002. In addition, only one of the developers (developer E — flats) managed to satisfy the air leakage criterion with all of their tested dwellings. The other four developers were unable to achieve the airtightness target in the majority of cases. This suggests that simply adopting Robust Construction Details, at least in their current

⁵ Apartments tend to be more airtight than other dwelling forms of equivalent area as they are more likely to have solid intermediate floors, fewer door and window openings, and fewer service penetrations.

form,⁶ provides no guarantee that the current regulatory standard will be achieved with any degree of consistency.

27 The small sample size precludes absolute certainty when comparing data either by developer or by construction type. However, accepting the qualification relating to sample size, the data suggest a difference in the air permeability between the different types of construction method adopted by the developers (see Figure 2 and Table 3). The tightest dwellings were those of mechanically/manually wet plastered masonry cavity construction (developer E). These dwellings are, on average, a factor 3 more airtight than those that were built using dry-lined masonry cavity construction. The reasons for this are likely to be two-fold. First of all, as previously mentioned, apartments tend to be more airtight than comparable dwellings of different built form. Secondly, wet plastered masonry dwellings tend to be intrinsically more airtight than comparable dry-lined masonry or steel frame construction (Olivier, 1999). The least airtight dwellings were those constructed using light steel frame (developer D). These dwellings were only marginally leakier than the dry-lined masonry cavity dwellings (mean air permeability of 13.5 as opposed to 12.8 m³/(h.m²) @ 50Pa) constructed by developers A, B and C. It is not certain whether the poor performance of the light steel framed dwellings is attributable to an intrinsic problem with the airtightness of steel framed construction, the quality of workmanship, or a combination of the two. However, large gaps were observed between a number of the components in dwellings D42 and D44, such as flooring panels and floor-wall junctions all of which, in the absence of a clearly defined and well constructed air barrier, would enable free passage of air to the outside.

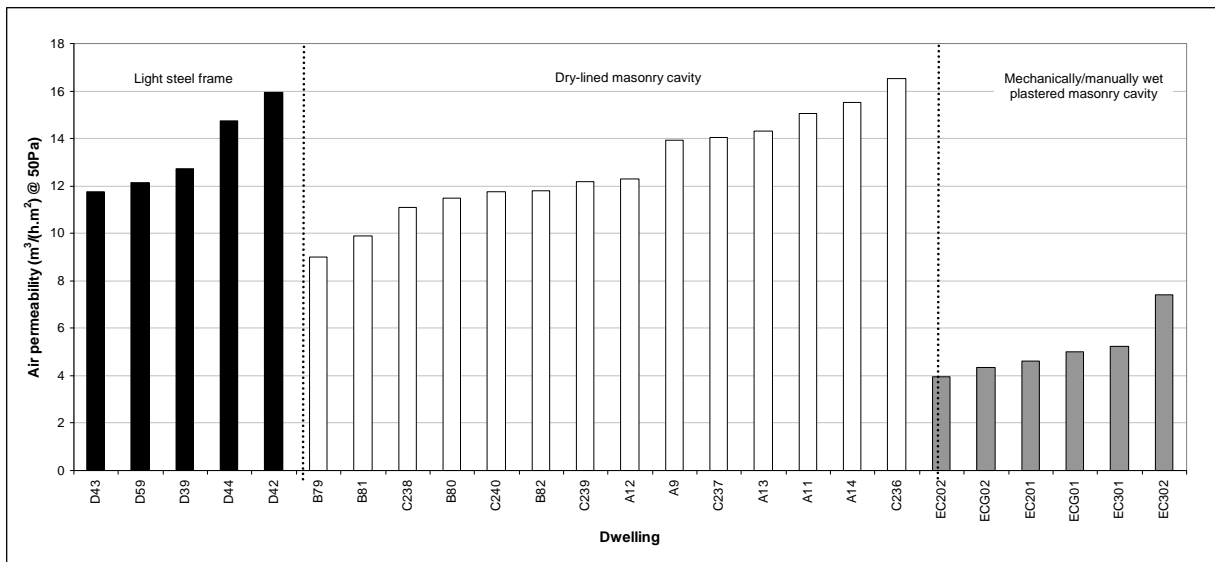


Figure 2 Mean air permeability of the tested dwellings by construction type.

Construction type	Mean permeability of all dwellings tested to date (m ³ /(h.m ²) @ 50Pa)
Wet plastered masonry cavity (Developer E)	5.1
Dry-lined masonry cavity (Developers A, B & C)	12.8
Light steel-frame (Developer D)	13.5

Table 3 Mean air permeability by construction type.

⁶ It is worth observing that the apparent failure of the adoption of Robust Details in these cases could be due to a wide range of causes relating not only to the intrinsic nature of the details themselves and the general level of guidance provided but also to the general quality control system into which they are embedded. In fact, evidence from elsewhere (Bell, Smith and Miles-Shenton 2005) would suggest that levels of awareness of the details themselves among designers and constructors is low and that their adoption is rarely seen in the context of a design and construction quality control system. This contrasts with the separate system of Robust Detail accreditation used by many developers in support of achieving the performance requirements of Part E (acoustics).

- 28 The data also show that there appears to be a difference in performance between the three developers that are building using dry-lined masonry cavity construction (developers A, B and C, see Table 4). The tightest dwellings were those constructed by developer B (mean air permeability of 10.5 m³/(h.m²) @ 50Pa), whilst the leakiest dwellings were those constructed by developer A (mean air permeability of 14.2 m³/(h.m²) @ 50Pa). Despite these results, no significant differences in the quality of the workmanship were observed between the dwellings constructed by developers A, B and C. Given the small sub-samples involved, the differences are more likely to be attributable to natural variations in construction rather than any intrinsic differences in approach by each developer.

Developer	Mean permeability of all dwellings tested to date (m ³ /(h.m ²) @ 50Pa)
A	14.2
B	10.5
C	13.1
D	13.5
E	5.1

Table 4 Mean air permeability by developer.

- 29 A number of common air leakage path entry points were also identified within the tested dwellings. These related to elements and junctions, fixtures and fittings, and service penetrations. The majority of these were indirect air leakage paths, which could be traced back to the construction issues that had been observed during construction. These indirect air leakage paths not only enable the air to freely communicate with other gaps and voids within the building, but they also add to the complexity of the air flows that exist within and through the building envelope. The result is that air leakage can be very difficult to trace and seal effectively once a dwelling has been completed.
- 30 A more detailed analysis of the pressurisation test results is contained within Appendices 5, 6 and 7.

Participatory Action Research — Phase 2

- 31 Phase 2 of the action research involved undertaking a participatory feedback and guidance seminar (see Appendix 6) with each of the developers. The seminars were held at the developer's offices or site offices and where possible included both management and site staff. The pressurisation results and, more importantly, the design and construction observations obtained during Phase 1 were fed back and discussed with the developers and their design and construction teams.
- 32 The developer's responses and the resulting discussions at the seminars were very positive, with all of the developers indicating that what had been observed on site during Phase 1 was typical of their construction standards nationally. They also supported the view that there is a general lack of awareness and understanding of airtightness issues at all levels, from site operatives and site supervisors through to site and senior management. For example, the concept of an air barrier was unfamiliar to all but one of the developers. Consequently, there was a perception from the developers that the way to improve airtightness is to adopt a 'gap-filling' approach involving the sealing of secondary junctions between finishes (for example the skirting board plasterboard or floor board junction), rather than concentrating on the design and construction of the primary air barrier. This suggests that there is a need for clear design guidance on airtightness which focuses on the design of the air barrier, its location, ways of maintaining continuity, and ensuring that it remains effective. This guidance would need to be followed up with further education within the industry at all levels of design and construction.
- 33 Following the feedback and the discussion, the developers identified a range of measures that could be put into practice to try and improve the airtightness performance of a further set of dwellings that would be assessed during Phase 3 of the project. They were also encouraged to set an informal airtightness standard (commensurate with existing ventilation strategies) for these dwellings. Further details relating to the seminars, the feedback and the discussions are provided in Appendices 7 and 8.

Participatory Action Research — Phase 3

34 This phase mirrored Phase 1 of the project. During this phase, a further set of dwellings from the same developers and sites, and of the same or similar house type were selected, monitored and assessed following the feedback and the enhanced understanding gained from Phase 2. In addition, a two-way dialogue was also established between the research team and each developer. This enabled observations made by the research team to be fed back to the developer concerned following each site visit.

Selection of house types

35 Twenty-eight dwellings were selected for inclusion in this phase of the project. Each of these dwellings was selected using the Phase 1 selection criteria. Table 5 details the size, built form and construction type of the dwellings selected to participate in this phase of the project.

Developer	Type of construction	Dwelling	Built form	Internal floor area (m ²)
A	Dry-lined masonry cavity, partial fill.	A64	Mid-terrace	75
		A65	Mid-terrace	75
		A66	End-terrace	77
		A79	Mid-terrace	117
		A80	End-terrace	117
B	Dry-lined masonry cavity, full fill.	B14	Detached	164
		B16	Semi-detached	132
		B17	Semi-detached	132
		B21	Semi-detached	132
		B22	Semi-detached	132
C	Dry-lined masonry cavity, full fill.	C17	End-terrace	61
		C18	Mid-terrace	72
		C19	Mid-terrace	71
		C20	End-terrace	61
		C21	End-terrace	61
		C193	Detached	106
		C194	Detached	106
D	Light steel frame.	D73	Detached	102
		D74	Detached	93
		D75	Detached	108
		D76	Detached	124
		D96	Detached	86
E	Wet plastered masonry cavity, partial fill.	EAG01	Ground-floor apartment	57
		EAG02	Ground-floor apartment	43
		EA201	Mid-floor apartment	58
		EA202	Mid-floor apartment	44
		EA301	Top-floor apartment	59
		EA302	Top-floor apartment	44

Table 5 Size, built form and construction type of the dwellings selected for Phase 3.

Design assessments and site surveys

36 As in Phase 1, assessments of the design drawings and site surveys were conducted on the dwellings that were selected to participate in this phase of the project. Whereas the site surveys conducted in Phase 1 were purely observational, in Phase 3 observations were reported back to the developers immediately, allowing on site alterations and remedial action (where necessary) to take place before construction progressed much further.

37 The design assessments and the site surveys were undertaken using the same protocols devised during Phase 1. The key points emerging from these were as follows:

- a) All of the developers made design changes to the dwellings participating in Phase 3 of the project, following feedback from the research team.
- b) Due to the costs involved, only minor changes were made to the Phase 3 dwellings. This, coupled with the small numbers of dwellings involved, has resulted in the developers choosing not to amend the design drawings associated with these dwellings. The consequence of this is that the drawings submitted for assessment suffer from the same limitations as those that were submitted for Phase 1 of the project (see Appendix 3).
- c) Any changes made to the dwellings' design were communicated to the site via informal means. For instance, verbally or in note/memorandum format. Although this approach may be appropriate for this project, it is unlikely to be successful if such measures are to be adopted on a national scale to improve performance overall.
- d) Observations from site indicated that all of the developers have acted upon the feedback from Phase 1 of the project and have actively participated in a two-way dialogue with the research team. The observations also indicated that the feedback from the research team, coupled with the approach undertaken by each developer, has resulted in the majority of the airtightness issues identified during Phase 1 of the project being addressed. However, other measures that tended to require design changes or were perceived to incur significant costs, remained unaddressed and are likely to contribute to air leakage within the selected dwellings.

Measures adopted to improve airtightness

- 38 Despite the cost limitations, a number of different measures were adopted by the developers for Phase 3 of the project. These measures were categorised into three separate approaches. These approaches were as follows:
- a) **General feedback** — In this approach no specific action was taken to improve the airtightness of the dwellings besides a general awareness raising approach based on the Phase 2 feedback.
 - b) **Detailed site quality control and feedback** — This approach involved improved workmanship, site supervision and tightening up on existing detailing following feedback from Phase 2 and the adoption of additional measures taken as a reaction to continuous on-site feedback, provided by the research team. Measures adopted by the developers included: ensuring that all apertures in external walls were core-drilled using appropriately sized holes; using appropriately sized holes for service penetrations through intermediate floors; sealing all service penetrations in external walls at pre-plaster stage; and sealing service penetrations through intermediate floors.
 - c) **Design-led changes** — In this approach design changes to the air barrier (or specific regions of the air barrier) were introduced. The identification of the primary air barrier was a key factor in this approach, and changes were adopted to ensure its continuity, particularly at junctions and changes of plane. Measures adopted included: applying a parging layer to the internal face of the blockwork on all external and party walls; pointing all internal blockwork at pre-plaster stage; and the use of tape, mastic and expanding foam to seal junctions, penetrations and the loft boundary at pre-plaster stage.
- 39 Developer E concentrated efforts on only one of the approaches to airtightness for this phase of the project: the detailed site quality control and feedback approach. The other four developers (A, B, C and D) adopted a staged approach to Phase 3, where a variety of methods were adopted across the selected dwellings. This enabled the effects of a range of different airtightness measures and approaches to be compared in a qualitative way.
- 40 Details of the individual measures adopted on each of the selected dwellings by each developer can be found within Appendices 8 and 9.

Airtightness results

- 41 The pressure tests results of the dwellings participating in Phase 3 of the project are detailed within Table 6 and Figure 3.

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability (m ³ /(h.m ²))@50Pa)
	Permeability (m ³ /(h.m ²))@50Pa)	r ² coefficient of determination	Permeability (m ³ /(h.m ²))@50Pa)	r ² coefficient of determination	
A64	10.68	0.996	10.19	0.999	10.44
A65	8.44	0.998	7.67	0.997	8.06

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability (m ³ /(h.m ²))@50Pa)
	Permeability (m ³ /(h.m ²))@50Pa)	r ² coefficient of determination	Permeability (m ³ /(h.m ²))@50Pa)	r ² coefficient of determination	
A66	8.01	0.999	7.96	0.999	7.98
A79	6.45	0.996	6.59	0.999	6.52
A80	5.54	1.000	5.65	1.000	5.59
B14	9.33	0.996	8.15	0.980	8.74
B16	5.50	0.987	5.69	0.993	5.59
B17	5.61	0.990	5.76	0.991	5.69
B21	7.31	0.996	7.27	0.997	7.29
B22	7.44	0.995	7.31	0.991	7.37
C17	6.17	1.000	5.95	1.000	6.06
C18	9.13	0.987	9.69	0.992	9.41
C19	7.45	0.996	7.66	0.996	7.56
C20	10.77	0.991	10.12	0.993	10.45
C21	10.40	0.990	9.60	0.994	10.00
C193	9.82	0.987	9.45	0.996	9.64
C194	15.90	0.996	14.02	0.992	14.96
D73	13.39	0.991	13.22	0.991	13.31
D74	12.62	0.970	12.80	0.949	12.71
D75	10.97	0.979	10.22	0.990	10.60
D76	9.23	0.982	8.56	1.000	8.89
D96	11.52	0.995	10.77	0.999	11.14
EAG01	6.56	0.999	6.57	0.997	6.56
EAG02	4.98	0.989	4.74	0.997	4.86
EA201	7.11	0.991	6.89	0.995	7.00
EA202	5.47	0.978	5.36	0.992	5.41
EA301	6.24	0.990	6.05	0.998	6.15
EA302	4.92	0.995	4.96	0.975	4.95

Table 6 Mean air permeability of the dwellings tested during Phase 3.

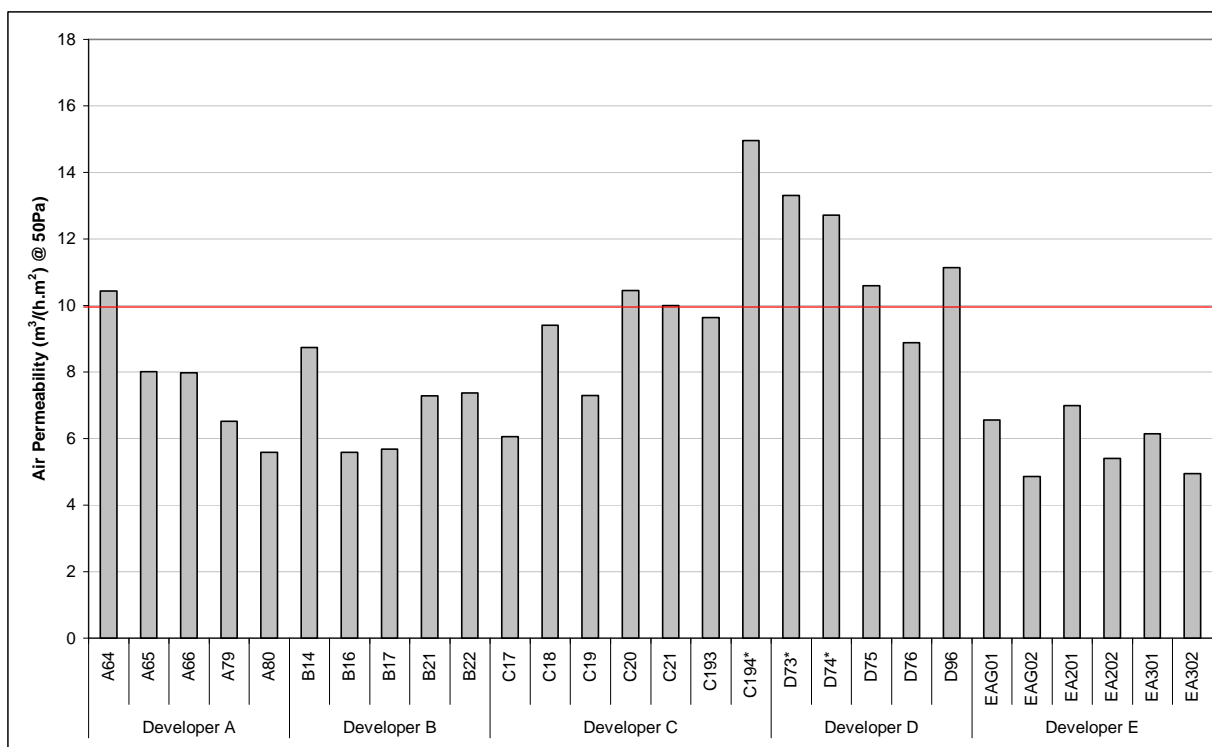


Figure 3 Mean air permeability of the dwellings tested during Phase 3. (* Plots C194, D73 and D74 were built as standard Phase 1 dwellings)

- 42 The results show that a relatively wide range of air permeability was measured for the tested dwellings, ranging from 4.9 to 15.0 m³/(h.m²) @ 50Pa, with a mean of 8.3 m³/(h.m²) @ 50Pa and a standard deviation of 2.7 m³/(h.m²) @ 50Pa. Only three of the 28 dwellings tested (Plots C194, D73 and D74) achieved an air permeability that was higher than or equal to the UK mean of 11.5 m³/(h.m²) @ 50Pa, all of which were dwellings that had been built as the Phase 1 dwellings, but were included in the project in order to compare the performance of alternative house designs.⁷ This suggests that, on average, the dwellings tested are more airtight than the average for the stock as a whole.
- 43 The results also show that in the majority of the dwellings where measures were identified and applied, reductions in air permeability from the Phase 1 mean were achieved (see Figure 3). The only instance where this was not the case was in four⁸ of the Phase 3 apartments constructed by developer E (Plots EAG01, EAG02, EA201 and EA202). The air permeability of these apartments was, on average, 1.5 m³/(h.m²) @ 50Pa (33%) higher than the corresponding apartments constructed during Phase 1 of the project. The reasons for the increase in air permeability was felt to be attributable to two factors. First of all, in Phase 1 the apartments were pressure tested by placing the blower door in the front door frame of each apartment. However, it was not possible to do this in Phase 3, as the closer mechanism for the front door prevented the blower door from being installed correctly. Therefore, the blower door was positioned in the patio door of the apartments. Air leakage was subsequently detected around the front door and its fixings that had not been possible to detect in Phase 1. Secondly, significant amounts of air leakage were detected around all of the window frames and sills in Phase 3 that had not been detected in Phase 1. This air leakage was occurring as no caulking or mastic had been applied around the window frames and cills prior to the test, and liner boards on dabs had been used at window reveals instead of wet plaster.

⁷ In the case of developer C, Plot C194 was included to explore the issues associated with constructing a different house type (in this case a detached dwelling as opposed to a semi-detached or terraced dwelling). Plots D73 and D74 were included by developer D so that they could examine the effect of new house designs and detailing that had been introduced in response to the introduction of the 2002 Building Regulations (the Phase 1 dwellings adopted an older design that had been adapted for 2002 compliance).

⁸ The other two Phase 3 apartments constructed by developer E (Plots EA301 and EA302) showed a reduction in air permeability from the corresponding Phase 1 apartments of around 12%.

44 The scale of the reductions in air permeability that were achieved also varied considerably, as did the absolute levels of air permeability (see Figure 4). Despite this, the results suggest that mass-produced housing in the UK can be constructed to be relatively airtight by UK standards, with an air permeability as low as 5 or 6 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa being obtainable with relatively small changes to the design and the approach to construction, and without incurring significant cost. However, ensuring consistency and robustness is likely to present the greatest challenge. To reliably reduce the air permeability to much lower levels (5 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa and below) will require more significant changes to the design and the approach to construction.

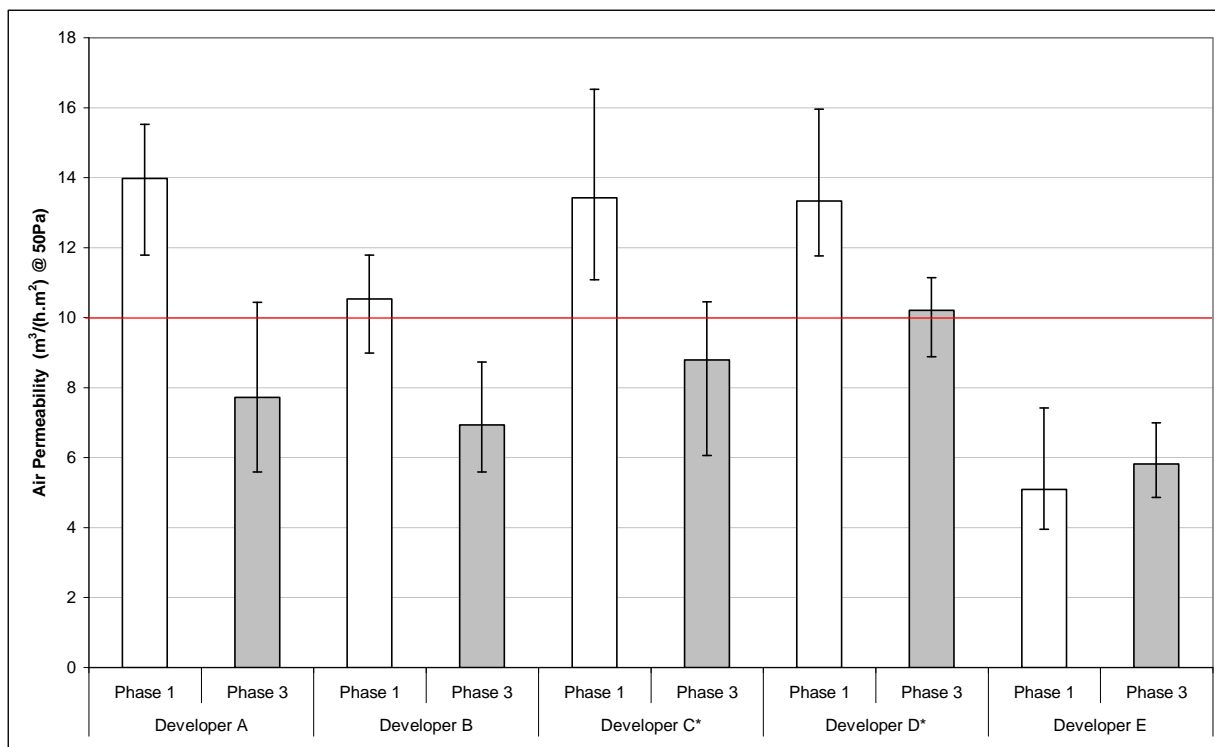


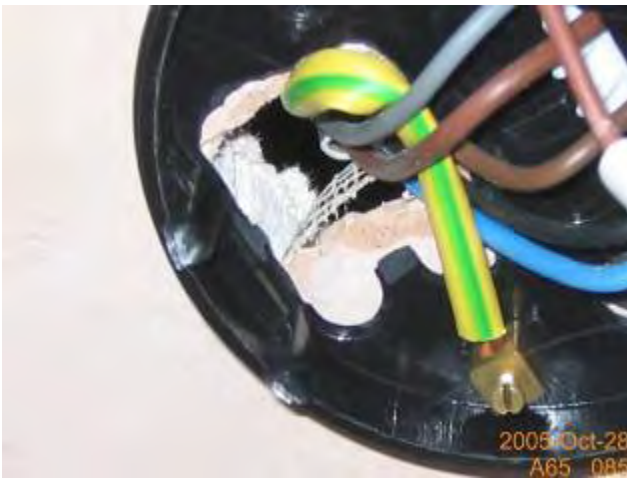



Figure 4 Comparison of Phase 1 and Phase 3 pressure test results, showing average air permeability and range of test results for each phase. (* Plots C194, D73 and D74 were built as standard Phase 1 dwellings, so have been included in the Phase 1 results)

- 45 Given the level of feedback provided in Phase 3 it is, perhaps, surprising that only 21 of the 28 dwellings tested to date have achieved air leakage values below the 10 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa level.⁹ As in Phase 1 of the project, all of the dwellings were using Part L Robust Details (DEFRA, 2001) as the basis of the application for regulatory approval. In addition to this, each developer also received detailed and targeted feedback from the research team on any potential areas or issues that may have had an influence on the eventual airtightness performance of the selected dwellings.
- 46 A number of common air leakage path entry points were also identified within the Phase 3 dwellings tested. These paths were also identified during Phase 1 of the project. The improved air permeability results obtained in Phase 3 suggest that there has been a general tightening in all areas rather than the elimination of specific infiltration paths. As none of the developers made any significant changes in material and product specification between Phase 1 and Phase 3, it can safely be assumed that improvements to the actual construction of the building envelope, rather than material/supply changes, are responsible for the increased airtightness in Phase 3.
- 47 A more detailed analysis of the pressurisation test results is contained within Appendix 8.
- 48 Parallel studies conducted on another site constructed by developer A revealed that similar airtightness results to those achieved utilising the design-led changes in Phase 3 can be achieved without the intensive inspection and feedback regime adopted in this project and without specific

⁹ With the three worst performing of the Phase 3 dwellings being constructed without any feedback being taken on board, the case could be argued for this being 21 out of 25 dwellings obtaining a test result of 10 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa or below.

additional design measures being undertaken. Three masonry cavity dwellings were tested on this site which all contained a measure of complex detailing (room-in-roof or integral garage) with air permeability measurements of between 4.7 and 7.0 m³/(h.m²) @50Pa being recorded. This was achieved by fastidious attention to detail demanded by the site supervisory staff in all activity on this site, the site manager in particular wanting to ensure that all workmanship on his site was performed at the highest possible quality throughout, and staff turnover kept to a minimum. The quality control observed on this site is amongst the highest encountered by the research team and is probably representative of the top 10% of quality control in UK housing developments. Figure 5 compares a number of examples of details observed on this additional site with those observed on developer A's site included in this project

Observations from developer A, Phase 3.	Observations from developer A, parallel studies.
	
<p>Significant air leakage detected through and around electrical consumer units in all of the dwellings tested on this site.</p>	<p>All gaps around wiring behind the consumer units sealed, and no air leakage detected at this point in any of the dwellings tested.</p>
	
<p>Air leakage detected into the ventilated roof space and intermediate floor voids through unsealed gaps.</p>	<p>All gaps around service penetrations, however small, sealed as a matter of course.</p>




Observations from developer A, Phase 3.	Observations from developer A, parallel studies.
	
<p>Mastic sealant applied around joist with little preparation and some edges missed, particularly on the top edge of the joists.</p>	<p>Excess mortar around joists removed prior to mastic sealant being applied on all four sides of the built-in joists.</p>
	
<p>Metal stud partitioning used. In A79 and A80 the holes and joints at top-floor ceiling level were painstakingly taped over to prevent air movement.</p>	<p>Timber studwork used at the site manager's insistence. All penetrations drilled at a suitable size and sealed with mastic at pre-plaster stage.</p>

Figure 5 Comparison of developer A detailing in Phase 3 and observations made during a parallel investigation on a further site where airtightness results significantly better than the national average were reported.

Discussion Papers

49 In addition to the literature review and the participatory action research, two discussion papers were also produced as part of this project. These papers were as follows:

- a) Discussion paper 1 — Performance and implementation.
- b) Discussion paper 2 — Impacts of pressure testing.

Discussion paper 1 — Performance and implementation

50 The aim of this paper was to analyse and discuss the project results with a view to identifying the levels of air permeability that could be achieved in new UK dwellings within the context of existing mainstream practice and readily available techniques. The project results highlighted a number of issues that require consideration when constructing dwellings to meet any particular airtightness target. These issues relate to:

- a) **Type of construction** — Certain construction types are intrinsically more airtight than others. The results illustrate that wet/mechanically plastered masonry cavity construction can default to

a reasonable level of airtightness by UK standards without much attention being given to airtightness. Other construction types, such as dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to achieve an air permeability below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. In the case of masonry the required design changes may be relatively minor. However, with existing light steel frame construction (warm frame) considerable effort is likely to be required, particularly at site level. It is also difficult to see how an air permeability consistently below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ could be achieved in light steel frame construction without significant revision of airtightness design in this form of construction.

- b) **Complexity of design** — Complexity of design is likely to have a significant impact on airtightness. Differences in air permeability of up to $4 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ from the mean were observed in dwellings of similar size, construction and form that had been constructed with comparable levels of workmanship and site supervision. The main difference observed between the dwellings was the complexity of the detailing. Higher levels of air permeability were consistently observed in those dwellings that contained the most complex detailing.
- c) **Airtightness approach adopted** — The approach that is adopted to improve airtightness can influence the eventual levels of air permeability that are achieved. The greatest reductions in air permeability were achieved where improved construction was undertaken in the form of designed changes with respect to the primary air barrier.
- d) **Feedback and guidance** — The level and consistency of any feedback and guidance that is provided on airtightness is important. The results suggest that the provision of general feedback and guidance to the developer on airtightness, prior to the dwellings construction, is likely to have little or no immediate effect on airtightness. Such guidance does little more than raise awareness and, although a necessary first step, it must lead to a system of quality control that provides continuous detailed feedback and guidance during construction. However, providing this sort of feedback and guidance on a dwelling by dwelling basis is onerous and labour intensive. As a consequence it is important that dwellings are designed with a clear understanding of the construction problems, so that designs are truly robust and able to be built within an affordable quality control regime.
- e) **Robustness of approach** — The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on basic workmanship coupled with secondary, remedial, sealing measures during construction are likely to be much less robust than those approaches that are based on an explicit attempt at the design stage to concentrate on ensuring that there is an effective and continuous air barrier. Detailed design that recognises the importance of buildability and simplifies the construction process is also likely to be more robust.
- f) **Repeatability** — Observations from site suggest that the knowledge and experience gained on airtightness does not appear to be filtering through to other dwellings on the same site. There are concerns that the other dwellings will not achieve the same sorts of levels of airtightness as the dwellings featured in this project. Clearly there remains a considerable amount of training and development work to be done to ensure that the house building industry is capable of producing a consistent standard of airtightness. This will not be a trivial task.

51 A detailed discussion of each of these issues can be found within Appendix 9.

Discussion paper 2 — Impacts of pressure testing

52 This aim of this paper was to review the pressure testing regime incorporated within Part L1A 2006 of the Building Regulations, analyse the logistics associated with compulsory pressure testing and discuss the effect that the testing regime is likely to have on new dwellings. The key findings that emerged from this paper were as follows:

53 The review (see Appendix 10) highlighted a number of issues associated with the pressure testing regime incorporated within Part L1A 2006. These issues related to the following:

- a) **Dwelling type** — With respect to pressure testing, ADL1A 2006 categorises dwellings by generic form. Such a categorisation is unlikely to capture a number of important house type issues that influence airtightness, particularly those relating to differences in geometry and complexity of construction. The results obtained from Phase 1 of the project and the Stamford Brook field trial¹⁰ suggest that differences in geometry and complexity of construction can result

¹⁰ The Stamford Brook field trial is a participatory action research project involving approximately 700 dwellings that are being built to an enhanced energy performance standard. Amongst other factors, this standard incorporates a maximum design air permeability

in variations in air permeability of up to $4 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa, with higher levels of air permeability being consistently observed in those dwellings containing the most complex detailing. The results also suggest that the issues associated with geometry and the complexity of the construction may have a much greater influence on the eventual airtightness of a dwelling than those issues associated with generic form alone.

- b) **Dwelling selection** — Little guidance is given within ADL1A 2006 relating to dwelling selection. Therefore, depending upon when developers are notified of the dwellings to be tested, there may be scope for additional measures to be undertaken on the selected dwellings to ensure that they meet the required airtightness target. In addition, ADL1A 2006 suggests that a significant proportion of the dwellings should be tested early on in the construction programme to enable any lessons learnt to be fed back into the construction and design process. However, this approach is based upon the premise that once a developer has demonstrated that the selected dwellings meet a particular air permeability target, the remaining dwellings will also be constructed to the same standard of airtightness. Anecdotal evidence obtained from Phase 3 of the project suggests that this is unlikely to be the case as there was a noticeable difference in the quality of workmanship in relation to airtightness in those dwellings that were participating in the project and those that were not. Consequently, the airtightness performance of those dwellings that are selected to be tested is unlikely to be representative of the performance of other dwellings of the same type on the same development.
- c) **Registered testers** — Local authorities are authorised to accept a certificate from a person who is registered by BINDT in respect of pressure testing for the airtightness of dwellings. However, there is no clear guidance given about who else can undertake the tests and issue certificates. It will therefore be up to individual BCBs to decide who is technically competent to undertake this work. This may lead to issues relating to equity and fairness if BCBs adopt different practices and developers are treated differently in different parts of the country.
- d) **Independence of the pressure testing** — There is no specific requirement for pressure tests to be carried out by an independent testing organisation. Consequently, a series of issues may arise if developers are allowed to test and issue certificates for their own dwellings.
- e) **Sampling frequency** — The sampling frequencies outlined in ADL1A 2006 are likely to result in a statistically insignificant non-random sample of dwellings being tested. The results suggest that the proportion of dwellings requiring testing is also likely to vary considerably between developments. In addition, where apartments are being constructed, a significantly greater proportion of apartments is likely to require testing than other dwelling types. This is despite the fact that apartments tend to be intrinsically more airtight than other dwelling forms of equivalent area.
- f) **Preparation for testing** — Experience suggests that developers appear to be unaware of how to prepare a dwelling for a pressure test and, in some instances, tests have had to be abandoned as the dwelling was not in a finished state. The incidence of unprepared and unfinished dwellings being presented for testing is likely to reduce in the medium to long term as developers become accustomed to pressurisation testing and realise that they will have to pay for the service irrespective of whether the dwelling is tested or not.
- g) **Air permeability target** — The design air permeability target for many dwelling designs is likely to be considerably lower than the maximum level of $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa specified within ADL1A 2006, particularly where fuels with a higher carbon intensity than gas are to be used. Modelling work suggests that an average air permeability of around 7, 5 and $3 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa would need to be achieved by a developer to meet a design air permeability target of 10, 7 and $5 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa, respectively, assuming a 10% initial failure rate. Although an average air permeability of $5 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa has been measured in new UK dwellings (measured at Stamford Brook), achieving an average air permeability of around $3 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa will be technically demanding. Such levels of air permeability are likely to require a fundamental rethink of airtightness design in new dwellings if they are to be consistently achieved in mass UK housing. Results from Stamford Brook also suggest that even when a demanding design air permeability target has been set, the air permeability of the dwellings constructed on site may increase over time due to a deterioration in site workmanship and quality.

target for the field trial dwellings of $5 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa. Further details of the field trial can be found within Roberts, Bell and Lowe (2005), Roberts, Andersson, Lowe, Bell and Wingfield (2005) and Wingfield, Bell, Bell and Lowe (2006).

- h) **Testing procedure** — The method of testing can influence the eventual levels of air permeability achieved and bias the results. The approved procedure for pressure testing a dwelling, ATTMA Technical Standard 1 (ATTMA, 2006), states that valid test results can be achieved by: pressurising the dwelling; depressurising the dwelling; or pressurising and depressurising the dwelling and averaging the results. The results obtained from Phase 1 and Phase 3 of the project illustrate that if the dwelling is depressurised only, the results obtained are in most cases lower than the corresponding pressurisation test results. This suggests that more favourable test results could be achieved by adopting by depressurising the dwellings only. In addition, the average difference between the pressurisation and the depressurisation results observed was 4.1%, with a measured maximum difference in excess of 14%.
- 54 The number of new dwellings requiring testing each year will be dependent upon the strategy adopted for regulatory compliance by the developer, the size of the development and the variation in dwelling types across the developments. Based on construction statistics for 2004 and 2005, it is estimated that the number of dwellings that will require testing will fall in the range 25,000–42,000 dwellings per year. The figure is likely to lie towards the higher end of this range due to re-tests and the trend towards constructing more multi-dwelling buildings.
- 55 Wind speed can have a significant effect on the accuracy of pressure tests. In addition, it can also have a major effect on the number of hours when a reliable pressure test result can be achieved. Assuming a working day from 8am to 6pm, an analysis of the CIBSE/Met Office weather data for a semi-empirical Test Reference Year (corrected to a height of 2 m above ground level) suggests that the average maximum number of hours available for testing in a year would be reduced by just over 7%. This analysis assumes a Terrain Category III, which simulates a suburban location. However, the actual number of hours available for testing is likely to reduce further as tests are undertaken in more exposed locations.
- 56 Taking into account seasonal trends in dwelling completions and the number of hours available for testing, the average number of tests that are required to be undertaken in a single day could exceed 200 or fall below 80, depending upon the month of the year. Assuming that an average of three to four tests could be undertaken by a single testing team in a day, a minimum of 20–25 testing teams would be required in January to cover the testing requirements, rising to a minimum of 50–65 testing teams in December.
- 57 The commercial charge for undertaking a single pressure test is currently of the order of £500 excluding VAT plus travel and subsistence. Additional tests performed on the same visit are of the order of £100 per test excluding VAT.
- 58 Limited data are available on the costs associated with undertaking remedial work in dwellings that have failed a pressure test. Experience obtained undertaking remedial airtightness work on a small number of field trial dwellings at Derwentside¹¹ suggests that this work could cost in the region of £1,200 per dwelling. However, there is no reliable data available that would enable a firm estimate to be provided.
- 59 Three separate approaches have been identified to address a number of the limitations previously identified with the pressure testing regime that is currently contained within ADL1A 2006. These are as follows:
- Direct quality control** — This approach involves making a number of amendments to the current edition of ADL1A 2006. These amendments concentrate on providing clearer and more detailed guidance on a range of factors such as dwelling type, dwelling selection, registered testers and dwelling preparation. In addition, it is also suggested that the current sampling frequency should be increased such that a representative sample of dwellings are tested on each development.
 - Indirect quality control** — This approach would involve putting in place an airtightness quality control system as an alternative to compulsory pressure testing. A random sample of visual inspections and pressure tests of completed dwellings would then take place to ensure that the dwellings are built as designed and meet the airtightness requirements of the Approved

¹¹ The field trial dwellings at Derwentside were built in the early 1970s using dry-lined load-bearing cavity masonry construction and, prior to the refurbishment, they were in a poor state of repair with an air permeability of between 24 and 26 m³/(h.m²) @ 50Pa. A programme of general and targeted airtightness work was carried out on the dwellings in conjunction with a partial refurbishment undertaken by Derwentside District Council. Following these works, the air permeability of the dwellings was reduced by almost 55%, to a mean of just over 11 m³/(h.m²) @ 50Pa. Further details of the work can be found within Johnston and Lowe (2006).

Document. Care would need to be taken with such an approach to ensure that the sample sizes chosen are representative of the dwellings being constructed and a greater proportion of dwellings are tested than would otherwise be the case under the current edition of Part L1A 2006.

- c) **Compulsory testing** — This is the most radical of all three approaches and would involve the compulsory pressure testing of all new dwellings. This is the only approach that would ensure that the air permeability of all new dwellings is within reasonable limits.

Suggestions for Further Work

60 Areas of further work have been defined as follows:

- a) The results of this project are not able to be used to provide a clear measure of the performance of new dwelling production in the UK as a whole. Throughout this and other projects seeking to support regulatory policy on airtightness, the lack of a reliable snapshot of existing performance has been keenly felt. It is possible, for example, for the shift in awareness that has taken place in the last 12 months to influence the airtightness of new housing and there is some anecdotal evidence that this may be taking place. However it is not possible from non-random and non-quality controlled data to have a high degree of confidence in either the existence or the extent of such an effect. We would therefore recommend that it is time to undertake a survey of a random sample of dwellings constructed to Part L 2006. Such a sample would be difficult to construct but once established the regulators would have a very powerful feedback tool as well as a sound data set upon which to make decisions in 2010.
- b) The project should be repeated to establish the effect that the revised regulatory process, particularly the requirement for testing, has had on the airtightness of new dwellings. The project should also seek to anticipate the sort of standards ($\text{sub } 10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$) that may be necessary in 2010 and beyond. It could be argued that an analysis of BCB data on test results would provide some of what is required. However, such an analysis will not be random and would not enable the results to be interpreted with respect to design and construction practices. The qualitative data provided in a project such as the one reported here would help to fill this gap and enable the further development of detailed design and construction guidance, post 2010.
- c) An analysis of the success of alternative dissemination strategies designed to increase awareness of airtightness issues at all levels within the construction would prove beneficial for future training policy. By gauging the success of different approaches to education and training; insight could be gained into which methods are likely to be most effective, taking into account specific sectors and levels within the industry.
- d) A programme targeted towards construction personnel at all levels, including designers, site management, site operatives that increases the awareness of airtightness issues and encapsulates training, site supervision, workmanship and quality control,

Conclusions

61 This report presents the overall conclusions obtained from the project and identifies areas of future work. The conclusions have been categorised into three key areas:

- a) Pressurisation test results.
- b) Constructing dwellings to be airtight.
- c) The existing testing regime and the logistics of compulsory pressure testing.

Pressurisation test results

62 The key conclusions that have emerged from the overall results are as follows:

- a) Although the size, structure and non-random nature of the sample preclude it being taken as representative of UK house production, the results obtained from Phase 1 suggest that the dwellings tested are broadly in line with the existing data on the stock as a whole and that, at least in these cases, the impact of the 2002 Edition of Approved Document Part L1 on airtightness has been minimal.
- b) Given the qualitative nature of the project it is not possible to extrapolate the Phase 1 results to the post 2002 new build stock with any degree of confidence. However, the results are broadly

in line with the results from pressurisation tests on 99 post 2002 dwellings (also not a random sample) reported by Grigg (2004).

- c) The failure of the majority of the dry-lined masonry cavity and steel framed dwellings included within Phase 1 to achieve the ADL1 2002 airtightness target also suggests that the adoption of Robust Construction Details, at least in their current form, provides no guarantee that the current regulatory standard will be achieved with any degree of consistency. As to whether the revised versions of the Part L Robust Construction Details (now available as Accredited Construction Details — Communities and Local Government, 2006) together with the increased awareness of airtightness following the 2006 revision of Part L make a significant difference remains to be seen.
- d) The results from Phase 3 of the project suggest that an air permeability of less than $6 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa is genuinely achievable within mass-produced housing in the UK using existing techniques, materials and practices, and without incurring significant cost.¹² However, to achieve such a standard in a consistent and robust way will require a mix of design modifications and a committed and targeted approach to quality control.

Constructing dwellings to be airtight

63 A number of issues were highlighted that need to be considered when constructing dwellings to meet a particular airtightness target. These issues were as follows:

- a) The results from the project overall suggest that certain construction types are intrinsically more airtight than others. Wet plastering and quasi-wet plastering (parging) of masonry cavity construction can default to a reasonable level of airtightness by UK standards since it creates a robust and easily distinguishable air barrier on external walls. However, a continuous air barrier at the loft boundary would appear more difficult to accomplish using current construction techniques, if successfully achieved this would increase the level of airtightness further. Dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to reliably achieve an air permeability much below $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa. The construction type that presented the greatest difficulty was light steel frame. Air permeability values of below $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa are possible with this type of construction, but are likely to require considerable additional attention to detail on site and changes to the design to ensure that continuity of the primary air barrier is maintained. In fact it is difficult to see how it would be possible to achieve an air permeability consistently less than $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa without a fundamental rethink of airtightness design in this form of construction.
- b) Complexity can have a significant effect on airtightness. Results illustrate that significant variations in air permeability can be observed in dwellings of the same form, constructed by the same site team, where the only observed difference was the number of complex details associated with these dwellings. These disparities were most common where certain design features required the primary air barrier to cope with complex changes in plane, negotiate structural members and accommodate changes in material. Such details included ground floor projections, rooms adjacent to semi-exposed areas, timber bays in masonry construction and complex junctions with ventilated cold roof loft-spaces. Conceptual and detail design approaches that recognise the importance of buildability, simplifies the construction process and gives priority to good communication at all levels are less likely to result in discontinuities in the primary air barrier and poor airtightness.
- c) The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on secondary sealing measures (such as many of those implied in the current edition of Part L robust details — DEFRA, 2001) are likely to be much less robust than those approaches that concentrate on ensuring that there is an effective and continuous primary air barrier. Approaches that are easy to build and are most amenable to simple and effective quality procedures are also likely to be more robust.
- d) The approach adopted to increase airtightness has been shown to influence the potential level of air permeability achievable. The lowest levels of air permeability were achieved where attention was given to design modifications in which the primary air barrier was designed and made explicit as well as ensuring that the design was executed successfully on site.

¹² The exception is light steel frame where much more thought at the design stage is likely to be required.

- e) The level and consistency of feedback and guidance is important. Results suggest that providing general feedback and guidance on airtightness may have little effect on the air permeability of dwellings constructed. Feedback and guidance should therefore be continuous and targeted. However, providing this sort of feedback and guidance on a site by site, or even dwelling by dwelling basis can be onerous and labour intensive. Although during any learning phase the need for such intensive feedback will be inevitable, in the long term, ensuring that airtight design is built into the routine quality control culture of design and site teams (including an element of testing) will be critical.
- f) Anecdotal observations of non-test dwellings on the sites involved during Phase 3 of this project would suggest that on-site knowledge and experience gained through feedback does not always appear to be utilised more generally. Although the research team were not able to carry out any random tests on non-test dwellings visual inspections suggest that it is unlikely that the other dwellings on site will achieve the same sorts of levels of airtightness as the dwellings featured in this project. The results also suggest that achieving consistent levels of airtightness in dwellings of the same size, construction type and form may be difficult within existing design and construction cultures.

The existing testing regime and the logistics of compulsory pressure testing

64 A number of issues were highlighted relating to the pressure testing regime incorporated within Part L1A 2006 of the Building Regulations. These issues were as follows:

- a) The testing regime incorporated within ADL1A 2006 categorises dwellings by generic form. Such a categorisation is unlikely to capture a number of important house type issues that influence airtightness. The results obtained from this project, and supported by parallel research, suggest that the geometry and complexity of the construction may have a much greater influence on the eventual airtightness of a dwelling than generic form. In the light of this finding it will be important to assess over the next few years the effectiveness the testing regime in ADL1A (2006).
- b) No guidance is given within ADL1A 2006 as to when the BCB should notify the developer of the dwellings that require testing. In addition, ADL1A suggests that a significant proportion of the testing be front loaded to enable any lessons to be learnt during construction to be fed back into the construction and design process. Anecdotal evidence from Phase 3 suggests that this is unlikely to be the case. Although the response of developers to Part L1A 2006 is uncertain, the experience obtained from this project would suggest a risk that the airtightness of those dwellings that are selected to be tested may not be representative of the performance of other dwellings of the same type on the same development. Further guidance indicating when dwellings should be selected and tested should be incorporated within ADL1A 2006.
- c) It is unclear from ADL1A 2006 who, apart from those registered by BINDT, can undertake pressure tests and issue certificates. This may lead to issues relating to equity and fairness if BCBs adopt different practices and developers are treated differently in different parts of the country. Also the question of the independence of testing arises if developers are allowed to test and issue certificates for their own dwellings. Guidance on this issue may be necessary.
- d) In most cases, the sampling frequencies outlined in ADL1A 2006 are likely to result in a statistically insignificant non-random sample of dwellings tested on each development. Therefore it will be very difficult for BCBs to be confident in the performance of those dwellings not tested. In addition, the results obtained from this project suggest that the proportion of dwellings requiring testing is likely to vary considerably between developments, with a greater proportion of apartments requiring to be tested than other dwelling types. This is despite the fact that apartments tend to be intrinsically more airtight than other dwelling forms of equivalent area. Sampling frequencies should be revised such that a randomly selected statistically significant sample of dwellings is tested on each development.
- e) Experience gained from this project suggests that developers appear to be unaware how to prepare a dwelling for a pressure test. This situation is likely to change in the medium to long term as developers become more familiar with pressurisation testing.
- f) The design air permeability target for many dwelling designs is likely to be considerably lower than the maximum recommended level of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ specified within ADL1A 2006, particularly where fuels with a higher carbon intensity than gas are to be used. Assuming a 10% initial failure rate, modelling work on statistical distributions suggests that an average air permeability of around 7, 5 and $3 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ would need to be achieved by a developer to meet a design air permeability target of 10, 7 and $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. Reliably achieving an

average air permeability of below $5 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa in mass UK housing will be technically demanding, and such levels of air permeability are likely to require a fundamental rethink of airtightness design in new dwellings.

- g) The way in which the dwelling is tested can influence the eventual levels of air permeability achieved and bias the results. The approved procedure for pressure testing a dwelling is contained within ATTMA Technical Standard 1 (ATTMA, 2006). This standard states that valid test results can be achieved in a variety of different ways: by pressurising the dwelling; by depressurising the dwelling; or by pressurising and depressurising the dwelling and averaging the results. The results from this project indicate that the difference between pressurisation and depressurisation can be as high as 14%, and the results obtained by depressurising the dwelling only are, in most cases, lower than the corresponding pressurisation test results. The ATTMA Technical Standard should be amended to remove any possibility of bias.
- 65 It is estimated that between 25,000 and 42,000 dwellings will require to be tested per year, based upon construction statistics for 2004 and 2005. Due to re-tests and the trend towards constructing more multi-dwelling buildings, it is likely that the figure will lie towards the higher end of this range or may even extend beyond it. This will place considerable strain on testing capacity and will have a disproportionate effect on small and medium size developers, many of whom may have to test a high proportion of their production. Although the number of tests would be high, the impact in quality control terms will be statistically inefficient and unbalanced since sample sizes will be extremely variable and are unlikely to be well constructed.
- 66 Assuming a working day from 8am to 6pm, an analysis of the CIBSE/Met Office weather data for a semi-empirical Test Reference Year suggests that the average maximum number of hours available for testing in a year would be reduced by over 7% due to unfavourable wind conditions. The number of hours available for testing is likely to reduce further when tests are undertaken in more exposed locations, increasing the incidence of less reliable test data. Time spent travelling between sites, in order to undertake tests in different locations on the same day, will also affect the number of tests that can be performed.
- 67 The average number of pressure tests that are likely to be required to be undertaken on a single day will vary considerably depending on completion rates at different times of year. For instance, it is conceivable that they could exceed 200 in June or December but fall below 80 in January. Assuming that a testing team is capable of undertaking an average of four pressure tests each working day, a minimum of 50 testing teams would be required in June and December, reducing to a minimum of 20 testing teams in January.
- 68 The commercial charge for undertaking a pressure test on a single dwelling on a single site is of the order of £500 excluding VAT plus travel and subsistence. The introduction of compulsory airtightness testing for dwellings may result in increased competition and economies of scale reducing this figure in the medium and long term. However, the dominating factor in estimating the cost per test is how many tests can be performed in a single visit, and it is currently uncommon for more than two or three dwellings to be ready for testing on any given day. Experience suggests that instances where greater numbers of dwellings are available for testing normally only occur with multi-dwelling buildings such as apartment blocks. The costs associated with undertaking any additional tests once on site are marginal, and are of the order of £100 per dwelling excluding VAT.
- 69 Limited data are available on the costs associated with undertaking remedial work in dwellings that have failed a pressure test. However, experience suggests that the costs could vary significantly and will be dependent upon the scale of the reductions in air permeability that will be required, the location of the main air leakage points and the amount and nature of the remedial work that is required to be undertaken. Experience obtained from undertaking remedial airtightness work on a small number of existing dwellings at Derwentside suggests a cost in the region of £1,200 per dwelling (see Johnston and Lowe, 2006). However, the lack of published data on this issue means that this figure is highly speculative. In addition, we believe that this cost is likely to exceed the costs of undertaking remedial airtightness work in newly constructed dwellings.
- 70 Little is also known about the additional costs associated with achieving the airtightness standards set out in ADL1A 2006, although they are likely to be dependent upon the method of construction used, the approach taken to make the dwelling airtight and the target air permeability rate. The results obtained from Phase 3 of this project suggest that an air permeability of less than $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa can be achieved at marginal cost. In addition, data obtained from the Stamford Brook project (see Lowe and Bell, 2002) suggest that very high levels of airtightness by UK Standards (mean air permeability of $4.9 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa), can be achieved for moderate costs.

- 71 In order to address a number of the limitations associated with the pressure testing regime contained within ADL1A 2006, three separate approaches have been proposed. These are as follows:
- a) Direct quality control — This approach involves making a number of amendments to the current edition of ADL1A 2006. These amendments concentrate on providing clearer and more detailed guidance on a range of factors such as dwelling type, dwelling selection, registered testers and dwelling preparation. In addition, it is also suggested that the current sampling frequency should be increased such that a representative sample of dwellings are tested on each development.
 - b) Indirect quality control — This quality control approach would be outside the regulatory loop along the lines of the Robust Details system used by many developers with respect to Part E. It involves putting in place a national airtightness quality control system as an alternative to compulsory pressure testing or a direct regulatory checking process. Within the context of the scheme a random sample of visual inspections and pressure tests of completed dwellings would then take place to ensure that the dwellings are built as designed and meet the airtightness requirements of the Approved Document. Care would need to be taken with such an approach to ensure that the sampling protocols ensure statistical validity.
 - c) Compulsory testing — This would involve the compulsory pressure testing of all new dwellings. Although this approach would be the most expensive, and the UK does not currently possess the necessary testing capacity to implement it, this is the only approach that would ensure that the air permeability of all new dwellings is as specified in the calculation of the Target Emission Rate.

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Appendix 1

Airtightness of buildings — towards higher performance

Interim Report D1 — Literature Review and Built Examples

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dr Jez Wingfield, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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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 $10 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 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 $10 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 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 20th 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.

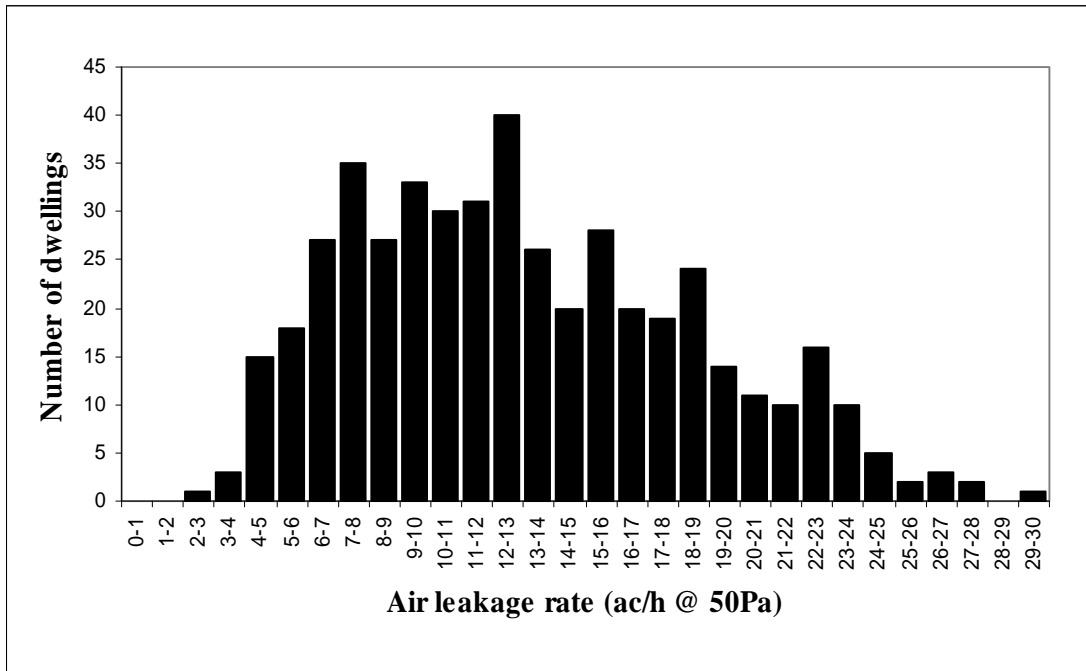


Figure 1 Distribution of air leakage rates in UK dwellings. After Stephen (2000).

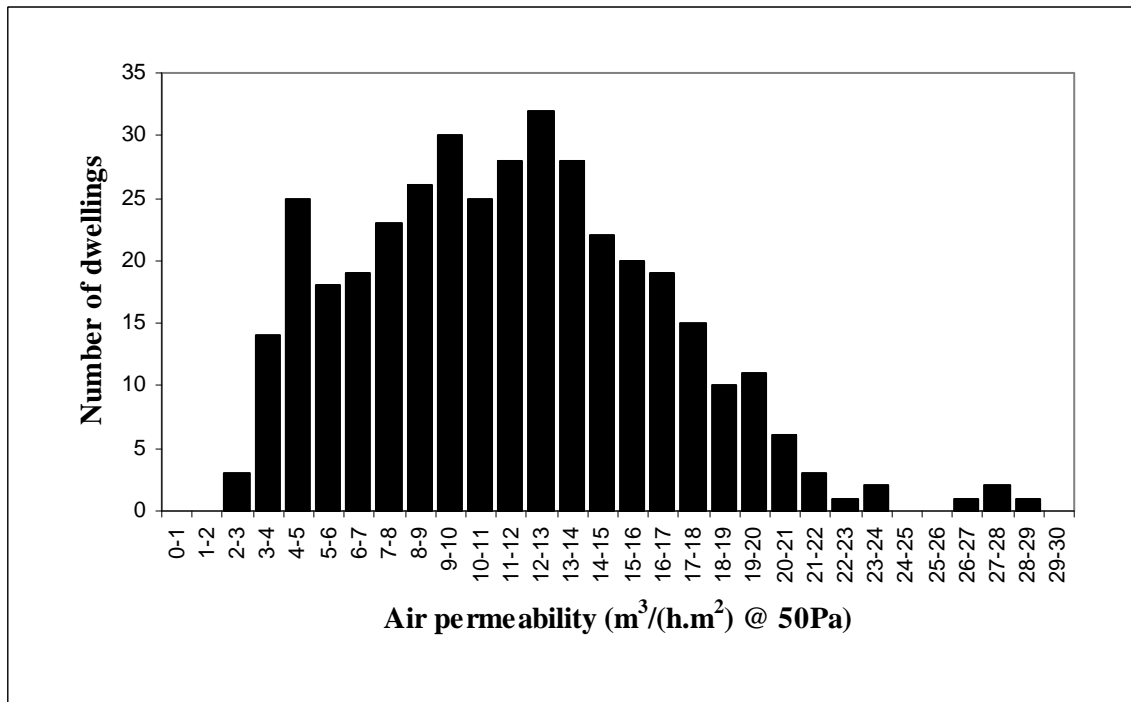


Figure 2 Distribution of air permeability of UK dwellings. After Stephen (2000).

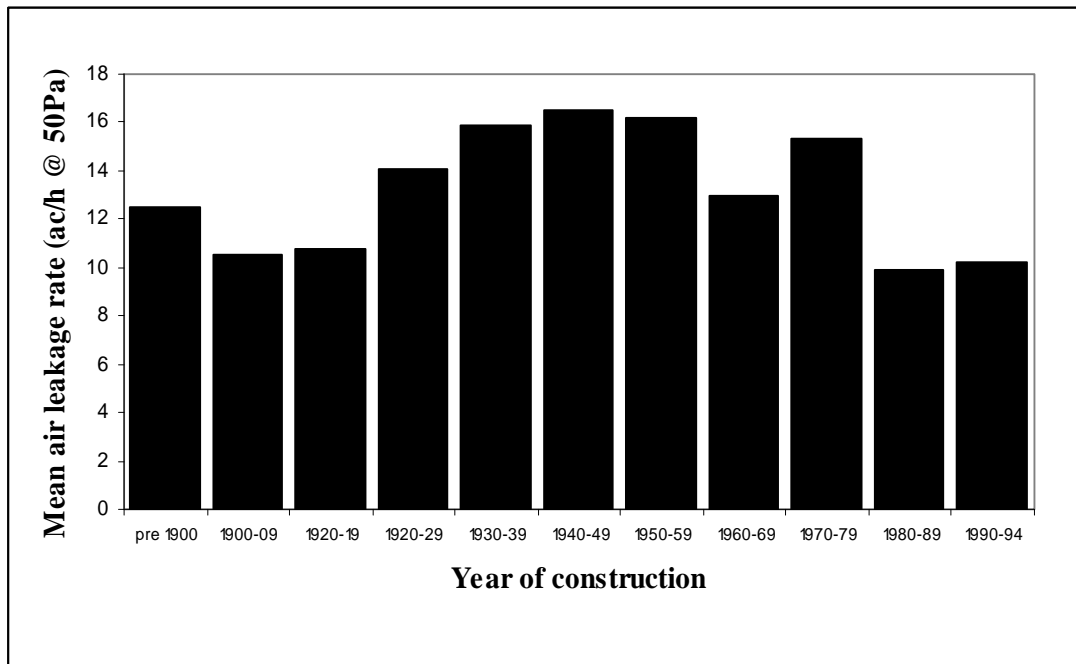


Figure 3 Relationship between dwelling age and air leakage. After Stephen (2000).

- 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 $19.3 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa), and that the average value is only marginally more airtight than the average for the stock as a whole (air permeability of $11.3 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa , as opposed to $11.48 \text{ m}^3/(\text{h.m}^2)$ @ 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 $10 \text{ m}^3/(\text{h.m}^2)$ @ 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 $\text{m}^3/(\text{h.m}^2)$ 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).

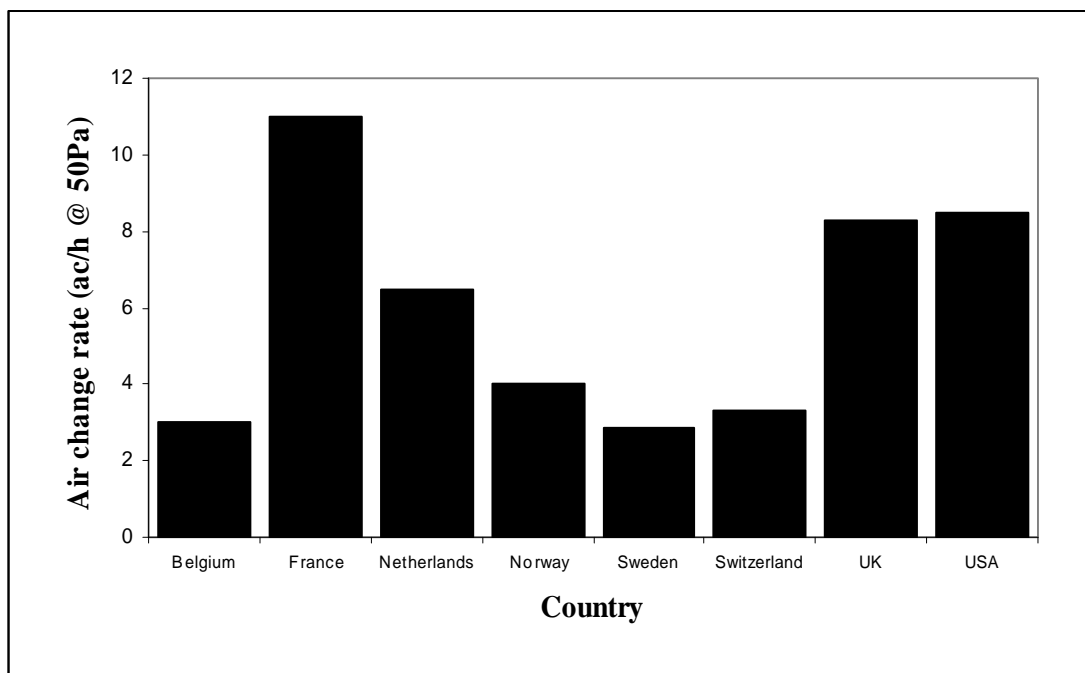


Figure 4 Comparison of maximum normalised air leakage criteria for dwellings.

- 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).

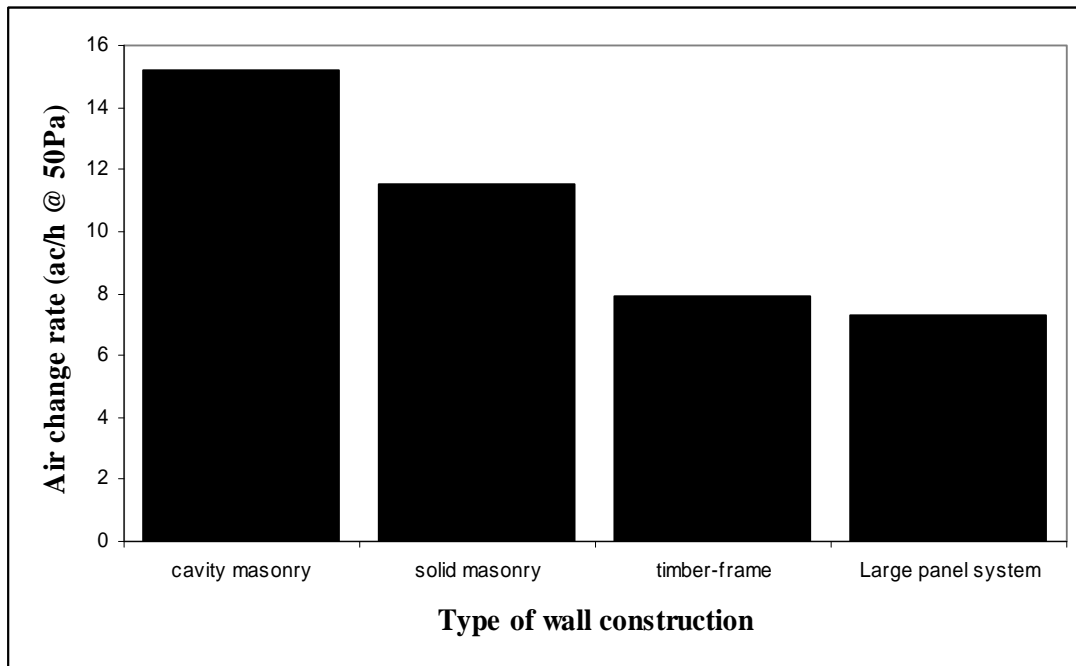


Figure 6 Influence of wall type on mean air leakage rate. After Stephen (2000).

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 techniques¹³ (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.

¹³ 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.

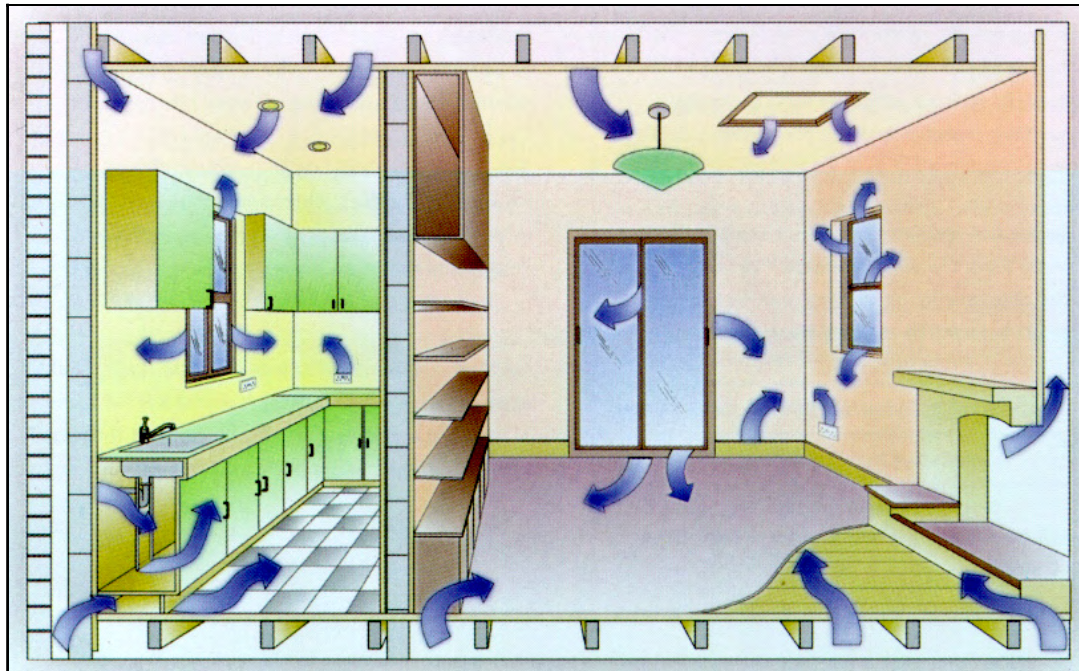


Figure 7 Typical air leakage paths in UK dwellings. After BRECSU (1997).

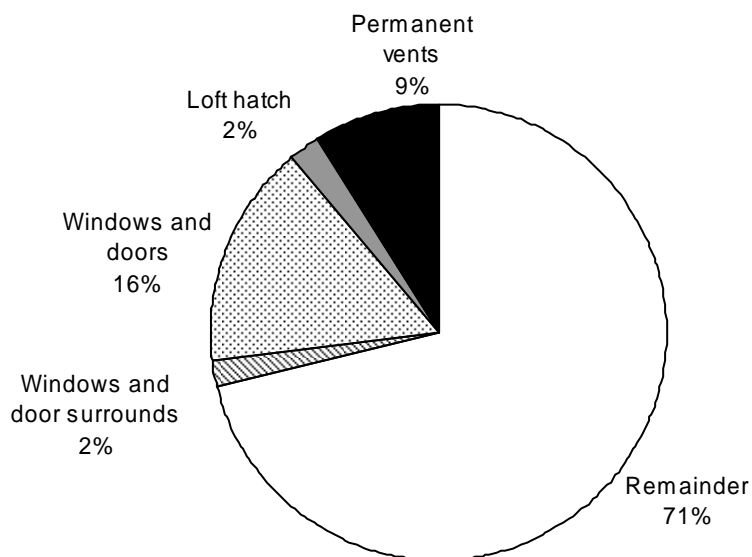


Figure 8 Component air leakage in UK dwellings. After Stephen (2000).

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.

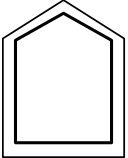
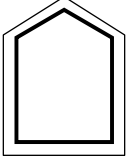
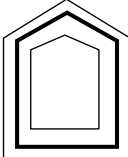
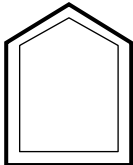
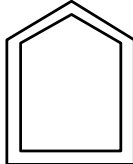
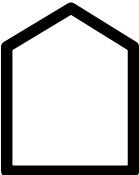
Construction principle	Advantages	Disadvantages
<p>Internal airtight cladding (e.g. plasterboard)</p> 	<p>Uses common sheet lining materials.</p>	<p>Risk of puncture damage. Joints and connection details must be sealed. Sensitive to movement and settlement.</p>
<p>Internal airtight vapour barrier (e.g.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

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 $10 \text{ m}^3/\text{h per m}^2$ 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 $15 \pm 5 \text{ mm}$ 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 extent 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.

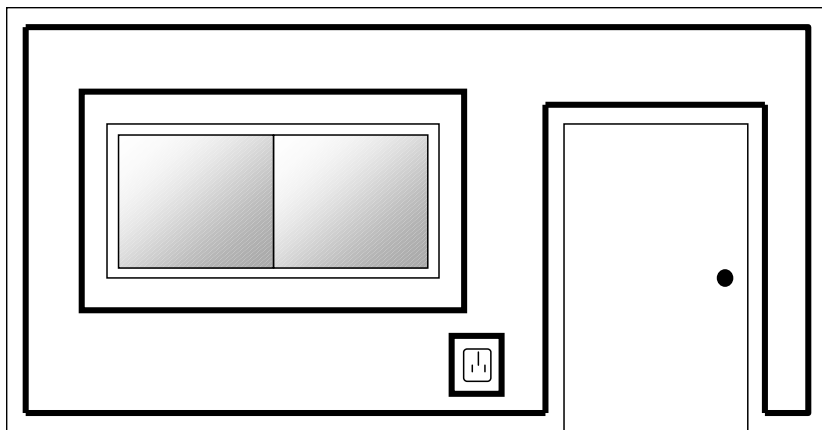


Figure 9 Schematic of sealing of perimeters of dry-lined wall.

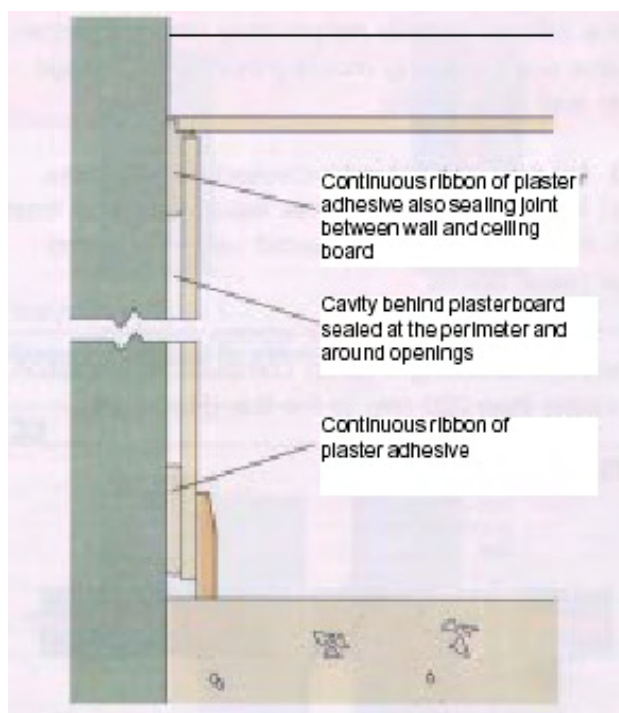


Figure 10 Sealing at the perimeter of dry-lining. After Stirling (2002).

- 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 be made from, e.g. closed cell foam, rubber, PVC or metal. Examples of different types of draught seals are shown in Figure 12.

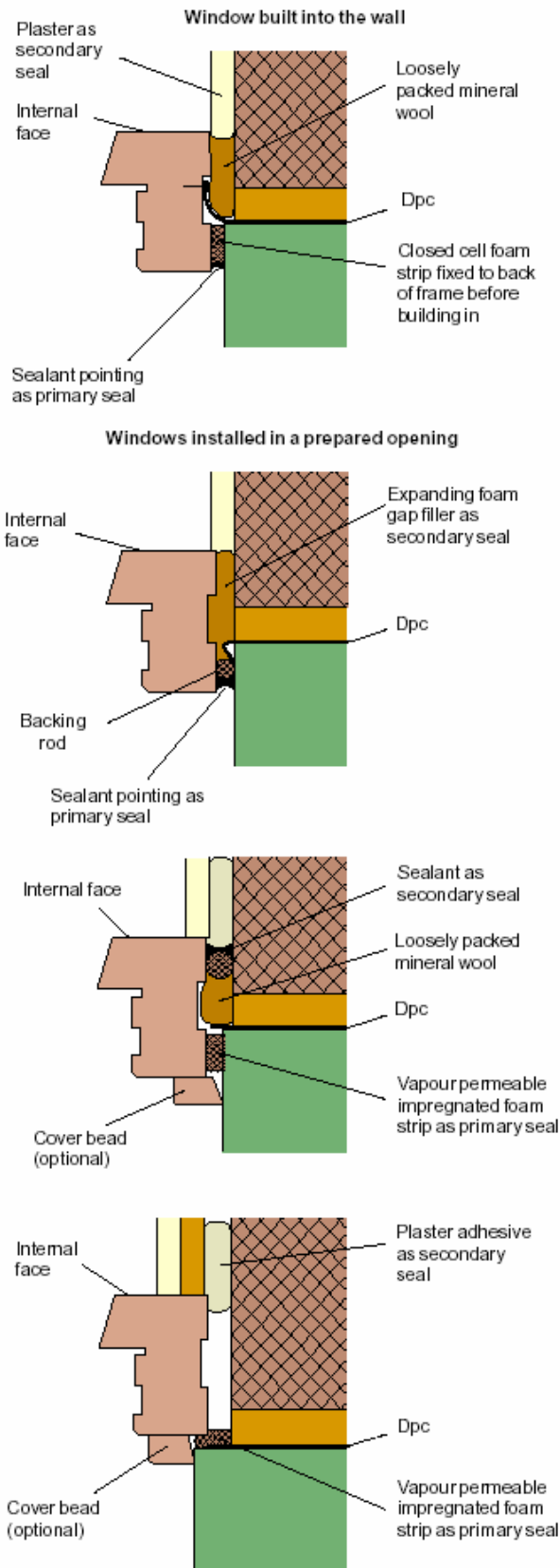


Figure 11 Examples of sealing at window to wall junctions. After Stirling (2002)

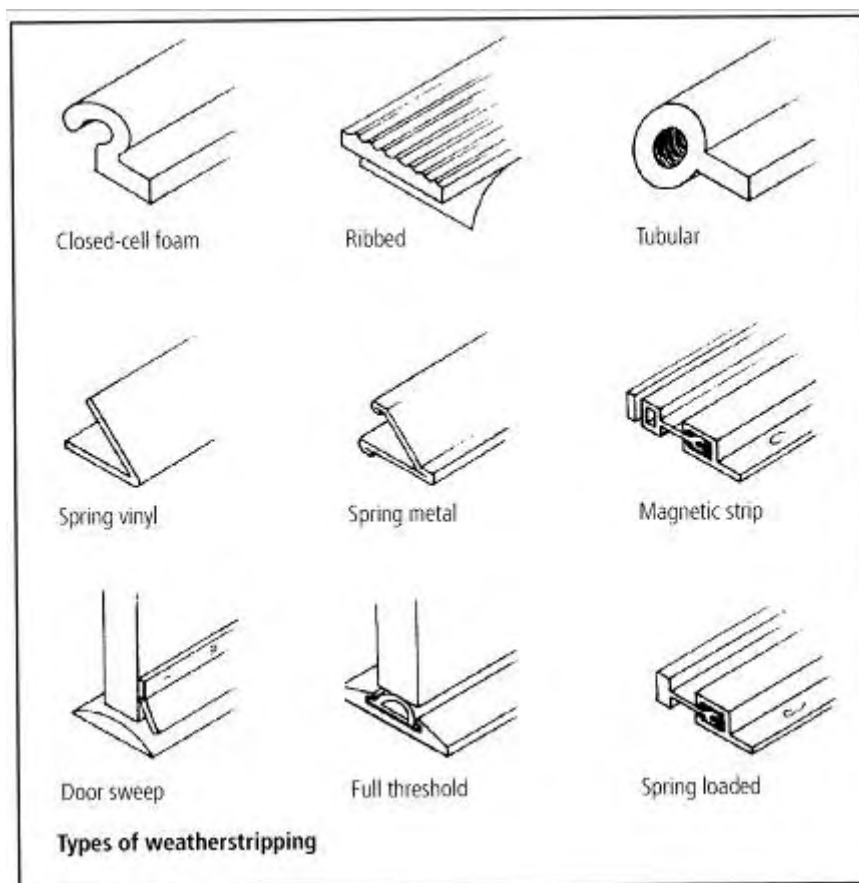


Figure 12 Examples of types of draughtstrip. After Natural Resources Canada (2002).

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 is 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/m² (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 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 through 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 used 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 is 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.

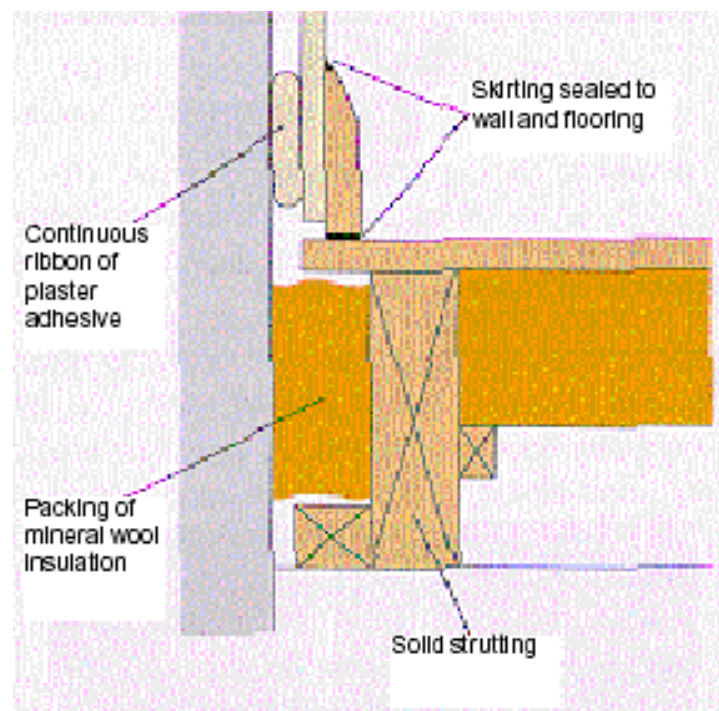


Figure 13 Insulating and sealing the floor perimeter. After Stirling (2002).

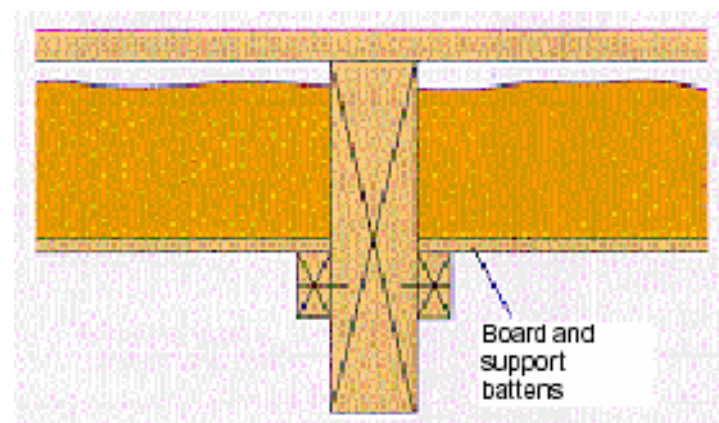


Figure 14 Quilt insulation supported on a board. After Stirling (2002).

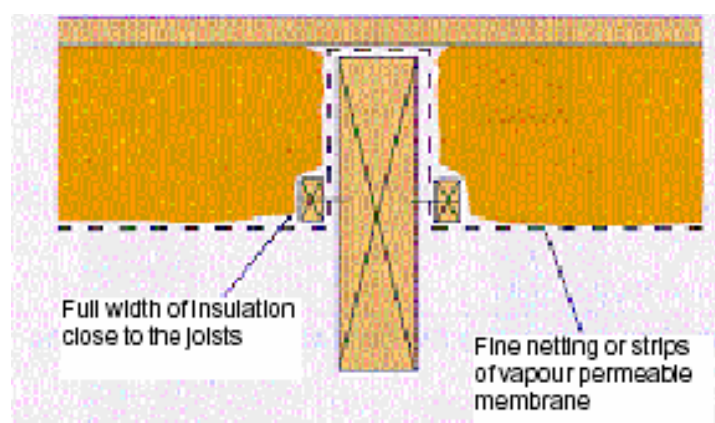


Figure 15 Quilt insulation supported on netting or vapour membrane. After Stirling (2002).

- 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 m², whilst the 4 bedroom dwelling has an internal floor area of 140 m². 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 CO₂ 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 m² (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 m² (Plot A Saturn house type) and 185 m² (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 m².

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.

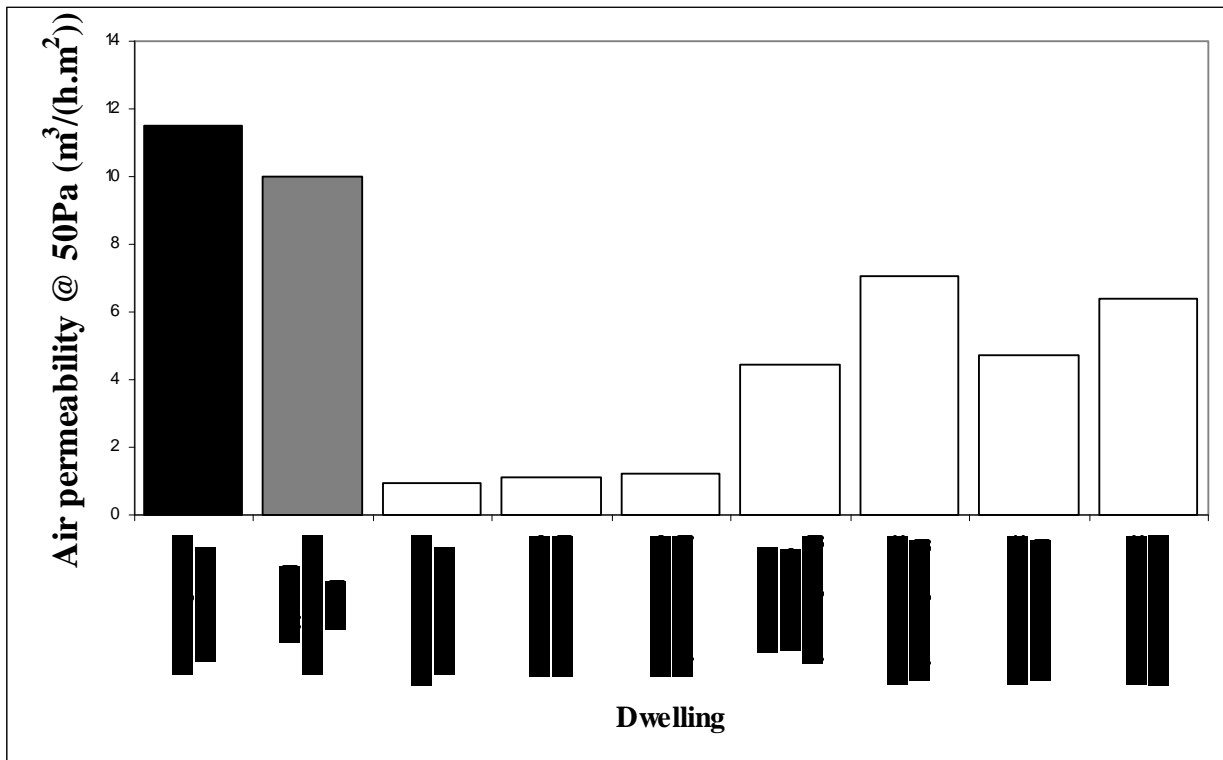


Figure 19 Mean air permeability of the case studies.

- 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:
- All of the dwellings tested are relatively airtight by UK standards, being significantly lower than the UK mean of $11.48 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa (Stephen, 2000), and the maximum specified level of $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa that is contained within the Building Regulations Approved Document Part L1 (ODPM, 2003).
 - 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 $7.1 \text{ m}^3/(\text{h.m}^2)$ @ 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 $4.43 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa, for a dwelling that was completed over 10 years ago).
 - 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 $1.23 \text{ m}^3/(\text{h.m}^2)$ @ 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.
 - 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.
 - 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.¹⁴ 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 m² 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 m² 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 m² 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 m² 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 m² 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 m³/(h.m²) @ 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.

Dwelling	Mean air change rate @ 50Pa (ac/h)
Hockerton Housing Project dwelling 1	1.09
Hockerton Housing Project dwelling 2	1.29

¹⁴ 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.

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.

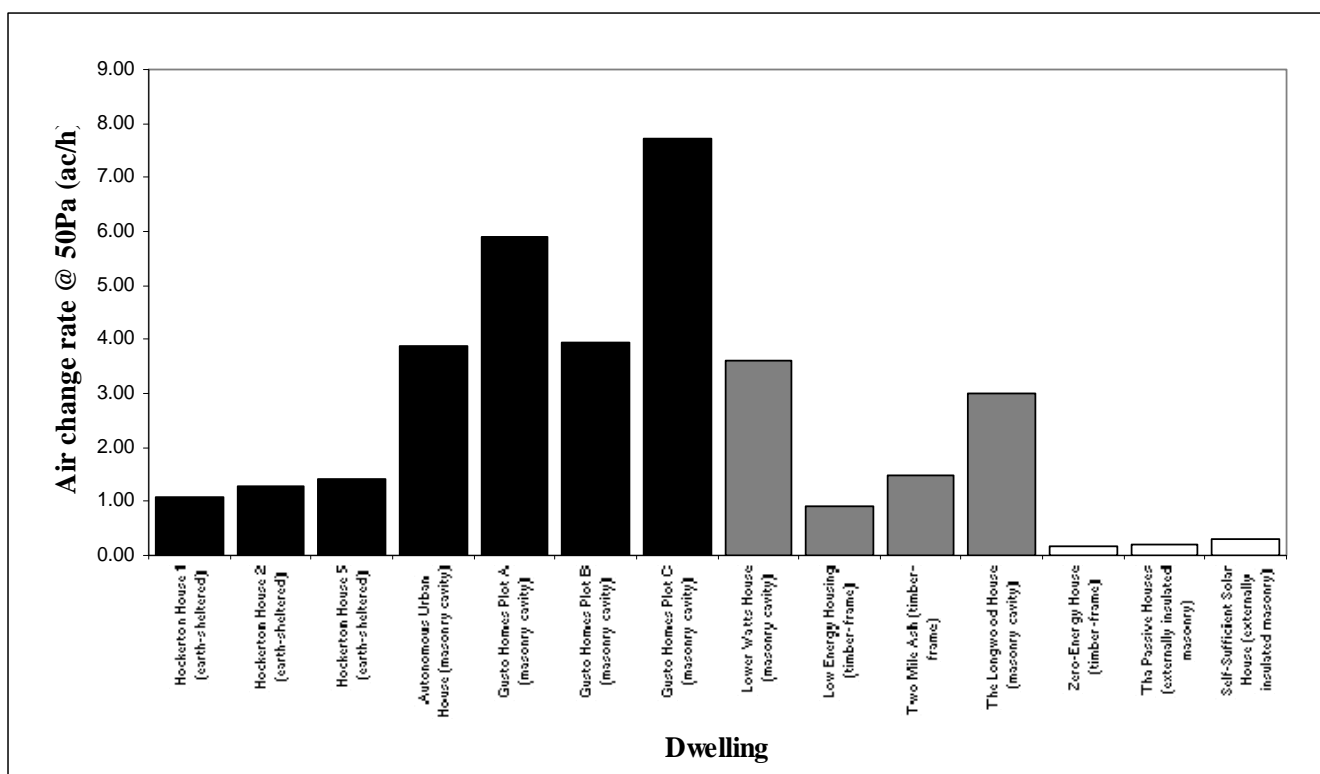


Figure 20 Comparison of air leakage rates.

- 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 returned¹⁵; two from the dwelling occupants and three from the designers and builders.

¹⁵ 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).

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 comfortable¹⁶, 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 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 $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$.
- 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.

¹⁶ 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.

- 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 m³/h/m² @ 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 m³/(h.m²) @ 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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Appendix 1A

Spot test measurements

Results of Pressurisation Test of The Hockerton Housing Project



1 Introduction

This report presents the results of the pressure tests carried out on the Hockerton Housing Project, Hockerton on 5 November 2003. The tests were carried out by Neil Prescott of Building Sciences Ltd.

2 Building Description

The Hockerton Housing Project consists of a terrace of five single storey earth-sheltered dwellings, each of which has an internal floor area of 122 m². A south-facing conservatory runs the full width of each dwelling.

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.

3 Air Leakage Standard

A new national standard – TM23 Testing buildings for air leakage (CIBSE, 2000) – has been introduced in the UK, which covers the pressure testing of all buildings. This has been adopted as the test standard for Part L1 of the Building Regulations 2000 (England and Wales), which came into force in April 2002 (ODPM, 2001).

Traditionally, the airtightness of dwellings has been expressed as an air leakage rate in air changes per hour (ac/h). However, the Approved Document Part L1 2002 (England and Wales) is written in terms of air permeability, and compliance can be demonstrated by pressure testing to show that the air permeability does not exceed 10 m³/(h.m²) @ 50Pa (although for dwellings a pressure test is not mandatory).

TM23 (CIBSE, 2000) defines air change rate and air permeability as follows:

Air change rate

This is the volume flow rate per cubic metre of building internal volume (ac/h) at a test pressure of 50Pa.

Air permeability

This is the leakage rate per square metre of building envelope (m³/(h.m²)) at a test pressure of 50Pa. The envelope area taken into account in calculating air permeability is the internal surface area of the external façade, and includes the walls, roofs and the total ground floor area. No deductions are made for partitions or the separating walls with adjacent buildings or garages.

The calculated internal volume and envelope area for each dwelling (excluding the conservatory) is 324 m³ and 372 m², respectively. If the conservatory is included, the internal volume and envelope area of each dwelling increases to 472 m³ and 491 m², respectively.

4 Fan Pressurisation System

Fan pressurisation systems are used to quantify the air leakage of the envelope of buildings. The leakiness of the envelope is quantified by connecting a single large fan or a series of fans into an external doorway and pressurising the building whilst measuring the air flow rate required to maintain a pressure difference across the building envelope. The leakier the building, the greater the air flow required to maintain a given pressure differential (in almost all cases a differential of 50Pa is used).

The fan system used on this project consisted of an Infiltec Blower Door (Model E3). All other external doors were kept closed during the test.

Tests are normally carried out when the outside wind speed is low to minimise any wind induced pressure variations. Air volume flow rate Q (m³/s) through the fans is measured by calibrated flow grids over a suitable range of building pressure differentials ΔP (Pa). These are then corrected for internal/external temperature difference, in accordance with TM23. A best-fit power-law profile of the form $Q=C_{env} (\Delta P)^n$ is fitted to the data where both the coefficient C_{env} and exponent n are constants.

C_{env} is then corrected for the measured barometric pressure to a specified test pressure of 50Pa, providing C_L .

The theoretical leakage rate at 50Pa is then calculated from the formula:

$$Q_{50}=C_L(\Delta P)^n$$

The air change rate can then be calculated by dividing the air volume flow rate (m³/h) through the building envelope at a pressure differential of 50Pa (Q_{50}), by the building volume (V). The result is expressed in terms of air changes per hour (ac/h).

To compare the envelope leakage characteristics between buildings of different shapes and sizes, air permeability (Q_{50}/S_T) is used. S_T is the total internal surface area (m²). The result is expressed in terms of m³ leakage per hour per m² of envelope area (m³/(h.m²)).

5 Test Procedure

The mean internal and external temperatures were measured and recorded during the tests. The temperature values recorded were used to standardise the air flow rate through the fan systems to commonly agreed conditions. A further parameter measured was wind speed. If the measured wind speed had been too high (i.e. ≥ 3 m/s) the test would not have been carried out.

The test procedure consisted of pressurising each dwelling to approximately 50Pa then taking a set of measurements of the building pressure differential and flow rate through the fans. The fan speeds were then reduced in several steps and the readings repeated at each of the speed settings. Each dwelling was then depressurised, and the test procedure repeated. The result is two sets of measurements; one for pressurisation and one for depressurisation.

The following temporary seals were in place at the time of the tests:

- The supply and extract ducts of the MVHR system were sealed using duct tape.
- The air bricks within the conservatory of the dwelling tested had been sealed by the dwellings occupants.

In addition, all of the trickle vents were adjusted to the closed position.

A number of air leakage tests were undertaken on three out of the five dwellings at Hockerton (see Figure 1). These tests were as follows:

- Each dwelling pressurised and depressurised, excluding the conservatory.
- Dwelling 2 was pressurised, including the conservatory. This test was undertaken to determine the airtightness of the conservatory. However, it should be noted that the conservatory is not part of the heated envelope and was never designed to be airtight.
- A progressive equalisation test on dwelling 2 was carried out (excluding the conservatory), during pressurisation. This involved undertaking a normal pressurisation test on dwelling 2, whilst dwelling 1 was maintained at a 50Pa pressure difference. This test was undertaken to measure the inter-dwelling air leakage between these two dwellings.

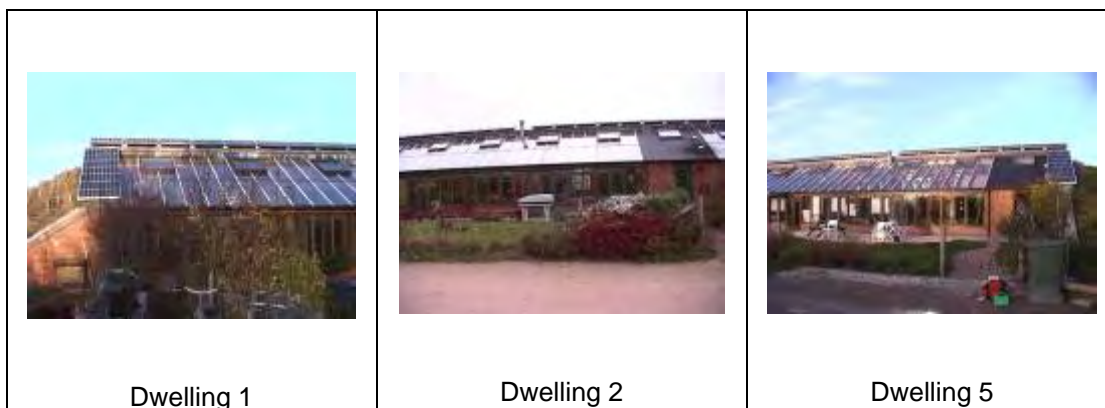


Figure 1 Dwellings tested at Hockerton.

6 Results

Each set of measurements of pressure difference and air volume flow rate was averaged and a best-fit power-law profile of the form $Q = C_{env} (\Delta P)^n$ was fitted to the data. The graphs showing the test results are included in Appendix A.

Air change rate

Using the power law profile $Q_{50}=C_L(\Delta P)^n$, the air change rate for each of the dwellings was determined using Q_{50}/V . The results are set out in Table 1 and Figure 2.

Dwelling	Air change rate @ 50Pa (ac/h)		
	Pressurisation test	Depressurisation test	Average
1 (no conservatory)	1.11	1.07	1.09
2 (no conservatory)	1.23	1.31	1.27
2 (with conservatory)	7.29		
5 (no conservatory)	1.29	1.51	1.40

Table 1 Air leakage rates of the dwellings tested at Hockerton.

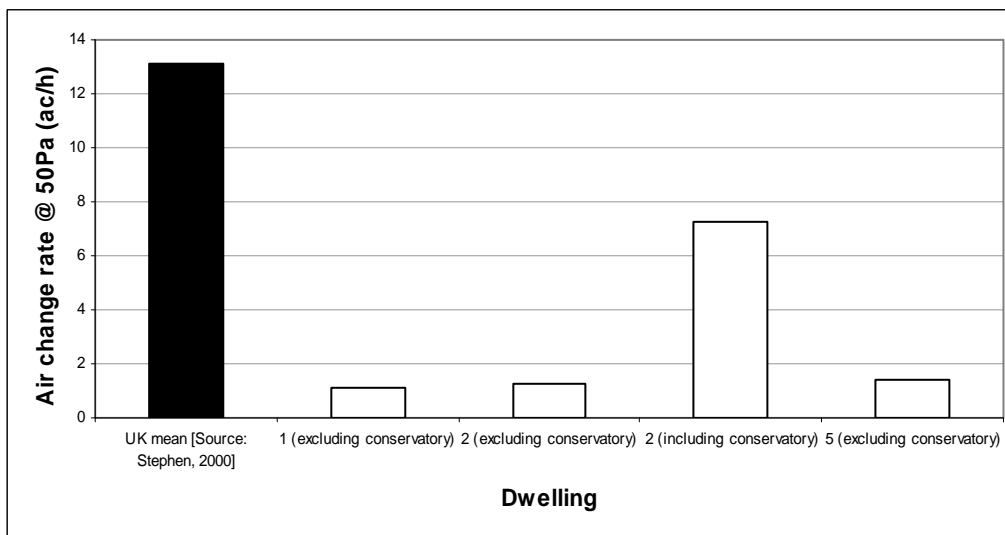


Figure 2 Mean air leakage rates of the dwellings tested at Hockerton.

Figure 2 illustrates that the mean air leakage rates of the dwellings tested at Hockerton (excluding the conservatory) lie between 1.1 and 1.4 ac/h @ 50Pa. These leakage rates are almost a factor of ten lower than the UK mean of 13.1 ac/h @ 50Pa (Stephen, 2000). In addition, the results suggest that the conservatory adds approximately 6 ac/h @ 50Pa to the envelope air leakage of dwelling 2.

Air permeability

Using the power law profile $Q_{50}=C_L(\Delta P)^n$, the air permeability of the dwellings was determined using Q_{50}/S_T . The results are illustrated in Table 2 and Figure 3.

Dwelling	Air permeability @ 50Pa ($\text{m}^3/(\text{h}.\text{m}^2)$)		
	Pressurisation test	Depressurisation test	Average
1 (no conservatory)	0.97	0.93	0.95
2 (no conservatory)	1.07	1.14	1.11
2 (with conservatory)	7.01		
5 (no conservatory)	1.13	1.32	1.23

Table 2 Air permeability of the dwellings tested at Hockerton.

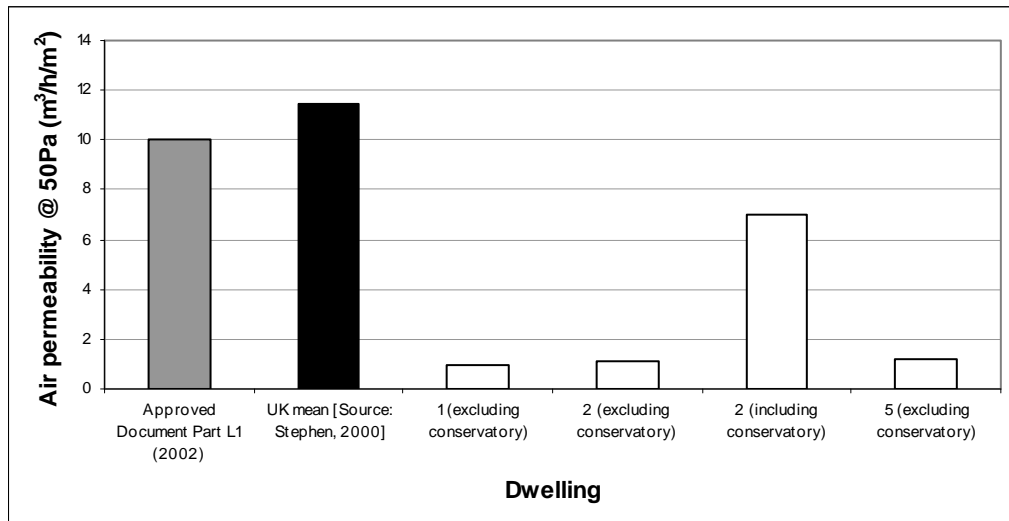


Figure 3 Mean air permeability of the dwellings tested at Hockerton.

Figure 3 illustrates that the mean air permeability of the dwellings at Hockerton (excluding the conservatory) lie between 0.95 and $1.23 \text{ m}^3/(\text{h}.\text{m}^2)$ @ 50Pa . This is considerably lower than the UK mean of $11.48 \text{ m}^3/(\text{h}.\text{m}^2)$, and the maximum specified level of $10 \text{ m}^3/(\text{h}.\text{m}^2)$ that is contained within the Approved Document Part L1 (ODPM, 2001). Even if the conservatory is included in the test, the air permeability of dwelling 2 only increases to $7 \text{ m}^3/(\text{h}.\text{m}^2)$. Therefore, all of the dwellings tested would satisfy the air leakage criterion set out in Approved Document Part L1.

Pressure equalisation test

The pressure equalisation test on dwelling 2 revealed that there was no significant inter-dwelling leakage between this dwelling and dwelling 1.

Leakage identification

The main air leakage paths within the dwellings were identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. Although it was possible to identify the main air leakage paths within the dwellings, it was not possible to quantify the contribution that these leakage paths made to the dwelling's overall air leakage. Nevertheless, the results were informative.

The main air leakage paths observed were as follows:

- Around trickle ventilators (see Figure B1).
- The opening casements of the French doors in all of the dwellings (see Figure B2).
- Service penetrations in the kitchen of dwelling 2 (see Figure B3).
- Service penetrations in the porch of dwelling 2.
- Through the boxed-in services in the master bedroom of all of the dwellings (see Figure B4).
- Through an exposed lighting loop in the party wall of dwelling 2 (see Figure B5).

References

CIBSE (2000) *Testing Buildings for Air Leakage: CIBSE Technical Memoranda TM23: 2000*. London, The Chartered Institute of Building Services Engineers.

ODPM (2001) *The Building Regulations 2000 Approved Document Part L1: Conservation of Fuel and Power in Dwellings. 2002 Edition*. Office of the Deputy Prime Minister, London, HMSO.

STEPHEN, R. (2000) *Airtightness in UK Dwellings*. BRE Information Paper IP 1/00, January 2000. Garston, Watford, Building Research Establishment.

Report Status

The information contained within this report has been produced for the purpose of a research project undertaken by Leeds Metropolitan University for Communities and Local Government. A copy of this report has been provided to the occupants of the Hockerton Housing Project for their own use. The information in this report may be used in material published by the Hockerton Housing Project with appropriate acknowledgement and reference.

Disclaimer

Whilst all reasonable care and attention has been taken in compiling this report, the author and Building Sciences Ltd do not accept any responsibility or liability for any statements contained within it that may be used or relied upon by any other party.

Appendix A

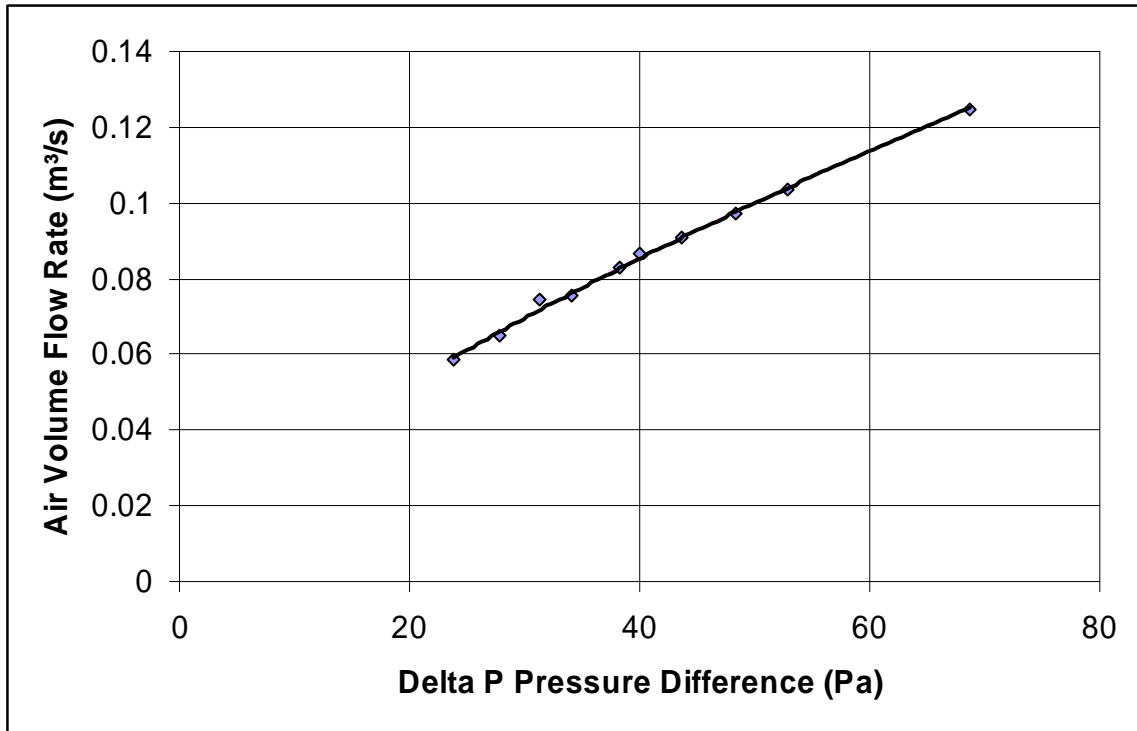


Figure A1 Dwelling 1 during pressurisation, excluding the conservatory.

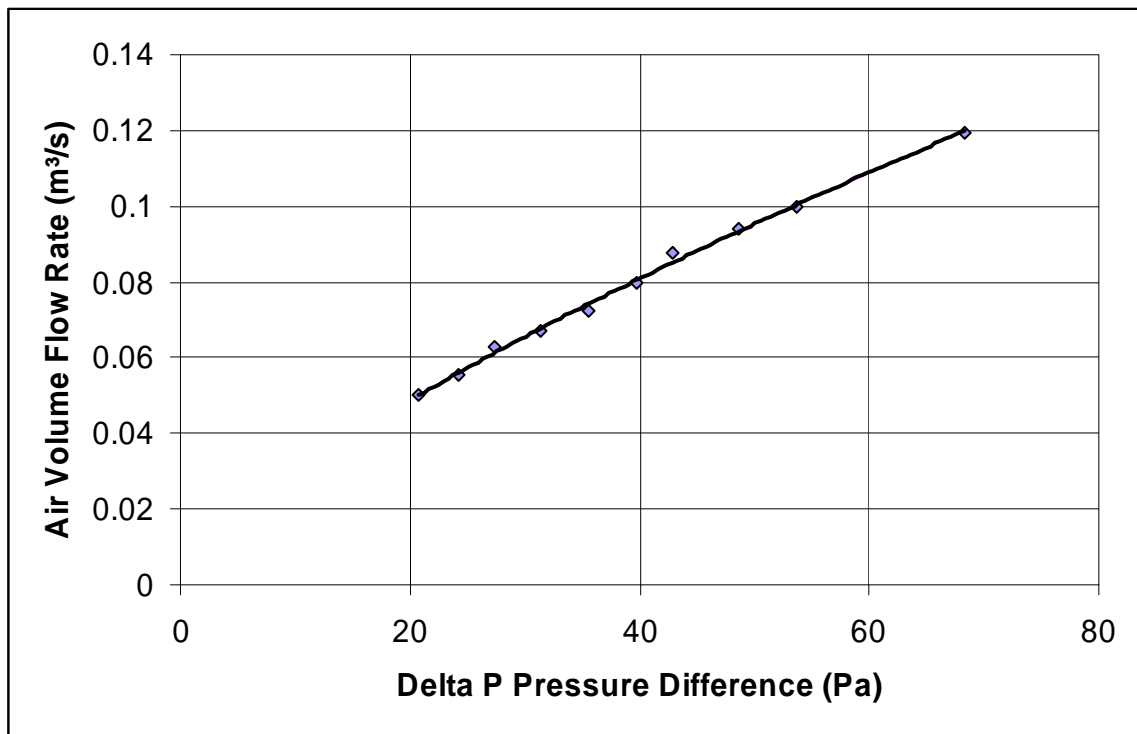


Figure A2 Dwelling 1 during depressurisation, excluding the conservatory.

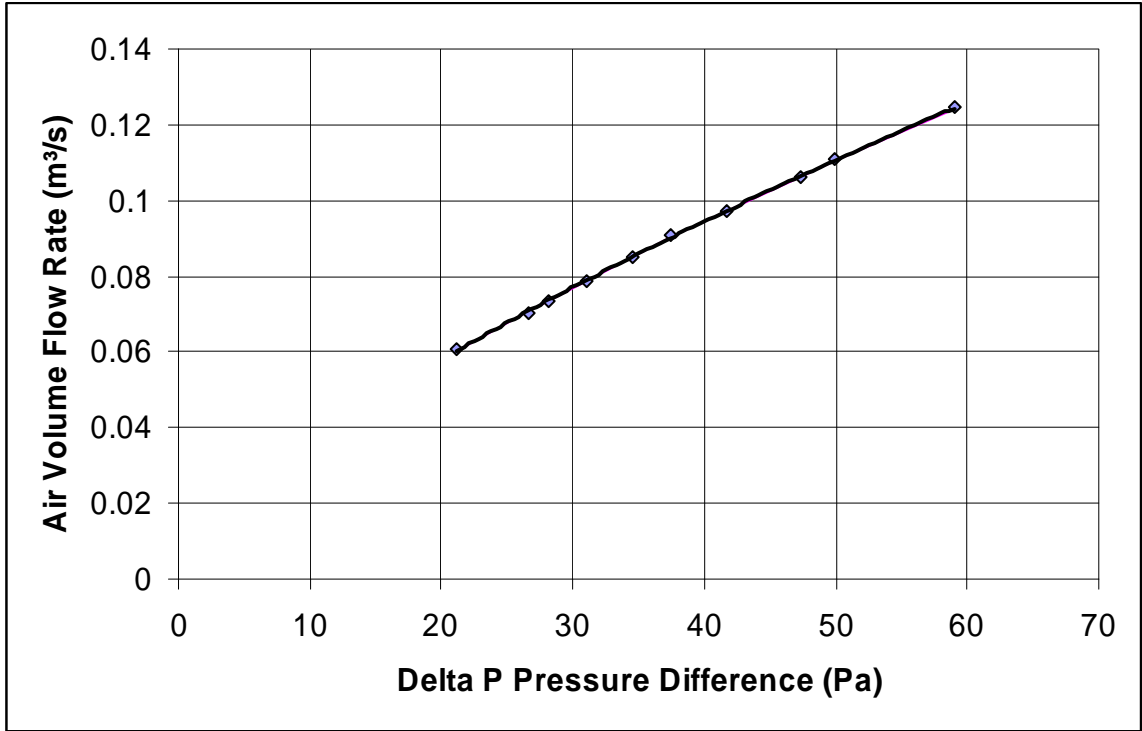


Figure A3 Dwelling 2 during pressurisation, excluding conservatory.

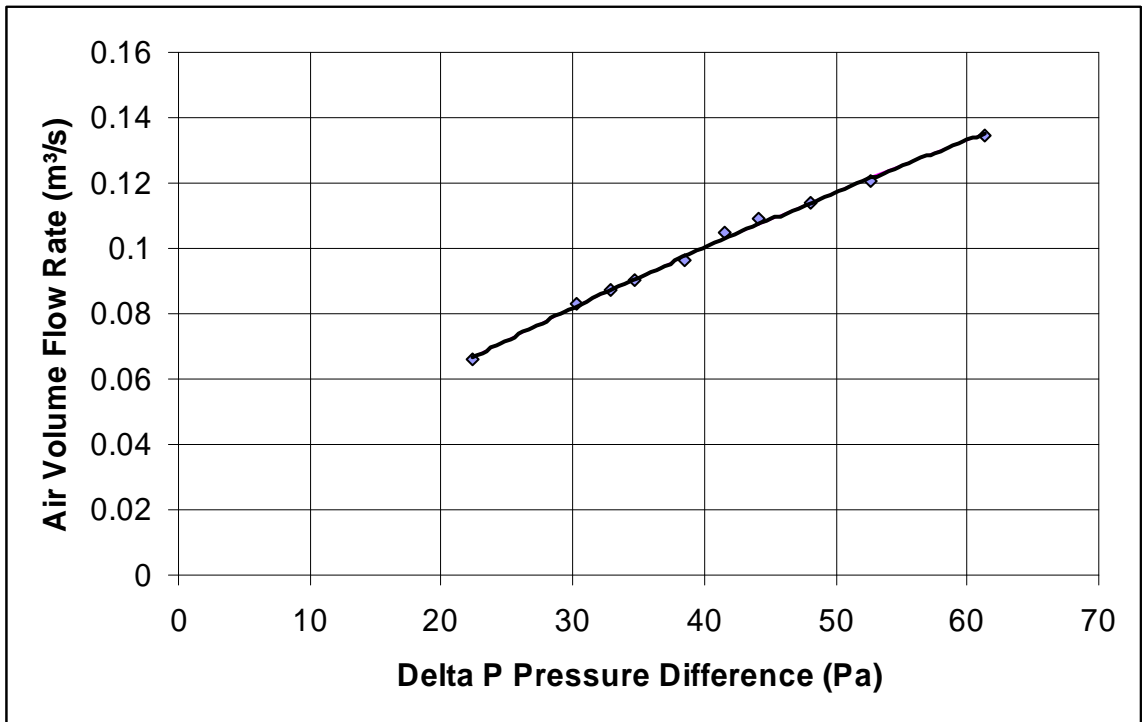


Figure A4 Dwelling 2 during depressurisation, excluding conservatory.

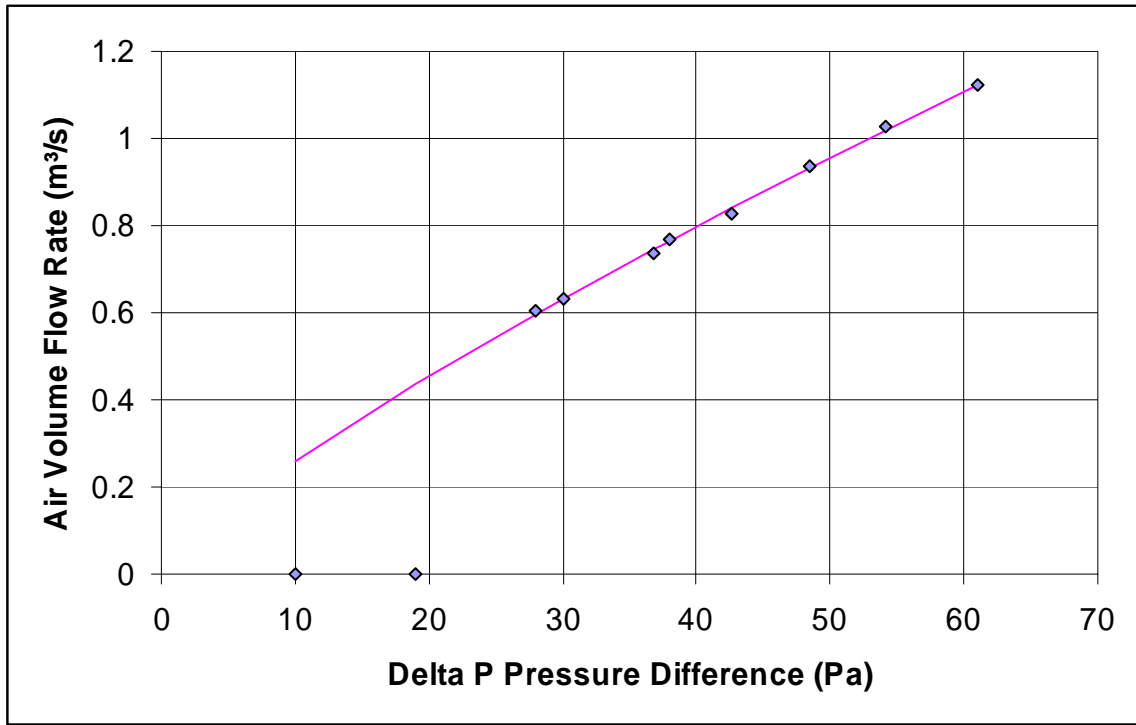


Figure A5 Dwelling 2 during pressurisation, including conservatory.

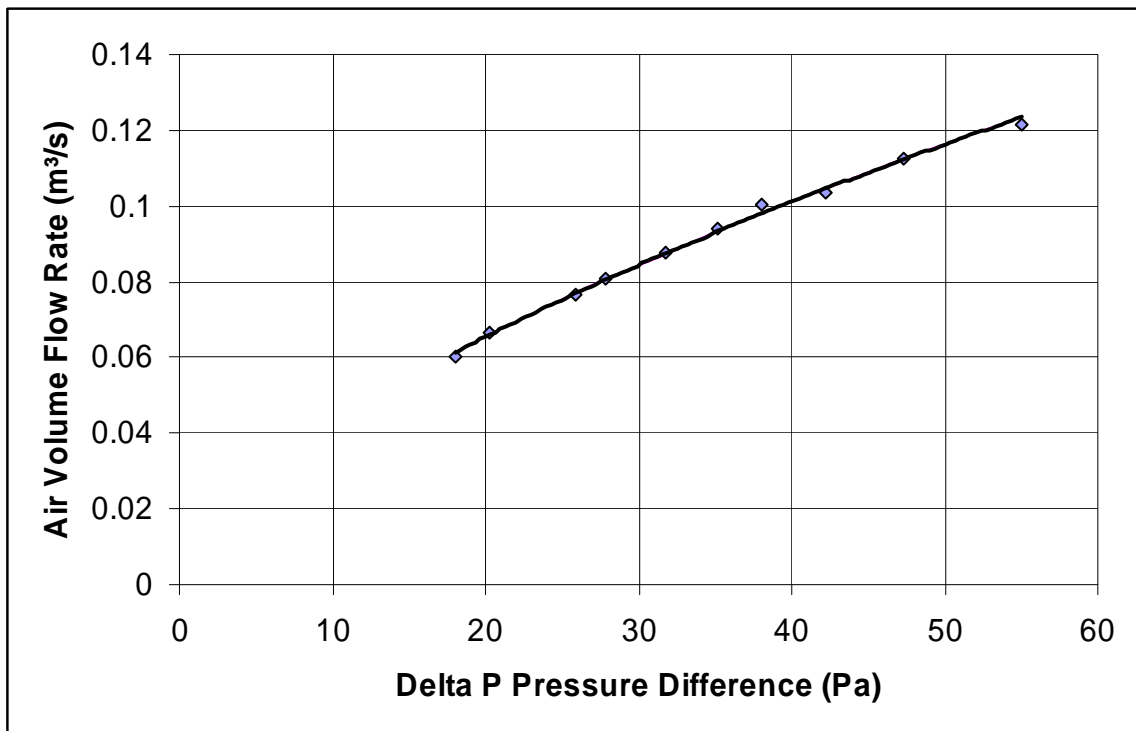


Figure A6 Dwelling 5 during pressurisation, excluding conservatory.

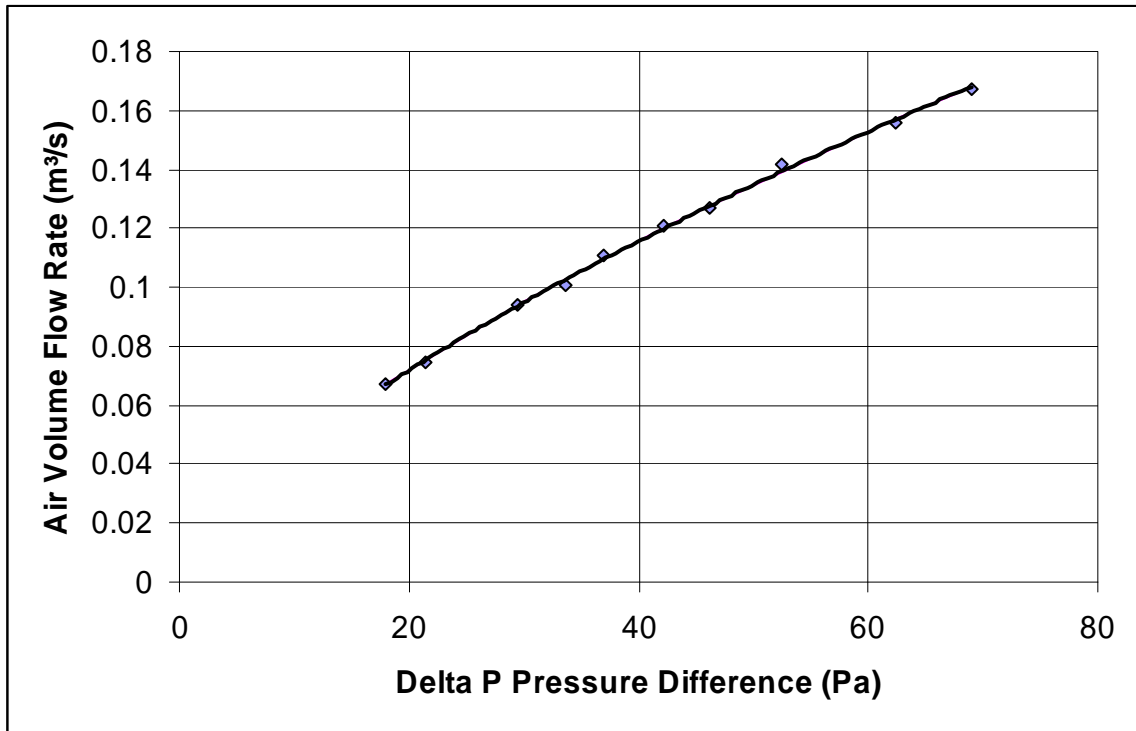


Figure A7 Dwelling 5 during depressurisation, excluding conservatory.

Appendix B



Figure B1 Leakage around trickle ventilator.

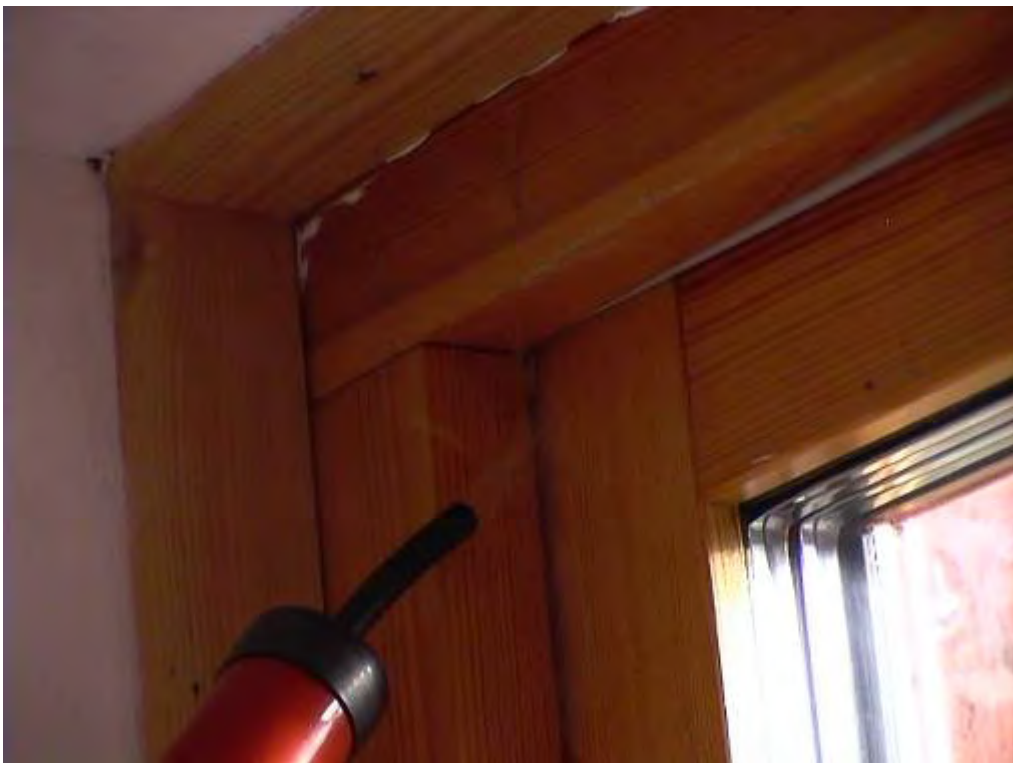


Figure B2 Leakage through opening casement of French door.



Figure B3 Leakage through service penetration in kitchen.



Figure B4 Leakage through boxed in services in the master bedroom.



Figure B5 Leakage through exposed lighting loop in party wall.

Results of Pressurisation Test of The Autonomous Urban House



1 Introduction

This report presents the results of the pressure test carried out on the Autonomous Urban House, Southwell, Nottinghamshire on 6 November 2003. The test was carried out by Neil Prescott of Building Sciences Ltd.

2 Building Description

The Autonomous Urban House is a 2½-storey, four bedroom detached house with an internal floor area of 169 m² (which excludes the unheated basement). A 2-storey lean-to conservatory is attached to the west-facing garden elevation of the dwelling.

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.

3 Air Leakage Standard

A new national standard – TM23 Testing buildings for air leakage (CIBSE, 2000) – has been introduced in the UK, which covers the pressure testing of all buildings. This has been adopted as the test standard for Part L1 of the Building Regulations 2000 (England and Wales), which came into force in April 2002 (ODPM, 2001).

Traditionally, the airtightness of dwellings has been expressed as an air leakage rate in air changes per hour (ac/h). However, the Approved Document Part L1 2002 (England and Wales) is written in terms of air permeability, and compliance can be demonstrated by pressure testing to show that the air permeability does not exceed 10 m³/(h.m²) @ 50Pa (although for dwellings a pressure test is not mandatory).

TM23 (CIBSE, 2000) defines air change rate and air permeability as follows:

Air change rate

This is the volume flow rate per cubic metre of building internal volume (ac/h) at a test pressure of 50Pa.

Air permeability

This is the leakage rate per square metre of building envelope (m³/(h.m²)) at a test pressure of 50Pa. The envelope area taken into account in calculating air permeability is the internal surface area of the external façade, and includes the walls, roofs and the total ground floor area. No deductions are made for partitions or the separating walls with adjacent buildings or garages.

The calculated internal volume and envelope area for the Autonomous Urban House is 429 m³ and 377 m², respectively.

4 Fan Pressurisation System

Fan pressurisation systems are used to quantify the air leakage of the envelope of buildings. The leakiness of the envelope is quantified by connecting a single large fan or a series of fans into an external doorway and pressurising the building whilst measuring the air flow rate required to maintain a pressure difference across the building envelope. The leakier the building, the greater the air flow required to maintain a given pressure differential (in almost all cases a differential of 50Pa is used).

The fan system used on this project consisted of an Infiltec Blower Door (Model E3). All other external doors were kept closed during the test.

Tests are normally carried out when the outside wind speed is low to minimise any wind induced pressure variations. Air volume flow rate Q (m^3/s) through the fans is measured by calibrated flow grids over a suitable range of building pressure differentials ΔP (Pa). These are then corrected for internal/external temperature difference, in accordance with TM23. A best-fit power-law profile of the form $Q=C_{\text{env}} (\Delta P)^n$ is fitted to the data where both the coefficient C_{env} and exponent n are constants.

C_{env} is then corrected for the measured barometric pressure to a specified test pressure of 50Pa, providing C_L .

The theoretical leakage rate at 50Pa is then calculated from the formula:

$$Q_{50}=C_L(\Delta P)^n$$

The air change rate can then be calculated by dividing the air volume flow rate (m^3/h) through the building envelope at a pressure differential of 50Pa (Q_{50}), by the building volume (V). The result is expressed in terms of air changes per hour (ac/h).

To compare the envelope leakage characteristics between buildings of different shapes and sizes, air permeability (Q_{50}/ST) is used. ST is the total internal surface area (m^2). The result is expressed in terms of m^3 leakage per hour per m^2 of envelope area ($\text{m}^3/(\text{h}\cdot\text{m}^2)$).

5 Test Procedure

The mean internal and external temperatures were measured and recorded during the tests. The temperature values recorded were used to standardise the air flow rate through the fan systems to commonly agreed conditions. A further parameter measured was wind speed. If the measured wind speed had been too high (i.e. ≥ 3 m/s) the test would not have been carried out.

The test procedure consisted of pressurising the dwelling to approximately 50Pa then taking a set of measurements of the building pressure differential and flow rate through the fans. The fan speeds were then reduced in several steps and the readings repeated at each of the speed settings. The dwelling was then depressurised, and the test procedure repeated. The result is two sets of measurements; one for pressurisation and one for depressurisation.

The following temporary seals were in place at the time of the tests:

- The through-the-wall balanced MVHR systems in the bathrooms and the kitchen were sealed using duct tape.

In addition, all of the trickle vents were adjusted to the closed position.

6 Results

Each set of measurements of pressure difference and air volume flow rate was averaged and a best-fit power-law profile of the form $Q = C_{env} (\Delta P)^n$ was fitted to the data. The graphs showing the test results are included in Appendix A.

Air change rate

Using the power law profile $Q_{50} = C_L (\Delta P)^n$, the air change rate for the dwelling was determined using Q_{50}/V . The results are illustrated in Table 1 and Figure 1.

Air change rate @ 50Pa (ac/h)		
Pressurisation test	Depressurisation test	Average
4.04	3.74	3.89

Table 1 Air leakage rates of the Autonomous Urban House.

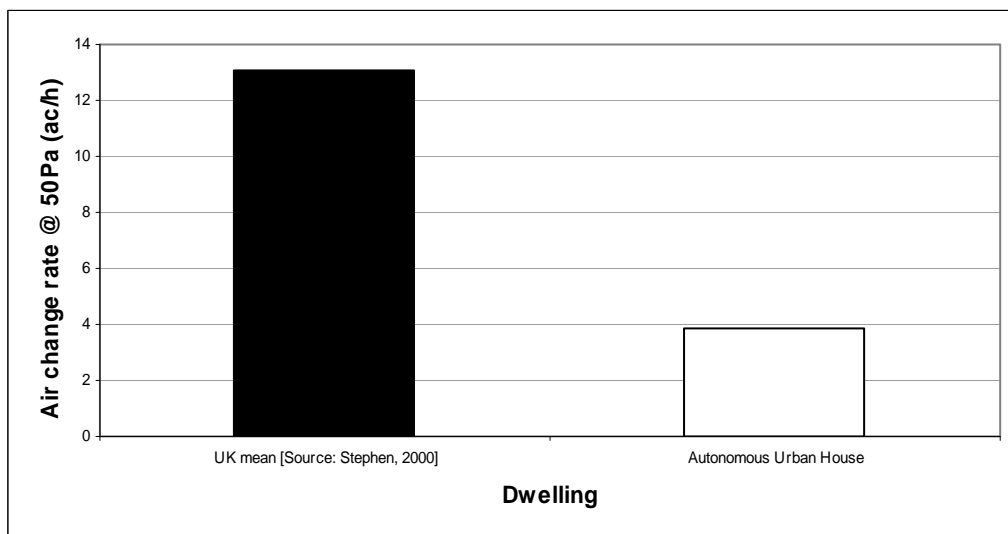


Figure 1 Mean air leakage rate of the Autonomous Urban House.

Figure 1 illustrates that the mean air leakage rate of the Autonomous Urban House is 3.9 ac/h @ 50Pa, a factor of three lower than the UK mean of 13.1 ac/h @ 50Pa (Stephen, 2000).

Air permeability

Using the power law profile $Q_{50}=C_L(\Delta P)^n$, the air permeability of the dwellings was determined using Q_{50}/S_T . The results are illustrated in Table 2 and Figure 2.

Air permeability @ 50Pa ($m^3/(h.m^2)$)		
Pressurisation test	Depressurisation test	Average
4.60	4.25	4.43

Table 2 Air permeability of the Autonomous Urban House.

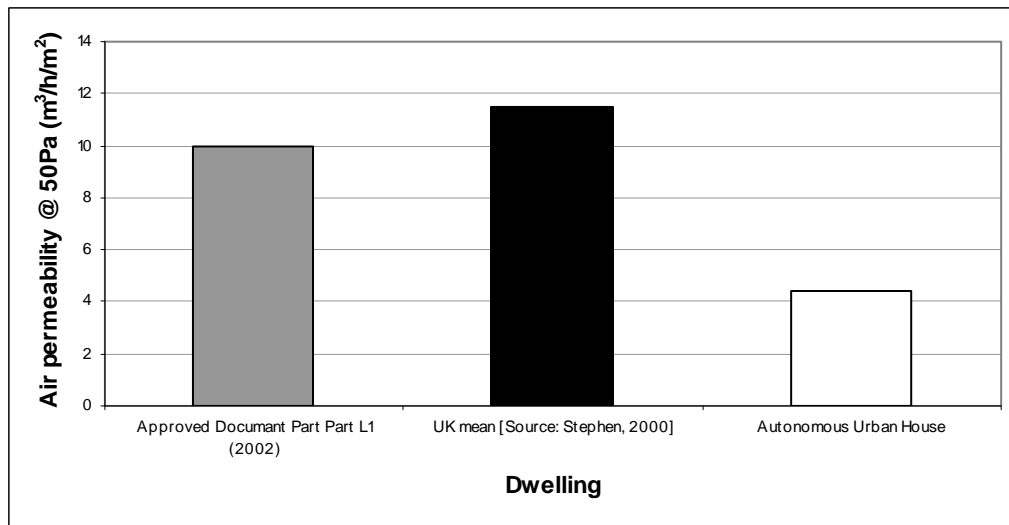


Figure 2 Mean air permeability of the Autonomous Urban House.

Figure 2 illustrates that the mean air permeability of the Autonomous Urban House is $4.4 m^3/(h.m^2)$ @ 50Pa. This is considerably lower than the UK mean of $11.48 m^3/(h.m^2)$, and the maximum specified level of $10 m^3/h/m^2$ that is contained within the Approved Document Part L1 (ODPM, 2001). Therefore, the Autonomous Urban House would satisfy the air leakage criterion set out in Approved Document Part L1.

Leakage identification

The main air leakage paths within the dwelling were identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. Although it was possible to identify the main air leakage paths within the dwelling, it was not possible to quantify the contribution that these leakage paths made to the dwelling's overall air leakage. Nevertheless, the results were informative.

The main air leakage paths observed were as follows:

- Around trickle ventilators.
- At the opening casements of the windows (see Figure B1).
- At the junction between the ceiling and the internal and external walls (see Figure B2).
- Where the vent stack for the composting toilet penetrates the ceiling (see Figure B3).
- At pipework penetrations through the ground floor (see Figure B4).
- Around the lid of the composting toilet (see Figure B5).
- In one instance, at the junction between the window frame and the external wall (see Figure B6).

References

CIBSE (2000) *Testing Buildings for Air Leakage: CIBSE Technical Memoranda TM23: 2000*. London, The Chartered Institute of Building Services Engineers.

ODPM (2001) *The Building Regulations 2000 Approved Document Part L1: Conservation of Fuel and Power in Dwellings. 2002 Edition*. Office of the Deputy Prime Minister, London, HMSO.

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Report Status

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Appendix A

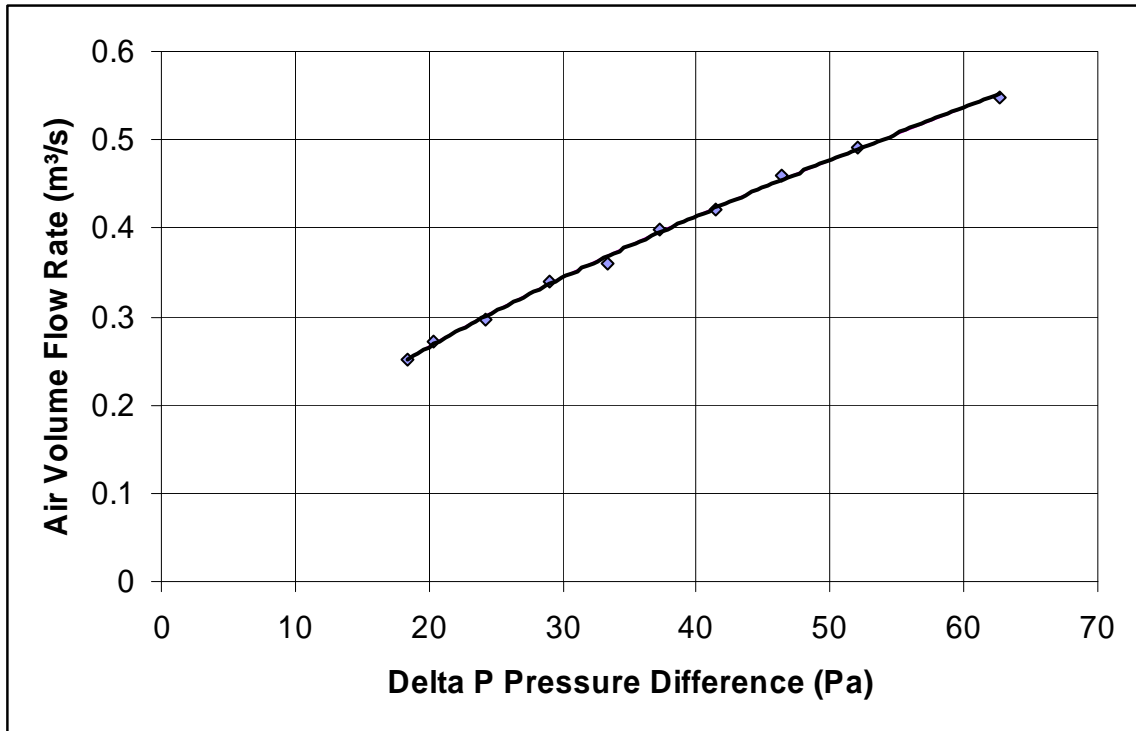


Figure A1 Dwelling during pressurisation.

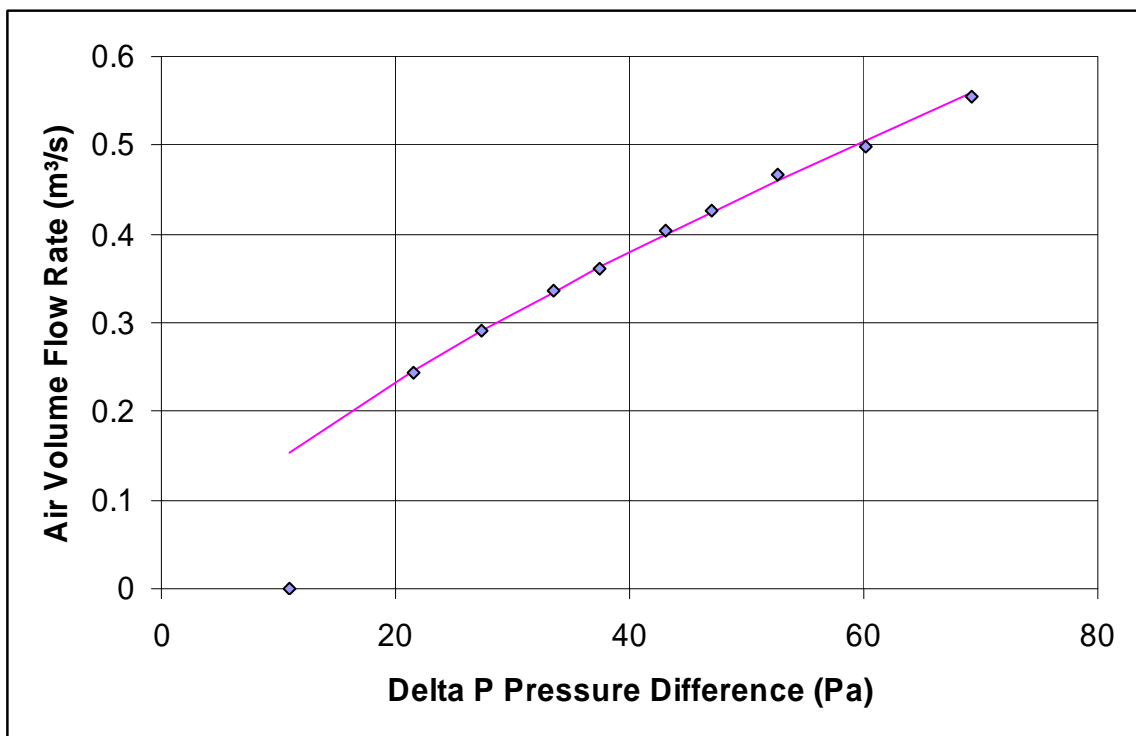


Figure A2 Dwelling during depressurisation.

Appendix B



Figure B1 Leakage through opening casement of window.



Figure B2 Leakage at junction between the ceiling and the internal and external walls.



Figure B3 Leakage at the junction between the vent stack and the ceiling.



Figure B4 Leakage at pipework penetrations through the ground floor.



Figure B5 Leakage around the lid of the composting toilet.



Figure B6 Junction between the window frame and the external wall.

Results of the Pressurisation Test of 3 Gusto Homes Properties



1 Introduction

This report presents the results of the pressure tests carried out on the Gusto Homes Bee Field and Millennium Green sites, on 6 November 2003. The tests were carried out by Neil Prescott of Building Sciences Ltd.

2 Building Description

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 2-storey, 4/5 bedroom detached properties with an internal floor area of 178 m² (Plot A Saturn house type) and 185 m² (Plot B Atlas house type). The Millennium Green dwelling was a 2-storey, 2 bedroom terraced property with an internal floor area of 67 m².

All of the dwellings had 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.

3 Air Leakage Standard

A new national standard – TM23 Testing buildings for air leakage (CIBSE, 2000) – has been introduced in the UK, which covers the pressure testing of all buildings. This has been adopted as the test standard for Part L1 of the Building Regulations 2000 (England and Wales), which came into force in April 2002 (ODPM, 2001).

Traditionally, the airtightness of dwellings has been expressed as an air leakage rate in air changes per hour (ac/h). However, the Approved Document Part L1 2002 (England and Wales) is written in terms of air permeability, and compliance can be demonstrated by pressure testing to show that the air permeability does not exceed 10 m³/(h.m²) @ 50Pa (although for dwellings a pressure test is not mandatory).

TM23 (CIBSE, 2000) defines air change rate and air permeability as follows:

Air change rate

This is the volume flow rate per cubic metre of building internal volume (ac/h) at a test pressure of 50Pa.

Air permeability

This is the leakage rate per square metre of building envelope (m³/(h.m²)) at a test pressure of 50Pa. The envelope area taken into account in calculating air permeability is the internal surface area of the external façade, and includes the walls, roofs and the total ground floor area. No deductions are made for partitions or the separating walls with adjacent buildings or garages.

The calculated internal volume and envelope area for each of the dwellings is shown within Table 1.

Dwelling	Volume (m ³)	Internal surface area (m ²)
Plot A Bee Field Development	433	362
Plot B Bee Field Development	476	399
Plot C Millennium Green Development	159	192

Table 1 Volume and internal surface area of the Gusto Homes dwellings.

4 Fan Pressurisation System

Fan pressurisation systems are used to quantify the air leakage of the envelope of buildings. The leakiness of the envelope is quantified by connecting a single large fan or a series of fans into an external doorway and pressurising the building whilst measuring the air flow rate required to maintain a pressure difference across the building envelope. The leakier the building, the greater the air flow required to maintain a given pressure differential (in almost all cases a differential of 50Pa is used).

The fan system used on this project consisted of an Infiltec Blower Door (Model E3). All other external doors were kept closed during the test.

Tests are normally carried out when the outside wind speed is low to minimise any wind induced pressure variations. Air volume flow rate Q (m³/s) through the fans is measured by calibrated flow grids over a suitable range of building pressure differentials ΔP (Pa). These are then corrected for internal/external temperature difference, in accordance with TM23. A best-fit power-law profile of the form $Q=C_{env} (\Delta P)^n$ is fitted to the data where both the coefficient C_{env} and exponent n are constants.

C_{env} is then corrected for the measured barometric pressure to a specified test pressure of 50Pa, providing C_L .

The theoretical leakage rate at 50Pa is then calculated from the formula:

$$Q_{50}=C_L(\Delta P)^n$$

The air change rate can then be calculated by dividing the air volume flow rate (m³/h) through the building envelope at a pressure differential of 50Pa (Q_{50}), by the building volume (V). The result is expressed in terms of air changes per hour (ac/h).

To compare the envelope leakage characteristics between buildings of different shapes and sizes, air permeability (Q_{50}/ST) is used. ST is the total internal surface area (m²). The result is expressed in terms of m³ leakage per hour per m² of envelope area (m³/(h.m²)).

5 Test Procedure

The mean internal and external temperatures were measured and recorded during the tests. The temperature values recorded were used to standardise the air flow rate through the fan systems to commonly agreed conditions. A further parameter measured was wind speed. If the measured wind speed had been too high (i.e. ≥ 3 m/s) the test would not have been carried out.

The test procedure consisted of pressurising each dwelling to approximately 50Pa then taking a set of measurements of the building pressure differential and flow rate through the fans. The fan speeds were then reduced in several steps and the readings repeated at each of the speed settings. Each dwelling was then depressurised, and the test procedure repeated. The result is two sets of measurements; one for pressurisation and one for depressurisation.

The following temporary seals were in place at the time of the tests:

- The supply and extract ducts of the MVHR system were sealed using duct tape.

In addition, all of the trickle vents were adjusted to the closed position.

6 Results

Each set of measurements of pressure difference and air volume flow rate was averaged and a best-fit power-law profile of the form $Q = C_{env} (\Delta P)^n$ was fitted to the data. The graphs showing the test results are included in Appendix A.

Air change rate

Using the power law profile $Q_{50} = C_L (\Delta P)^n$, the air change rate for each of the dwellings was determined using Q_{50}/V . The results are set out in Table 2 and Figure 1.

Dwelling	Air change rate @ 50Pa (ac/h)		
	Pressurisation test	Depressurisation test	Average
Plot A Bee Field Development	6.09	5.72	5.91
Plot B Bee Field Development	4.06	3.83	3.95
Plot C Millennium Green Development	7.95	7.49	7.72

Table 2 Air leakage rates of the Gusto Homes dwellings.

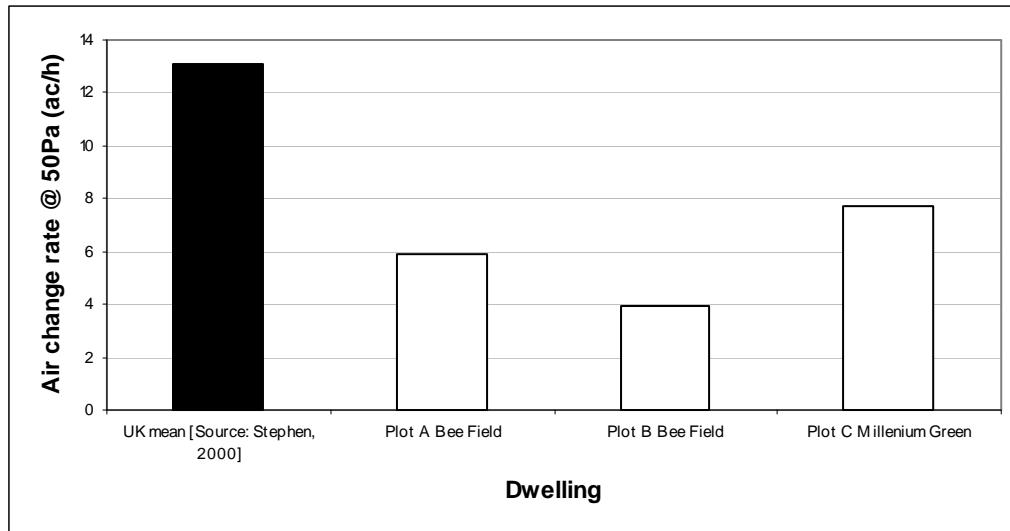


Figure 1 Mean air leakage rates of the Gusto Homes dwellings.

Figure 1 illustrates that the mean air leakage rates of the Gusto Homes dwellings lie between 4 and 7.7 ac/h @ 50Pa. These leakage rates are a factor of two lower than the UK mean of 13.1 ac/h @ 50Pa (Stephen, 2000).

Air permeability

Using the power law profile $Q_{50}=C_L(\Delta P)^n$, the air permeability of the dwellings was determined using Q_{50}/S_T . The results are illustrated in Table 3 and Figure 2.

Dwelling	Air permeability @ 50Pa ($m^3/(h.m^2)$)		
	Pressurisation test	Depressurisation test	Average
Plot A Bee Field Development	7.28	6.84	7.06
Plot B Bee Field Development	4.85	4.58	4.72
Plot C Millennium Green Development	6.59	6.20	6.40

Table 3 Air permeability of the Gusto Homes dwellings.

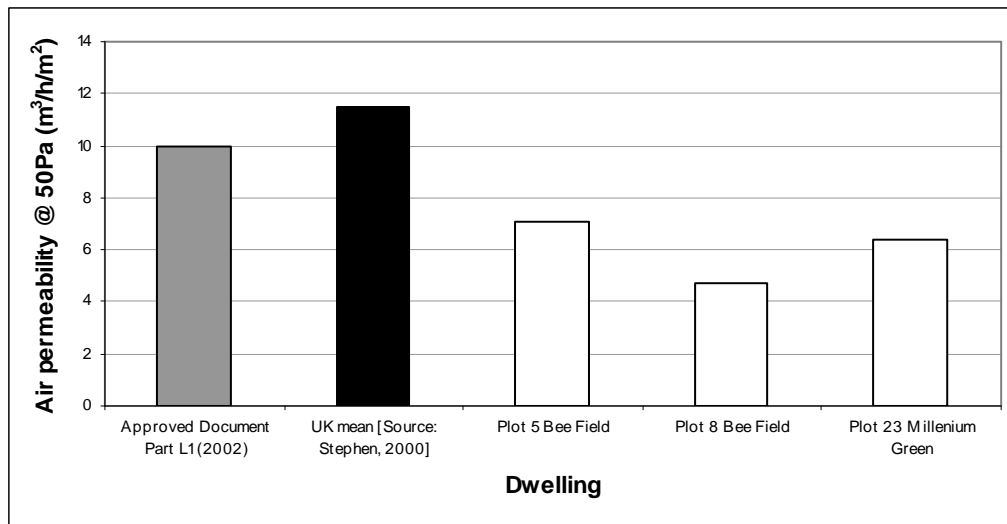


Figure 2 Mean air permeability of the Gusto Homes dwellings.

Figure 2 illustrates that the mean air permeability of the Gusto Homes dwellings lie between 4.7 and 7.1 m³/(h.m²). These figures are significantly lower than the UK mean of 11.48 m³/(h.m²), and the maximum specified level of 10 m³/(h.m²) that is contained within the Approved Document Part L1 (ODPM, 2001). Therefore, all of the dwellings would satisfy the air leakage criterion set out in Approved Document Part L1.

Leakage identification

The main air leakage paths within the dwellings were identified by pressurising the buildings, and locating the main areas of air leakage using hand held smoke generators. Although it was possible to identify the main air leakage paths within the dwellings, it was not possible to quantify the contribution that these leakage paths made to the dwellings' overall air leakage. Nevertheless, the results were informative.

The main air leakage paths observed were as follows:

- Around trickle ventilators.
- The opening casements of the windows and French doors (see Figures B1 and B2).
- Around the loft hatch (see Figure B3).
- Service penetrations in the kitchen of Plot A (see Figure B4).
- At the junction between the upper floor and the external wall (see Figure B5).
- Service penetrations through the first floor of Plot A (see Figures B6 and B7) and Plot C.
- Poorly fitting external door (Plot C).

References

CIBSE (2000) *Testing Buildings for Air Leakage: CIBSE Technical Memoranda TM23: 2000*. London, The Chartered Institute of Building Services Engineers.

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Report Status

The information contained within this report has been produced for the purpose of a research project undertaken by Leeds Metropolitan University for Communities and Local Government. A copy of this report has been provided to Gusto Homes for their own use. The information in this report may be used in material published by Gusto Homes with appropriate acknowledgement and reference.

Disclaimer

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Appendix A

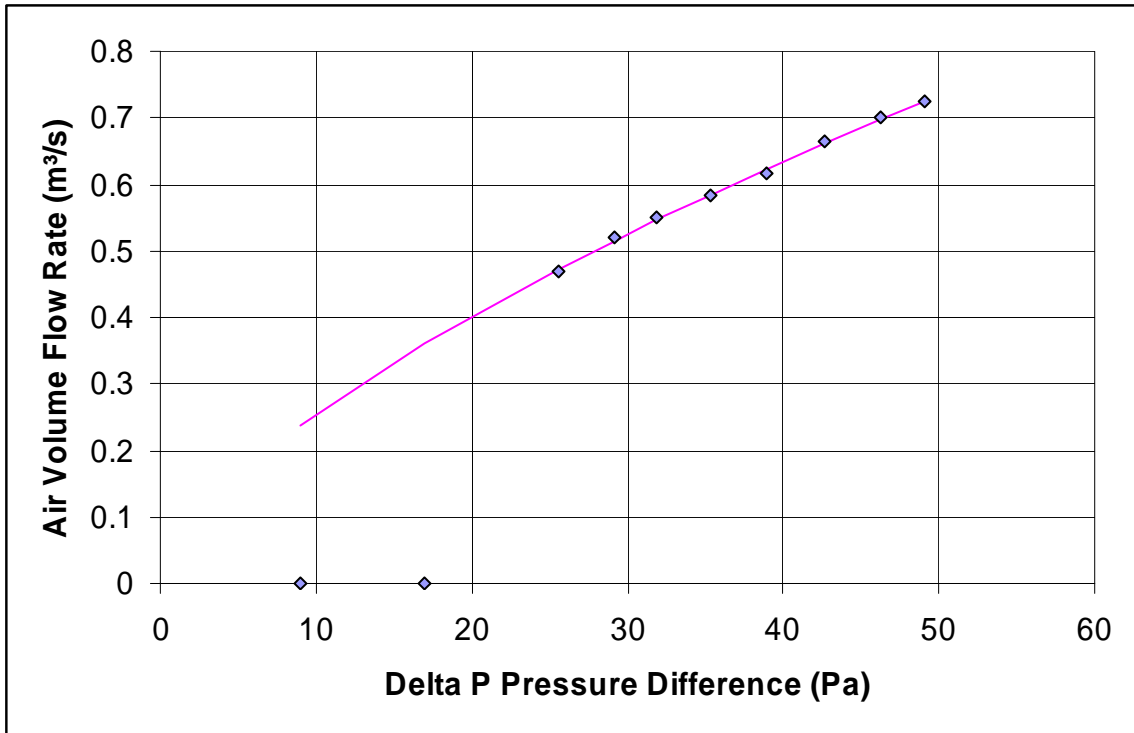


Figure A1 Plot A Bee Field Development during pressurisation.

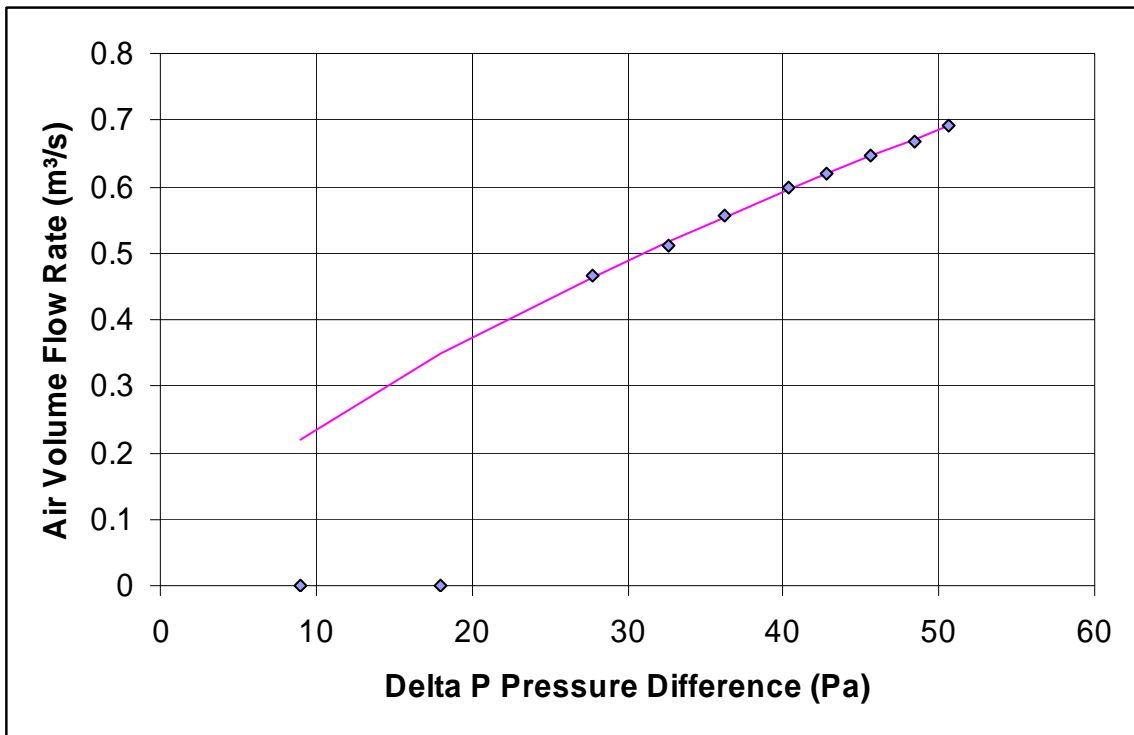


Figure A2 Plot A Bee Field Development during depressurisation.

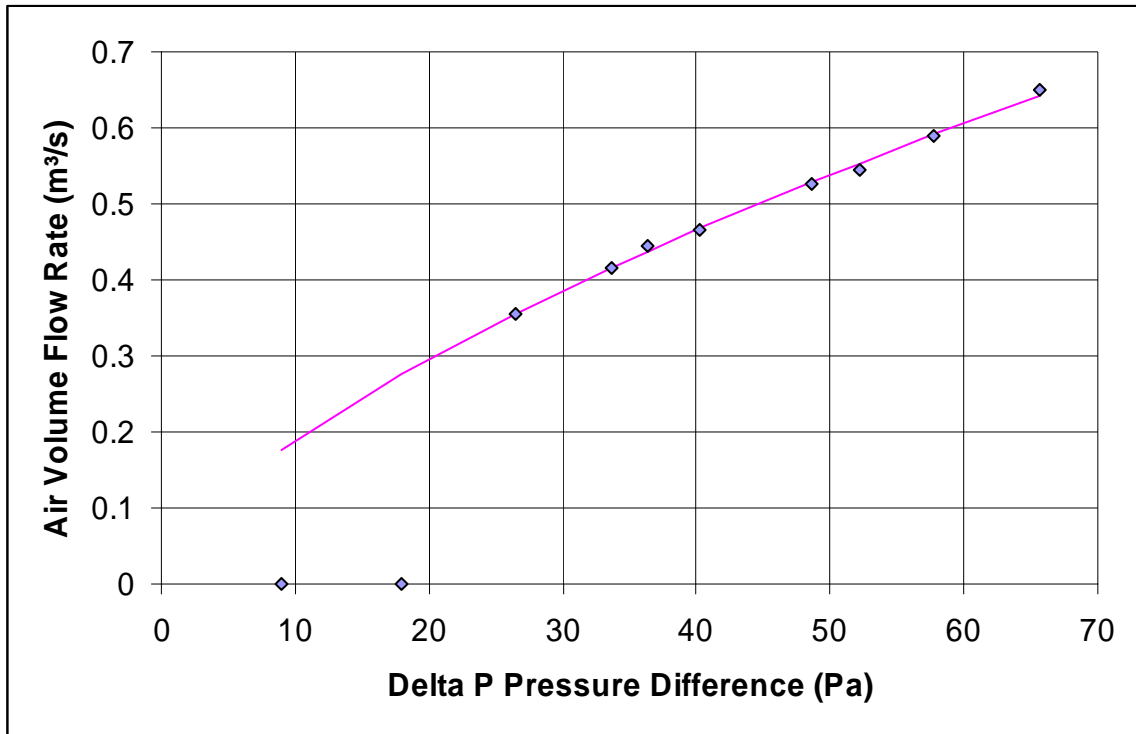


Figure A3 Plot B Bee Field Development during pressurisation.

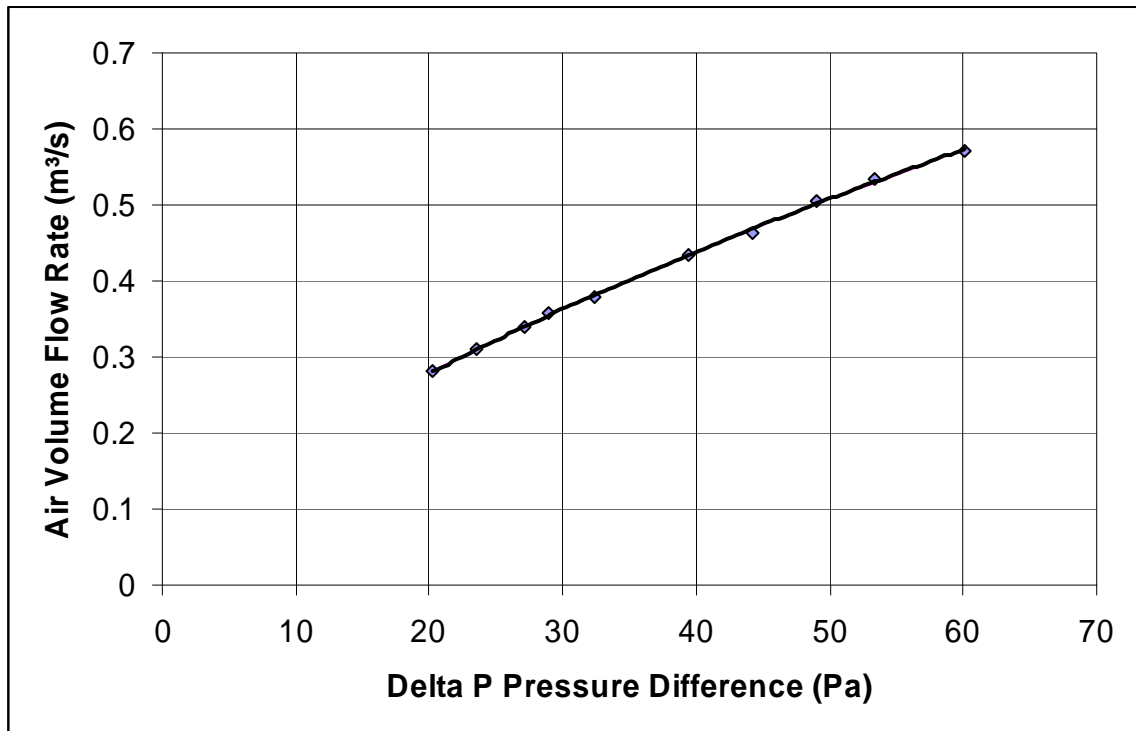


Figure A4 Plot B Bee Field Development during depressurisation.

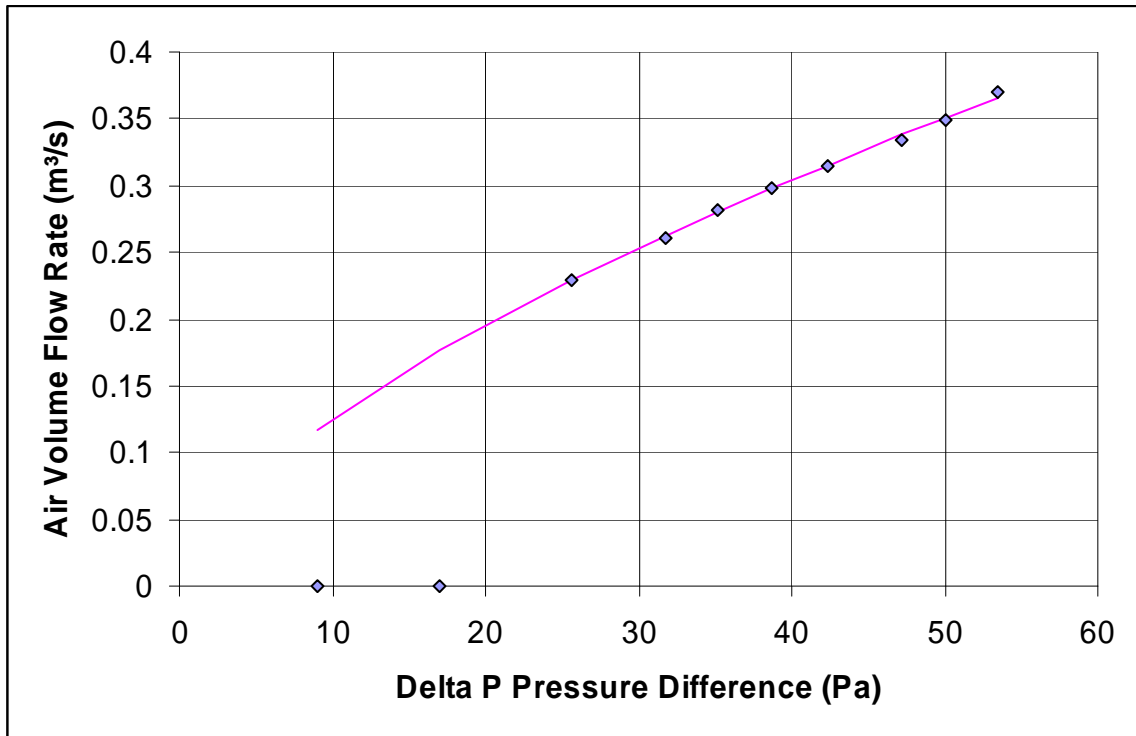


Figure A5 Plot C Millennium Green Development during pressurisation.

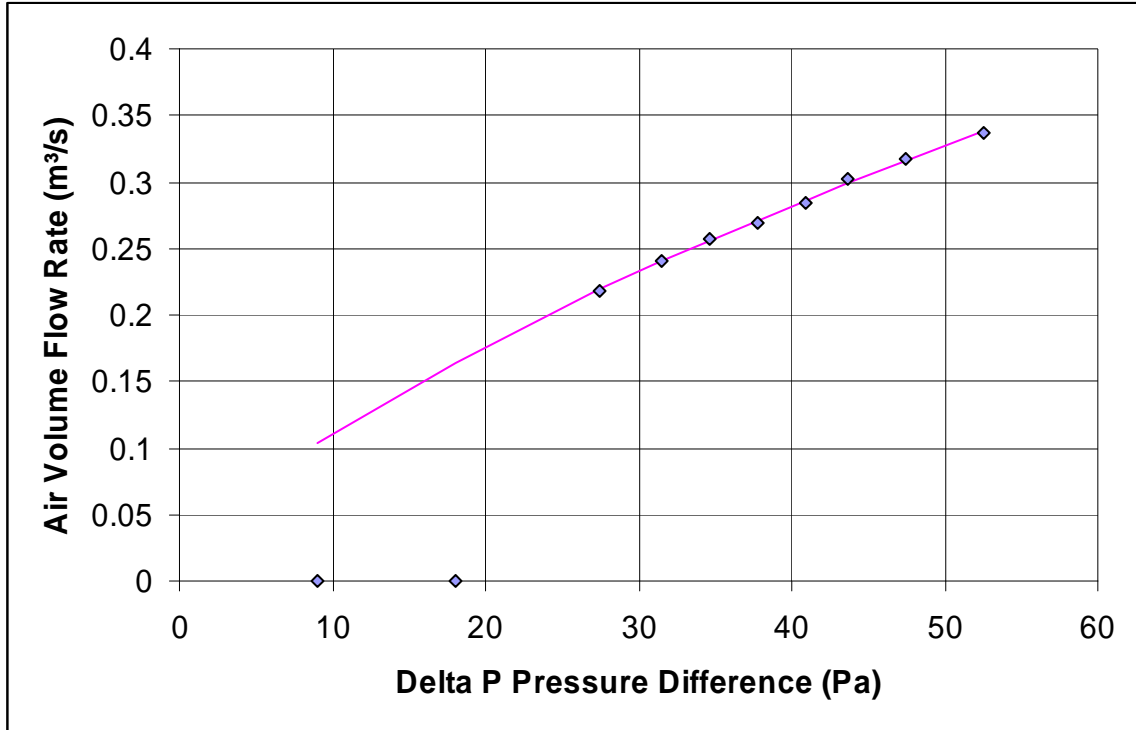


Figure A6 Plot C Millennium Green Development during depressurisation.

Appendix B



Figure B1 Leakage through opening casement of French door.



Figure B2 Leakage through opening casement in window.



Figure B3 Leakage around the loft hatch.



Figure B4 Leakage through service penetrations in the kitchen of Plot A.



Figure B5 Leakage at the external wall/upper floor junction.



Figure B6 Leakage through service penetrations in the first floor bathroom of Plot A.



Figure B7 Leakage through service penetrations in the airing cupboard of Plot A.

Appendix 2

Questionnaires

Airtightness of Buildings — Towards Higher Performance

Occupant questionnaire

A. INTERVIEWEE DETAILS

Name:

Profession:

B. DWELLING DETAILS (obtained from direct observation)

Address:

Type:

detached / semi-detached / terrace / end-terrace

Orientation:

N / S / E / W / other (please specify)

Level of overshadowing:

low / medium / high

Level of exposure:

*sheltered-very sheltered / sheltered-moderate /
moderate-severe / severe / very severe*

C. OCCUPANCY & RESIDENCE DETAILS

First of all, I would like to ask you a number of questions about how your house is occupied and how long you have lived in the house.

1 **How many people live in the house?** *adults* *children*

2 **On average, how is the house occupied?**

- During the day.
- At night.

3 **How long have you lived in this house?** *years* *months*

4 **What type of house did you previously live in?**

- Was it detached / semi-detached / terrace / end-terrace?
- Was it smaller / larger / about the same size as this house?

D. OCCUPANT EXPERIENCE OF THE DWELLING

I would now like to ask you some questions about your experience of living within this house.

5 Could you tell me what your experience has been of ventilation within the house?

In general:

- Has the house ever felt too hot? If so, which parts of the house and when?
- Has the house ever felt too cold? If so, which parts of the house and when?
- Has the house ever felt stuffy? If so, which parts of the house and when?
- Do smells tend to linger or do they dissipate quickly?
- Have you ever experienced any draughts? If so, which parts of the house and when?

6 Could you tell me if you have ever experienced any condensation within the dwelling?

- If yes, could you describe where, when and how often it has occurred?
- Did you take any measures to deal with the condensation?
- If yes, what measures did you undertake?
- Do you feel that these measures were effective?

7 Could you tell me what are the fuel bills like in comparison to other houses that you have lived in?

- Are they higher, lower or about the same?
- What do you think is likely to be the reason for this difference?

E. VENTILATION SYSTEM

Finally, I would like to ask you some questions about how you ventilate your house.

8 How is your house ventilated?

- By opening and closing the windows?
- By operating the trickle ventilators?
- By a mechanical ventilation and heat recovery system?
- By extract fans in the kitchen and bathrooms?
- By a passive stack ventilation system?

9 How do you ventilate the house in the summer / winter?

10 How much control do you feel that you have over ventilation?

- Very little control?
- A reasonable degree of control?
- A lot of control?

11 Do you feel that the ventilation system installed within the house is effective?

Yes

No

- If yes, why do you feel that it is effective?
- If no, why do you feel that it is not effective?

12 Have you ever experienced any problems in ventilating the house?

Yes

No

- If yes, could you describe the sorts of problems that you have encountered?

Thank you for completing this questionnaire.

Airtightness of Buildings — Towards Higher Performance

Designer and builders questionnaire

A. INTERVIEWEE DETAILS

Name:

Profession:

Company:

Number of units constructed per year:

B. DWELLING DETAILS (obtained from direct observation)

Dwelling:

Type of ground floor construction:

solid slab on ground

suspended timber

suspended solid

Type of intermediate floor construction:

timber joists built into wall

timber joists on hangers

concrete

Type of external wall construction:

concrete

cavity masonry timber-frame

other (please specify)

Type of roof construction:

trussed rafter

timber I beam

concrete

other (please specify)

Internal wall finish:

plasterboard dry-lining

wet plaster

Position of airtight barrier within dwelling:

Design air leakage rate:

Has the dwelling previously been pressure tested:

Yes

No

- If yes, what was the result?

C. EXPERIENCE OF DESIGNING THE DWELLING(S)

First of all, I would like to ask you a number of questions about the experienced that you gained when designing the dwelling(s).

1 How did you tackle the problem of ensuring that the dwellings(s) were airtight?

Did you undertake any special measures in terms of:

- Detailed design.
- Site supervision.
- Workmanship.
- Training.
- Education.

2 How would you rate the level of difficulty when designing the dwelling(s) for airtightness?

Was it:

- Very difficult.
- Difficult.
- Not at all difficult.

Why was it:

- Very difficult.
- Difficult.
- Not at all difficult.

3 If you had the opportunity to design the dwelling(s) again, is there anything that you would do differently, during the design phase?

Yes

No

- If yes, what sort of things would you do differently?

D. EXPERIENCE OF CONSTRUCTING THE DWELLING(S)

I would now like to ask you some questions about the experience that you gained when designing the dwelling(s).

4 How did you ensure that airtightness was achieved on-site?

5 How would you rate the level of difficulty when constructing the dwelling(s) for airtightness?

Was it:

- Very difficult.
- Difficult.
- Not at all difficult.

Why was it:

- Very difficult.
- Difficult.
- Not at all difficult.

6 If you had the opportunity to construct the dwelling(s) again, is there anything that you would do differently, during the construction phase?

Yes

No

- If yes, what sort of things would you do differently?

E. VENTILATION SYSTEM

Finally, I would like to ask you some questions about how the dwelling(s) are ventilated.

7 How are the dwelling(s) intended to be ventilated?

- By opening and closing the windows?
- By operating the trickle ventilators?
- By a mechanical ventilation and heat recovery system?
- By extract fans in the kitchen and bathrooms?
- By a passive stack ventilation system?

8 How are the dwelling(s) intended to be ventilated in the summer / winter?

9 How much control do you feel that the occupants have over ventilation?

- Very little control?
- A reasonable degree of control?
- A lot of control?

10 Why did you adopt this particular type of ventilation system?

Thank you for completing this questionnaire.

Appendix 2

Airtightness of buildings — towards higher performance

Interim Report D2 — Developers, Sites and Protocols

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report reviews the progress that has been made on identifying participating developers, suitable developments and house types and establishing the design assessment and site survey protocols.
- 2 Five developers from the commercial and social housing sectors have agreed to participate in the project in principal. However, identification of sites and dwelling types is proving problematic, as a number of available sites are not Part L1 2002 compliant or do not fit in with the project programme. In addition, incorporating certain dwelling types, such as apartments, into the project may prove difficult due to site programming constraints.
- 3 Potential sites have been identified for two of the developers and their programmes are being studied to identify specific dwelling types. For the other three developers, a number of sites have been identified and these are currently being investigated to determine their suitability. Identification of all of the sites and dwelling types will be completed by March 2004.
- 4 A design assessment and a site survey protocol have been devised in order to assess the design and construction phases of each dwelling type. These protocols are based upon a checklisting approach, with the data being stored in a Microsoft Access based project database. This database will incorporate graphic as well as alpha numeric data, and all of the project information will be inter-linked, creating a valuable and searchable resource bank.
- 5 A site access protocol has also been produced. This protocol will be common to both the C1 and L2 projects and will form part of a site and data access agreement for each site.

Introduction

- 6 This report is milestone D2: Developers, sites and protocols of the ODPM Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance*.
- 7 The aim of this report is to identify participating developers, suitable developments and house types and establish the design assessment and site survey protocols (tasks 2.1 and 2.2 of the project proposal).

Identification of Participating Developers, Suitable Developments and House Types

- 8 Five developers from the commercial and social housing sector have agreed to participate in the project in principal. Of the five, three of the developers are large volume house builders, one is an SME which is currently building some social housing and the remaining developer is part of a large privately owned property development company (see Table 1). All five developers were selected based upon their ability to participate in the project, and their involvement in developments in Yorkshire and/or Lancashire.

Developer	Type of company
Developer A	Large volume house builder.
Developer B	Large volume house builder.
Developer C	Large volume house builder.
Developer D	SME
Developer E	Housing arm of a large privately owned property development company.

Table 1 Participating developers.

- 9 In order to select suitable sites (one per developer) and house types (five per site), a set of site selection criteria were devised. These criteria are set out in Table 2 and are based upon the need for the selected dwellings to be as representative of new build as possible.

Criteria	Commentary
Sites must be Part L1 2002 compliant.	
Sites should reflect the principal forms of construction in England and Wales.	The intention is to select sites that are of masonry cavity and timber frame construction. However, finding suitable timber frame sites may prove difficult and will be dependent upon the participating developers.
Sites should have a sufficient number of dwellings available at an appropriate stage of construction.	First five dwellings from each site should be due for completion in May/June 2004. Second five dwellings should be due for completion in May/June 2005.
Dwelling types should reflect the main housing forms that are currently being constructed in England and Wales.	Sites will be selected to give coverage of the following built forms: Detached Semi-detached Terraced Apartments

Table 2 Site selection criteria.

- 10 A number of difficulties have been experienced when trying to identify suitable sites and house types for each of the developers within the allocated timescale. The reasons for these difficulties are as follows:

- a) Gaining agreement, even in principal, from the five developers took longer than anticipated.
 - b) Early feedback from the developers indicated that there may be problems identifying appropriate sites, as a number of the currently available sites were designed to comply with Part L of the 1995 Building Regulations and not Part L1 of the 2002 Building Regulations. This has been compounded by the fact that the chosen sites are also required to fit in with the project programme.
 - c) Feedback from the developers has also indicated that there may be problems identifying certain dwelling types to fit in with the project programme. For instance, apartments have much longer build times than other housing forms and all of the units within a particular block tend to be completed and handed over at the same time. This means that it is very unlikely that any apartments will be ready for pressure testing in May/June 2004, and it may also be difficult to find a site where a second phase of apartments will be ready for pressure testing in May/June 2005.
- 11 These difficulties have meant that it has only been possible to identify potential sites for two of the developers (A and E). Details of these sites can be seen in Table 3. The programmes associated with these sites are currently being investigated to determine appropriate dwelling types. With respect to the three remaining developers, a number of potential sites have been identified, all of which are currently being investigated to determine their suitability.

	Type of development	Type of construction	Dwelling types
Developer A	Private	Masonry cavity	Mixture of apartments, terraced, detached and semi-detached properties — specific examples to be defined depending on programme.
Developer E	Social housing	Masonry cavity	Apartments

Table 3 Details of identified sites.

Impact on the Project Programme

- 12 The issues outlined above have meant that although it has been possible to identify developers and potential sites, it has not been possible to commit to specific sites and dwelling types within the allocated timescale. Despite this, feedback from the developers on identifying specific sites and dwelling types is encouraging and progress is being made on developing the project database (see below). It is anticipated that all of the sites and dwelling types will be identified by the end of March 2004. This is not expected to have any major impact on the overall research programme and it is envisaged that all of the remaining milestones will be unaffected. Details of the sites and the dwelling types will be included within milestone D3: Assessments of Design and Pilot Site Data, which is due at the end of May 2004.

Design Assessment and Site Survey Protocols

- 13 In order to be able to assess the design and the construction of each house type (five house types per developer), two protocols have been developed:
- a) **Design assessment protocol.** This protocol assesses and records the information contained within the detailed design drawings.
 - b) **Site survey protocol.** This protocol assesses and records the construction work on site.
- 14 It is intended that the design assessment protocol will be completed as soon as detailed design drawings can be forwarded onto the project team. Information obtained from the literature review (see Interim Report D1 — Literature Review and Built Examples by Johnston, Wingfield and Bell, 2004) on factors such as; the main air leakage paths, the position of the air barrier, continuity of the air barrier, etc. will be used to inform the design assessment.
- 15 The literature review will also be used to inform the site assessment. The site assessment will be completed in three separate stages. These stages are as follows:

- a) **Stage 1: During intermediate floor construction.** This will enable inspection of the method of supporting the intermediate floors and enable any potential leakage problems to be identified.
 - b) **Stage 2: During dry-lining/wet plaster phase.** This will enable inspection of the internal leaf of the external walls, the application of the dry-lining, inspection of window/wall junctions, inspection of service penetrations, etc.
 - c) **Stage 3: Completion.** This will enable identification of any potential leakage areas that have not been picked up during the 'snagging' process.
- 16 Both the design assessment and the site survey protocols are based upon the checklisting approach developed by the BRE (see Webb and Barton, 2001 and Webb, Barton and Scivyer, 2001). Consequently, both protocols contain a series of checklists that cover the main elements of each dwelling. These checklists are not only designed to be compatible with one another, but they are also designed to be compatible with the data input requirements of the project database.
- 17 The checklists that are incorporated within each protocol are as follows:
- a) Dwelling details.
 - b) Dimensions and built form.
 - c) Ground floor.
 - d) External walls.
 - e) External windows and doors.
 - f) Intermediate flooring.
 - g) Ceiling junction.
- 18 A copy of the design assessment and the site survey protocol can be found within Appendices 1 and 2, respectively.

Site Access Protocol

- 19 In addition to the design assessment and site survey protocols, a site access protocol has also been produced. The protocol seeks to ensure clarity on matters of role and to enable key ethical issues, such as informed consent and the preservation of anonymity, to be dealt with and agreed between the research team and the individual developers and site staff. This protocol has been developed for both the L2 (Reference No: CI 61/6/16 BD2429) and the C1 (Reference No: CI 71/6/1 BD2414) projects (see Smith and Bell, 2004), and will be used as part of a site and data access agreement for each site. A copy of the protocol is contained within Appendix 3. Copies of this protocol have been circulated to the developers for comment and adoption.

Project database

- 20 The data obtained from the design assessment and site survey protocols will be stored in a project database. This database will be common to both the L2 (Reference No: CI 61/6/16 BD2429) and the C1 (Reference No: CI 71/6/1 BD2414) projects. As well as holding information obtained from the design assessment and site survey protocols, the database will also store further graphical and alpha numeric information that has been obtained from drawings, site visits and other updates. All of these data will be inter-linked to provide a valuable, searchable resource bank.
- 21 Microsoft Access will be used to create the database, with hyperlinks set up to allow for the viewing of photographs, Microsoft Excel analysis spreadsheets, Autodesk AutoCAD drawing files, and any additional information (e.g. word documents, adobe acrobat files, etc.).
- 22 The opening screen will be a switchboard containing various command buttons. These buttons will allow access to custom made forms, with lists of records generated by predetermined sorts, filters and queries. Examples of these are contained within Appendix 4. To ensure confidentiality developers will only be referred to by reference numbers and site locations will only be listed as a region; details of both will be available to group members through either intranet permissions or internet passwords.
- 23 The database will initially be held on a PC within the Centre for the Built Environment (CeBE). Full administrative privileges will only be available to members of the group who need to input data, run filters and queries, and alter designs; read-only access will be available to other group members through intranet links and file sharing permissions. This will develop, allowing web access, with confidential information accessible only by the use of registered user names and passwords.
- 24 The user will be able to search a list of sites and view details, which may include links to photographs, drawings (with appropriate permission if required), and site analysis. Various

automated searches, queries and filters will be available – e.g. search by project, search by construction type, filter by date, etc. the results of which will be presented on screen in either form or report format, whichever is most suitable.

- 25 Group members will be able to access the developer details and additional site details (address and contact details) to utilise the database further.

Conclusions

- 26 This report reviews the progress that has been made on identifying participating developers, suitable developments and house types, and establishing the design assessment and site survey protocols.
- 27 Five developers have agreed to participate in the project in principal. Three of the developers are large volume house builders; one is an SME and the other is the housing arm of a large privately owned property development company.
- 28 Criteria have been devised to aid the selection of sites and dwelling types from each developer. However, identification of appropriate sites is proving problematic. The reasons for this appear to be three-fold. First of all, gaining agreement, even in principal, from the developers took longer than expected. Secondly, a number of potential sites are either not Part L1 2002 compliant or do not fit in with the project programme. Finally, utilising certain dwelling types, for instance apartments, may prove difficult due to programming constraints.
- 29 Potential sites have been identified for two of the developers and their programmes are currently being investigated in order to identify specific dwelling types. Various sites have been identified for the other three developers, and these are currently being investigated to determine their suitability. It is anticipated that all of the sites and dwelling types will be identified by the end of March 2004 and this will not have any adverse impact on the overall project programme.
- 30 A design assessment and a site survey protocol have been produced. These protocols compliment one another and consist of a series of checklists that cover the main elements of each dwelling. The data obtained from these checklists will be stored in a Microsoft Access based project database, which will also incorporate graphical and alpha numeric information that has been obtained from drawings, site visits and the pressurisation tests. The adoption of such a platform will enable all of the project information to be inter-linked, creating a valuable and searchable resource bank.
- 31 A site access protocol has also been produced. This protocol will be common to both the C1 and L2 projects and will form part of a site and data access agreement for each site.

References

JOHNSTON, D. WINGFIELD, J. and BELL, M (2004) Airtightness of Buildings — Towards Higher Performance. *Interim Report D1— Literature Review and Built Examples*. A Report to Communities and Local Government Building Regulations Division Under the Building Operational Performance Framework. Project Reference Number CI 61/6/16 (BD2429), Leeds Metropolitan University, Leeds.

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Appendix 1

Design assessment protocol

Design assessment protocol

Name of assessor:

Date of assessment:

Dwelling details	
Site reference	
Plot No.	
Location	
Address	
Developer	
Development type	Private
	Social housing
Development size	(total number of units)
Programme start date	
Programme end date	
Other details	

Dimensions & Build Form	
Ground floor area	m ²
Total envelope surface area	m ²
Volume	m ³
No. of storeys	
Type of dwelling	Detached Semi-detached Mid-terrace End-terrace Apartment
Construction type	Masonry cavity full fill Masonry cavity partial fill Timber frame
Position of air barrier	
Other details	

Ground Floor				
Construction type	Concrete slab on ground	Concrete suspended	Timber T&G	Timber butted
Is air barrier continuous between ground floor & ext. walls?	Yes		No	
If Yes, give details				
Are service penetrations sealed?	Yes		No	
If Yes, give details				
Other details				

External Walls			
Construction type	Masonry cavity full fill	Masonry cavity partial fill	Timber frame
Internal finish	Dry-lining		Wet plaster
If dry-lining, are continuous ribbons of plaster used?	Yes		No
Are service penetrations sealed?	Yes		No
If Yes, give details			
Other details			

External Windows and Doors		
Are windows/doors draughtstripped?	Yes	No
Are window/door frames sealed to external wall internally?	Yes	No
If Yes, give details		
Are window/door frames sealed to external wall externally?	Yes	No
If Yes, give details		
Are window/door sills/thresholds sealed to external wall internally?	Yes	No
If Yes, give details		
Are window/door sills/thresholds sealed to external wall externally?	Yes	No
If Yes, give details		
Do windows contain trickle vents?	Yes	No
Other details		

Intermediate Flooring			
Construction type	Timber joist	Timber I-beam	Concrete
External wall junction/method of support	Built-In		Joist hangers
Is external wall/intermediate floor junction sealed?	Yes		No
If Yes, give details			
Are service penetrations sealed?	Yes		No
If Yes, give details			
Other details			

Ceiling Junction		
Is air barrier continuous between ceiling and external walls?	Yes	No
If Yes, give details		
Is ceiling continuous above partition walls?	Yes	No
Are service penetrations sealed?	Yes	No
If Yes, give details		
Is loft hatch draughtstripped?	Yes	No
If Yes, give details		
Is loft hatch sealed to ceiling?	Yes	No
If Yes, give details		
Other details		

Appendix 2

Site survey protocol

Site survey protocol

Name of assessor:

Date of visit:

Dwelling details	
Site reference	
Plot No.	
Location	
Address	
Developer	
Development type	Private
	Social housing
Development size	(total number of units)
Programme start date	
Programme end date	
Other details	

Dimensions and Build Form	
Ground floor area	m ²
Total envelope surface area	m ²
Volume	m ³
No. of storeys	
Type of dwelling	Detached Semi-detached Mid-terrace End-terrace Apartment
Construction type	Masonry cavity full fill Masonry cavity partial fill Timber frame
Position of air barrier	
Other details	

Ground Floor				
Construction type	Concrete slab on ground	Concrete suspended	Timber T&G	Timber butted
Is air barrier continuous between ground floor & ext. walls?	Yes		No	
If Yes, give details				
Are service penetrations sealed?	Yes		No	
If Yes, give details				
If No, give details				
Are there any additional service penetrations?	Yes		No	
If Yes, give details				
Other details				

External Walls			
Construction type	Masonry cavity full fill	Masonry cavity partial fill	Timber frame
Internal finish	Dry-lining		Wet plaster
If dry-lining, are continuous ribbons of plaster used?	Yes		No
If No, give details			
Are perpend fully filled?	Yes		No
Are there any obvious cracks or gaps in the external walls?	Yes		No
If Yes, give details			
Are there any areas of unfinished plaster/dry-lining?	Yes		No
If Yes, give details			
Are service penetrations sealed?	Yes		No
If Yes, give details			
If No, give details			
Other details			

External Windows and Doors		
Are windows/doors draughtstripped?	Yes	No
Does draughtstripping compress when windows/doors are closed?	Yes	No
If No, give details		
Are window/door frames sealed to external wall internally?	Yes	No
If Yes, give details		
Are window/door frames sealed to external wall externally?	Yes	No
If Yes, give details		
Are window sills/door thresholds sealed to external wall internally?	Yes	No
If Yes, give details		
Are window sills/door thresholds sealed to external wall externally?	Yes	No
If Yes, give details		
Do windows/doors fit and close correctly?	Yes	No
If No, give details		
Do windows contain trickle vents?	Yes	No
If Yes, do trickle vents close completely?	Yes	No
If No, give details		
Other details		

Intermediate Flooring			
Construction type	Timber joist	Timber I-beam	Concrete
External wall junction/method of support	Built-In		Joist hangers
If built-in, method of sealing joists to external walls			
Is external wall/intermediate floor junction sealed?	Yes	No	
If Yes, give details			
If No, give details			
Are service penetrations sealed?	Yes	No	
If Yes, give details			
If No, give details			
Are there any additional service penetrations?	Yes	No	
If Yes, give details			
Other details			

Ceiling Junction		
Is air barrier continuous between ceiling and external walls?	Yes	No
If Yes, give details		
If No, give details		
Is ceiling continuous above partition walls?	Yes	No
Are service penetrations sealed?	Yes	No
If Yes, give details		
Are there any additional service penetrations?	Yes	No
If Yes, give details		
Is loft hatch draughtstripped?	Yes	No
If Yes, give details		
Is loft hatch sealed to ceiling?	Yes	No
If Yes, give details		
Other details		

Appendix 3

Site access protocol

Standard Protocol on the Access to Development Sites for the Purposes of Data Collection

Information to developers

Prior to researchers undertaking site observations the developer will be provided with a summary of the research project which will include an outline of the purposes of the site data collection.

Health and safety

It is acknowledged that construction sites are potentially dangerous places and that every one has a responsibility for their own health, safety and wellbeing and that of those around them. In gaining access to any site, each researcher will wear appropriate personal protective equipment. In all cases this will consist of a safety helmet, safety boots and a high visibility vest or coat. Additional equipment will be used as appropriate depending on the requirements of a particular site. On their first visit to a site each researcher will expect to receive a safety briefing given by a designated member of the site management team. On every visit researchers will inform site management of their presence and of the areas they expect to work. When they leave a site, researchers will inform site management. A site visit risk assessment will be carried out by the research team and lodged in the university.

Insurance

The university will maintain all necessary indemnity insurance cover for its staff working on the developer's site.

Site data collection

The role of the researcher is to collect data on the design and construction works taking place on the site in question. This may be done by way of personal observation involving sketching, note taking and the taking of photographs or video material. In specified circumstances and with the agreement of the site manager and site personnel concerned, data may also be collected by way of interview (either individually or in groups) which may be recorded using photographs or audio/video tape or in written notes. Any tape recording will only be done with the express permission of the person being interviewed and will be subject to the general safeguards on photographs and video and audio tape recording set out below.

Observations relating to construction and design quality

As part of the research project observations will often involve items that could be classed as defects in either design and/or construction. Such observations will normally be part of the project and will be referred to in project reports, subject to the general assurances on reporting outlined below. In general, researchers will be under no obligation to report specific instances to the developer, or any other person outside the research team unless the defect observed is thought likely to have an adverse impact on health and safety. In such cases the researcher will bring the instance to the attention of the person in charge of the site. It will then be the responsibility of the site management to take the appropriate action.

Professional responsibility of researchers

The responsibility of researchers extends to the recording and interpretation of data for the purposes of the research project only. Researchers will be under strict instructions not to interfere with construction processes or give advice to site staff or operatives. Nothing that is done or not done by researchers in the course of their work should be interpreted as providing a professional service to the developer or his consultants, contractors or subcontractors. Researchers are instructed not to give advice, irrespective of their professional qualifications, and any comments they may make or questions they ask should not be interpreted as providing a professional service or professional advice.

Photographs

In general photographs of sites, buildings and building details will seek to avoid the inclusion of people and items that could identify the site. Where this is unavoidable and individuals are likely to be recognisable or where it is desirable to include people, the verbal permission of the individuals in question will be sought at the time of taking the photograph. In seeking permission it will be made clear that the picture could appear in project publications. Where it is not possible to avoid signs or site boards that could identify a particular site, either permission to use the picture in research publications will be sought from the developers or any published version of the photograph will have identification signs obscured or removed.

Video and audio recording

In every case where a researcher wishes to record an interview or group discussion, the permission of the interviewee or group will be sought. As a minimum, this will be done verbally immediately prior to the recording. All recorded material will be kept secure and used only for reference purposes by the research team. Following the production of the final report on a project the tapes will be erased and will not be included in the project data archive. In some cases transcripts of recordings may be produced and these will be returned to the interviewee for comment prior to the production of a final version. Checked transcripts and notes compiled with the aid of the recorded material may be retained, in anonymous form, as part of the data archive. Short illustrative extracts of recordings may be used in project reports but anonymity will be preserved unless agreed by the interviewee before the extract is attributed. Agreement to the taping of an interview will be on this basis.

Anonymity

As a general principle the anonymity of developers and their staff will be preserved where ever possible. However, it is expected that developers will wish to be acknowledged as a partner in the research. The appropriate and feasible level of anonymity will be discussed with each developer prior to their confirmation of involvement in the research project and reviewed during the course of the project. If a high degree of anonymity is important to a developer the company must be aware of the risks before agreeing to take part. However, the anonymity of individuals is more straightforward unless the project involves a high profile individual.

Project reports

Descriptions of sites and organisations will be in accordance with the level of anonymity agreed with each developer and/or individuals involved. The use and attribution of photographs, drawings and interview material collected by researchers, together with any material provided by the developer or their consultants or contractors, will adhere to the appropriate level of anonymity agreed prior to publication.

Provision of reports to developers

Wherever feasible and subject to the research needs of the project, developers will be provided with a report on the data collected from their site. This report will identify the developer's site or sites and will, normally be a confidential report. An anonymous version of the report will be retained in the data archive and the data and other material will be used in project reports, as indicated above. Subject to the terms of the Building Regulations framework agreement the project report will also be made available to the developer so that they can judge the findings from their sites against the general findings of the project as a whole.

Copyright

All material produced by the research team, including site sketches, notes and photographs will rest with the research team and be subject to the terms of the framework contract. Material provided by third parties (principally drawings provided by developers and their designers and contractors) will be subject to copyright. It should be made clear to the owners of the copyright that in supplying the material they agree to its use for illustration and review purposes in project publications with suitable attribution commensurate with an agreed level of anonymity.

Confidentiality

The data collected from the developer during the normal course of the research project will not be considered to be confidential but it will be subject to an agreed level of anonymity as indicated above. However, during the course of the project researchers may have access to sensitive information. Where researchers are provided with material that is not part of the normal data collection required for the conduct of the project, they will be expected to confirm its confidentiality status with the developer. Where the developer requires it, the material will be treated as confidential and not disclosed outside the research team. Where such material comes into the hands of researchers inadvertently, that material will be treated as confidential, the developer informed and the material in question returned as soon as possible.

Malcolm Bell and Melanie Smith
Leeds Metropolitan University
20 January 2004

Signed.....
For and on behalf of Leeds Met University

Dated.....

Signed.....
For and on behalf of XXXXXXX (Partner)

Dated.....

Appendix 4

Project database

The screenshot shows a Microsoft Access window titled "Microsoft Access - [Developers]". The form displays the following data:

DeveloperID	1
Developer	Lemmeleg Building and ContractingLtd
Contact Name	Phil Hughes
Contact Title	Managing Director
Address	3 West Parade
City	Wakefield
Post Code	WF1 1LT
County	West Yorkshire
Phone Number	01924 369726
Fax Number	01924 215161
Email Address	admin@lemmeleg.co.uk
Notes	Mob. 07734 983860 - philh@lemmeleg.co.uk Construction Manager: Geoff Roberts, Mob. 07764 377932 - geoffr@lemmeleg.co.uk

Record: 1 of 2
Form View

Example of a form from the project database.

The screenshot shows a Microsoft Access window titled "Microsoft Access - [Sites by Region]". The report displays the following data:

State/Province	Project Begin Date	Project End Date	Project ID
West Yorkshire	Mar 2004	Dec 2004	1
Project Description			
3 Executive Houses, Masonary, Filled cavity			
Notes			
DeveloperID			
1			

19 February 2004 Page 1 of 1

Example of a report from the project database.

Appendix 3

Airtightness of buildings — towards higher performance

Interim Report D3 — Assessments of design and pilot site data

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report reviews the progress that has been made on assessing the design drawings and the site survey data that have been obtained for the selected sites.
- 2 The design assessment and site survey protocols have been piloted on one of the selected sites and modified as appropriate. In addition, an Airtightness Rating has been incorporated into both of the protocols. This rating is a judgement based upon the following: the extent to which the design as specified is likely to achieve an airtight construction; and, the extent to which the specification can or will be achieved on site. The higher the rating, the greater the chance that the specification will be achieved on site and the greater the chance that the dwelling will be airtight. The rating will be used to rank the selected dwellings against one another.
- 3 Drawings have been received from three of the five developers. Design assessments have been undertaken for 10 of the selected dwellings and site surveys have commenced on 12 of the dwellings. The main points that have been obtained from the drawing assessments and site surveys are as follows:
 - a) There is considerable variation in the way in which the information relating to air leakage is presented in the submitted drawings. In the case of two of the developers, the majority of the information is textual material which is contained within a general arrangement drawing and very little reference is made to any other drawings. This contrasts with the approach adopted by one of the other developers, where some reference to air leakage is made within the general arrangements drawings, but the majority of the textual and graphical information on air leakage is contained within various standard details that are drawn to a scale of 1:10 and indicate explicitly where sealing work has to be undertaken. Although we are yet to see how the information contained within the drawings is used on site, it is expected that the greater the amount of detail on airtightness that is presented within the drawings, the higher the levels of airtightness that will be achieved.
 - b) All of the drawings submitted state that they have been amended to comply with Approved Document L1 or are designed in accordance with Robust Details (DEFRA, 2001).
 - c) None of the drawings contains an explicit air leakage target other than a general reference to Approved Document L1 or Robust Details.
 - d) None of the drawings makes reference to a higher standard of air leakage than that contained within Approved Document L1.
 - e) None of the dwellings submitted identifies the location of the air barrier either within the text or on the drawings. In addition, none of the drawings states that the air barrier should be continuous around the envelope.
 - f) It has been inferred from the submitted drawings that the construction principle used to achieve airtightness within all of the dwellings is the airtight internal cladding approach (see Elmroth and Levin, 1983 and Carlsson, Elmroth and Engvall, 1980).
 - g) All of the drawings that have been submitted identify areas where attention to detail is required on site to achieve airtightness. In some cases, this will be very difficult to achieve. For instance, applying sealing around the perimeter of plasterboard linings to external walls and openings with continuous ribbons of plaster.
 - h) For two of the developers, the drawings state that the timber I-beams that are used to support the intermediate floors are built into the internal leaf of the external wall, sealed with mortar, and then sealed using a mastic sealant. Site observations indicate that in a number of cases, the mastic has only been partially applied around the bottom flange and the web of the timber I-beams. In addition, since the mastic sealant has been applied after the floor finish has been installed, it is very difficult or impossible to seal the top flange of the timber I-beams.
 - i) For two of the developers, the timber I-beams that are used to support the intermediate floors are offset from the inner leaf of the external/party wall to allow services to be run from one floor to the next. In a number of dwellings this offset is so small that it is not possible to seal the area between the joist and the external/party wall using mortar and mastic sealant. The result is that in a number of the dwellings, it is possible to see through the cavity to the external brick skin.
- 4 There appears to be real practical problems achieving certain specifications on site. This may be attributable to a lack of foresight during detailed design or a lack of understanding by the operatives that undertake this work on site.

Introduction

- 5 This report is milestone D3: Assessment of the Design and Pilot Site Data of the Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003).
- 6 The aim of this report is to summarise the progress that has been made on assessing the design drawings and the site data that have been obtained for Phase 1 of the above project (tasks 2.1.3 and 2.1.4 of the project proposal). Details of the developers, the sites and the dwellings that are participating in this phase of the project are set out in Table 1.

Developer	Type of development	Type of construction	Selected dwelling types
Developer A	Combination of private and social housing	Dry-lined masonry cavity, partial fill	<ul style="list-style-type: none"> • A 2-storey 3 bedroom mid terrace with an internal floor area of 83 m². • A 3-storey 3 bedroom mid-terrace with an internal floor area of 117 m². • A 2½-storey 3 bedroom end terrace with an internal floor area of 117 m². • A 2-storey 3 bedroom semi-detached with an internal floor area of 81 m². • A 2-storey 4 bedroom detached with an internal floor area of 118 m².
Developer B	Private housing	Dry-lined masonry cavity, full fill	<ul style="list-style-type: none"> • A 2-storey 4 bedroom detached property with an internal floor area of 129 m². • A 2½-storey 5 bedroom detached property with an internal floor area of 164 m². • A 2½-storey 3 bedroom detached property with an internal floor area of 149 m². • Two 2-storey 3 bedroom detached properties with an internal floor area of 100 m².
Developer C	Private housing	Dry-lined masonry cavity, full fill	<ul style="list-style-type: none"> • Two 2-storey semi-detached properties with an internal floor area of 69 m². • A 2-storey end terrace with an internal floor area of 61 m². • Two 2-storey mid-terraces with an internal floor area of 71 m².
Developer D	Private housing	Steel frame	<ul style="list-style-type: none"> • A 2-storey 3 bedroom semi-detached property with an internal floor area of 72 m². • Two 2-storey properties with an internal floor area of 91 m². • A 2-storey 3 bedroom detached property with an internal floor area of 84 m². • A 2-storey 3 bedroom detached property with an internal floor area of 102 m².
Developer E	Social housing	Wet-plastered masonry cavity, partial fill	<ul style="list-style-type: none"> • A 2 bedroom apartment with an internal floor area of 58 m². • Two 2 bedroom apartments with an internal floor area of 57 m². • Two 1 bedroom apartments with an internal floor area of 43 m².

Table 1 Details of selected sites and dwelling types.

Design Assessment and Site Survey Protocols

- 7 As previously stated in deliverable D2: Developers, sites and protocols (see Johnston, Miles-Shenton and Bell, 2004) a design assessment and a site survey protocol has been developed in order to assess the design and construction phases of each dwelling type. The design assessment and site survey protocols are based upon the checklisting approach developed by the BRE (see Webb and Barton, 2001 and Webb, Barton and Scivyer, 2001). Both of these protocols have been piloted on one of the selected sites (developer A) and modified as appropriate in order to collect the relevant data. The main difference between the developed protocols and the BRE checklists are as follows:
 - a) The BRE checklists were originally developed for non-domestic buildings. These checklists have been modified to ensure that they can be used to assess domestic buildings.
 - b) The BRE use qualitative information from their checklists as input into an air leakage predictor tool. This is a quantitative tool that uses the qualitative information to estimate an air leakage index and air permeability. The protocols developed for this project adopt a different, but complimentary approach. Qualitative information obtained from the protocols will be used to define a number of individual qualitative 'Airtightness Ratings'. These ratings will assess a number of aspects of the dwellings construction that were identified within the literature review as having an influence on air leakage (Johnston, Wingfield and Bell, 2004). For instance, the type of internal wall finish, the method used to construct the intermediate floors and whether service penetrations are sealed or not. The individual airtightness ratings will be based upon a five-point scale (see Appendix 1), and provide a rating for each aspect of construction which is a judgement based upon the following: the extent to which the design as specified is likely to achieve an airtight construction; and, the extent to which the specification can or will be achieved on site. The higher the rating, the greater the chance that the specification will be achieved on site and the greater the chance that the dwelling will be airtight. The individual airtightness ratings will then be used to determine an overall airtightness rating for each dwelling, which will use the same five-point scale as the individual ratings. Although the same rating system will be used, the overall rating for the dwelling will not simply be a mathematical value that has been derived from an average of all of the individual ratings. The reason being that different aspects of the dwellings construction will make different contributions to the dwellings overall air leakage rate. For instance, it is well documented that the use of plasterboard dry-lining is likely to contribute significantly more to air leakage than loft hatches (see Stephen, 2000). Instead, the overall rating for the dwelling will be a qualitative judgement that is based upon all of the individual ratings, the influence that various aspects of the construction are likely to have on the dwellings overall air leakage and previous site experience. In order to maintain transparency, it is felt important that the overall dwelling rating is not converted into a quantitative measure of airtightness, for instance an air leakage index or air permeability value. Rather, the qualitative rating will be used to rank the selected dwellings against one another and to refine our judgements about the various factors that contribute to airtightness. The airtightness ratings that are obtained from the design assessments will be preliminary ratings. These ratings will be modified as appropriate, based upon the information that is obtained from the site surveys. Once the dwelling is complete, the final ratings will then be compared against actual pressure test data. It is important to note that this approach to rating airtightness is developmental. It will be modified accordingly throughout the project and the final report will discuss its usefulness in providing guidance on design assessment methods for building control officers.
- 8 All of the information obtained from the developed protocols will be stored on the Microsoft Access based project database (see Johnston, Miles-Shenton and Bell, 2004).
- 9 Drawings have been received from three of the five developers (developers A, B and C). Design assessments have been completed for 10 of the 25 selected dwellings (five from developer A and five from developer B). Site surveys have commenced on 12 of the 25 selected dwellings (five from developer A, five from developer C and two from developer E). A typical example of a completed design assessment and a Stage 1 site survey are contained within Appendices 1 and 2.

Interim Results of the Design Assessments and Site Surveys

- 10 This section summarises the progress that has been made to date on the design assessments and the site surveys and presents the interim results.

- 11 The main points that have been obtained from the completed design assessments can be summarised as follows:
- a) There is considerable variation in the way in which the information relating to air leakage is presented on the submitted drawings. In the case of developers B and C, the majority of the information on air leakage is textual material, which is contained within a general arrangement drawing and very little reference is made to any other drawings. In these drawings it is not always clear where or why sealing work has to be undertaken. This contrasts with the approach adopted by developer A, where some textual information on air leakage is referred to within the general arrangement drawings, but the majority of the textual and graphical information on air leakage is contained within various standard detail drawings that are referred to within the general arrangement drawings and are common to more than one house type. The majority of the standard details are drawn to a scale of 1:10, and indicate explicitly where sealing work has to be undertaken. Although we are yet to see how the information contained within the general arrangement and standard detail drawings is used on site, it is expected that the greater the amount of detail and information on airtightness that is presented within the drawings, the greater the chance that higher levels of airtightness will be achieved.
 - b) All of the drawings submitted state that they have been amended to comply with Approved Document L1 or are designed in accordance with the DEFRA and DTLR Robust Details (DEFRA, 2001).
 - c) None of the drawings contains an explicit air leakage target with the exception of a general reference to Approved Document L1 or Robust Details.
 - d) None of the drawings makes reference to a higher standard of air leakage than that contained within Approved Document L1.
 - e) None of the dwellings submitted identifies the location of the air barrier either within the text or on the drawings. In addition, none of the drawings states that the air barrier should be continuous around the envelope.
 - f) It has been inferred from the submitted drawings that the construction principle used to achieve airtightness within all of the dwellings is the airtight internal cladding approach (see Elmroth and Levin, 1983 and Carlsson, Elmroth and Engvall, 1980). For all of the dwellings that have been assessed, it has been assumed that the plasterboard dry-lining will form the principle air barrier.
 - g) All of the drawings that have been submitted identify areas where attention is required to very specific construction activities on site to achieve airtightness. In a number of instances, this attention to detail will be very difficult to achieve on site. For instance, the drawings indicate that the perimeter of all of the external walls and openings should be sealed with continuous ribbons of plaster. In our opinion, this would be very difficult to carry out, as practical difficulties would mean that without careful site supervision, the process of sealing the perimeter of the dry-lining could be missed out entirely, and it would be difficult to check compliance after the dry-lining was in position. In addition, none of the drawings describes this 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.
- 12 The site surveys are intended to be completed in three separate stages (see Johnston, Miles-Shenton and Bell, 2004). These stages are as follows:
- a) **Stage 1: During intermediate floor construction.** This will enable inspection of the method of supporting the intermediate floors and enable any potential leakage problems to be identified.
 - b) **Stage 2: During dry-lining/wet plaster phase.** This will enable inspection of the internal leaf of the external walls, the application of the dry-lining, inspection of window/wall junctions, inspection of service penetrations, etc.
 - c) **Stage 3: Completion.** This will enable identification of any potential leakage areas that have not been picked up during the 'snagging' process.
- 13 In addition to completing the site survey protocol, data on the site will also be collected and recorded using photographs, sketches and audio/video tape.
- 14 So far, only Stage 1 site visits have been undertaken on 12 of the 25 selected dwellings. These visits have resulted in the generation of approximately 250 photographs. The main points that have been obtained from the site observations are detailed below.
- a) For developers A and B, the drawings state that the timber I-beams that are used to support the intermediate floors are built into the internal leaf of the external wall, sealed with mortar, and are then sealed using a mastic sealant. Site observations indicate that there is considerable

variation in the way in which the silicone mastic has been applied on site, and in a number of cases, the mastic sealant only appears to have been applied to areas where the mortar has been missed out (see Figure 1). In addition, since the mastic sealant is applied after the intermediate floor finish has been installed, it is very difficult to seal the top flange of the timber I-beams with sealant. There is a risk that in areas where the mastic sealant has not been applied, the mortar seal will crack as the timber shrinks and the mortar dries out, resulting in a number of air leakage paths.

- b) For developers A and B, the timber I-beams that are used to construct the intermediate floors are offset from the inner leaf of the external/party wall to allow services, such as electrical cables, to be run from one floor to the next. In a number of cases the offset is so small that it is not possible to apply mortar and mastic to the area between the joist and the external/party wall in order to seal this junction. In some cases, this has resulted in gaps of approximately 38 mm x 240 mm extending through the full thickness of the inner leaf of blockwork (see Figure 2).
- c) Both of the above observations suggest that even when specific operations are specified within the drawings and the operatives attempt to undertake these operations, there can be real practical problems achieving the specification. This could be attributable to a lack of understanding by the operatives as to why they are undertaking a particular task or a lack of foresight in the detailed design stage, resulting in awkward gaps in the construction that are very difficult to fill.



Figure 1 Partial application of mastic sealant (developer B).

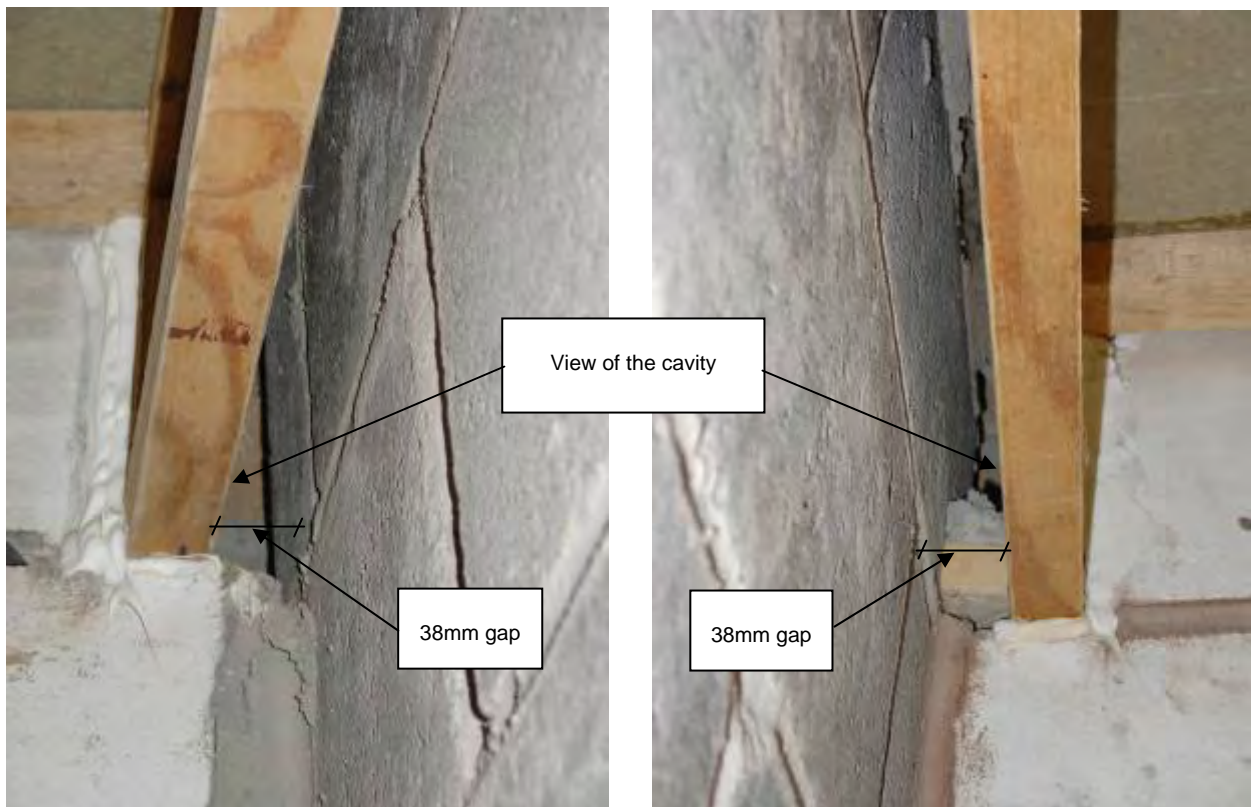


Figure 2 Gaps between the joist and the external/party wall (developer A).

Conclusions

- 15 This report reviews the progress that has been made in assessing the design drawings and the site data that has been obtained for the selected sites and presents interim results.
- 16 An analysis of the design assessments and site surveys indicates that there is a considerable difference in the way in which the developers present information on air leakage to those on site and the level of detail that this information contains. The presented information varies from the use of general arrangement drawings that contain general textual material, to sets of detailed 1:10 scaled drawings that indicate explicitly where sealing work has to be undertaken.
- 17 There is also considerable variation in the work that has been undertaken on site to achieve a particular specification. Site observations illustrate that a mixture of approaches have been undertaken to achieve the same specification. This suggests that the operatives undertaking this work do not fully understand the importance of the detail.
- 18 The site observations have also identified areas where there appears to have been a lack of foresight in the detailed design stage. This has resulted in specifications that are practically very difficult to achieve.

References

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DEFRA (2001) *Limiting Thermal Bridging and Air Leakage. Robust Construction Details for Dwellings and Similar Buildings*. Department for the Environment, Food and Rural Affairs. London, HMSO.

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JOHNSTON, D. WINGFIELD, J. and BELL, M (2004) *Airtightness of Buildings – Towards Higher Performance. Interim Report Number 1- Literature Review and Built Examples*. A Report to Communities and Local Government Building Regulations Division Under the Building Operational Performance Framework. Project Reference Number CI 61/6/16 (BD2429), Leeds Metropolitan University, Leeds.

STEPHEN, R. (2000) *Airtightness in UK Dwellings*. BRE Information Paper IP 1/00, January 2000. Garston, Watford, Building Research Establishment.

WEBB, B. and BARTON, R. (2001) *Estimation of actual airtightness based on design and workmanship assessment – Methodology of assessing design drawings*. Project Report Number 202559, Undertaken for AEA Technology by the Building Research Establishment, Garston, Watford.

WEBB, B. BARTON, R. and SCIVYER, C. (2001) *Estimation of actual airtightness based on design and workmanship assessment – Development of site checklist on workmanship*. Project Report Number 202561, Undertaken for AEA Technology by the Building Research Establishment., Garston, Watford.

Appendix 1

Example of a completed design assessment protocol

Design assessment protocol

Name of assessors: Dominic Miles-Shenton
Dr David Johnston

Date of assessment: 6th April 2004

Dwelling details			
Site reference	C236/7		
Plot No.	236/7		
Location	Omitted to maintain anonymity		
Address	Omitted to maintain anonymity		
Developer	C		
Development type	<table border="1" style="width: 100%; text-align: center;"> <tr> <td style="width: 50%;">Private</td> <td style="width: 50%;">Social housing</td> </tr> </table>	Private	Social housing
Private	Social housing		
Development size	278 (total number of units)		
Programme start date	Unknown		
Programme end date	Unknown		
Drawing reference			
Type of drawings submitted	General arrangement drawings that make very little reference to any other drawings.		
Other details	Mixture of 6 house types (mid-terrace, end-terrace, semi-detached and detached properties). Site is developing on a speculative basis		

	YES	NO	
--	-----	----	--

Dimensions & Build Form	(√)	(√)	Notes
Ground floor area	71		m ²
Total envelope surface area	203		m ²
Volume	167		m ³
No. of storeys	2		
Type of dwelling:		✓	
Detached		✓	
Semi-detached		✓	
Mid-terrace	✓		2 Bedroom
End-terrace		✓	
Apartment		✓	
Construction type:	✓		100mm cavity, filled with blown mineral fibre. Fibre is to be injected through the inner leaf.
Masonry cavity full fill		✓	
Masonry cavity partial fill		✓	
Timber frame		✓	
Position of air barrier	The position of the air barrier is not identified within the drawings. Inferred from the drawings that the construction principle used to achieve airtightness is the internal airtight cladding approach (plasterboard dry-lining).		
Other details			

	YES (√)	NO (√)	Notes:
Ground floor		✓	
Construction type:		✓	
Concrete slab on ground		✓	

*Airtightness Rating	—		
Concrete suspended *Airtightness Rating	✓ 4		Concrete beam & concrete block, 50mm sand/cement screed. Micro-Porous Floor Insulation Membrane (Foil Type) (laid below beams) as underfloor insulation. The concrete beam & block floor should provide an excellent air barrier provided that all of the service penetrations through it are sealed.
Timber T&G *Airtightness Rating	—	✓	
Timber butted *Airtightness Rating	—	✓	
Is air barrier continuous between ground floor & external walls? *Airtightness Rating		✓ 0	Continuity of the air barrier between the ground floor and the external walls is essential to prevent air leakage at this junction. The junction between the wall and the floor should be sealed prior to the fixing of the skirting boards. There is little evidence from the drawings that this is understood.
Are service penetrations sealed? *Airtightness Rating	✓ 4		Drawings contain a note stating that all pipes/cables passing through ground floor are to be sealed with close fitting plasterboard and mastic sealant. Sealing these penetrations is essential as they can be a significant route for air leakage.
Other details			

External walls	YES (✓)	NO (✓)	Notes:
Construction type: <div style="text-align: right;">Masonry cavity full fill</div>	✓		100mm facing brick, 100mm cavity filled with blown mineral fibre (fibre is to be injected through the inner leaf), 100mm 4.2N standard concrete block. Drawings do not specify that or how the holes that are used to inject the mineral fibre into the cavity will be sealed. It is essential that these holes are adequately sealed prior to the commencement of the plasterboard dry-lining, to prevent air leakage.
Masonry cavity partial fill		✓	
Timber frame		✓	
Internal finish: <div style="text-align: right;">Dry-lining</div> *Airtightness Rating	✓ 1		9.5mm plasterboard on dabs with a 3mm Gypsum skim finish. Drawings state that all gaps between dry-lining and masonry at the perimeter of door/window openings and wall to floor and wall to ceiling junctions are to be sealed with continuous ribbon of plasterboard adhesive. In our opinion, this is very difficult to achieve. In addition, none of the drawings describe this process in any detail and do not say, for example, how wide or thick the adhesive ribbons should be, or how far they should be from the perimeter.
Wet plaster *Airtightness Rating	—	✓	
Other *Airtightness Rating	—	✓	
Are service penetrations sealed? *Airtightness Rating	✓ 4		Drawings contain a note stating that all pipes/cables passing through walls are to be sealed with close fitting plasterboard and mastic sealant. Sealing these penetrations is essential as they can be a significant route for air leakage.
Other details			

External windows & doors	YES (√)	NO (√)	Notes:
Are windows/doors draught-stripped? *Airtightness Rating	✓ 4		Drawings state that all windows are to be PVCu double glazed with double sealed opening casements and external doors are to be fully draught sealed.
Are window/door frames sealed to external wall internally? *Airtightness Rating	✓ 3		Drawings state that sealant is to be applied to front and back of frame. However, the drawings do not specify how this is to be achieved. It is essential that the junction between the window/door frame and the plasterboard dry-lining is sealed, as it can be a significant route for air leakage.
Are window/door frames sealed to external wall externally? *Airtightness Rating	✓ 3		Drawings state that sealant is to be applied to front and back of frame. However, the drawings do not specify how this is to be achieved.
Are window sills/door thresholds sealed to external wall internally? *Airtightness Rating	✓ 3		Drawings state that sealant is to be applied to front and back of frame. However, the drawings do not specify how this is to be achieved. It is essential that the junction between the window sill/door threshold and the plasterboard dry-lining is sealed, as it can be a significant route for air leakage.
Are window sills/door thresholds sealed to external wall externally? *Airtightness Rating	✓ 3		Drawings state that sealant is to be applied to front and back of frame. However, the drawings do not specify how this is to be achieved.
Do windows contain trickle vents?			Unknown.
Other details	Background ventilation requirements of 8000mm ² in habitable rooms and 4000mm ² in kitchen / bathroom / utility room are specified. However, the drawings do not specify how this will be achieved.		

Intermediate flooring		YES (√)	NO (√)	Notes:
Construction type:	Timber joist	✓		18mm T&G moisture resistant flooring grade chipboard glued to joists and with glued joints, on regulated softwood joists. Drawings do not indicate how the junctions between the flooring panels are to be sealed. It is essential that the junction between the floor panels is sealed, as it can be a route for air leakage.
*Airtightness Rating		4		
	Timber I beam		✓	
*Airtightness Rating		—		
	Concrete		✓	
*Airtightness Rating		—		
Method of support at external wall junction:	Built-in	✓		Drawings state that all joists are to be built solid into walls, bearing 90mm into wall, with all joints filled solid with mortar and sealed with mastic as SDL 274. It is essential that built-in joists are sealed to the inner leaf of the external wall, as it can be a significant route for air leakage.
*Airtightness Rating		1		
	Joist hangers			Trimmed joists to be on joist hangers fixed to trimmer
*Airtightness Rating		—		
Is external wall/intermediate floor junction sealed?			✓	Continuity of the air barrier between the first floor and the external walls is essential to prevent air leakage at this junction. The junction between the wall and the floor should be sealed prior to the fixing of the skirting boards. There is little evidence on the drawings that this is understood.
*Airtightness Rating			0	
Are service penetrations sealed?		✓		Drawings contain a note stating that all pipes/cables passing through ceilings are to be sealed with close fitting plasterboard and mastic sealant. Sealing these penetrations is essential as they can be a significant route for air leakage.
*Airtightness Rating		4		
Other details				

	YES	NO	

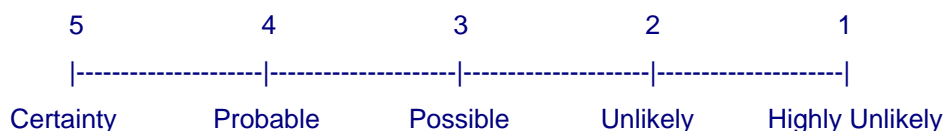
Ceiling junction	(√)	(√)	Notes:
Is air barrier continuous between ceiling & external walls? *Airtightness Rating	✓ 4		Drawing state that all gaps between dry-lining and masonry at the wall to floor and wall to ceiling junctions are to be sealed with continuous ribbon of plasterboard adhesive. In our opinion, this is very difficult to achieve. In addition, none of the drawings describe this process in any detail and do not say, for example, how wide or thick the adhesive ribbons should be, or how far they should be from the perimeter.
Is air barrier continuous above partition walls? *Airtightness Rating		✓ 0	Concrete block ground floor internal partitions and timber stud partitions to upper floor. Continuity of the air barrier at ceiling level is essential to prevent air leakage. The junction between the timber stud partitions on the upper floor and the ceiling should be sealed, as the junction can be a significant route for air leakage.
Are service penetrations sealed? *Airtightness Rating	✓ 4		Drawings contain a note stating that all pipes/cables passing through ceilings are to be sealed with close fitting plasterboard and mastic sealant. Sealing these penetrations is essential as they can be a significant route for air leakage.
Is the loft hatch draught-stripped? *Airtightness Rating	—		Unknown. Insufficient detail contained within drawings.
Is loft hatch sealed to ceiling? *Airtightness Rating	—		Unknown. Insufficient detail contained within drawings.
Other details			

Overall airtightness rating = 2

*Airtightness Rating:

This figure is based on the 5 point scale illustrated below. The rating provided is a judgement based on the following:

- The extent to which the design as specified is likely to achieve an airtight construction, and
- The extent to which the specification can or will be achieved on site.



Ratings on this scale are determined by a number of factors, including the experience of the assessment team and knowledge evolved from previous visits to this particular site and/or developer.

APPENDIX 2

Example of a completed site survey protocol

Site survey protocol

Name of assessors: Dominic Miles-Shenton
Dr David Johnston

Date of assessment: 12th May 2004

Dwelling details			
Site reference	B79		
Plot No.	79		
Location	Omitted to maintain anonymity.		
Address	Omitted to maintain anonymity.		
Developer	B		
Development type	<table border="1" style="width: 100%; text-align: center;"> <tr> <td style="width: 50%;">Private</td> <td style="width: 50%;">Social housing</td> </tr> </table>	Private	Social housing
Private	Social housing		
Development size	86 (total number of units)		
Programme start date	Unknown.		
Programme end date	Unknown.		
Drawing type and reference	General arrangement drawings that make very little reference to any other drawings/details.		
Other details	Mixture of 16 different house types (flats, town houses, semi-detached and detached)		

Dimensions & Build Form	YES (√)	NO (√)	Notes
Total floor area	129		m ²
Total envelope surface area	285		m ²
Volume	327		m ³
No. of storeys	2		
Type of dwelling:	✓		4 bedroom
Detached		✓	
Semi-detached		✓	
Mid-terrace		✓	
End-terrace		✓	
Apartment		✓	
Construction type:	✓		75mm cavity, filled with cavity foam to BS5617 and 5618. Foam is to be injected through the inner leaf.
Masonry cavity full fill		✓	
Masonry cavity partial fill		✓	
Timber frame		✓	
Position of air barrier	The position of the air barrier is not identified within the drawings. Inferred from the drawings that the construction principle used to achieve airtightness is the internal airtight cladding approach (plasterboard dry-lining).		
Other details	At the time of this initial site visit, construction of this plot was at the second lift stage with intermediate floor in place and blockwork up to eaves level. Photograph B 79/1 - plot on 12-May-04, at the time of the visit.		

Ground floor	YES (✓)	NO (✓)	Notes:		
Construction type:	✓ 4		150mm, well compacted and blinded hardcore, 1200 gauge visqueen DPM, 50mm thick polystyrene insulation and 100mm concrete with power float finish.		
Concrete slab on ground					
*Airtightness Rating					
Concrete suspended				✓	The concrete beam & block floor should provide an excellent air barrier, provided that all of the service penetrations through it are sealed effectively.
*Airtightness Rating				-	
Timber T&G	✓				
*Airtightness Rating	-				
Timber butted	✓				
*Airtightness Rating	-				
Is air barrier continuous between ground floor & external walls?		✓	Continuity of the air barrier between the ground floor and the external walls is essential to prevent air leakage at this junction. The junction between the wall and the floor should be sealed prior to the fixing of the skirting boards. There is little evidence from the drawings that this is understood.		
*Airtightness Rating	-				
Are service penetrations sealed?	✓		Drawings state that all boxing for concealed services is to be sealed at floor level. Sealing these penetrations is essential as they can provide a significant route for air leakage.		
*Airtightness Rating	3				
Other details	Details to be in accordance with details set out by DEFRA & DTLR Robust Details				

External walls	YES (✓)	NO (✓)	Notes:
Construction type:	✓		102.5mm facing brick, 75mm cavity filled with cavity foam to BS5617 and 5618 (Foam to be injected through the inner leaf), 100mm block inner leaf. Drawings do not specify how the holes that are used to inject the mineral fibre into the cavity will be sealed. It is essential that these holes are adequately sealed prior to the commencement of the plasterboard dry-lining, to prevent air leakage.
Masonry cavity full fill			
Masonry cavity partial fill			
Timber frame		✓	
Internal finish:	✓		9.5mm plasterboard and skim on plaster dabs. Drawings state that all gaps between dry-lining and masonry walls at the edges of all openings through external walls to be sealed with continuous bands of fixing plaster. In our opinion, this is very difficult to achieve. In addition, none of the drawings describe this process in any detail and do not say, for example, how wide or thick the adhesive ribbons should be, or how far they should be from the perimeter.
Dry-lining *Airtightness Rating	1		
Wet plaster *Airtightness Rating	–	✓	
Other *Airtightness Rating	–	✓	
Are service penetrations sealed? *Airtightness Rating	✓		Drawings state that all service pipes penetrating into hollow constructions or voids to be sealed. Sealing these penetrations is essential as they can provide a significant route for air leakage.
Other details	Details to be in accordance with details set out by DEFRA & DTLR Robust Details B 79/15,25 - internal blockwork		

External windows & doors	YES (✓)	NO (✓)	Notes:
Are windows/doors draught-stripped? *Airtightness Rating	✓ 4		Drawings state that all opening elements of windows, doors and rooflights are to draught stripped with an approved sealer.
Are window/door frames sealed to external wall internally? *Airtightness Rating	✓ 3		Drawings do not explicitly identify whether this needs to be added, but do state that all construction details are to be in accordance with robust standard details.
Are window/door frames sealed to external wall externally? *Airtightness Rating	✓ 3		The robust details state that sealant should be applied to the front and back of the frame.
Are window sills/door thresholds sealed to external wall internally? *Airtightness Rating	✓ 3		It is essential that the junctions between the window/door frame and the plasterboard dry-lining and the window sill/door threshold and the plasterboard dry-lining are sealed, as these can be a significant route for air leakage
Are window sills/door thresholds sealed to external wall externally? *Airtightness Rating	✓ 3		
Do windows contain trickle vents?	✓		Where indicated on plan
Other details	Details to be in accordance with details set out by DEFRA & DTLR Robust Details B 79/2 – front door threshold B 79/3,13,14 – cavity closure at windows		

	YES (√)	NO (√)	Notes:
Intermediate flooring			
Construction type: Timber joist *Airtightness Rating	—	✓	22mm moisture resistant chipboard on engineered joists.
Timber I beam *Airtightness Rating	✓ 3		Drawings do not indicate how the junctions between the flooring panels are to be sealed. It is essential that the junction between the floor panels is sealed, as it can be a route for air leakage.
Concrete *Airtightness Rating	—	✓	
Method of support at external wall junction: Built-in *Airtightness Rating	✓ 1		Drawings state that all joists are to be built-in to external walls in accordance with drawing no. PH/BJE rev A.
Joist hangers *Airtightness Rating	—		It is essential that built-in joists are sealed to the inner leaf of the external wall, as it can be a significant route for air leakage.
Is external wall/intermediate floor junction sealed? *Airtightness Rating	—	✓	Continuity of the air barrier between the first floor and the external walls is essential to prevent air leakage at this junction. The junction between the wall and the floor should be sealed prior to the fixing of the skirting boards. There is little evidence on the drawings that this is understood.
Are service penetrations sealed? *Airtightness Rating	✓ 3		Drawings state that all boxing for concealed services is to be sealed at floor and ceiling levels and service pipes penetrating into hollow constructions or voids are to be sealed. Sealing these penetrations is essential as they can provide a significant route for air leakage. Drawings do not specify how the holes that are used to inject the mineral fibre into the cavity will be sealed. It is essential that these holes are adequately sealed prior to the commencement of the plasterboard dry-lining, to prevent air leakage.
Other details	Details to be in accordance with details set out by DEFRA & DTLR Robust Details B 79/4-12,16-19, 21-24 – built in joists B 79/20 – intermediate floor edges		

	YES (√)	NO (√)	Notes:
Ceiling junction			

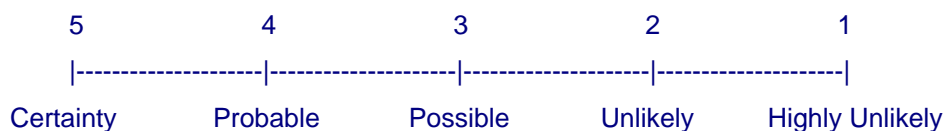
Is air barrier continuous between ceiling & external walls? *Airtightness Rating	✓ 4		Drawings do not explicitly identify whether this junction needs to be sealed, but do state that all construction details are to be in accordance with robust standard details. The robust details state that sealant continuous ribbons of plasterboard adhesive should be applied to fix the dry-lining at the perimeter walls.
Is air barrier continuous above partition walls? *Airtightness Rating	—	✓	Continuity of the air barrier at ceiling level is essential to prevent air leakage. The junction between the timber stud partitions on the upper floor and the ceiling should be sealed, as the junction can be a significant route for air leakage.
Are service penetrations sealed? *Airtightness Rating	✓ 3		Drawings state that boxing for concealed services is to be sealed at floor and ceiling levels and service pipes penetrating into hollow constructions or voids are to be sealed. Sealing these penetrations is essential as they can provide a significant route for air leakage.
Is the loft hatch draught-stripped? *Airtightness Rating	✓ —		Drawings state that loft access is to be draught striped with approved sealer.
Is loft hatch sealed to ceiling? *Airtightness Rating	—		Unknown, insufficient detail contained within drawings.
Other details	Details to be in accordance with details set out by DEFRA & DTLR Robust Details		

Overall dwelling airtightness rating = 2

*Airtightness Rating:

This figure is based on the 5 point scale illustrated below. The rating provided is a judgement based on the following:

- The extent to which the design as specified is likely to achieve an airtight construction.
- and
- The extent to which the specification can or will be achieved on site.



Ratings on this scale are determined by a number of factors, including the experience of the assessment team and knowledge evolved from previous visits to this particular site and/or developer.

Appendix 4

Airtightness of buildings — towards higher performance

Interim Report D4 — Airtightness Results from Phase 1

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report reviews the progress that has been made on pressurisation testing the dwellings that have been selected to participate in Phase 1 of this project and summarises the progress that has been made in assessing the design drawings and the site data for these dwellings.
- 2 Drawings have been received from four of the five developers (developers A, B, C and D). Design assessments have been completed for 20 of the selected dwellings and site surveys have commenced on 22 of the dwellings.
- 3 Pressurisation tests have been undertaken on only one of the selected dwellings. The results show that this dwelling is slightly leakier than the UK mean of $11.48 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa and would fail to satisfy the air leakage criterion set out in the 2002 edition of the Building Regulations Approved Document Part L1 (DTLR, 2001). The measured permeability for the dwelling was $12.72 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa.
- 4 The main air leakage paths within the dwelling were also identified. Common leakage paths included: service penetrations, the loft hatch, the junction between the floors and the skirting board, poorly fitting trickle vents, the patio doors and the junctions between the first floor panels.
- 5 The leakage identification also highlighted that the air permeability of the dwelling could be improved by undertaking a number of relatively simple measures. For instance, sealing the junction between the skirting board and the floors with an appropriate sealant, fitting an appropriate locking mechanism to the loft hatch which compressed the seal, and sealing service penetrations using an appropriate sealant.

Introduction

- 6 This report is milestone D4 — Airtightness Results from Phase 1 of Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003).
- 7 The aim of this report is to summarise the progress that has been made on pressure testing the dwellings that have been selected to participate in Phase 1 of the above project (task 2.1.5 of the project proposal). The report also summarises the progress that has been made in assessing the design drawings and the site data that have been obtained for Phase 1 of this project (tasks 2.1.3 and 2.1.4 of the project proposal).

Summary of Progress to Date

- 8 Drawings have been received from four of the five developers (developers A, B, C and D). Design assessments have been completed for 20 of the 25 selected dwellings (five from developers A, B, C and D. Site surveys have commenced on 22 of the 25 selected dwellings (five from developers A, B C and D and two from developer E). Interim results from a number of the assessments and surveys are documented within deliverable D3 — Assessments of Design and Pilot Site Data (see Johnston, Miles-Shenton and Bell, 2004).
- 9 In terms of the pressurisation testing, only one of the 25 selected dwellings has been completed and tested to date (dwelling D39). Another two dwellings from developer D are also complete (dwellings D40 and D41), but due to very quick completion dates, both of these dwellings are now occupied and are no longer available for testing. In order to maintain the total number of dwellings, two alternative dwellings have been selected from the same developer and site. These consist of two 3 bedroom 2-storey detached properties (dwellings D44 and D59), both of which are due to be completed by the end of August 2004. Details of the current stage of construction and anticipated completion dates for all of the dwellings that are participating in this phase of the project are set out in Table 1.
- 10 As can be seen from Table 1, it is anticipated that the majority of the selected dwellings will be completed and pressure tested within the programme timescale. The only exception to this relates to the five apartments that are currently being constructed by developer E, which are not due to be completed until November 2004. The reasons for the late completion date can be attributed to the much longer build times associated with apartments compared with other housing forms, and the fact that all of the units within a particular block tend to be completed and handed over at the same time. Despite this, it is anticipated that the late testing of the apartments will not have any major impact on the overall research programme and all of the remaining milestones will be unaffected.

Developer	Type of construction	Dwelling type	Current stage of construction	Anticipated completion date
A	Dry-lined masonry cavity, partial fill.	• A9 - 2 storey 3 bedroom mid terrace.	2 nd fix.	August 2004
		• A11 - 3 storey 3 bedroom mid terrace.	2 nd fix.	July 2004
		• A12 - 2½ storey 3 bedroom end terrace.	2 nd fix.	July 2004
		• A13 - 2 storey 3 bedroom semi-detached.	1 st fix.	September 2004
		• A14 - 2 storey 4 bedroom detached.	1 st fix.	September 2004
B	Dry-lined masonry cavity, full fill.	• B79 - 2 storey 4 bedroom detached.	2 nd fix.	September 2004
		• B80 - 2½ storey 4 bedroom detached.	2 nd fix.	August 2004
		• B81 - 2½ storey 4 bedroom detached.	2 nd fix.	August 2004
		• B82 - 2 storey 3 bedroom detached.	2 nd fix.	August 2004
		• B86 - 2 storey 3 bedroom detached.	2 nd fix.	September 2004
C	Dry-lined masonry cavity, full fill.	• C236 - 2 storey semi-detached.	1 st fix.	August 2004
		• C237 - 2 storey semi-detached.	1 st fix.	August 2004
		• C238 - 2 storey end terrace.	Superstructure.	Unknown
		• C239 - 2 storey mid terrace.	Superstructure.	Unknown
		• C240 - 2 storey mid terrace.	Superstructure.	Unknown
D	Steel frame.	• D39 - 2 storey 3 bedroom semi-detached.	Completed.	July 2004
		• D42 - 2 storey 3 bedroom detached.	2 nd fix.	August 2004
		• D43 - 2 storey 3 bedroom detached.	2 nd fix.	August 2004
		• D44 - 2 storey 3 bedroom detached.	1 st fix.	August 2004
		• D59 - 2 storey 3 bedroom detached.	1 st fix.	August 2004
E	Wet-plastered masonry cavity, partial fill.	• CG01 - 2 bedroom apartment.	Superstructure.	November 2004
		• CG02 - 1 bedroom apartment.	Superstructure.	November 2004
		• C202 - 2 bedroom apartment.	Superstructure.	November 2004
		• C301 - 1 bedroom apartment.	Superstructure.	November 2004
		• C302 - 2 bedroom apartment.	Superstructure.	November 2004

Table 1 Details of the selected dwellings, their current stage of construction and their anticipated completion date.

Results of the Pressurisation Tests

11 Pressurisation tests have so far been undertaken only one of the 25 selected dwellings (dwelling D39). The test was carried out by Leeds Metropolitan University using an Energy Conservatory Minneapolis Model 3 Blower Door. Details of the test can be found within Table 2.

Dwelling	Volume (m ³)	Internal surface area (m ²)	Personnel present during test
D39	178	198	Dr David Johnston (LeedsMet) Dr Jez Wingfield (LeedsMet) Dominic Miles-Shenton (LeedsMet)

Table 2 Test details.

- 12 In addition to the pressurisation tests, the main air leakage paths within dwelling D39 were also identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators.
- 13 All of the pressurisation tests and the air leakage paths associated with the dwelling were video recorded and photographed. This information will be used at the feedback seminars (see task 2.2.1 of the project proposal) to provide important feedback to the developers on the airtightness performance of their dwellings. Although the only individuals that were present during the completed test were from Leeds Metropolitan University, it is intended that key personnel from each developer will be invited to attend at least one of the five pressurisation tests on their dwellings.
- 14 A detailed pressurisation report on the dwelling D39 can be found within Appendix 1.

Air permeability

- 15 The results of the air permeability test on dwelling D39 are set out in Table 3 and Figure 1.

Dwelling	Mean air permeability @ 50Pa ($\text{m}^3/(\text{h}\cdot\text{m}^2)$)
D39	12.72

Table 3 Mean air permeability of dwelling D39.

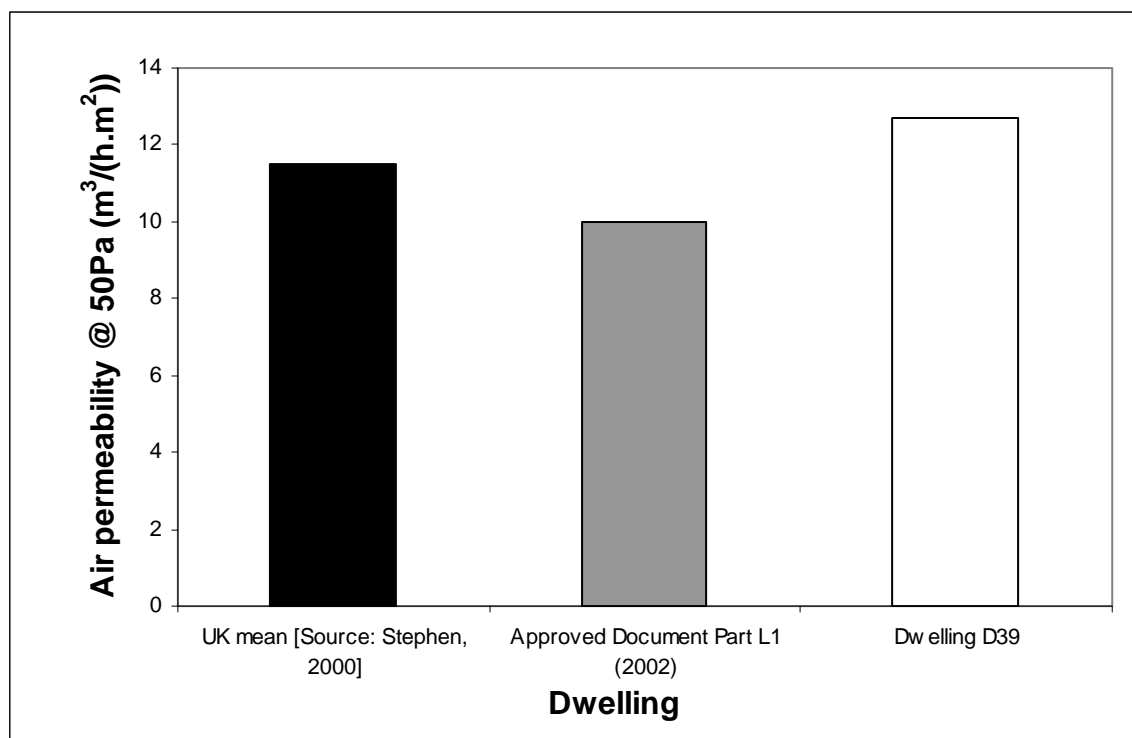


Figure 1 Mean air permeability of dwelling D39.

- 16 Figure 1 compares the air permeability of dwelling D39 with the UK mean¹ and the level set in the 2002 Edition of the Building Regulations Approved Document Part L1 (DTLR, 2001). The result for

¹ The UK mean has been derived from the Building Research Establishment's (BRE's) air leakage database, which is the largest and most comprehensive source of information on the airtightness of UK dwellings (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. However, despite its size, this database is not the result of random sampling and cannot claim to be unequivocally representative of the UK housing stock.

D39 ($12.72 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa) is slightly higher than the UK mean of $11.48 \text{ m}^3/(\text{h.m}^2)$, and the maximum specified level of $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa that is contained within the 2002 edition of Approved Document Part L1. Therefore, the dwelling would fail to satisfy the air leakage criterion set out in Approved Document Part L1 (DTLR, 2001). This result was achieved despite the developer's use of Robust Details (see DEFRA, 2001) as the basis of the application for regulatory approval.

Leakage identification

- 17 It was not possible to quantify the contribution that each leakage path made to the dwellings overall air leakage, but the smoke tests that were carried out enabled the main leakage paths within the dwelling to be identified. These are as follows:
- a) Gaps between skirting board and ground floor.
 - b) Service penetrations in kitchen.
 - c) Service penetrations in downstairs toilet.
 - d) Hole in kitchen floor (approximately 100 mm x 50 mm in size).
 - e) Poorly fitting trickle vents.
 - f) Patio doors.
 - g) Gaps between wall and ceiling in the cupboard under the stairs.
 - h) Pipework penetrations behind the radiators.
 - i) Poorly locking loft hatch which did not compress seal fully when closed.
 - j) Gaps between skirting board and first floor.
 - k) Gaps between flooring panels on the first floor.
 - l) Service penetrations in the bathroom and around the bath panel.
 - m) Service penetrations and gaps between the ceiling and wall junction in the boiler cupboard.

Photographs of all of these leakage paths can be found within the pressurisation test report that is contained within Appendix 1.

- 18 The leakage identification also highlighted that the air permeability of dwelling D39 could be improved by undertaking a number of relatively simple measures. For instance, sealing the junction between the skirting board and the floors with an appropriate sealant, fitting an appropriate locking mechanism to the loft hatch which compressed the seal, sealing the kitchen floor, and sealing service penetrations using an appropriate sealant.

Conclusions

- 19 This report reviews the progress that has been made on pressure testing the dwellings that have been selected to participate in Phase 1 of this project.
- 20 An analysis of the pressurisation test results indicates that the dwelling tested is leakier than the UK norm and would fail to satisfy the air leakage criterion that is contained within the 2002 edition of the Building Regulations Approved Document Part L1 (DTLR, 2001). The air permeability of the tested dwelling was $12.72 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa.
- 21 A number of air leakage paths were observed within the dwelling tested. These included: service penetrations, the loft hatch, the junction between the floors and the skirting board, poorly fitting trickle vents, the patio doors and first floor joints. However, if simple measures were undertaken to address a number of these leakage paths, such as seal service penetrations using an appropriate sealant, it is likely that the air permeability of this dwelling could be improved.

References

BORLAND, S. and BELL, M. (2003) *Airtightness of Buildings — Towards Higher Performance*. A Project Proposal to Communities and Local Government Building Regulations Division Under the Building Operational Performance Framework. Project Reference Number CI 61/6/16 (BD2429), Building Sciences Limited, Ardington.

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Appendix 1

Pressurisation test report

Phase 1 Air Leakage Test Results for Developer D

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

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Introduction

- 1 This report details the results of a pressure test carried out on one dwelling from Developer D that is participating in Phase 1 of Communities and Local Government Project reference CI 61/6/16 (BD2429) Airtightness of Buildings — Towards Higher Performance (Borland and Bell, 2003). The tests were carried out by Dr David Johnston, Dominic Miles-Shenton and Dr Jez Wingfield of the Centre for the Built Environment, Leeds Metropolitan University in July 2004.

Building Description

- 2 The dwelling tested is a 2-storey three bedroom semi-detached property (dwelling D39, as shown in Figure 1). It has been constructed using a proprietary light steel framing system, which is dry-lined internally with 12.5 mm plasterboard and is clad externally in brick, a 50 mm wall cavity and 35 mm of rigid insulation board. The ground floor is a concrete slab-on-ground construction with the insulation placed below the slab, whilst the first floor has been constructed using a steel lattice joist cassette system finished with chipboard. The roof is of a traditional tiled pitched design with insulation at ceiling level.



Figure 1 Dwelling D39.

- 3 The calculated envelope area for the dwelling is 198 m².

Air Leakage Standard

- 4 A new national standard – TM23 Testing buildings for air leakage (CIBSE, 2000) – has been introduced in the UK, which covers the pressure testing of all buildings. This has been adopted as the test standard for Part L1 of the Building Regulations 2000 (England and Wales), which came into force in April 2002 (ODPM, 2001).
- 5 Traditionally, the airtightness of dwellings has been expressed as an air leakage rate in air changes per hour (ac/h). However, the Approved Document Part L1 2002 (England and Wales) is written in terms of air permeability, and compliance can be demonstrated by pressure-testing to show that the air permeability does not exceed 10 m³/(h.m²) @ 50Pa (although for dwellings a pressure test is not mandatory).
- 6 TM23 (CIBSE, 2000) defines air change rate and air permeability as follows:

Air change rate:

This is the volume flow rate per cubic metre of building internal volume (ac/h) at a test pressure of 50Pa.

Air permeability:

This is the leakage rate per square metre of building envelope ($\text{m}^3/(\text{h}\cdot\text{m}^2)$) at a test pressure of 50Pa. The envelope area taken into account in calculating air permeability is the internal surface area of the external façade, and includes the walls, roofs and the total ground floor area. No deductions are made for partitions or the separating walls with adjacent buildings or garages.

Fan Pressurisation System

- 7 Fan pressurisation systems are used to quantify the air leakage of the envelope of buildings. The leakiness of the envelope is quantified by connecting a single large fan or a series of fans into an external doorway and pressurising the building whilst measuring the air flow rate required to maintain a pressure difference across the building envelope. The leakier the building, the greater the air flow required to maintain a given pressure differential (in almost all cases a differential of 50Pa is used).
- 8 The fan system used for this test was an Energy Conservatory Minneapolis Model 3 Blower Door equipped with a DG-3 pressure gauge.
- 9 Tests are normally carried out when the outside wind speed is low to minimise any wind induced pressure variations. Air volume flow rate Q (m^3/s) through the fans is measured by calibrated flow grids over a suitable range of building pressure differentials ΔP (Pa). These are then corrected for internal/external temperature difference, in accordance with TM23. A best-fit power-law profile of the form $Q=C_{\text{env}}(\Delta P)^n$ is fitted to the data where both the coefficient C_{env} and exponent n are constants. C_{env} is then corrected for the measured barometric pressure to a specified test pressure of 50Pa, providing C_L . The theoretical leakage rate at 50Pa is then calculated from the formula:
$$Q_{50}=C_L(\Delta P)^n$$
- 10 The air change rate can then be calculated by dividing the air volume flow rate (m^3/h) through the building envelope at a pressure differential of 50Pa (Q_{50}), by the building volume (V). The result is expressed in terms of air changes per hour (ac/h).
- 11 To compare the envelope leakage characteristics between buildings of different shapes and sizes, air permeability (Q_{50}/S_T) is normally used. S_T is the total internal surface area (m^2). The result is expressed in terms of m^3 leakage per hour per m^2 of envelope area ($\text{m}^3/(\text{h}\cdot\text{m}^2)$).

Test Procedure

- 12 The mean internal and external temperatures were measured and recorded during the tests. The temperature values recorded were used to standardise the air flow rate through the fan systems to commonly agreed conditions. A further parameter assessed was wind speed. If the estimated wind speed had been too high (i.e. > 3 m/s) the test would not have been carried out.
- 13 The test procedure consisted of pressurising the dwelling to approximately 60Pa then taking a set of measurements of the building pressure differential and flow rate through the fan. The fan speed was then reduced in several steps and the readings repeated at each of the speed settings. The dwelling was then depressurised, and the test procedure repeated. The result is two sets of measurements; one for pressurisation and one for depressurisation.
- 14 The following temporary seals and measures were in place at the time of the tests:
 - a) The mechanical extract fan in the bathroom and the cooker hood in the kitchen were closed.
 - b) All the trickle vents were adjusted to the closed position (with the exception of a missing trickle vent on the living room window which was sealed using masking tape).
 - c) All water traps and U-bends were filled with water.
 - d) All external doors were closed.
 - e) All internal doors were opened.

Results

Air permeability

- 15 The air permeability was determined using Q_{50}/S_T . A summary of the test results is illustrated in Table 1.

Dwelling	Pressurisation test		Depressurisation test		Mean Permeability (m ³ /(h.m ²))
	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	
D39	12.82	0.992	12.61	0.984	12.72

Table 1 Air permeability results.

- 16 Graphs showing the test data in the form pressure difference ΔP (Pa) versus air volume flow rate (m³/s) are illustrated in Figures 2 and 3.

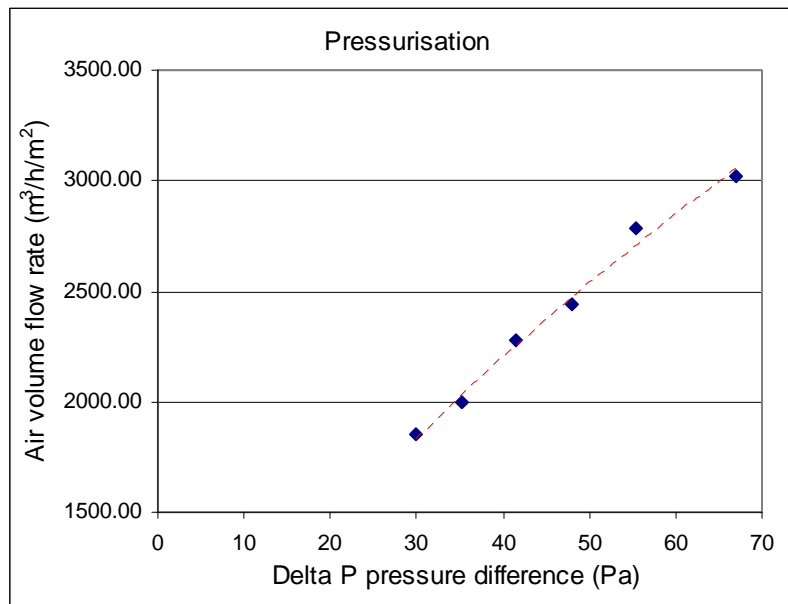


Figure 2 Dwelling D39 pressurisation graph.

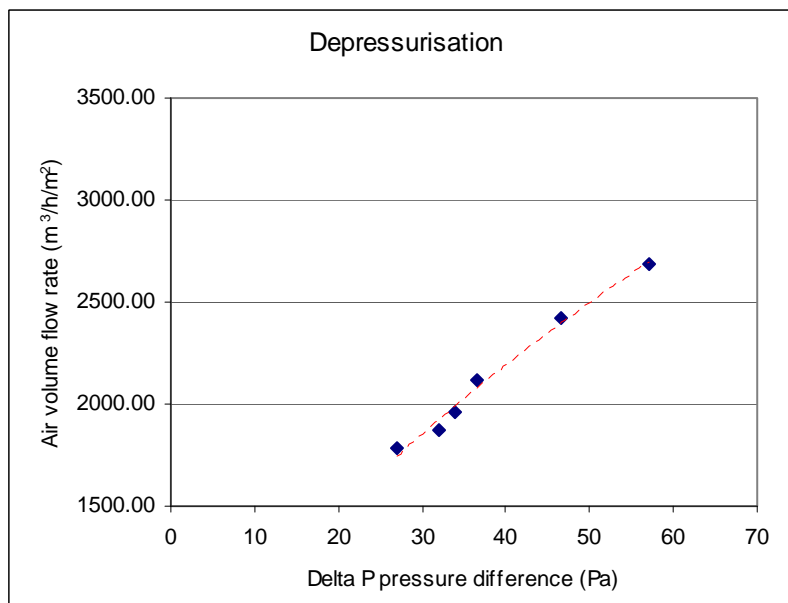


Figure 3 Dwelling D39 depressurisation graph.

Leakage detection

- 17 The main air leakage paths within the dwelling were identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. Although it was possible to be able to identify the main air leakage paths within the dwelling, it was not possible to quantify the contribution that these leakage paths made to the dwellings overall air leakage. Nevertheless, the results were informative.
- 18 The main air leakage paths observed were as follows:
- a) Gaps between skirting board and ground floor.



Figure 4 Leak at gap between skirting board and floor.

- b) Service penetrations in kitchen.



Figure 5 Leak around gas outlet pipe to hob.



Figure 6 Leak around waste pipe.



Figure 7 Leaks around water pipes.



Figure 8 Leaks around pipes leading from the boiler.

c) Service penetrations in downstairs toilet.



Figure 9 Leaks around water pipes to wash hand basin.



Figure 10 Leaks around water and waste pipes to toilet.



Figure 11 Leaks around electrical fuse box.

- d) Hole in kitchen floor (approximately 100 mm x 50 mm in size).



Figure 12 Leak at hole in kitchen floor.

- e) Poorly fitting trickle vents.



Figure 13 Leaks around poorly fitting trickle vents.

f) Patio doors.



Figure 14 Leaks around junction at top of patio doors.



Figure 15 Leaks around bottom of patio doors.

- g) Gaps between wall and ceiling in the cupboard under the stairs.



Figure 16 Leaks in cupboard under the stairs.

- h) Pipework penetrations behind radiators.



Figure 17 Leaks as pipework penetrates dry-lining behind radiators.

- i) Poorly locking loft hatch which did not compress seal fully when closed.



Figure 18 Poorly locking loft hatch lifting during leakage identification.

- j) Gaps between skirting board and first floor.



Figure 19 Dust illustrating the leakage paths at the junction between the skirting board and the first floor.

- k) Gaps between flooring panels on the first floor.



Figure 20 Leaks at the junction between flooring panels.

- l) Service penetrations in the bathroom and around the bath panel.

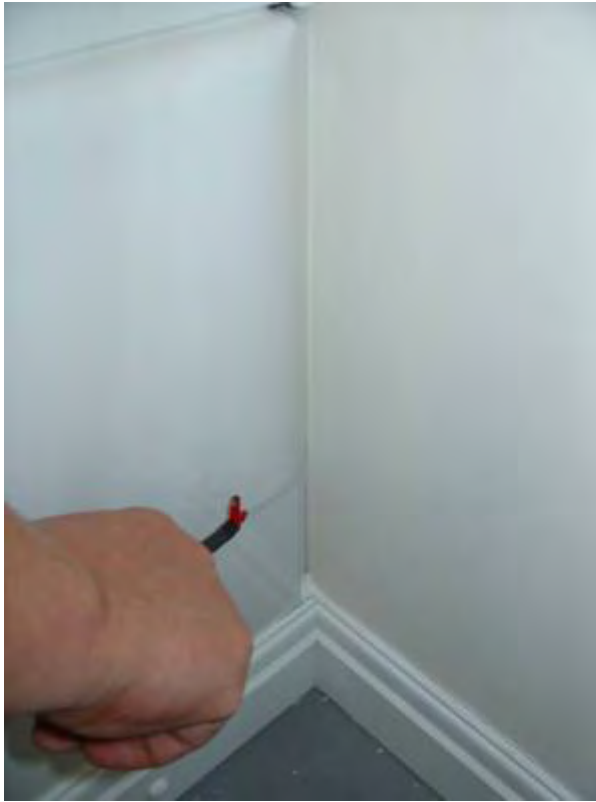


Figure 21 Leaks at the side of the bath panel.

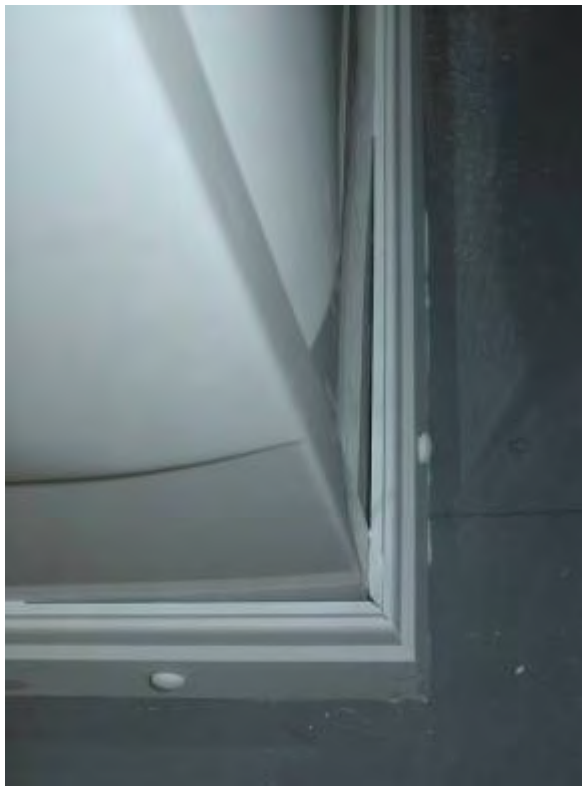


Figure 22 Leaks at the bottom of the bath panel.



Figure 23 Leaks around water and waste pipes to toilet.

m) Service penetrations and gaps between the ceiling and wall junction in the boiler cupboard.

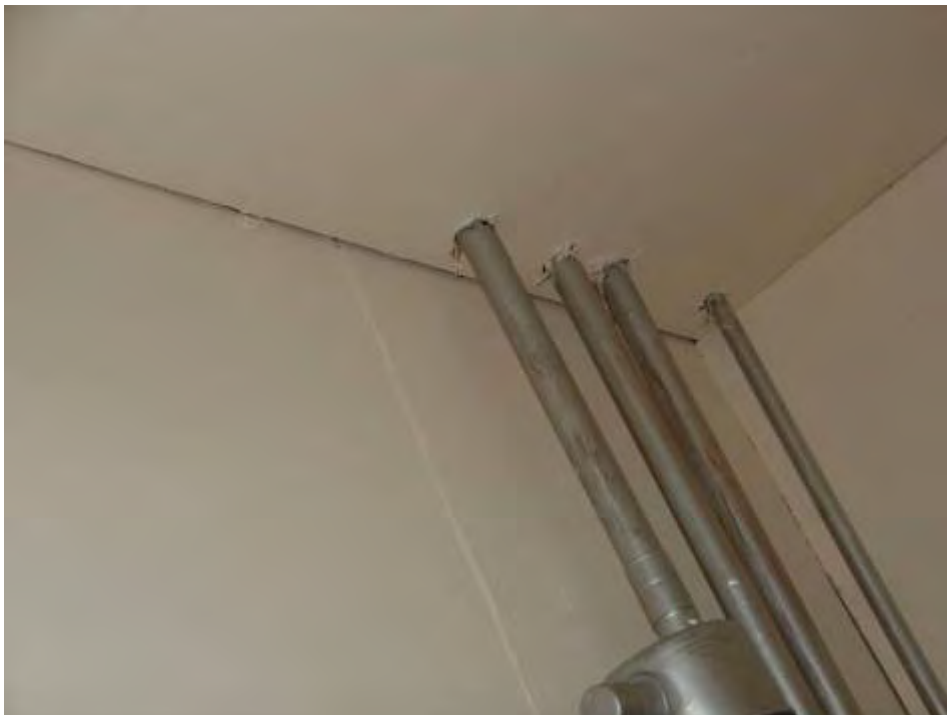


Figure 24 Leaks around service penetrations and at ceiling junction in boiler cupboard.

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Appendix 5

Airtightness of buildings — towards higher performance

Interim Report D5 — Site Assessments and Feedback Material

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

Dr Jez Wingfield, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report reviews the progress on the assessment of site survey data that have been obtained for the selected sites. The report also details the results of pressurisation tests on dwellings constructed by participating developers as part of Phase 1 of the project.
- 2 Pressurisation test results show a relatively narrow range of airtightness for all of the tested dwellings, ranging from 9 to 16 m³/(h.m²) @ 50Pa. Only three of the 16 tested dwellings had an air permeability that was better than the UK mean of 11.5 m³/(h.m²), with the mean for all 16 being 12.8. However, given the number of dwellings tested and the range of values measured, there is not a statistically significant difference between the sample and the UK mean. Only two of the tested dwellings had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) set in Part L1 2002, despite the developer's use of Robust Details as the basis of the application for regulatory approval. This suggests that Robust Details in their current form and implementation are failing to deliver the required level of airtightness in dwellings.
- 3 Although the small sample size precludes certainty, the airtightness results do appear to show a difference in air permeability between the different types of construction method used for the selected dwellings. The tightest dwellings were those of masonry cavity construction with full fill blown fibre cavity insulation, whilst the leakiest dwellings were those of masonry cavity construction with partial fill cavity insulation. This suggests that full fill blown mineral fibre cavity wall insulation may assist in improving airtightness, perhaps by increasing the resistance to air flow within and along the cavity wall.
- 4 The data show that the tightest dwellings tested were those constructed by developer B. The leakiest dwelling was constructed by developer D (dwelling D42), which was of steel frame construction. In the case of this dwelling (and to a lesser extent for other dwellings built by the same developer) large gaps were observed between the flooring panels and at the floor/wall junctions, enabling free passage of air to the outside. Therefore, the poor performance of this dwelling was felt to be attributable to factors such as poor tolerances of components, quality of workmanship, site supervision and training, and possibly stemming from unfamiliarity with the steel frame construction technique.
- 5 The most common air leakage paths were identified as: service penetrations; the junction between the floors and the skirting board; the junctions between intermediate flooring panels; around the bath panel and the shower tray; around the stairs; around kitchen units; through poorly fitting trickle vents; via the loft hatch; through gaps between patio doors and through holes in the ground floor.
- 6 The types of leakage paths identified suggest that the air permeability of the dwellings could be improved by undertaking a number of relatively simple measures. For instance, sealing the junction between the skirting board and the floors with an appropriate sealant, sealing the kitchen floor, including areas concealed under kitchen units and sealing all service penetrations using an appropriate sealant, including those concealed behind baths and showers.
- 7 Design assessments have been completed for all 25 selected dwellings and site surveys have commenced on 22 of the 25 selected dwellings. Some of the main points that have been obtained from the site surveys are as follows:
 - a) Incomplete sealing was found around built-in timber I-beams and joists, sometimes exacerbated by difficult access to the gaps where joists are positioned close to a wall.
 - b) Incomplete application of scratch coats was observed where applied to cavity walls, especially when applied after the stairs and services had been installed.
 - c) Plasterboard dry-lining on dabs is not being applied with the required continuous ribbons of adhesive around the perimeter or around services and windows.
 - d) Gaps and cracks were frequently observed in the external blockwork, and perpendes were often not completely filled with mortar.
 - e) Service penetrations are rarely properly sealed, especially where they are hidden, for example behind cupboards, panels, boxing or radiators. This task is frequently made much more difficult by the excessive size of the holes when compared with the size of pipe or duct.
 - f) Holes in flooring and gaps between the flooring panels were observed in the intermediate floors of a number of the dwellings.
 - g) Ground floor concrete slabs were often observed to be incomplete at the corners of a room and in particular around patio doors.

- h) In most dwellings the trickle vents in the windows either did not fit tightly in the prepared hole in the window frame, or the closure for the vent would not shut properly.
 - i) Occasionally, windows or doors were found to be of a poor fit, with a visible gap between the frame and door or window. This was most often seen for patio doors.
 - j) Large gaps at the floor to wall junction were observed in nearly all dwellings. Some developers had made attempts to seal these gaps, but not consistently throughout the whole dwelling. Some developers had made no attempt to seal these gaps at all.
 - k) In some cases, loft hatches were incorrectly fitted such that the hatch was not compressing the seal properly, or they were fitted in such a way as to make it impossible to seal the frame to the ceiling.
- 8 Feedback to the developers from Phase 1 of the project will comprise a workshop for each of the developers, making five workshops in total. The workshops will make use of all of the material that has been gathered during Phase 1 in order to provide information and tailored advice specific to each of the developers. It is intended that the workshops will include presentations from the research team on the site specific results, a discussion of opportunities for improvement and the development of a plan of action to improve airtightness based on the observations and discussions.

Introduction

- 9 This report is milestone D5: Site Assessments and Feedback Material of Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). The report summarises the progress that has been made on the assessment of site data obtained as part of Phase 1 of the project and discusses the material that will be used as feedback to the individual developers (task 2.2.1). The results of completed pressure tests of dwellings from Phase 1 are also illustrated (task 2.1.5).
- 10 Details of the developers, the sites and the dwellings that are participating in this phase of the project are set out in Table 1.

Developer	Type of development	Type of construction	Selected dwelling types
Developer A	Combination of private and social housing.	Dry-lined masonry cavity, partial fill.	<ul style="list-style-type: none"> • A 2-storey 3 bedroom mid-terrace with an internal floor area of 83 m². • A 3-storey 3 bedroom mid-terrace with an internal floor area of 117 m². • A 2½-storey 3 bedroom end terrace with an internal floor area of 117 m². • A 2-storey 3 bedroom semi-detached with an internal floor area of 81 m². • A 2-storey 4 bedroom detached with an internal floor area of 118 m².
Developer B	Private housing.	Dry-lined masonry cavity, full fill.	<ul style="list-style-type: none"> • A 2-storey 4 bedroom detached property with an internal floor area of 129 m². • A 2½-storey 5 bedroom detached property with an internal floor area of 164 m². • A 2½-storey 3 bedroom detached property with an internal floor area of 149 m². • Two 2-storey 3 bedroom detached properties with an internal floor area of 100 m².
Developer C	Private housing.	Dry-lined masonry cavity, full fill.	<ul style="list-style-type: none"> • Two 2-storey semi-detached properties with an internal floor area of 69 m². • A 2-storey end terrace with an internal floor area of 61 m². • Two 2-storey mid-terraces with an internal floor area of 71 m².
Developer D	Private housing.	Steel frame	<ul style="list-style-type: none"> • A 2-storey 3 bedroom semi-detached property with an internal floor area of 72 m². • Two 2-storey 3 bedroom detached properties with an internal floor area of 91 m². • Two 2-storey 3 bedroom detached properties, one with an internal floor area of 84 m² and one with an internal floor area of 102 m².
Developer E	Social housing.	Wet-plastered masonry cavity, partial fill.	<ul style="list-style-type: none"> • A 2 bedroom apartment with an internal floor area of 58 m². • Two 2 bedroom apartments with an internal floor area of 57 m². • Two 1 bedroom apartments with an internal floor area of 43 m².

Table 1 Details of selected sites and dwelling type.

Summary of Progress to Date

- 11 Drawings have been received from all five developers. Design assessments have been completed for all of the 25 selected dwellings. Site surveys have commenced on 22 of the 25 selected dwellings (five from developers A, B C and D and two from developer E).
- 12 In terms of the pressurisation testing, pressure tests have been undertaken on 16 of the 25 selected dwellings (five from developer A, four from developer B, two from developer C and five from developer D). Another dwelling from developer B is also complete (dwelling B86), but due to the very quick completion date requested by the buyer, this dwelling is now occupied and is no longer available for testing. Details of the current stage of construction and anticipated completion dates for all of the dwellings that are participating in this phase of the project are set out in Table 2.
- 13 As can be seen from Table 2, it is anticipated that the majority of the selected dwellings will be completed and pressure tested within the programme timescale. The only exception to this relates to the five apartments that are currently being constructed by developer E and three of the dwellings that are being constructed by developer C (C236, C237 and C238). With respect to developer C, market conditions have had a considerable impact upon the construction programme. This has resulted in three of the dwellings remaining at DPC level since June 2004. These dwellings are not expected to be completed and tested until the end of November 2004. The five apartments that are currently being constructed by developer E are also not due to be completed until November 2004. The reasons for the late completion date can be attributed to the much longer build times associated with apartments compared with other housing forms, and the fact that all of the units within a particular block tend to be completed and handed over at the same time.
- 14 The late testing of the dwellings being constructed by developer C and the apartments being constructed by developer E is not expected to have a major impact on the overall research programme.

Developer	Type of construction	Dwelling type	Current stage of construction	Anticipated completion date
A	Dry-lined masonry cavity, partial fill.	• A9 - 2-storey 3 bedroom mid-terrace.	Completed.	
		• A11 - 3-storey 3 bedroom mid-terrace.	Completed.	
		• A12 - 2½-storey 3 bedroom end terrace.	Completed.	
		• A13 - 2-storey 4 bedroom detached.	Completed.	
		• A14 - 2-storey 3 bedroom semi-detached.	Completed.	
B	Dry-lined masonry cavity, full fill.	• B79 - 2-storey 4 bedroom detached.	Completed.	
		• B80 - 2½-storey 4 bedroom detached.	Completed.	
		• B81 - 2½-storey 4 bedroom detached.	Completed.	
		• B82 - 2-storey 3 bedroom detached.	Completed.	
		• B86 - 2-storey 3 bedroom detached.	Completed.	
C	Dry-lined masonry cavity, full fill.	• C236 - 2-storey mid-terrace.	Superstructure.	November 2004
		• C237 - 2-storey mid-terrace.	Superstructure.	November 2004
		• C238 - 2-storey end terrace.	Superstructure.	November 2004
		• C239 - 2-storey semi-detached.	Completed.	
		• C240 - 2-storey semi-detached.	Completed.	
D	Steel frame.	• D39 - 2-storey 3 bedroom semi-detached.	Completed.	
		• D42 - 2-storey 3 bedroom detached.	Completed.	
		• D43 - 2-storey 3 bedroom detached.	Completed.	
		• D44 - 2-storey 3 bedroom detached.	Completed.	
		• D59 - 2-storey 3 bedroom detached.	Completed.	
E	Wet-plastered masonry cavity, partial fill.	• CG01 - 2 bedroom apartment.	Superstructure.	November 2004
		• CG02 - 1 bedroom apartment.	Superstructure.	November 2004
		• C202 - 2 bedroom apartment.	Superstructure.	November 2004
		• C301 - 1 bedroom apartment.	Superstructure.	November 2004
		• C302 - 2 bedroom apartment.	Superstructure.	November 2004

Table 2 Details of the selected dwellings, their current stage of construction and anticipated completion date.

Results of the Pressurisation Tests

15 Pressurisation tests have so far been undertaken on 16 of the 25 selected dwellings. All of these tests were carried out by Leeds Metropolitan University using an Energy Conservatory Minneapolis Model 3 Blower Door. The internal volumes and exposed external areas of the tested dwellings are listed in Table 3.

Dwelling	Volume (m ³)	Exposed internal surface area (m ²)
A9	193	209
A11	268	257
A12	268	257
A13	273	262
A14	185	209
B79	327	306
B80	420	341
B81	385	323
B82	385	323
C239	162	189
C240	162	189
D39	178	198
D42	225	250
D43	208	218
D44	225	250
D59	237	263

Table 3 Details of the tested dwellings

- 16 In addition to the pressurisation tests, the main air leakage paths within each of the dwellings were identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. All of the pressurisation tests and the air leakage paths associated with each dwelling were video recorded and photographed. The air permeability data and leakage path information will be used at the feedback seminars (see task 2.2.1 of the project proposal) to assist the developers in identifying problems areas and to improve the airtightness performance of their dwellings.
- 17 Detailed pressurisation reports relating to each of the developers are available on request.

Air permeability

- 18 The results of all the individual air permeability tests are shown in Table 4 and Figure 1. The mean air permeabilities for those dwellings tested to date for each developer and construction type are given in Tables 5 and 6 (no data are available yet for developer E).

Dwelling	Pressurisation test		Depressurisation test		Mean permeability (m ³ /(h.m ²))
	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	
A9	13.95	0.999	13.86	0.999	13.91
A11	15.46	0.996	14.66	0.997	15.06
A12	12.12	0.990	12.49	0.999	12.31
A13	14.51	0.999	14.16	0.999	14.33
A14	15.33	0.993	15.71	0.994	15.52
B79	8.96	1.000	9.02	0.983	8.99
B80	11.76	0.992	11.20	0.990	11.48
B81	10.11	0.999	9.66	0.993	9.89
B82	12.04	0.996	11.53	0.999	11.79
C239	12.46	0.997	11.90	0.986	12.18
C240	12.11	0.971	11.40	0.981	11.76
D39	12.82	0.992	12.61	0.984	12.72
D42	15.55	1.000	16.37	0.999	15.96
D43	12.10	0.997	11.44	0.999	11.77
D44	14.58	1.000	14.94	1.000	14.76
D59	12.50	0.990	11.76	0.984	12.13

Table 4 Mean air permeability of the tested dwellings.

Developer	Mean permeability of all dwellings tested to date (m ³ /(h.m ²))
A	14.2
B	10.5
C	12.0
D	13.5

Table 5 Mean air permeability by developer.

Construction type	Mean permeability of all dwellings tested to date (m ³ /(h.m ²))
Dry-lined masonry cavity, full fill (Developers B and C)	11.0
Dry-lined masonry cavity, partial fill (Developer A)	14.2
Steel frame (Developer D)	13.5

Table 6 Mean air permeability by construction type.

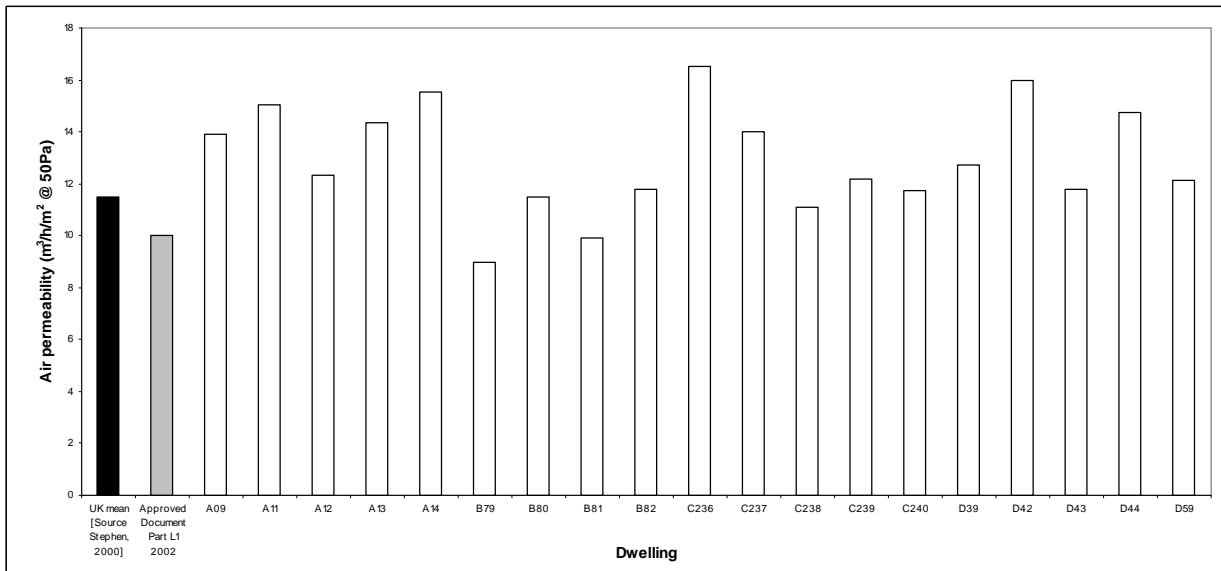


Figure 1 Mean air permeability of the tested dwellings.

- 19 Figure 1 illustrates the air permeability of the 16 tested dwellings compared with the UK mean¹ and the recommended maximum level set in the 2002 edition of the Building Regulations Approved Document Part L1 of 10 m³/(h.m²) @ 50Pa (ODPM, 2001). The data show that a relatively narrow range of airtightness was measured for the 16 tested dwellings. The air permeability ranged from 9 to 16 m³/(h.m²) @ 50Pa with a mean of 12.8 m³/(h.m²) and standard deviation of 1.9 m³/(h.m²). Only three of the 16 dwellings (dwelling B79, B80 and B81) had an air permeability that was lower than or equal to the UK mean of 11.5 m³/(h.m²). The mean of all 16 results (12.8 m³/(h.m²) @ 50Pa) suggests that these dwellings are less airtight than the average for the UK stock as a whole (11.5 m³/(h.m²) @ 50Pa). However, given the number of dwellings tested and the range of values measured, there is not a statistically significant difference between the sample and the UK mean.
- 20 Perhaps of most importance is that only two of the tested dwellings (dwellings B79 and B81) had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa set in the 2002 edition of the Approved Document Part L1 (ODPM, 2001). Therefore, the results suggest that only two of the 16 dwellings would satisfy the air leakage criterion set out in Approved Document Part L1. However, given the small sample size and the range of values measured, there is not a statistically significant difference. All five developers were using Robust Details (see DEFRA, 2001) as the basis of the application for regulatory approval. Despite this, the developers were unable to achieve the airtightness target in the majority of cases. This could be due to a lack of on-site quality control relating to the construction of Robust Details, poor communication, poor inherent construction design relating to airtightness, a lack understanding of how Robust Details work or possibly even that the Robust Details themselves may be difficult to achieve in practice, impractical or insufficiently tolerant of site variability — so called 'buildability'. We understand that the impact of Robust Details on whole dwelling air leakage was not subjected to empirical testing when the current catalogue was compiled. This report suggests that empirical testing would be needed as part of a process of developing a catalogue of details capable of reliably delivering an air leakage target.
- 21 The small sample size of this survey precludes absolute certainty when comparing data either by developer or by construction type. However, ignoring the issue of sample size, the data do show a difference in the air permeability between the different types of construction method covered in this survey (see Table 6). The tightest dwellings were those of masonry cavity construction with full fill blown fibre cavity insulation. The leakiest dwellings were those of masonry cavity construction with partial fill cavity insulation. A somewhat unlikely explanation for this is the better performance of the

¹ The UK mean has been derived from the Building Research Establishment's (BRE's) air leakage database, which is the largest and most comprehensive source of information on the airtightness of UK dwellings (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. However, despite its size, this database is not the result of random sampling and cannot claim to be unequivocally representative of the UK housing stock.

fully filled cavity insulated dwellings, as opposed to the partially filled cavity insulated dwellings, is that the blown mineral fibre will fill some of the cracks and gaps in the construction and will also increase the resistance to air flow within and along the cavity wall, in effect becoming a secondary air barrier. Partially filled cavity walls will not provide a barrier to air movement around the cavity and, as is the case for this particular developer, air movement will be allowed at the joint between rigid insulation boards where the gaps have not been sealed with adhesive tape. Given the small size of the sample, and the high probability of confounding variables, further work (both field tests on whole dwellings and laboratory tests on construction samples) is needed to establish whether this difference is real, or whether it has occurred by chance.

- 22 The data also show that the tightest dwellings tested were those constructed by developer B (Table 5). We observed no significant differences in the quality of workmanship between the masonry cavity dwellings constructed by developers A, B and C, so we believe that workmanship alone is unlikely to be the cause of difference in performance between these three developers. The difference is likely to be due to a combination of factors such as design, quality control, site supervision and workmanship.
- 23 The leakiest dwelling was D42 constructed by developer D. All of the dwellings constructed by developer D were of steel frame construction. It is not certain whether the poor performance of the dwellings from developer D is attributable to an intrinsic problem with the airtightness of steel framed construction, the quality of workmanship, or a combination of the two. However, large gaps were observed between a number of the components in dwellings D42 and D44, such as flooring panels and floor/wall junctions. Such gaps in the defined air barrier would enable free passage of air to the outside. This suggests that the poor air leakage of these dwellings may therefore be attributable to factors such as poor tolerances of components, quality of workmanship, site supervision and training, or unfamiliarity with the construction technique.

Leakage identification

- 24 It was not possible to quantify the contribution that each leakage path made to each of the dwellings overall air leakage, but the smoke tests that were carried out enabled the main leakage paths within each of the dwellings to be identified. All of the dwellings were found to have a number of common air leakage paths. These are identified within Table 7 below.

Elements and junctions	Fixtures and fittings	Service penetrations
Gaps between skirting board and ground floor. Hole in kitchen floor.	Around kitchen units. Around trickle vents. Patio doors. Gaps around the stairs. Around loft hatch. Gaps between skirting board and first floor. Gaps between flooring panels on the first floor. Gaps around the bath panel and the shower tray.	Service penetrations in the kitchen and utility room. Service penetrations in downstairs toilet. Around electrical fuse box. Electrical sockets. Pipework penetrations behind the radiators. Service penetrations in the bathrooms and en-suites. Around extract fans. Service penetrations in the airing cupboard.

Table 7 Main air leakage paths.

- 25 In addition to a number of common air leakage paths, leakage paths were also identified that were particular to specific dwellings. These were as follows:
- Holes in the wall for wall-mounted light fittings in dwelling B79.
 - Around the fireplace in dwelling B79.
 - Holes in the ground floor in dwelling B79.
 - Around the window hinge in dwelling B79.
 - Around the door to the integral garage in dwelling B81.
 - Around isolation switch for extract fan in dwelling B82.

- g) Gaps between the back door and the door frame in dwellings B79, B80, B81 and B82.
 - h) Gaps between wall and ceiling in the cupboard under the stairs in dwelling D39.
 - i) Holes in the ground floor in dwelling D42.
 - j) Holes in first floor in dwelling D42.
 - k) Holes at the window/wall junction in dwelling D44.
- 26 Photographs of all of these leakage paths can be found within the relevant pressurisation test reports for each developer.
- 27 The leakage identification also highlighted that the air permeability of all of the tested dwellings could be improved by undertaking a number of relatively simple measures. These include:
- a) Sealing the junction between the skirting board and the floors with an appropriate sealant.
 - b) Sealing the kitchen floor, including areas concealed under kitchen units.
 - c) Sealing all service penetrations, including those concealed beneath baths and showers, using an appropriate sealant.

Interim Results of the Site Assessments

- 28 This section summarises the progress that has been made to date on the site surveys and presents the interim results.
- 29 The site surveys were undertaken in three separate stages and information on each particular dwelling on each site was recorded on a site survey protocol (see Johnston, Miles-Shenton and Bell, 2004). The three stages of the site surveys were as follows:

Stage 1: During intermediate floor construction. This will enable inspection of the method of supporting the intermediate floors and enable any potential leakage problems to be identified.

Stage 2: During dry-lining/wet plaster phase. This will enable inspection of the internal leaf of the external walls, the application of the dry-lining, inspection of window/wall junctions, inspection of service penetrations, etc.

Stage 3: Completion. This will enable identification of any potential leakage areas that have not been picked up during the 'snagging' process.

- 30 In addition to completing a site survey protocol, data on each site have also been collected and recorded using photographs, sketches and video tape. To date, Stage 3 site visits have been undertaken on 17 of the 25 selected dwellings and Stage 1 site visits have been undertaken on the remaining eight dwellings. These visits have resulted in the generation of approximately 2000 photographs. The general observations that have been obtained from the site surveys are summarised below.

Built-in Joists

- 31 For developers A, B and C, the drawings state that the timber I-beams that are used to support the intermediate floors are built into the internal leaf of the external/party wall, sealed with mortar, and then sealed using a mastic sealant. Site observations indicate that in a number of cases, the mastic has only been partially applied around the bottom flange and the web of the timber I-beams (see Figure 2). In addition, since the mastic sealant has been applied after the floor finish has been installed, it is very difficult or impossible to seal the top flange of the timber I-beams. There is a risk that in areas where the mastic sealant has not been applied, the mortar seal will crack as the timber shrinks and the mortar dries out, resulting in a number of air leakage paths from the intermediate floor void to the external/party wall cavity and then to outside.
- 32 In several cases where built-in joists were used and when observed at the stage prior to final sealing, very large gaps were visible between the joist and blockwork, often with the joist resting at an angle. This would make it much more difficult to properly seal the gaps between block and joist.
- 33 For developers A, B and C the timber I-beams that are used to support the intermediate floors are offset from the inner leaf of the external/party wall to allow services to be run from one floor to the next. In a number of dwellings this offset is so small that it is not possible to seal the area between the joist and the external/party wall using mortar and mastic sealant. The result is that in a number of the dwellings it is possible to see through the cavity to the external brick skin (see Figure 3). These gaps will enable air within the intermediate floor void to leak through to the external/party wall cavity and then to outside.



Figure 2 Partial application of mastic sealant (developer B).

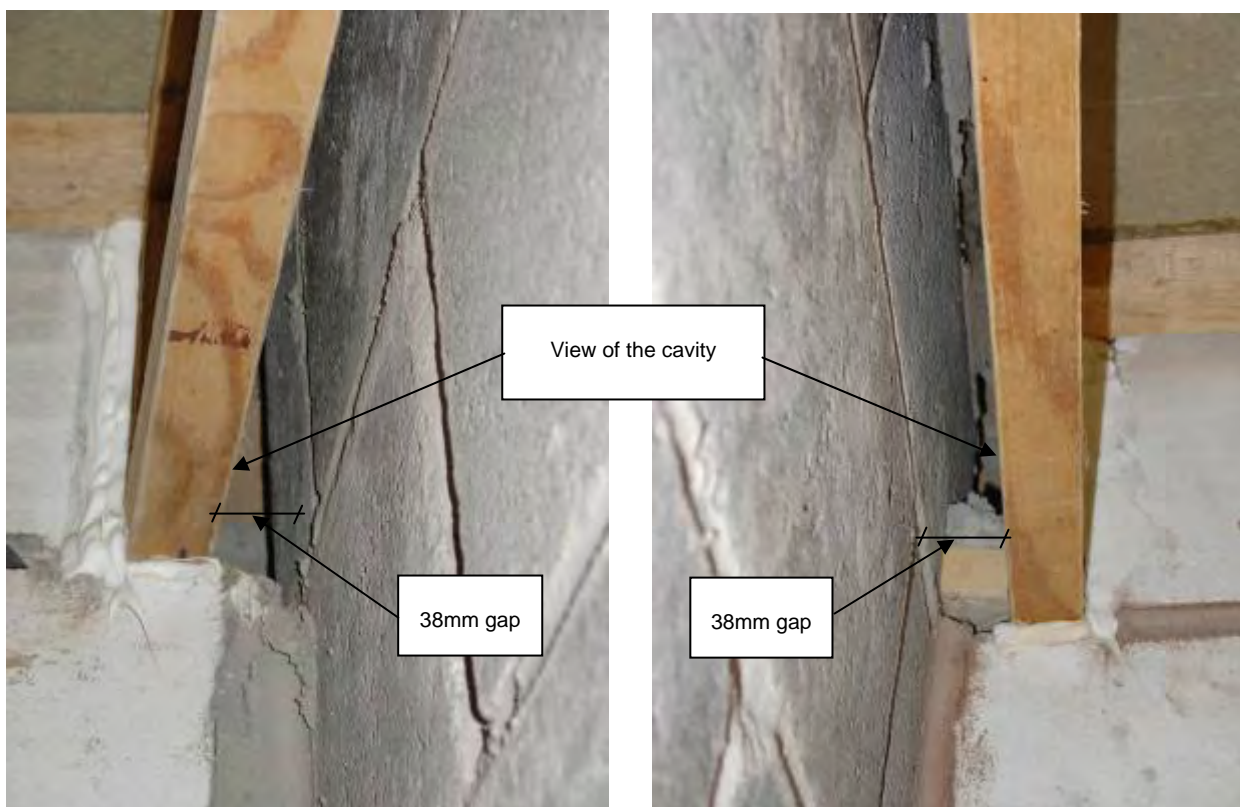


Figure 3 Gaps between the joist and the external/party wall (developer A).

Blockwork

- 34 Site observations have identified a number of areas where cracks and gaps are visible on the internal blockwork leaf of the external/party wall (see Figure 4), and perpendents have not been fully filled (see Figure 5). Any cracks or gaps in the blockwork inner leaf of the external wall could result in air leakage to the external/party wall cavity and then to outside.



Figure 4 Cracks in internal blockwork leaf of external wall.

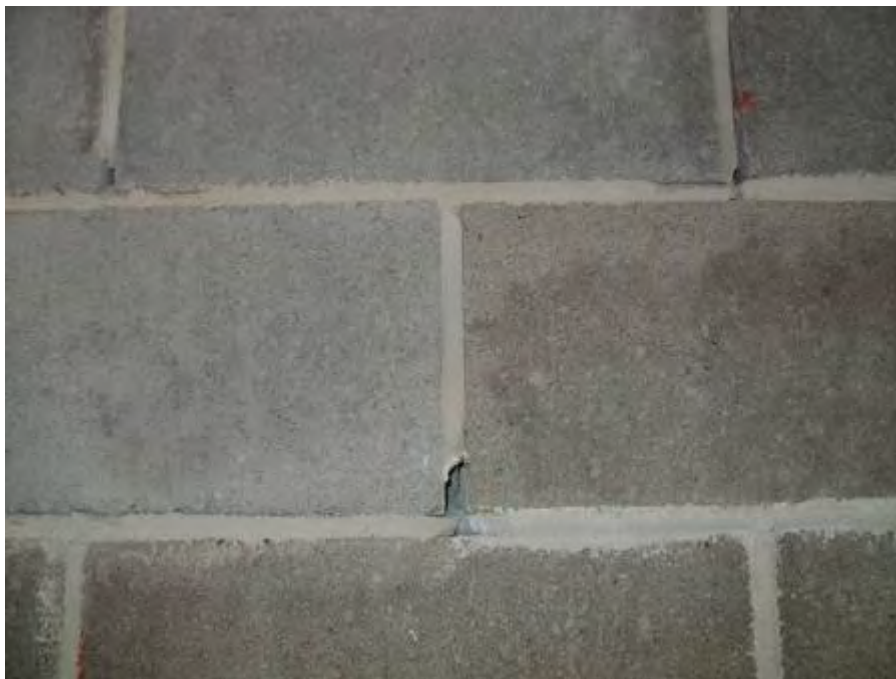


Figure 5 Perpend not fully filled in internal blockwork leaf of external wall.

Party Walls

35 The drawings for developer C state that a sand and cement scratch coat is to be applied to the party walls. This coat has been applied to improve the acoustic performance of the masonry aggregate block party wall, by sealing the blockwork and covering up any deficiencies in workmanship, prior to the application of the dry-lining. This coat also has the potential to improve the air permeability of the party wall by acting as an additional air barrier. Site observations indicate that the scratch coat has not been applied across the entire party wall (see Figure 6) in dwellings C239 and C240, and it is also being applied after the stairs and services have been installed (see Figures 6 and 7). The partial application and sequencing of the scratch coat means that it has not been possible to completely seal the blockwork party walls in these dwellings. Consequently, there

is a risk that air may leak through badly pointed joints, shrinkage cracks, or gaps in the party wall to the wall cavity and then to outside, in locations where the scratch coat has not been applied.



Figure 6 Incomplete scratch coat applied to party walls around services.



Figure 7 Incomplete scratch coat applied to party walls around stairs.

Plasterboard Dry-lining

- 36 One of the main air leakage paths within UK dwellings is plasterboard dry-lining (see Stephen, 1998 and 2000). Problems arise with plasterboard dry-lining when air can freely move into the gap between the plasterboard and the masonry wall, especially where the plasterboard is fixed to the wall using adhesive dabs. The air gap between the plasterboard sheet and the masonry wall then acts as a plenum, effectively interconnecting all of the leakage paths within the dwelling. To limit air leakage through plasterboard dry-lining, the report on Robust Construction Details (see DEFRA, 2001) recommends that continuous ribbons of adhesive are used to seal the dry-lining at the perimeter of external walls, openings, and services on external walls. This is illustrated in Figure 8.

In our opinion, the process of applying plaster ribbons in such a way as to seal all potential leakage sites is technically difficult to carry out. Observations from site confirm this (see Figures 9 to 11). Figures 10 and 11 also illustrate that the overall thermal performance of these dwellings will be degraded, as the discontinuous ribbons of adhesive will enable air to bypass the internal insulation.

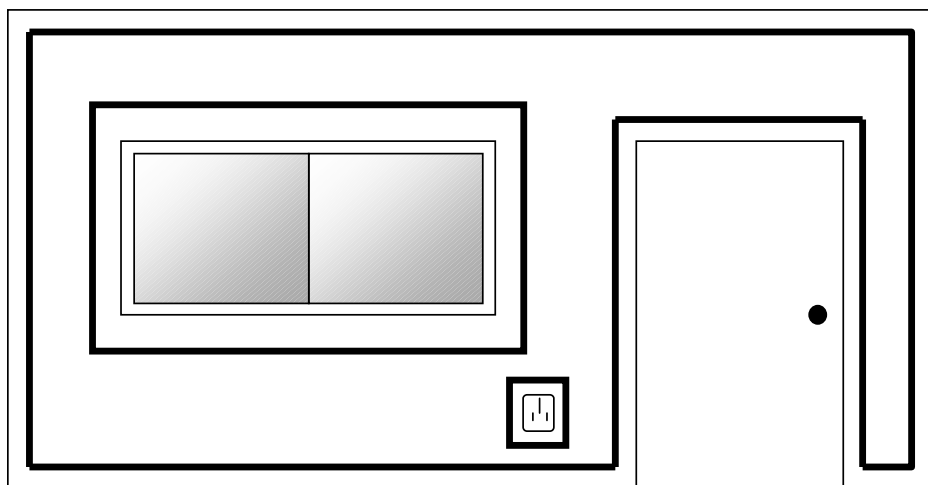


Figure 8 Schematic of continuous sealing of perimeters of a dry-lined wall.



Figure 9 Discontinuous ribbons of adhesive used to seal plasterboard dry-lining.



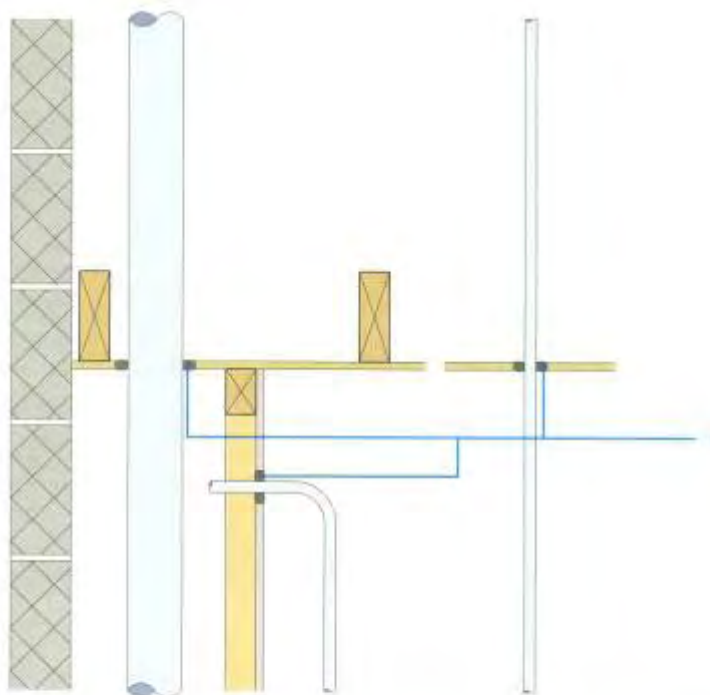
Figure 10 Discontinuous ribbons of adhesive around window opening.



Figure 11 Discontinuous ribbons of adhesive around door opening.

Service Penetrations

- 37 Service penetrations are known to be a significant route for air leakage (see Stephen 1998 and 2000). The report on Robust Construction Details (DEFRA, 2001) states that particular care on site should be paid to service penetrations and all service penetrations should be sealed with expanding foam or other suitable sealant, whether in the wall, ground floor, intermediate floor or ceiling (see Figure 12). Where large voids exist, mineral wool or some other backing material should be used to support the sealant. Observations from site illustrate that little attempt has been made to seal the majority of service penetrations through walls, ground floors, intermediate floors and ceilings, and where attempts at sealing have been made, the penetrations are generally inadequately sealed and inappropriate sealants have been used to seal gaps around the service penetrations. These points are illustrated in Figures 13 to 17.
- 38 In some cases, problems with service penetrations arose due to incorrect sequencing of work. For example, gas pipework which should have been placed in position at an early stage in the build sequence was omitted (due to missing details on drawings) and then had to be added at a later stage, requiring additional penetrations through the fabric that might otherwise have been unnecessary. In many cases, larger holes are made than are strictly necessary for the pipework, in order to allow for positioning (see Figure 13). These large holes are then much more difficult to seal. Another problem is that service penetrations that are subsequently hidden behind boxing or panels (for example the bath panel, shower tray, shower pod, in an under sink unit, in airing cupboard or in an under stairs cupboard) are often left unsealed, whilst visible penetrations in the same dwelling have been sealed. This suggests a lack of understanding of the importance of these areas, with the selection criteria being used when deciding to seal or not being one of cosmetic appearance rather than airtightness.



Notes

1. Seal all service penetrations with expanding foam or other suitable sealant. For large voids mineral wool or other material may be used to provide a backing for the sealant.

These details also apply to service penetrations through ground floors.

Figure 12 Diagram illustrating sealing of service penetrations [Source: DEFRA, 2001].



Figure 13 Unsealed service penetrations around WC.



Figure 14 Unsealed soil stack penetrating through intermediate floor.



Figure 15 Unsealed pipework penetrations behind radiator.



Figure 16 Unsuccessful attempt at sealing around water pipes.



Figure 17 Inappropriate use of sealant to seal service penetrations.

Intermediate Floors

- 39 Holes in the flooring and gaps between the flooring panels were observed in the intermediate floors of a number of the dwellings (see Figures 18 to 22). In two dwellings (D42 and D44) the gaps in the flooring panels were up to 25 mm wide. Any holes or gaps in the floor will enable air to leak into the intermediate floor void where it may then leak through the external/party walls to outside.

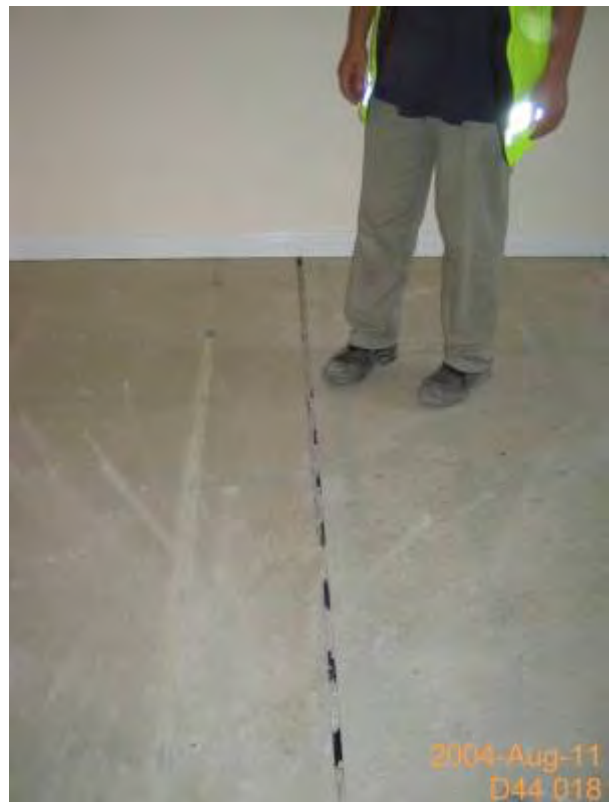


Figure 18 Leaks at the junction between flooring panels.



Figure 19 Leaks at the junction between flooring panels.



Figure 20 Holes in the flooring panels.



Figure 21 Screw holes in the flooring panels.



Figure 22 Holes in bathroom floor.

Incomplete Ground Floor Slabs

- 40 The ground floor slabs in a number of the dwellings were observed to be incomplete, particularly around the patio door area, resulting in holes in the ground floor slab (see Figures 23 and 24). Any holes in the ground floor slab will result in an air leakage path from the inside to the outside of the dwelling.



Figure 23 Hole in ground floor slab at patio door.



Figure 24 Hole in ground floor slab hidden by floor covering.

Windows and Doors

- 41 Windows and doors can be a significant source of air leakage (see Stephen, 1998 and 2000). Any poorly fitting or sealed windows, trickle vents or doors will result in an air leakage path directly from the inside to the outside of the dwelling. It was observed on a number of the dwellings that the trickle vents were either of a poor fit or would not close properly allowing passage of air either through the vent itself (when in the closed position) or through a gap between the vent and window.
- 42 In several cases the patio doors did not fit correctly such that the seals were uncompressed and in the worst cases there were observable gaps between the external door and the surrounding door frame. These points are illustrated in Figures 25 to 27.



Figure 25 Leakage through poorly fitting trickle vents.



Figure 26 Poorly fitting patio door with visible gap.

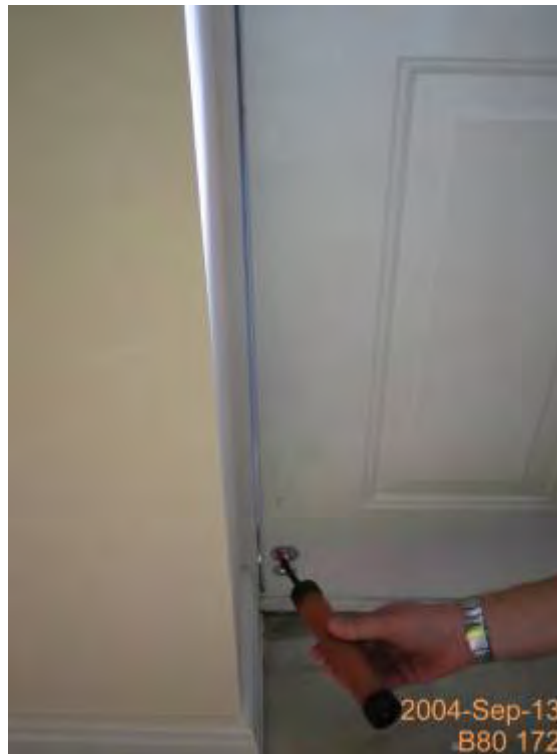


Figure 27 Observable gap between external door and frame.

Wall/floor Junction

- 43 The report on Robust Construction Details (DEFRA, 2001) states that particular care on site should be paid to joints between structural components, for instance, walls to floors. Observations from site illustrate that a number of gaps exist between the ground floor and the skirting board and the intermediate floor and the skirting board (see Figures 28 to 30). Any gaps will result in an air leakage path. Indeed, in the case of one of the developers (developer D) the air leakage between the wall and intermediate floor was so bad that a flow pattern was observed in the dust on the floor where air had flowed into the building during the depressurisation test (see Figure 29).



Figure 28 Leak at gap between skirting board and ground floor.



Figure 29 Leak at gap between skirting board and ground floor.



Figure 30 Gaps at the junction between the skirting board and the first floor.

Loft Hatch

- 44 Loft hatches are known to contribute to air leakage. Site observations illustrate that the loft hatches specified by one of the developers (developer D) had been installed in such a way that the hatch was not hinged, it could only be secured on one side and it did not compress the seal fully when it was closed. This was confirmed during a pressurisation test on one of the dwellings where the loft hatch was observed to leak and lift during the test (see Figures 31 and 32). In addition, a number of loft hatches have not been adequately sealed to the ceiling, resulting in air leakage between the loft

hatch frame and ceiling. In one case sealing was made more difficult by the proximity of the loft hatch frame to the wall (see Figure 33).

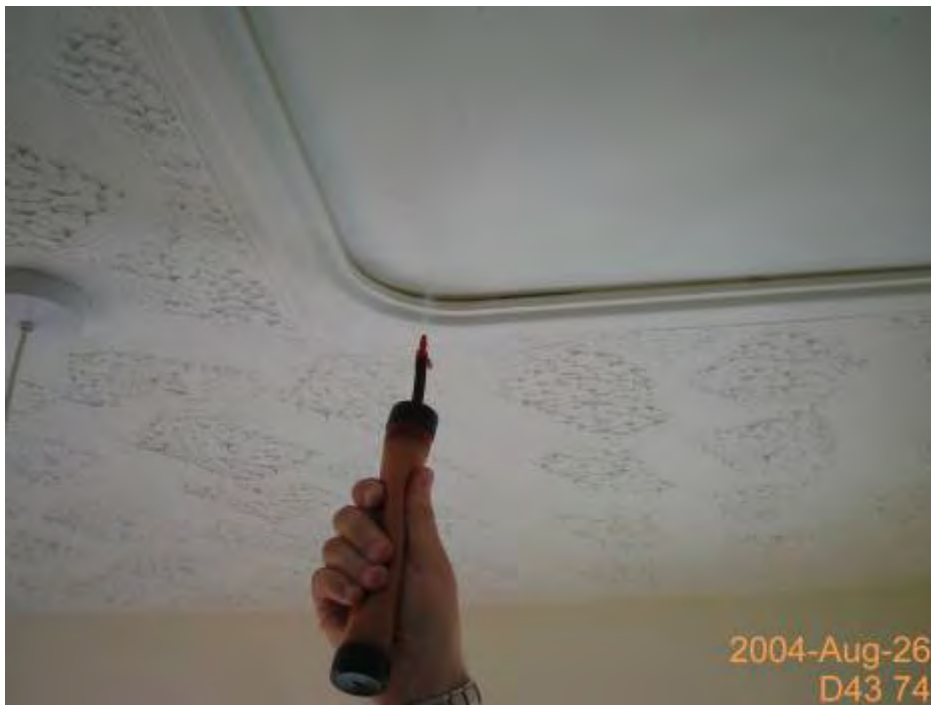


Figure 31 Leak through poorly sealed loft hatch.



Figure 32 Loft hatch lifting during pressurisation test.



Figure 33 Loft hatch not adequately sealed to the ceiling.

Feedback Material

- 45 Feedback from Phase 1 of the project will comprise a workshop for each of the developers, making five workshops in total. The workshops will make use of all of the material that has been gathered during Phase 1 of the project to provide information and tailored advice specific to each of the developers.
- 46 The form of each workshop will be established in conjunction with each developer but, as much as possible, a common pattern will be established. The workshops will be around a half day's duration and will make use of data, notes photographs and video recordings collected during Phase 1 to provide feedback and advice. A two-way dialogue will be facilitated to allow feedback from the developers back to the research team. The workshops will be recorded in note form and a report provided to each developer on the main outcomes.
- 47 The workshops will take place at the developer's offices. It is proposed that those present will include representatives from senior management, site management and operative supervision. The attendees at each workshop may vary for each developer and will be dependent upon the structure of the organisation and availability of personnel. However, it is expected that the participants will include someone from the design team, the site manager or assistant manager from the site tested, the technical director for design and development or similar, a regional director, and if possible a number of trade supervisors and site operatives.
- 48 Prior to the workshop, the developer's team will be presented with a copy of the design assessments and the pressurisation test report for their site. This will enable them to gather their thoughts and to investigate any of the issues raised in the reports prior to attendance at the workshop.
- 49 The workshops will include the following activities:
 - a) The workshop will begin with a presentation from the research team which will include the following information:

Details of the pressurisation tests, how they are undertaken, why they are undertaken, their importance with regard to energy performance of dwellings and the airtightness requirements of the current Building Regulations and expected changes to the Building Regulations with respect to airtightness.

Airtightness results for the developer in question. The results will be compared against those for the rest of the tested cohort, the UK mean and Building Regulation requirements. Precise details of the leakage paths and construction issues observed on site will be outlined.

- b) A discussion of the results will then follow. This will take the form of directed questioning with opportunities for brainstorming using simple idea generation techniques if thought necessary.

The developer's team will be asked whether they agree with the findings of the survey and whether what was observed was typical practice for the developer in question.

The developers team will be asked to identify what changes could be put in place to address the issues raised in specific areas such as dwelling design, availability/completeness of drawings, Robust Details, planning/sequencing, quality of components, quality control, workmanship, site management and training. If considered appropriate, some of these issues could be observed first hand on the site.

- c) Finally the developers will be asked to agree to a plan of action that seeks to improve the airtightness performance of their dwellings. It is hoped that this will include the developers agreeing to an informal airtightness target for the dwellings that will be tested as part of Phase 3 of the project.

50 A draft agenda for the workshops can be found within Appendix 1.

Conclusions

- 51 The failure of the majority of the tested dwellings to achieve the required airtightness target under ADL2002 of $10 \text{ m}^3/(\text{h.m}^2)$ raises questions about the effectiveness of Robust Details in its current form as a method for achieving compliance with airtightness requirements. The poor performance of the dwellings could be attributable to range of factors. These might include a lack of understanding of Robust Details, poor quality control of Robust Details on site, poor communication of the importance of Robust Details, poor inherent design for airtightness, a lack of adequate training, lack of necessary details on drawings or difficulties in achieving current Robust Details in practice (so called 'buildability'). Such concerns should feed into the development of Robust Details for the 2005 review of Part L.
- 52 It may be concluded on the basis of the admittedly small data set, that the airtightness of UK dwellings has not improved since the introduction of ADL2002. If anything, the data suggest that performance has actually worsened when compared with the existing UK housing stock. If these results are a true reflection of the airtightness of UK dwellings currently being built then it could have serious implications for the industry and its preparedness for the proposed changes to Part L. Some of the issues that need to be addressed would include areas such as training, quality control and building design. The next stages of this project will give more focus on these issues.
- 53 A number of common air leakage paths were observed within the dwellings tested. It is suggested that some relatively simple measures and procedures could be adopted by the developers that would address a number of these leakage paths. Such measures would include sealing all visible and hidden service penetrations using an appropriate sealant, sealing between the skirting board and floor, and ensuring that continuous ribbons of adhesive are used at the perimeter of plasterboard.
- 54 This report not only reveals a wealth of problems at the level of individual details, but also problems at the strategic and conceptual levels. The latter manifest themselves through sequencing problems that make it difficult or impossible to seal around services and at junctions in construction and through defects that suggest that the workforce does not understand why it is being asked to do certain things. The 'catalogue of details' approach to providing advice on airtightness does not address process or conceptual issues.

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Appendix 1

Workshop agenda

Draft Feedback Workshop Agenda

1. Welcome
2. General Introduction to Airtightness of Dwellings and Testing Procedures
3. Presentation of Airtightness Results for Developer 'x'
4. Presentation of Site Survey Results for Developer 'x'
5. Discussion of Results
6. Brainstorm Solutions
7. Agree Plan of Action
8. Additional Feedback to Research Team and Comments

Appendix 6

Airtightness of buildings — towards higher performance

Interim Report D6 — Seminars and Developer Feedback

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report reviews progress on the feedback and guidance seminars that have been undertaken with each developer as part of Phase 2 of the project and reports on the interim results. The report also details the measures that each developer intends to undertake for Phase 3 of the project.
- 2 Pressurisation tests have been undertaken on all but two of the dwellings that are participating in Phase 1 of the project. Both of these dwellings are expected to be completed and tested by early May 2005. In addition, feedback and guidance seminars have been undertaken with three of the five developers involved in the project. Of the two remaining seminars, one is scheduled to take place in early May 2005, whilst the other will be arranged as soon as the remaining dwellings have been completed and pressure tested.
- 3 Pressurisation test results show a relatively wide range of airtightness for the dwellings tested, ranging from 4.0 to 16.5 m³/(h.m²) @ 50Pa. The mean for all of the dwellings was 11.5 m³/(h.m²) @ 50Pa, suggesting that the group of dwellings are broadly in line with the average for the UK stock as a whole. Despite all of the developers using Robust Details as the basis of the application for regulatory approval, only six of the tested dwellings had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa set in the 2002 edition of Approved Document Part L1. If the four flats tested are excluded (flats tend to be a more airtight dwelling form), only two out of 19 houses met the 2002 Part L target. This suggests that simply adopting Robust Details, at least in their current form, provides no guarantee that the current regulatory standard will be achieved with any degree of consistency.
- 4 Although the small sample size precludes certainty, the airtightness results do appear to show a difference in permeability between the different types of construction method used by the various developers. The tightest dwellings were those of mechanically plastered masonry cavity construction (since these were flats, their performance could also be a function of form as well as construction), whilst the leakiest dwellings were those of steel framed construction. The results also appear to show a difference in performance between the three developers that are building using dry-lined masonry cavity construction. Since no significant differences in the quality of workmanship were observed between these three developers, workmanship alone is unlikely to have caused this difference. It is more likely that the observed difference in performance is attributable to a combination of design, and site quality control as well as the workmanship of operatives.
- 5 A number of common air leakage paths were identified within the tested dwellings. These related to elements and junctions, fixtures and fittings, and service penetrations. The majority of these were indirect air leakage paths, which could be traced back to the observations of design and construction made during Phase 1 of the project.
- 6 Site observations have highlighted a number of common construction issues which are likely to have had an influence on the eventual airtightness of the tested dwellings. These issues related to the method of construction, openings and service penetrations.
- 7 The feedback received to date from the developers has been very positive. All of the developers indicated that what had been observed on site was typical of their construction standards nationally.
- 8 The concept of an air barrier was unfamiliar to all but one of the developers. Therefore, it was no surprise to find that none of the developers was aware of the construction principle that they were using to achieve an airtight envelope and none of them had explicitly identified the position of the air barrier on their drawings.
- 9 There is a perception from the developers that the way to improve the airtightness of their dwellings is to identify all of the individual air leakage points at internal surfaces and then adopt the 'gap-filling' approach. This is generally at odds with the need for a design that is clear about the location and role of an air barrier. The discussions that took place during the seminars and the responses from the developers indicated that there is a general lack of awareness and understanding of the issues surrounding airtightness. This exists at all levels, from site operatives up to senior management. Consequently, there is a need for further education, guidance, training and advice within the industry on airtightness.

Introduction

- 10 This report constitutes milestone D6 (Seminars and Developer Feedback) of Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). It reviews the progress that has been made on undertaking the feedback and guidance seminars to each of the individual developers as part of Phase 2 of the project and reports the interim results. The general lessons learnt from Phase 1 of the project are highlighted and details of the sites and the dwelling types that are participating in Phase 3 of the project are also illustrated (task 2.2.1).

Summary of Progress to Date

- 11 This project is a participatory action research project involving five developers from the commercial and social housing sectors. The project is designed to be undertaken in three distinct phases:
- Phase 1 — Assessment of the design and construction of five house types per developer (total 25 types) and undertake pressurisation tests and leakage identification for each house type.
 - Phase 2 — Undertake a participatory seminar (one per developer) in which the results of Phase 1 and airtightness guidance will be discussed with the developer and design and construction teams. Where possible the developer will be encouraged to set an airtightness standard (commensurate with existing ventilation strategies) for the design and construction of a further set of dwellings that would be assessed and tested in Phase 3.
 - Phase 3 — This phase mirrors Phase 1 in which the design and construction of a further set of dwellings (five from each developer) will be monitored following the feedback and enhanced understanding gained during Phase 2. Upon completion and testing, a feedback seminar will be held to review the design and construction experience from the developer's point of view.
- 12 Site surveys for Phase 1 of the project have been completed for 23 of the 25 selected dwellings (five from developers A, C and four from developers B and E). The site surveys for the remaining two dwellings are expected to be completed by the end of April 2005.
- 13 Of the 25 dwellings selected as part of Phase 1, 23 have been pressure tested. It was not possible to test one dwelling from developer B prior to occupation due to the very quick completion date requested by the buyer. In order to maintain the number of selected dwellings, an addition dwelling was selected from developer E (dwelling EC201). Site surveys on this dwelling have been completed and the dwelling has also been pressure tested. With respect to the two remaining apartments that are being constructed by developer E, pressurisation tests have not been undertaken due to delays in construction. These delays have been caused by inclement weather. It is anticipated that the two remaining apartments will be completed and pressure tested by the end of April 2005.
- 14 Feedback and guidance seminars have been undertaken with three of the five developers (developers A, B and D). The feedback seminar for developer C is arranged for the second week in May 2005. The seminar for developer E will be arranged as soon as possible after all of the apartments have been completed and pressure tested.
- 15 Five dwellings have been selected from developers A and D to participate in Phase 3 of the project, and we are in the process of selecting five dwellings from developer B. Due to staff changes within developer A, the five dwellings originally selected are currently under review.
- 16 Site visits have commenced for Phase 3 of the project. To date, three site visits have been undertaken to developer D.

Update on the Pressurisation Test Results

- 17 This section updates the pressurisation test results and leakage identification work that was previously reported in milestone D4 — *Airtightness Results from Phase 1* (Johnston, Miles-Shenton and Bell, 2004).
- 18 The results of all the individual air permeability tests undertaken to date are shown in Table 1 and Figure 1. The mean air permeability for those dwellings tested to date for each developer and construction type are given in Figure 2 and Tables 2 and 3.

Dwelling	Pressurisation test	Depressurisation test	Mean
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	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	permeability (m ³ /(h.m ²))
A9	13.95	0.999	13.86	0.999	13.91
A11	15.46	0.996	14.66	0.997	15.06
A12	12.12	0.990	12.49	0.999	12.31
A13	14.51	0.999	14.16	0.999	14.33
A14	15.33	0.993	15.71	0.994	15.52
B79	8.96	1.000	9.02	0.983	8.99
B80	11.76	0.992	11.20	0.990	11.48
B81	10.11	0.999	9.66	0.993	9.89
B82	12.04	0.996	11.53	0.999	11.79
C236	16.81	1.000	16.26	1.000	16.53
C237	14.08	1.000	13.98	1.000	14.03
C238	11.17	0.998	11.02	1.000	11.09
C239	12.46	0.997	11.90	0.986	12.18
C240	12.11	0.971	11.40	0.981	11.76
D39	12.82	0.992	12.61	0.984	12.72
D42	15.55	1.000	16.37	0.999	15.96
D43	12.10	0.997	11.44	0.999	11.77
D44	14.58	1.000	14.94	1.000	14.76
D59	12.50	0.990	11.76	0.984	12.13
ECG01	5.13	0.999	4.90	0.996	5.01
ECG02	4.37	0.998	4.32	0.997	4.35
EC201	4.79	1.000	4.43	0.997	4.61
EC202	3.94	0.999	3.96	1.000	3.95

Table 1 Mean air permeability of the tested dwellings.

Developer	Mean permeability of all dwellings tested to date (m ³ /(h.m ²) @ 50Pa)
A	14.2
B	10.5
C	13.1
D	13.5
E	4.5

Table 2 Mean air permeability by developer.

Construction type	Mean permeability of all dwellings tested to date (m ³ /(h.m ²) @ 50Pa)
Mechanically plastered masonry cavity (Developer E)	4.5
Dry-lined masonry cavity (Developers A, B and C)	12.6

Table 3 Mean air permeability by construction type.

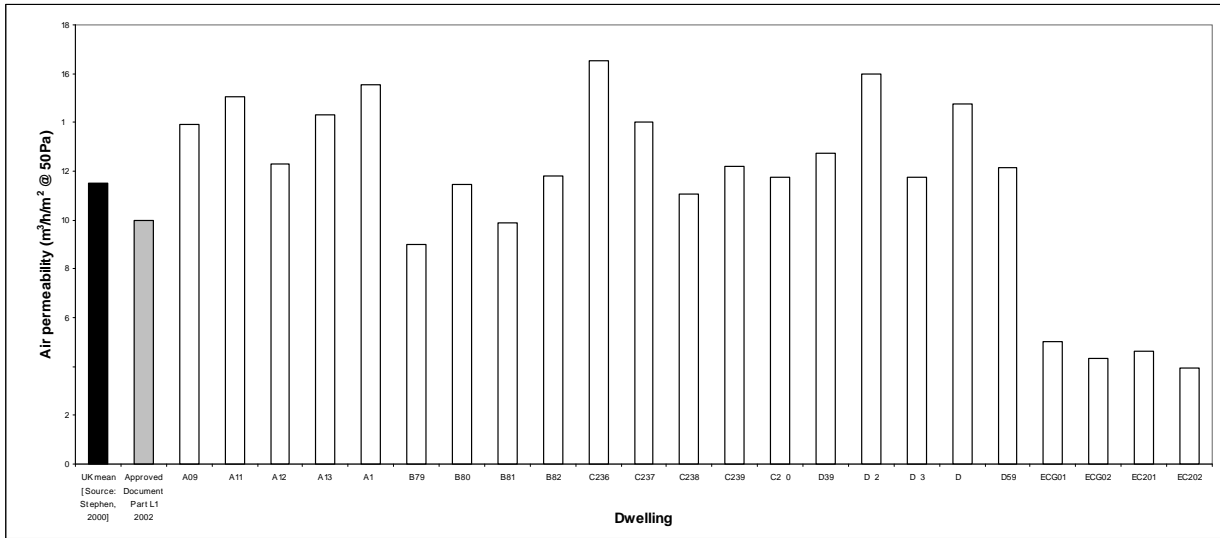


Figure 1 Mean air permeability of the tested dwellings.

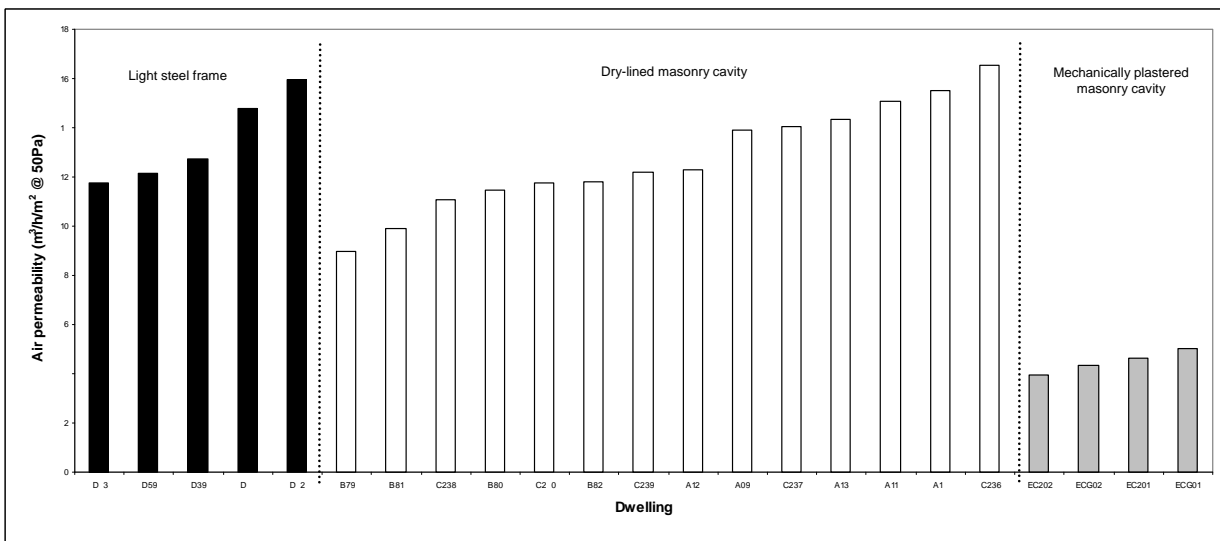


Figure 2 Mean air permeability of the tested dwellings by construction type.

19 Figure 1 illustrates the air permeability of the 23 tested dwellings compared to the UK mean¹ and the recommended maximum level set in the 2002 edition of the Building Regulations Approved Document Part L1 of 10 m³/(h.m²) @ 50Pa (ODPM, 2001). The data show that a relatively wide range of airtightness was measured for the 23 tested dwellings. The air permeability of the dwellings ranged from 4.0 to 16.5 m³/(h.m²) @ 50Pa, with a mean of 11.1 m³/(h.m²) and standard deviation of 3.9 m³/(h.m²). Although the range of air permeability that was measured within the

¹ The UK mean has been derived from the Building Research Establishment's (BRE's) air leakage database, which is the largest and most comprehensive source of information on the airtightness of UK dwellings (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. However, despite its size, this database is not the result of random sampling and cannot claim to be unequivocally representative of the UK housing stock.

tested dwellings is consistent with some recent measurements undertaken by Grigg (2004),¹ the mean for the dwellings tested in this project is higher (11.1 as opposed to Grigg's 9.2 m³/(h.m²) @ 50Pa). This is probably a result of the larger proportion of apartments² (36%) that were included in the sample tested by Grigg (2004) compared with our sample (24%).

- 20 Only eight of the 23 dwellings (35%) had an air permeability that was lower than or equal to the UK mean of 11.5 m³/(h.m²). The mean of all 23 results (11.5 m³/(h.m²) @ 50Pa) suggests that these dwellings are as airtight as the average for the UK stock as a whole (11.5 m³/(h.m²) @ 50Pa).
- 21 One of the most important results to be obtained from Figure 1 is that only six of the tested dwellings (four flats and two houses) (26%) had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa set in the 2002 edition of the Approved Document Part L1 (ODPM, 2001). Of the 19 houses tested only two achieved a level below the value given in ADL1, However, given the small sample size and the range of values measured, no claims of statistical significance can be made. All five developers were using Robust Details (see DEFRA, 2001) as the basis of the application for regulatory approval. Given this, only one of the developers (developer E) has managed to satisfy the air leakage criterion with all of their dwellings that have been tested. The other four developers were unable to achieve the airtightness target in the majority of cases. The reasons for this could be due to a lack of on site quality control relating to the construction of Robust Details, poor communication, poor inherent construction design relating to airtightness, a lack understanding of how Robust Details work or possibly even that the Robust Details themselves may be difficult to achieve in practice, impractical or insufficiently tolerant of site variability - so called 'buildability'. We understand that the impact of Robust Details on whole dwelling air leakage was not subjected to empirical testing when the current catalogue was compiled. This report suggests that empirical testing would be needed as part of a process of developing a catalogue of details capable of reliably delivering an air leakage target.
- 22 The small sample size of this survey precludes absolute certainty when comparing data either by developer or by construction type. However, ignoring the issue of sample size, the data do show a difference in the air permeability between the different types of construction method covered in this survey (see Figure 2 and Table 3). The tightest dwellings were those of mechanically plastered masonry cavity construction (developer E). These dwellings are on average a factor 3 more airtight than those that were built using dry-lined masonry cavity construction. The reasons for this are likely to be two-fold. First of all, wet plastered masonry dwellings tend to be intrinsically more airtight than comparable dry-lined masonry or steel frame construction (Olivier, 1999). Secondly, as previously mentioned, apartments tend to be more airtight than comparable dwellings of different built form. The least airtight dwellings were those constructed using light steel frame (developer D). These dwellings were only marginally leakier than the dry-lined masonry cavity dwellings (mean air permeability of 13.5 as opposed to 12.6 m³/(h.m²) @ 50Pa) constructed by developers A, B and C. It is not certain whether the poor performance of the light steel framed dwellings is attributable to an intrinsic problem with the airtightness of steel framed construction, the quality of workmanship, or a combination of the two. However, large gaps were observed between a number of the components in dwellings D42 and D44, such as flooring panels and floor/wall junctions. Assuming that the air barrier within these dwellings is formed by the plasterboard dry-lining, such gaps between components would enable free passage of air to the outside. This suggests that the poor air leakage of these dwellings may therefore be attributable to factors such as poor tolerances of components, quality of workmanship, site supervision and training, or unfamiliarity with the construction technique.
- 23 The data also show that there appears to be a difference in performance between the three developers that are building using dry-lined masonry cavity construction (developers A, B and C). The tightest dwellings were those constructed by developer B (mean air permeability of 10.5 m³/(h.m²) @ 50Pa), whilst the leakiest dwellings were those constructed by developer A (mean air permeability of 14.2 m³/(h.m²) @ 50Pa). Despite these results, no significant differences in the quality of the workmanship were observed between the dwellings constructed by developers A, B and C. Therefore, we believe that workmanship alone is unlikely to have caused the difference in performance that has been observed between these three developers. It is more likely that the

¹ The measurements undertaken by Grigg (2004) are based upon a non-random sample of 99 dwellings that were constructed to the provisions contained within the 2002 edition of the Building Regulations Approved Document Part L1.

² Apartments tend to be more airtight than other dwelling forms of equivalent area as they are more likely to have solid intermediate floors, fewer door and window openings and fewer service penetrations.

difference in performance is due to a combination of design, and site quality control processes as well as workmanship.

- 24 It is important to note that given the small size, the non-random nature of the sample of dwellings that have been tested, and the high probability of confounding variables, it not possible to establish whether there is a difference between the developers and if so, whether this difference is attributable to such factors as differences in construction type, dwelling form or site supervision and workmanship. Therefore, further work (both field tests on whole dwellings and laboratory tests on construction samples) is needed to establish whether such differences are real, or whether they have occurred purely by chance.

Leakage identification

- 25 In addition to the pressurisation tests, the main air leakage paths within each of the dwellings were identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. It was not possible to quantify the contribution that each leakage path made to each of the dwellings overall air leakage, but the smoke tests that were carried out enabled the main leakage paths within each of the dwellings tested to be identified. The results of the leakage identification work are summarised in Tables 4 and 5.

Elements and junctions	Fixtures and fittings	Service penetrations
Between skirting board and ground floor. Around the stairs. Between skirting board and intermediate floor. Between flooring panels on the intermediate floor.	Around kitchen units. Around trickle vents. Around French door and patio doors. Around loft hatch. Around the bath panel and the shower tray. Through sliding mechanism of patio doors.	Service penetrations in the kitchen and utility room. Service penetrations in the toilets, bathroom and en-suite. Pipework penetrations behind the radiators. Service penetrations in the bathrooms and en-suite. Around electrical fuse box. Around extract fans.

Table 4 Main air leakage paths associated with developers A, B, C and D (all houses).

Elements and junctions	Fixtures and fittings	Service penetrations
Ceiling/wall junction in airing cupboard.	Around patio doors. Around bath panel.	Service penetrations in the kitchen. Service penetrations in the bathroom. Around purpose provided ventilation openings. Around electrical fuse box. Through spot lights.

Table 5 Main air leakage paths associated with developer E (flats).

- 26 As can be seen from Tables 4 and 5, the majority of the dwellings tested were found to have a number of common air leakage paths, which could be categorised under the following three headings: elements and junctions, fixtures and fittings and service penetrations. The tables illustrate that there are fewer air leakage paths within the mechanically plastered masonry cavity apartments being constructed by developer E, than in the dry-lined masonry cavity and light steel framed dwellings being constructed by developers A, B, C and D. Therefore, it is no surprise that the apartments being constructed by developer E are more airtight than the dwellings being constructed by all of the other developers. Tables 4 and 5 also illustrate that there are a number of common air leakage paths relating to all of the tested dwellings. These principally relate to service penetrations within the kitchens and the bathrooms.
- 27 The majority of the air leakage paths identified within Tables 4 and 5 are indirect air leakage paths, rather than direct air leakage paths. Indirect air leakage paths not only enable the air to freely communicate with other gaps and voids within the building, but they also add to the complexity of

the air flows that exist within and through the building envelope. The result is that air leakage can be very difficult to trace and seal effectively.

- 28 The majority of the leakage paths identified within Tables 4 and 5 can also be traced back to various construction issues that were observed on site.
- 29 In addition to a number of common air leakage paths, leakage paths were also identified that were particular to specific dwellings. Details of these are contained within the individual developer pressurisation test reports, which are available in the project archive.

Feedback Seminars

- 30 Feedback from Phase 1 of the project consisted of a feedback and guidance seminar for each of the developers, making five seminars in total. Three of these seminars have been undertaken to date, each of which has lasted around half a day. To ensure confidentiality, the seminars were undertaken at the developer's offices. Where possible, the participants included regional directors, the technical director for design and development, someone from the design team, the site manager or assistant site manager and a number of trade supervisors and site operatives. Each seminar made use of all of the material that had been gathered during Phase 1 of the project, such as photographs and video recordings, to provide tailored feedback and advice to each of the developers. In addition, a two-way dialogue was facilitated to allow feedback from the developers to the research team.
- 31 Prior to each seminar, the developer's team were presented with a copy of the design assessments and the pressurisation test report for the dwellings that were selected on their site. This information was provided to the developers to enable them to gather their thoughts and investigate any of the issues raised in the reports prior to their attendance at the seminar.
- 32 Although the seminars were tailored towards each particular developer, where possible, a common approach was used. This approach was as follows:

- a) The seminar began with a PowerPoint presentation from the research team which included the following information:

Introduction to airtightness, the importance of airtightness with regard to the energy performance of dwellings, the airtightness requirements of the current Building Regulations and expected changes to the Building Regulations with respect to airtightness.

Details of the pressurisation tests, how they are undertaken, why they are undertaken and methods of leakage detection.

Airtightness results for the developer in question. The results will be compared against those for the rest of the tested cohort, the UK mean and the current Building Regulation requirements.

Details of the construction issues observed on site.

Precise details of the leakage paths observed on site.

General advice and guidance given on airtightness.

- b) The results from the site observations and the pressurisation tests were then discussed. The developer's team were also asked whether they agreed with the findings and whether what was observed on-site was typical practice for the developer in question. They were also asked to identify what changes could be put in place to address the issues raised during the seminar, such as dwelling design, availability/completeness of drawings, Robust Details, planning/sequencing, quality of components, quality control, workmanship, site management and training.
- c) Finally, the developers were asked to agree to a plan of action that seeks to improve the airtightness performance of their dwellings. They were also asked to agree to an informal airtightness target for the dwellings that will be tested during Phase 3 of the project.

- 33 Copies of the individual PowerPoint presentations for each of the developers are available in the project archive.
- 34 The main issues that were fed back to the developers during the feedback sessions are set out in the following subsections.

Construction observations

- 35 Observations from site highlighted a number of construction issues that could potentially affect the eventual airtightness performance of the selected dwellings. A number of these issues were common to the majority of the developers. These issues related to the following:

a) Method of construction

Dry-lining. The inadequacy of dry-lining as an effective air barrier was highlighted within the dry-lined masonry cavity dwellings. Technically it is very difficult to seal the dry-lining using continuous ribbons of plasterboard adhesive at the perimeter of external walls, openings, and services on external walls. The result is that air can move freely into the gap between the plasterboard and the masonry wall. This air gap then acts as a plenum, effectively connecting all of the leakage paths within the dwelling.

Light steel frame construction. These dwellings used a warm frame construction, with the external face of the insulation boards acting as the air barrier. The joints between the insulation boards were not always sealed, particularly around window and door openings, around service penetrations and at the intermediate and ground floor junction, resulting in a number of potential air leakage paths at these points.

Built-in joists. Where built-in joists were used, difficulties were experienced sealing the joists to the external/party walls. This was a particular problem where the joists had been offset from the external wall to enable services to run from one floor to the other. The result was a number of hidden air leakage paths from the intermediate floor void to the cavity.

Blockwork. In the masonry cavity dwellings, cracks and gaps were visible on the internal leaf of the external/party walls, perpendents were not always fully sealed and the buttering of joists resulted in a number of potential air leakage paths through these walls.

Wall, floor and roof junctions. There was no evidence of continuity of the air barrier at these junctions. Gaps were observed around the edges of intermediate floors and at the junction between the skirting boards and the ground/intermediate floors. Internal partitions had also been erected before the ceiling, resulting in hidden air leakage paths at the partition/ceiling junction.

Ground and intermediate floors. Ground floor slabs were incomplete, particularly around the patio door area, resulting in holes in the ground floor slab. Holes were also observed in the intermediate flooring, as well as gaps between the intermediate flooring panels.

Rooms-in-the-roof. There was no evidence of continuity of the air barrier in dwellings that incorporated rooms-in-the-roof. Gaps were also observed around rooflights and dormer windows, allowing air movement from behind the dry-lining to the roof and rafter voids.

b) Openings

Windows and doors. Trickle vents were either of a poor fit or would not close properly allowing the passage of air either through the vent itself (when in the closed position), or through a gap between the vent and window. In several cases, the patio doors did not fit correctly such that the seals were uncompressed. In the worst cases, there were observable gaps between the external door and the surrounding door frame.

Loft hatch. Hatches had not been adequately sealed to the ceiling, resulting in air leakage between the loft hatch frame and ceiling. In addition, a number of the hatches did not compress the draught seals fully when they were closed. With one of the developers this was due to the method of installation.

c) Service penetrations

Through walls, floors and ceilings. Little attempt had been made to seal the majority of service penetrations through walls, floors and ceilings. Where attempts had been made, the penetrations are generally inadequately sealed and/or inappropriate sealants have been used. In a number of cases, larger holes than necessary had also been made for services to allow for positioning. These large holes are then much more difficult to seal.

In kitchens, utility rooms, bathrooms, toilets and en-suites. Penetrations in these areas were often left unsealed as they would subsequently be hidden behind boxing, panels or units.

36 Photographs of all of the construction issues associated with each developer can be found within the respective PowerPoint presentations, which are retained in the project archive.

Air permeability results and leakage identification

37 All of the air permeability results that have been undertaken to date were presented and compared against the UK mean and the current Building Regulations requirements. These results indicated the following:

- a) A relatively wide range of airtightness was encountered.
- b) Only a small number of the dwellings tested had an air permeability that was lower than or equal to the UK mean of $11.5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$.
- c) The majority of the dwellings tested failed to satisfy the air leakage criterion set out in Approved Document Part L1.
- d) No obvious difference in construction quality was observed between the various developers.

- e) In our opinion, the air permeability target of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ could be achieved by all of the developers. However, work needs to be done if all of the dwellings are to achieve this level of airtightness.
- 38 The individual results associated with each developer were then discussed in detail.
- 39 The main air leakage paths within each of the tested dwellings were also identified. The dwellings were found to have a number of common air leakage paths. These leakage paths related to elements and junctions, fixtures and fittings and service penetrations.
- 40 Details of the individual developer air permeability results and air leakage paths are contained within the respective PowerPoint presentations.

Advice and guidance

- 41 General advice and guidance on airtightness was given to each of the developers during the feedback presentation. This was as follows:

Prior to construction

- a) Identify the construction principle that will be used to achieve an airtight building envelope.
- b) Identify the position of the air barrier on the drawings — make it explicit!
- c) Undertake a 'pen on section' test to ensure continuity of air barrier — continuity is crucial!
- d) Ensure air barrier can be easily installed, is durable and accessible for maintenance.
- e) Avoid or minimise penetrations through the air barrier.
- f) Avoid complex detailing.
- g) Where possible, ensure that the air barrier is in the same plane throughout the structure.
- h) Identify those areas where attention to detail is required to ensure airtightness.
- i) Provide explicit details and guidance at any potential air leakage point.

During construction

- j) Ensure that site supervision and workmanship are good.
- k) Ensure all construction staff are aware of airtightness issues.

After construction

- l) Some relatively simple measures could be adopted that may improve the airtightness of the dwellings once they have been constructed:

Seal all visible and hidden service penetrations using an appropriate sealant.

Seal all junctions between the walls, floors and ceilings.

- m) However, it is important to realise that these measures do not address the hidden air leakage paths!

Response from the Developers on the Feedback

- 42 The response to the three feedback seminars that have been undertaken to date has been very positive. All three developers fully participated in the seminars, resulting in a number of interesting discussions and debates. The main responses from the developers are summarised as follows:
 - a) The majority of the developers lacked a general understanding of airtightness, the importance that airtightness has with regard to the energy performance of buildings, how airtightness is measured, the factors that are known to influence airtightness, the location of the main air leakage paths within UK dwellings, the difference between direct and indirect air leakage paths and how air leakage paths can be detected.
 - b) All of the developers agreed with the findings of the site observations, the pressurisation tests and the leakage identification work. They also agreed that what had been observed on site was typical of their construction practice nationally. In fact, at least one developer commented that what had been observed was actually good practice.
 - c) Two of the three developers (developers B and D) were under the perception that all they needed to do to improve the airtightness of their dwellings was to identify all of the individual air leakage points at internal surfaces and then simply go around and fill in all of the gaps. For instance, they felt that effort should be put into sealing the junction between floor boarding and intermediate floors, skirtings at floor/wall junctions and sealing of service entries to into internal service ducts. This is problematic and unlikely to be successful since it creates a very complex

and disjointed air barrier that is not robust. Experience from North America and Scandinavia where low levels of air leakage have been part of national standards for a long time lays stress on the identification of a single and continuous primary air barrier, rather than filling gaps at internal surfaces.

- d) Only one of the developers (developer A) had any real understanding of the concept of an air barrier, although it was apparent that this understanding, mainly at senior management level, was not widely disseminated to the sites studied.
- e) None of the developers was aware of the construction principle that they were using to achieve an airtight envelope and none had explicitly identified the position of the air barrier on their drawings.
- f) Although none of the dwellings tested had an explicit air barrier, all of the developers were adopting the internal airtight barrier approach by default (mainly dry-lining). The fact that only two of the dry-lined masonry cavity and steel framed dwellings achieved air leakage values less than $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ was more by chance, rather than the developers making any conscious effort to build airtight dwellings.
- g) All of the developers agreed that the quality of workmanship and site supervision were issues that were influencing the level of airtightness obtained on-site and both of these issues could be and should be improved on site.

43 The developers that participated in the feedback seminars were also asked to identify what measures they would undertake during Phase 3 of the project to improve the airtightness of their dwellings and to agree to an informal air leakage target. The measures identified and the targets agreed by each developer are illustrated within Table 6.

Developer	Measures identified	Air leakage target ($\text{m}^3/(\text{h.m}^2) @ 50\text{Pa}$)
A	<p>Workshops to be held with key trades who need to improve the quality of their workmanship. Key trades identified include: bricklayers, window and door installers, carpentry, heating and plumbing, electrician and dry-liner.</p> <p>Site Toolbox training tasks aimed at management, and sub-contractors supervisors.</p> <p>Pre-Test Inspection Checklist to include all builders' work completed to air seal the envelope, including doors, windows, hatches, sills and services.</p> <p>A gallery of unacceptable work will be displayed in the canteen and regular inspections of the work will be conducted with the subcontractor's supervisors.</p> <p>Expansion of specific Air Leakage Robust Details to be added to national construction details sets.</p> <p>Assessment of practical sealant measures and product development (windows, fans, plumbing and electrical punctuations, etc.) and comparison with alternative 'all over paring' air barrier – subject of re-testing regime at selected plots.</p> <p>Sequencing issues will be highlighted and addressed by production and site management in conjunction with trades.</p>	To be confirmed.
B	To be confirmed.	To be confirmed.
D	<p>Implementation of new dwelling designs which have amendments to ground floor slabs. This should improve the airtightness of the slab and wall junction.</p> <p>Re-evaluate intermediate floor construction. Apply chipboard flooring to the floor cassette after the frame has been erected rather than using cassettes with attached flooring.</p> <p>Establish an air barrier at ceiling level. This could be done by having a continuous plasterboard ceiling with partitioning installed afterwards, rather than having the frame assemblers installing the top floor partitions prior to dry-lining. Services might then be</p>	7.0

	held in trays in the loft space, reducing the need for excessive individual service penetrations.	
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Table 6 Measures identified and agreed air leakage targets for each developer.

Conclusions

- 44 The results of the pressurisation tests undertaken to date suggest that mechanically plastered masonry cavity construction can default to a reasonable level of airtightness by UK standards ($< \sim 5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$), without much attention being given to airtightness. However, the failure of the majority of the dry-lined masonry cavity and steel-framed dwellings to achieve the required airtightness target contained within Approved Document Part L1 of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, raises serious questions about using Robust Standard Details as a method of achieving compliance with airtightness standards. The poor air leakage performance of the majority of the dwellings could be attributable to a range of factors such as poor inherent design for airtightness, a lack of adequate training on the issues surrounding airtightness, lack of necessary details on drawings, incomplete understanding of Robust Details, poor quality control of Robust Details on site, poor communication of the importance of Robust Details or difficulties in achieving current Robust Details in practice.
- 45 Although the size, structure and non-random nature of the sample precludes certainty, the results also suggest that dwellings built to the requirements of Approved Document Part L1 2002 are no more airtight than the mean of the current existing UK housing stock. If this result is true, then it could have serious implications for the industry and its preparedness for the proposed changes to Part L. Some of the issues that need to be addressed would include areas such as training, quality control and building design. The next stages of this project will give more focus on these issues.
- 46 A number of common air leakage paths were observed within the dwellings tested. The majority of these were indirect air leakage paths relating to elements and junctions, fixtures and fittings and service penetrations. Although a number of relatively simple measures could be adopted by the developers to reduce these leakage paths once the dwellings had been completed, such as sealing all visible and hidden service penetrations using a suitable sealant, these measures do not address the issues associated with indirect air leakage paths.
- 47 The current approach to providing advice on airtightness via Robust Details does not address process or conceptual issues.
- 48 The developers' responses at the feedback sessions indicated that the observations from site were typical of their current construction standards nationally. As all but two of the dwellings tested from developers A, B, C and D failed to meet the maximum specified level of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ set in Part L1 2002, and all of the sites were using Robust Details as the basis of regulatory approval, this study suggests that simply adopting Robust Details, at least in their current form, provides no guarantee that the current regulatory standard will be achieved with any degree of consistency.
- 49 The responses from developers and discussion at the seminar supported the view that there is a general lack of awareness and understanding of airtightness issues at all levels, from site operatives and site supervisors through to site and senior management. Consequently, there is a perception from the developers that the way to improve airtightness is to adopt the 'gap-filling' approach, rather than concentrating on the design of the air barrier. Therefore, there is a need for clear design guidance on airtightness which focuses on the design of the air barrier, its location, ways of maintaining continuity and ensuring that it remains effective. This guidance needs to be followed-up with further education within the industry, greater and more specific levels of training and advice and higher levels of site supervision and workmanship.

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Appendix 7

Airtightness of buildings — towards higher performance

Interim Report D7 — Design Assessments

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report reviews the progress that has been made on assessing the design drawings and the site survey data that have been obtained for the selected sites that are participating in Phase 3 of the project and reports on the interim results.
- 2 Drawings for Phase 3 of the project have been received from all five developers. Design assessments have been undertaken for all of the 26 selected dwellings and site surveys have commenced on 11 of these dwellings. Four of the dwellings selected from developer D have been completed and pressure tested.
- 3 The main points that have been obtained from the drawing assessments are as follows:
 - a) All of the developers have made design changes to the dwellings that are participating in Phase 3 of the project, following feedback from the research team.
 - b) The developers did not feel able to make significant design changes to the house types and the design drawings that are participating in Phase 3 of the project, the time and cost of this process being the prohibitive factors. Consequently, the submitted drawings suffer from the same limitations as those that were assessed during Phase 1 of the project (see Johnston, Miles Shenton and Bell, 2004). For instance, the way in which information on air leakage is presented on the drawings varies considerably between the developers, the drawings do not contain an explicit air leakage target, none of the drawings makes reference to a higher air leakage rate than that which is contained within Approved Document Part L1, the drawings do not identify the location of the air barrier, there is no continuity of the air barrier, none of the drawings identify the construction principle that will be used to achieve an airtight building envelope and although some of the drawings identify areas where attention to detail is required to achieve airtightness, they do not state how this will be achieved on site.
 - c) It appears that due to the small number of dwellings involved in this phase of the project, any changes to the dwelling designs appear to have been communicated to the site via informal means, predominantly verbally or in note/memorandum form. Although appropriate for this project, such an approach is unlikely to be successful if various airtightness measures are to be replicated on a national scale.

Introduction

- 4 This report is milestone D7 — Design Assessments of Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). The aim of this report is to summarise the progress that has been made on assessing the design modifications that have been made for the dwellings to be studied during Phase 3 of the project (task 2.3.1 of the project proposal). It also presents the results of the pressurisation tests and the feedback seminars that were outstanding from milestone D6 — Seminars and Developer Feedback (Johnston, Miles-Shenton and Bell, 2005).

Summary of Progress to Date

- 5 Site surveys for Phase 1 of the project have been completed for all 25 of the selected dwellings (four from developer B, five from developers A, C and D and six from developer E).
- 6 All of the dwellings selected for Phase 1 of the project have been pressure tested.
- 7 Feedback and guidance seminars reporting on Phase 1 of the project have been undertaken with all five developers.
- 8 Five dwellings have been selected from developers A, B, C and D, and six from developer E (26 dwellings in total) to participate in Phase 3 of the project. Drawings have been received from the developers for all but one of the dwellings.²²
- 9 Design assessments have been completed for all of the selected dwellings. Site surveys have been commenced on 11 of the 26 selected dwellings (five from developers C and D and one from developer B).
- 10 Pressurisation tests have been completed on four of the Phase 3 dwellings from developer D.

Update on the Pressurisation Test Results

- 11 This section presents the results of the two remaining pressurisation tests from developer E (dwellings EC301 and EC302) that were not previously reported in milestone D6 — Seminars and Developer Feedback (Johnston, Miles-Shenton and Bell, 2005).
- 12 The air permeability results for dwellings C301 and C302 are shown in Table 1. The mean air permeability results for all of the dwellings that participated in Phase 1 of the project are illustrated in Figures 1 and 2 and Tables 2 and 3.

Dwelling	Pressurisation test		Depressurisation test		Mean Permeability (m ³ /(h.m ²))
	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	
EC301	5.53	0.999	4.97	0.995	5.25
EC302	7.46	0.995	7.38	0.997	7.42

Table 1 Mean air permeability of the dwellings EC301 and EC302.

²² New drawings have only been submitted for those dwelling types that had not previously been assessed during Phase 1 of the project. The remaining dwellings have been assessed using the drawings submitted for Phase 1.

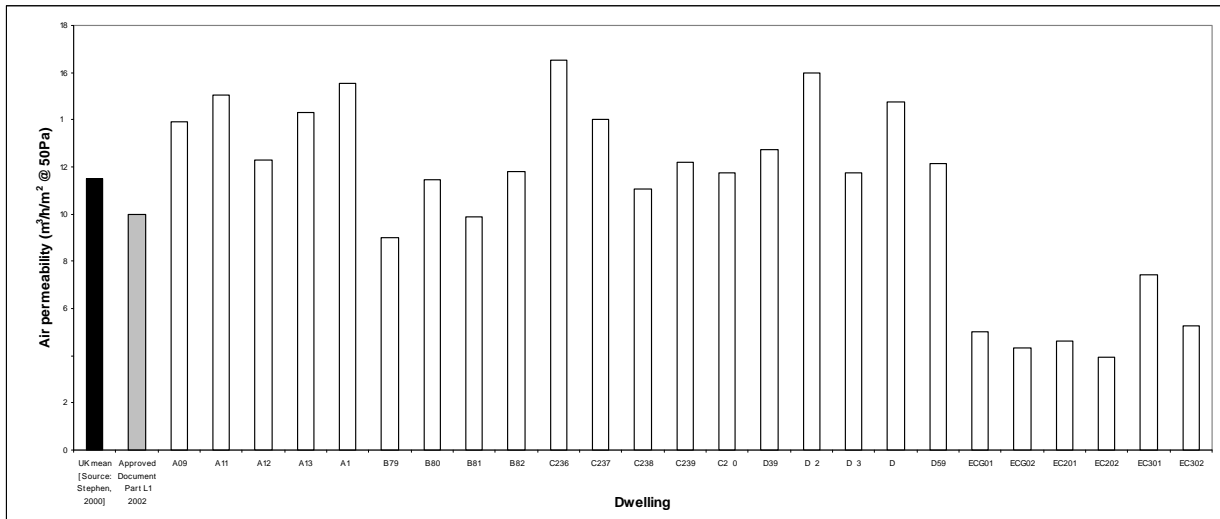


Figure 1 Mean air permeability of the tested dwellings.

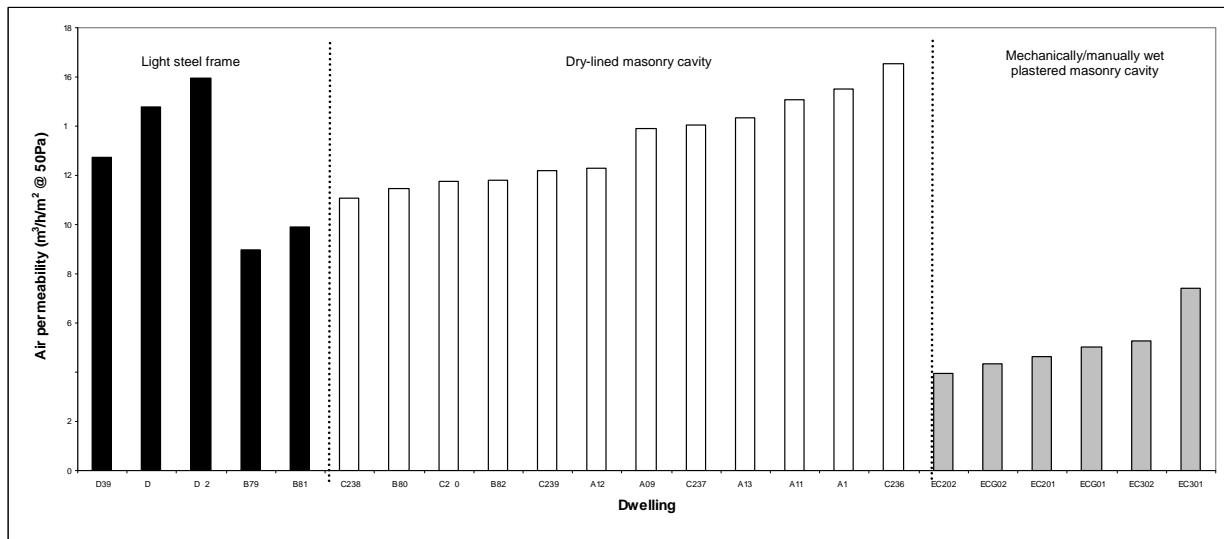


Figure 2 Mean air permeability of the tested dwellings by construction type.

Developer	Mean permeability of all dwellings tested to date (m³/(h.m²))
A	14.2
B	10.5
C	13.1
D	13.5
E	5.1

Table 2 Mean air permeability by developer.

Construction type	Mean permeability of all dwellings tested to date (m ³ /(h.m ²))
Wet plastered masonry cavity (Developer E)	5.1
Dry-lined masonry cavity (Developers A, B and C)	12.6
Light steel-frame (Developer D)	13.5

Table 3 Mean air permeability by construction type.

- 13 The air permeability results for dwellings EC301 and EC302 are slightly higher than those that were recorded for the other apartments constructed by developer E. The reasons for the slightly higher air leakage can be attributed to a number of air leakage paths that were particular to these apartments. As top-floor apartments, both had a traditional ventilated timber roof construction rather than a concrete intermediate floor above; leakage particular to these dwellings was observed through and around the mezzanine storage deck and increased air movement through the wall/floor junctions and ceiling service penetrations was also detected. The net effect of these two results is an increase in the mean air permeability for developer E from 4.5 m³/(h.m²) to 5.1 m³/(h.m²) @ 50Pa.

Update on the Feedback Seminars

- 14 This section reports the results of the feedback seminars undertaken with developers C and E that were not previously reported in milestone D6 — Seminars and Developer Feedback (Johnston, Miles-Shenton and Bell, 2005).
- 15 Feedback and guidance seminars have been undertaken with the two remaining developers (developers C and E). The developers' response to these seminars was very positive. The main points arising from these seminars are summarised as follows:
- a) Both developers displayed only a notional understanding of airtightness, with a lack of in-depth knowledge in a number of areas:
 - The importance that airtightness has with regard to the energy performance of buildings.
 - How air permeability is measured.
 - The difference between air infiltration and natural ventilation.
 - Many of the factors known to influence airtightness.
 - The location of the main air leakage paths within UK dwellings.
 - The difference between direct and indirect air leakage paths.
 - How air leakage paths can be detected.
 - b) Both developers agreed with the findings of the site observations, the pressurisation tests and the leakage identification work. They also agreed that what had been observed on site was generally typical of their construction practice nationally.
 - c) Observations from site highlighted a number of construction issues that could potentially affect the eventual airtightness performance of the selected dwellings. For developer C, these issues related to the dry-lining; the built-in joists; the blockwork; the wall, floor and roof junctions; the ground and intermediate floors; the windows and doors; the loft hatches and service penetrations. For developer E, significantly fewer construction issues were observed on site, even though they appeared to have a similar level of understanding of airtightness issues as all of the other developers. The reasons for the difference were felt to be attributable to a higher build quality coupled with the adoption of an intrinsically more airtight method of construction, namely: the use of a mechanical/wet plaster internal finish and pre-cast concrete intermediate floor slabs. The construction issues that were observed for developer E related to the intermediate floor/wall junction; patio doors; the mezzanine storage deck; the loft hatches and service penetrations.
 - d) Developer E was particularly pleased with the results of the pressurisation tests, as all of the dwellings that were tested achieved an air permeability significantly lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa that is contained within the 2002 edition of the Approved Document Part L1 (ODPM, 2001). The dwellings constructed by developer E were also

significantly more airtight than the dwellings constructed by all of the other developers.²³

Although developer E was constructing relatively airtight dwellings by UK standards, they did not seem to understand why their dwellings were performing so well.

- e) Neither of the developers had any real understanding of the concept of an air barrier, they were unaware of the construction principle that they were using to achieve an airtight envelope and neither of them had explicitly identified the position of the air barrier on their drawings.
- f) Although none of the dwellings tested had an explicit air barrier, both developers were adopting the internal airtight barrier approach by default (developer C was using the dry-lining whilst developer E was using the mechanical/wet plaster finish). The fact that all of the mechanically/wet plastered apartments constructed by developer E achieved air leakage values less than $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ appeared to be due to a high build quality and the method of internal finish and intermediate floor construction that was chosen, rather than the developers making any conscious effort to build airtight dwellings.
- g) Developer C agreed that quality of workmanship and inadequate site inspection were issues that were influencing the level of airtightness obtained on site and both of these issues could and should be improved on site.

16 Both developers were also asked to identify measures that they would undertake during Phase 3 of the project to improve the airtightness performance of their dwellings and to agree to an informal air leakage target. The measures identified and the targets agreed by each developer are illustrated within Table 4. Table 4 also identifies the measures that plan to be undertaken by developer B, which were not previously reported in milestone D6 — Seminars and Developer Feedback (Johnston, Miles-Shenton and Bell, 2005).

Developer	Measures identified	Air leakage target ($\text{m}^3/(\text{h.m}^2) @ 50\text{Pa}$)
B	<p>Staged approach adopted.</p> <p>Four identical semi-detached dwellings chosen. Various measures undertaken on each dwelling for comparison:</p> <ul style="list-style-type: none"> - One to be built as standard.²⁴ - One to be built as standard with all apertures to external walls filled. - One to be built as standard with all light fitting cables through pattresses and all switch boxes, heating cable boxes and pipes penetrating external walls sealed at plaster stage. - One to be built as standard with all external walls parged prior to them being dry-lined. 	To be confirmed.
C	<p>Staged approach adopted.</p> <p>Block of four terraced dwellings chosen. Various measures undertaken on each dwelling for comparison:</p> <ul style="list-style-type: none"> - Parging coat to be applied to one mid- and one end-terrace. - Other mid- and end-terrace to be built as standard. <p>Greater attention to workmanship on all dwellings.</p>	To be confirmed.
E	<p>Address a number of detailing issues, namely: around the patio doors; the mezzanine decking in the top-floor flats; the cylinder tank ceiling and look at measures to reduce air leakage around/through the service risers.</p>	To be confirmed.

Table 4 Measures identified and agreed air leakage targets for developers B, C and E.

²³ Part of this difference may be attributable to the built form of the dwellings that were being constructed by developer E. Developer E was the only developer constructing apartments. Apartments tend to be more airtight than other dwelling forms of equivalent area as they are more likely to have solid intermediate floors, fewer doors and window openings and fewer service penetrations.

²⁴ In this case, 'as standard' refers to the same specification as those dwellings that participated in Phase 1 of the project.

Design Assessments

17 This section summarises the progress that has been made to date on the design assessments and presents the interim results. Details of the dwellings that are participating in this phase of the project are set out in Table 5.











Developer	Type of development	Type of construction	Selected dwelling types
Developer A (5 dwellings)	Combination of private and social housing. 	Dry-lined masonry cavity, partial fill. 	<ul style="list-style-type: none"> • A 3-storey 3 bedroom end terrace with an internal floor area of 117 m². • Two 2-storey 3 bedroom mid-terraces with an internal floor area of 113 m². • A 2-storey 3 bedroom end terrace with an internal floor area of 116 m². • A 2-storey 3 bedroom end terrace with an internal floor area of 113 m².
Developer B (5 dwellings)	Private housing. 	Dry-lined masonry cavity, full fill. 	<ul style="list-style-type: none"> • Four 3-storey 3 bedroom semi-detached properties with an internal floor area of 132 m². • A 2½-storey 4 bedroom detached property with an internal floor area of 164 m².
Developer C (5 dwellings)	Private housing. 	Dry-lined masonry cavity, full fill. 	<ul style="list-style-type: none"> • A 2-storey 4 bedroom detached property with an internal floor area of 106 m². • Two 2-storey end terraces with an internal floor area of 61 m². • Two 2-storey mid terraces with an internal floor area of 71 m².
Developer D (5 dwellings)	Private housing.  	Steel frame 	<ul style="list-style-type: none"> • A 2-storey 4 bedroom detached property with an internal floor area of 85 m². • A 2-storey 4 bedroom detached property with an internal floor area of 124 m². • A 2-storey 4 bedroom detached property with an internal floor area of 108 m². • A 2-storey 3 bedroom detached property with an internal floor area of 93 m². • A 2-storey 4 bedroom detached property with an internal floor area of 117 m².
Developer E (6 dwellings)	Social housing. 	Wet-plastered masonry cavity, partial fill.	<ul style="list-style-type: none"> • A 2 bedroom apartment with an internal floor area of 58 m². • Two 2 bedroom apartments with an internal floor area of 57 m². • Three 1 bedroom apartments with an internal floor area of 43 m².

Table 5 Details of selected dwelling types for Phase 3 of the project.

18 As previously mentioned, drawings have been received from all five developers and design assessments have been undertaken on all of the 26 selected dwellings.

19 The main points that have been obtained from the completed design assessments can be summarised as follows:

- a) Following detailed feedback from Phase 1 of the project, all of the developers have made design changes to the dwellings that are participating in Phase 3 of the project.
- b) A variety of approaches to improving the airtightness of the dwellings participating in Phase 3 of the project have been adopted by the developers. Due to the design costs involved, no substantial design changes have been made to the design documentation used on site. Consequently, the submitted drawings suffer from the same limitations as those that were assessed during Phase 1 of the project (see Johnston, Miles-Shenton and Bell, 2004). These were as follows:
- Considerable variation in the way in which the information relating to air leakage is presented.
 - None of the drawings contains an explicit air leakage target.
 - None of the drawings makes reference to a higher air leakage rate than that which is contained within Approved Document Part L1.
 - None of the drawings identifies the location of the air barrier or states that it should be continuous around the envelope.
 - None of the drawings identifies the construction principle that will be used to achieve an airtight building envelope.
 - Although some of the drawings identify areas where attention to detail is required to achieve airtightness, they do not state how this is to be achieved on site.
- c) Despite cost limitations, the developers have adopted a number of different approaches to improve the airtightness of their dwellings. Two of the developers have tightened up the existing detailed design approach, whilst the remaining three developers have adopted a staged approach to integrating various airtightness measures enabling a comparison to be made between different airtightness measures at minimal cost. The approach undertaken by each developer is summarised as follows:
- Developer A — Tightening up the existing detailed design approach by placing a focus on workmanship. This will include: holding workshops for key trades; Toolbox training talks aimed at management and subcontractors supervisors; a pre-test inspection checklist; displaying a gallery of unacceptable work in the canteen; regular inspections of work; and addressing sequencing issues.
 - Developer B — Staged approach. One of the dwellings to have all the external walls parged based upon some recent results of paring at Stamford Brook in Altrincham (Lowe and Bell, 2001). Remaining dwellings to incorporate a range of measures such as filling all apertures in external walls, installing light fitting cables through pattress boxes and sealing all boxes and pipes that penetrate external walls at plaster stage.
 - Developer C — Staged approach. Two dwellings to have all the external walls parged based upon the parging results at Stamford Brook. Remaining dwellings to be built as standard. Greater attention to be given to workmanship on all of the dwellings.
 - Developer D — Staged approach coupled with the introduction of new dwelling designs, which should address the issues associated with the slab/wall junction, and the application of the chipboard flooring on site. Greater attention given to workmanship on one dwelling and attempts made to create a continuous air barrier at the external wall and ceiling level on another dwelling.
 - Developer E — Tightening up the existing detailed design approach by concentrating effort on a number of areas that contributed to air leakage during Phase 1 of the project. For instance, around the patio doors; the mezzanine decking in the top-floor flats; the cylinder tank ceiling and look at measures to reduce air leakage around/through the service risers.
- d) Due to the small number of dwellings involved per developer, any changes to the dwellings design appear to have been communicated to the site via informal means. Although such an approach may be appropriate for this project, it is unlikely to be successful if various airtightness measures are to be adopted on a much larger scale to improve performance overall.

Conclusions

- 20 This report reviews the progress that has been made in assessing the design drawings that have been submitted for Phase 3 of the project and presents the interim results.

- 21 An analysis of the design assessments indicates that due to the costs involved, only minor changes have been made to the house types that are participating in Phase 3 of the project. This, coupled with the fact that only small numbers of dwellings are involved in the project, has resulted in the developers choosing not to amend the design drawings associated with these dwellings. The consequence of this is that the drawings submitted for assessment suffer from the same limitations as those that were submitted for Phase 1 of the project. Therefore, any changes to the dwellings design have been communicated to the site via informal means. Although this approach may be appropriate for the small numbers of dwellings selected to participate in this project, this approach is unlikely to be successful if such measures are to be adopted on a much larger scale to improve performance overall.
- 22 Despite the cost limitations, a number of different approaches have been adopted by the developers for Phase 3. Two of the developers are concentrating efforts on the existing detailed design, whilst the other two are adopting a staged approach which will enable the effect of different airtightness measures to be compared.

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Appendix 8

Airtightness of buildings — towards higher performance

Interim Report D8 — Site Assessments and Test Results

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This report details the results of pressurisation tests on dwellings constructed by the participating developers as part of Phase 3 of the project. The report also reviews the progress on the assessment of site survey data that have been obtained for the selected sites.
- 2 Drawings have been received from all five developers. Design assessments have been completed for all 26 selected dwellings and site surveys have commenced on 24 of these dwellings. Eleven of the 26 selected dwellings (five from developer B, one from developer C and five from developer D) have been completed and pressure tested.
- 3 A number of different approaches have been adopted by the developers for Phase 3 of the project. Two of the developers have concentrated efforts on the existing detailed design (developers A & E), whilst the other three (developers B, C and D) have adopted a staged approach, enabling the effects of a range of different airtightness measures to be compared.
- 4 Phase 3 site observations indicate that all the developers have reacted to information supplied in the Phase 2 feedback sessions, to varying degrees. The two-way dialogue established between the research team and the developers throughout Phase 3 has assisted in ensuring that the intended measures have been successfully introduced, and has also raised further issues which in many cases have resulted in the adoption of additional modifications. The result is that a number of issues from Phase 1 have been resolved. However, certain other issues remain unresolved; most notably those which require major revisions to detail design drawings or which may incur other significant expense.
- 5 In terms of the pressurisation testing, the results undertaken to date show a relatively wide range of airtightness, ranging from 5.6 to 15.0 m³/(h.m²) @ 50Pa and with a mean of 9.7 m³/(h.m²) @ 50Pa. Only three of the 11 dwellings tested to date achieved an air permeability that was higher than or equal to the UK mean of 11.5 m³/(h.m²) @ 50Pa. This suggests that the dwellings tested are more airtight than the average for the stock as a whole. However, more importantly, only six of the 11 dwellings tested had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa set in Part L1 2002. This was despite each developer receiving detailed and targeted feedback on airtightness from the Leeds Met research team during the dwellings' construction and the use of Robust Details as the basis of the application for regulatory approval.
- 6 The data also show that in the majority of cases, the dwellings tested during Phase 3 of the project were more airtight than those tested during Phase 1. This suggests that the combination of the measures undertaken by the developers coupled with feedback from the Leeds Met research team has had a positive impact on the airtightness of the dwellings that have been tested.
- 7 The scale of the reductions in air leakage that has been achieved by each of the developers has varied and is dependent upon the measures undertaken. The greatest reductions in air leakage to date have been achieved by developer B, who achieved a 50% reduction in air leakage from the Phase 1 mean in two of the tested dwellings (B16 and B17). These reductions were achieved by pointing all of the joints and apertures prior to the application of the dry-lining in B16 and parging all of the external walls prior to dry-lining in B17. This suggests that pointing and parging can make sizeable contributions to the overall reduction in air leakage rate. Developer B is also the only developer to date where all Phase 3 dwellings tested achieved an air permeability of less than 10 m³/(h.m²) @ 50Pa.
- 8 A number of common air leakage paths were identified within the Phase 3 tested dwellings. These relate to:
 - a) Junctions of the ground floor and external walls.
 - b) Junctions of intermediate floors and walls.
 - c) Thresholds.
 - d) Stairs.
 - e) Trickle vents.
 - f) Patio/French doors.
 - g) Bath panels and shower trays.
 - h) Around kitchen units.
 - i) Kitchen and bathroom service penetrations.
 - j) Service penetrations around the hot water cylinder.

- 9 All the above paths were also identified during Phase 1 of the project. The improved air permeability results obtained in Phase 3 to date indicate that as many of the air paths noted in Phase 1 still remain, there must be a reduction in the amount of infiltration through at least some of these critical areas. In the cases of stairs, trickle vents and patio doors none of the developers has made any changes in specification between Phase 1 and Phase 3, suggesting that improvements to the actual construction of the building envelope rather than material/supply changes are responsible for the increased airtightness in Phase 3.

Introduction

- 10 This report is milestone D8 — Site Assessments and Test Results of Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003).
- 11 The aim of this report is to summarise the progress that has been made on the assessment of the site data that has obtained as part of Phase 3 of the project (tasks 2.3.1 and 2.3.2 of the project proposal). It also presents the results of the pressurisation tests that have been undertaken to date.
- 12 Details of the developers, the sites and the dwellings that are participating in this phase of the project are set out in Table 1.











Developer	Type of development	Type of construction	Selected dwelling types
Developer A (5 dwellings)	Combination of private and social housing. 	Dry-lined masonry cavity, partial fill. 	<ul style="list-style-type: none"> A 3-storey 3 bedroom end terrace with an internal floor area of 117 m². Two 2-storey 3 bedroom mid-terraces with an internal floor area of 113 m². A 2½-storey 3 bedroom end terrace with an internal floor area of 116 m². A 2-storey 3 bedroom end terrace with an internal floor area of 113 m².
Developer B (5 dwellings)	Private housing. 	Dry-lined masonry cavity, full fill. 	<ul style="list-style-type: none"> Four 3-storey 3 bedroom semi-detached properties with an internal floor area of 132 m². A 2½-storey 4 bedroom detached property with an internal floor area of 164 m².
Developer C (5 dwellings)	Private housing. 	Dry-lined masonry cavity, full fill. 	<ul style="list-style-type: none"> A 2-storey 4 bedroom detached property with an internal floor area of 106 m². Two 2-storey end terraces with an internal floor area of 61 m². Two 2-storey mid-terraces with an internal floor area of 71 m².
Developer D (5 dwellings)	Private housing.  	Steel frame 	<ul style="list-style-type: none"> Four 2-storey 4 bedroom detached properties with internal floor areas of 85, 108, 117 and 124 m². A 2-storey 3 bedroom detached property with an internal floor area of 93 m².
Developer E (6 dwellings)	Social housing. 	Wet-plastered masonry cavity, partial fill.	<ul style="list-style-type: none"> A 2 bedroom apartment with an internal floor area of 58 m². Two 2 bedroom apartments with an internal floor area of 57 m². Three 1 bedroom apartments with an internal floor area of 43 m².

Table 1 Details of selected dwelling types for Phase 3 of the project.

Summary of Progress to Date

- 13 Drawings have been received from all five developers. Design assessments have been completed for all of the 26 selected dwellings (five from developers A, B, C and D and six from developer E). Site surveys have commenced on 24 of the 26 selected dwellings, the remaining two are due to commence construction in November 2005.
- 14 In terms of the pressurisation testing, pressure tests have been undertaken on 11 of the 26 selected dwellings (five from developer B, one from developer C and five from developer D). Details of the current stage of construction and anticipated completion dates for all of the dwellings that are participating in this phase of the project are set out in Table 2.
- 15 As can be seen from Table 2, it is anticipated that the selected dwellings will be completed and pressure tested within the project timescale. Two dwellings being constructed by developer A (A79 and A80) may encompass additional design alterations dependent upon the pressure test results of the three plots that are currently being observed, and have an expected completion date of February 2006. The apartments being constructed by developer E are not expected to be completed until March 2006 as a result of inclement weather experienced during Phase 1 of the project. This issue has been the subject of a programme revision which was approved in April 2005, and is not expected to have any additional impact on the timing of remainder of this project. However, any further delays in the build programmes for either of these developers may necessitate a further programme revision to allow the results of these dwellings to be included in the final report on domestic airtightness.

Developer	Type of construction	Dwelling type	Current stage of construction	Anticipated completion date
A	Dry-lined masonry cavity, partial fill.	• A64 — 2-storey 3 bed mid-terrace.	1 st fix.	November 2005.
		• A65 — 2-storey 3 bed mid-terrace.	1 st fix.	November 2005.
		• A66 — 2-storey 3 bed end terrace.	1 st fix.	November 2005.
		• A79 — 2½-storey 3 bed mid-terrace.	Sub-structure.	February 2006.
		• A80 — 3-storey 3 bed end terrace.	Sub-structure.	February 2006.
B	Dry-lined masonry cavity, full fill.	• B14 — 2½-storey 4 bed detached.	Completed.	
		• B16 — 3-storey 4 bed semi-detached.	Completed.	
		• B17 — 3-storey 4 bed semi-detached.	Completed.	
		• B21 — 3-storey 4 bed semi-detached.	Completed.	
		• B22 — 3-storey 4 bed semi-detached.	Completed.	
C	Dry-lined masonry cavity, full fill.	• C17 — 2-storey end terrace.	1 st fix.	December 2005.
		• C18 — 2-storey mid-terrace.	1 st fix.	December 2005.
		• C19 — 2-storey mid-terrace.	1 st fix.	December 2005.
		• C20 — 2-storey end terrace.	1 st fix.	December 2005.
		• C194 — 2-storey 4 bed detached.	Completed.	
D	Steel frame.	• D73 — 4 bed detached.	Completed.	
		• D74 — 3 bed detached.	Completed.	
		• D75 — 4 bed detached.	Completed.	
		• D76 — 4 bed detached.	Completed.	
		• D96 — 4 bed detached.	Completed.	
E	Wet-plastered masonry cavity, partial fill.	• AG01— 2 bedroom ground floor apartment.	Superstructure.	March 2006.
		• AG02 — 1 bedroom ground floor apartment.	Superstructure.	March 2006.
		• A201 — 2 bedroom 2 nd floor apartment.	Superstructure.	March 2006.
		• A202 — 1 bedroom 2 nd floor apartment.	Superstructure.	March 2006.
		• A301 — 2 bedroom top floor apartment.	Superstructure.	March 2006..
		• A302 — 1 bedroom top floor apartment.	Superstructure.	March 2006.

Table 2 Details of the selected dwellings, their current stage of construction and anticipated completion date.

Interim Results of the Site Assessments

- 16 This section summarises the progress that has been made to date on the site surveys undertaken during Phase 3 of the project and presents the interim results.
- 17 As with Phase 1 of the project, the site surveys were undertaken in three separate stages (see Johnston, Miles-Shenton, Bell and Wingfield, 2005) and information on each of the selected dwellings was recorded on a site survey protocol. Details of the site survey protocol can be found within Johnston, Miles-Shenton and Bell (2004). To date, Stage 3 site visits have been undertaken on 11 of the 26 selected dwellings and Stage 1 site visits have been undertaken on 13 of the remaining 15 dwellings.
- 18 A two-way dialogue has been facilitated between the research team and the developers, during Phase 3 of the project. This approach has been adopted to enable any observations from site on

the airtightness performance of each of the selected dwellings to be fed back to the developers. In practice, the feedback has taken the form of a short written report, supplemented by photographs, highlighting any potential areas or issues that may have an influence on the eventual airtightness performance of the dwellings in question. An example of such a report for each developer can be found within the Appendix. The report has also been supplemented with a discussion with the site team prior to the next site visit. By providing such feedback to the developers, it gives them the opportunity to identify and rectify any issues relating to airtightness on site, prior to the dwellings being completed and tested.

- 19 The approach adopted by the research team during this phase of the project contrasts with the approach adopted during Phase 1. During Phase 1 the research team's role was purely observational and no advice or guidance was given to the developers on airtightness.
- 20 Details of the approach undertaken by each developer and the general observations that have been obtained from the site surveys to date are summarised below for each developer. The results have been presented by individual developer to reflect the fact that each developer has taken a different approach to airtightness during this phase of the project.

Developer A

- 21 The general approach taken by this developer has been to tighten up the existing detailed design where possible, by placing a focus on workmanship and training the operatives in airtightness awareness. Three of the dwellings (A64, A65 and A66) have been constructed using this approach, making only minor adaptations without incurring any significant additional costs. Depending upon the air leakage results from these three dwellings, additional work may be undertaken on the remaining 2 dwellings (A79 and A80) with extra-over costs.
- 22 Observations from site are summarised below, with some illustrated examples contained in Table 3.
 - a) Increased attention to detail has been paid to the ground floor construction, where incorrectly positioned service penetrations are no longer a problem.
 - b) There were no observed examples of damaged blocks or unfilled perpends in the current phase of building, problems which were regularly observed in Phase 1.
 - c) External wall penetrations have been made more accurately in the current phase, enabling sealing around them to be done more successfully. All small penetrations observed have been sealed using mastic prior to dry-lining, this was not always the case in Phase 1. Examples of both are shown in Table 3.
 - d) Built-in joists in close proximity to parallel walls were a problem in Phase 1 (Table 3). This problem has been addressed by ensuring that these gaps are being filled during construction, rather than relying on retrospective sealing where access is limited.
 - e) Intermediate floor penetrations have been made more accurately in the current phase, with neat holes being created more suited to the size of the respected penetration.
 - f) Potential air leakage into the loft-space through the metal studwork and around plasterboard ceilings is an 'as yet' unaddressed problem. The Leeds Met research team have brought this to the attention of the developer.
 - g) Thresholds are now being sealed using proprietary cavity closers during construction (Table 3). The retro-filling of the cavity after dry-lining in Phase 1 did not produce an airtight detail.
 - h) Window sill boards and jamb liners are to be fixed with solid layers of mortar and plasterboard adhesive, respectively; this should prevent the movement of air between the cavity around the opening and the void behind the plasterboard dry-lining. The same potential air path through the perforated metal lintels has been prevented by taping over the perforations prior to dry-lining.
 - i) The positioning of the shower tray creates a potential air leakage path from beneath the shower tray, through the metal stud partitioning, directly into the ventilated loft-space as illustrated in Table 3. This was a potential path observed in Phase 1 and still remains in Phase 3.



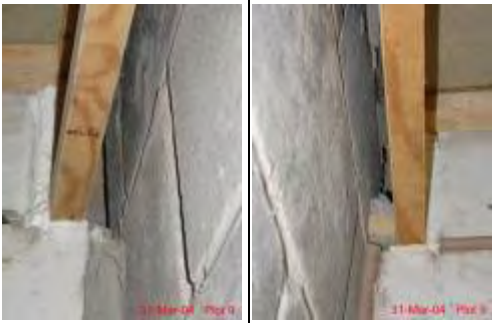


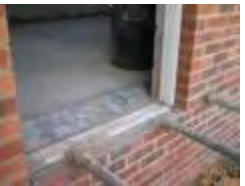


Detail	Phase 1 Observations		Phase 3 Observations	
External Wall Service Penetrations				
	<p>Larger penetrations smashed through blockwork retrospectively (example shows a cooker hood extract duct).</p> <p>Many smaller penetrations remaining unsealed at dry-lining stage.</p>		<p>Larger penetrations have purpose made gaps left (as above for a cooker hood extract duct) or suitably sized holes bored.</p> <p>Smaller penetrations all sealed at pre-plaster stage.</p>	
Built-In Joists				
	<p>Gaps through to cavity observed at a number of instances where joists are in close proximity to walls.</p>		<p>No corresponding gaps observed at these junctions, although mastic is rarely applied to these less accessible areas.</p>	
Threshold				
	<p>Threshold not sealed until after dry-lining, creating potential air paths from behind the dry-lining into the cavity.</p>		<p>Proprietary cavity closers used to seal the cavity at the threshold prior to dry-lining.</p>	
Shower				
	<p>Air paths exist from underneath the shower tray, through the metal stud partitioning, into the ventilated loft-space.</p>		<p>The same possible air paths still exist in this phase, as the site staff are continuing to build to the design drawings unless formally instructed otherwise.</p>	

Table 3 Selected alterations to detailing between Phase 1 and Phase 3 adopted by developer A.

Developer B

- 23 This developer has undertaken a staged approach. One dwelling (B14) has been built as standard, taking on board the feedback that was given to the developer at the end of Phase 1 of the project. One dwelling (B21) has been built as B14, with the developer acting upon the on-site feedback from Leeds Met research team where applicable. One dwelling (B22) has been built as B21, plus all of the light fitting cables have been installed through pattress boxes and all electrical and radiator pattress boxes have been sealed. Another dwelling (B16) has been built as B21, plus all of the apertures in the external walls have been sealed at pre-plaster stage. The remaining dwelling (B17) has been built as B21, plus all of the external walls have been parged.
- 24 Observations from site indicate that some of the issues raised from Phase 1 have been addressed in Phase 3. Further issues diagnosed in Phase 3 have also been acted upon, as a result of the continued feedback given during Phase 3. These issues are listed below, with examples illustrated in Table 4.
- a) Incorrectly positioned ground floor service penetrations continue to be a problem, although in Phase 3 awareness of this problem has resulted in attempts to seal around these prior to boxing in.
 - b) The issue of unfilled perpend, again a problem which was regularly observed in Phase 1, was also observed in Phase 3 albeit at a reduced severity. This was due in part to a more informed site management team and was further reduced as all separating walls were rendered for Part E compliance. In addition, specific measures to counteract this issue were taken in B16 and B17 as shown in Table 4.
 - c) Sealing around external wall penetrations appears to have been done more successfully in Phase 3, by sealing penetrations at an earlier stage of construction. Sealing around these penetrations has, in most cases in Phase 3, been attempted at the pre-plaster stage; which was seldom the case in Phase 1.
 - d) A number of issues relating to the built-in joists in Phase 1 have also been addressed. Gaps around I-beam web stiffeners still exist, but in general spaces around the joists have been pointed around more successfully, mastic has been applied more thoroughly and fewer spaces are left where joists are fitted in close proximity to walls.
 - e) Intermediate floor penetrations have been made with far more attention to detail than in Phase 1, with holes being created more suited to the size of the respected penetration and more accurately positioned for the location of the penetration (Table 4).
 - f) Potential for air leakage into the loft-space through service penetrations has been reduced as with intermediate floor penetrations, by more careful positioning of penetrations and more suitably sized holes. However, this is still an issue around the perimeter of the plasterboard ceilings particularly whilst continuous ribbons of plasterboard adhesive are not being used at the wall/ceiling junctions.
 - g) Thresholds are now being partially sealed at an earlier stage of construction. The retro-filling of the cavity after dry-lining in Phase 1 did not produce an airtight detail (Table 4). The loose-fill then screed methods adopted in Phase 3 have substantially reduced this problem but not eliminated it completely.
 - h) Window sills and jambs are now being pointed before dry-lining to help prevent the movement of air directly into the cavity and mastic sealant is applied around the closers, as shown in Table 4. The jamb/head junctions are no longer relying on mineral wool to plug the gaps between the tops of the closers and the lintels, a number of methods have been adopted to solve this problem.

Detail	Phase 1 Observations		Phase 3 Observations	
External Wall Blockwork				
	Gaps observed in blockwork and unfilled perpend which often remain unsealed, hidden in floor voids and behind the 'dot and dab' dry-lining.		Parging applied to party walls between floor and ceiling levels, visible apertures pointed up in B16, all external walls parged (including between joists) in B17.	
Intermediate Floor Service Penetrations				
	Excessively sized and incorrectly located holes for penetrations commonplace.		More suitably sized holes. Incorrectly positioned holes have been repaired.	
Threshold				
	Threshold not sealed until after dry-lining, creating potential air paths from behind the dry-lining into the cavity.		Cavity below thresholds filled prior to dry-lining, making it possible to seal the junction at pre-plaster stage.	
Jambs and Jamb/Head Junctions				

	Potential leakage paths from behind the dry=lining and jamb liners into the cavity, with jamb/head junctions often relying on mineral wool as the plugging material.	All gaps around closers sealed with mineral wool and mastic, expanding foam and mastic, or fully parged (B17).
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Table 4 Selected alterations to detailing between Phase 1 and Phase 3 adopted by developer B.

Developer C

- 1 This developer has also undertaken a staged approach. One dwelling (C194) has been built as standard in order to compare this dwelling, which is detached, to the semi-detached and terraced dwellings constructed during Phase 1 of the project. Two of the dwellings (C19 and C20) are being built as C194 with the party walls parged only and the site management are looking out for any potential airtightness issues as raised in the feedback session at the end of Phase 1. The remaining two dwellings (C17 and C18) are being built as C194, plus all of the external walls are being parged.
- 2 Observations from site indicate that little change has so far been made to the way the superstructure has been constructed between Phase 1 and Phase 3. On-going feedback from the Leeds Met research team to the developers has resulted in a review of certain aspects of the detailed design. This is currently being undertaken, and may mean further measures being adopted for the remaining four properties in this phase.

Developer D

- 3 This developer has also undertaken a staged approach. Two of the dwellings (D73 and D74) have been built as standard, both of which have been constructed to new designs that have been developed to comply with Part L1 2002. The performance of these two dwellings will be compared with the dwellings constructed during Phase 1, which were constructed to old designs that were adapted to comply with Part L1 2002. Two dwellings (D75 and D96) have been built as D73 and D74 with greater care being taken to seal around the primary air barrier (in these dwellings the Kingspan insulation). The remaining dwelling (D76) has incorporated a number of design changes that have not incurred significant cost. Such changes have included: taping tops of metal studwork at first floor ceilings, taping insulation at intermediate floor level, taping around windows and service penetrations, sealing the external wall/floor junction, plus on-going changes as discussed with site management and the Leeds Met research team.
- 4 Site observations for Phase 3 indicate that there is little difference in the airtightness of the designs adapted for 2002 compliance and the new designs made specifically for this purpose, with regards to airtightness. Table 5 contains selected illustrated examples of the observations summarised below.
 - i) Phase 3 amendments to the ground floor slab construction have been introduced to improve the airtightness of the junction of slab and wall, using sacrificial blockwork as a former for the slab edge rather than polystyrene. This solved some problems (i.e. misplaced slab extensions at thresholds) but not others such as the horizontal misalignment of frame and slab shown in Table 5.
 - j) In D76 the gaps under the steel frame sole plate, between shims used for levelling, were sealed internally using a mastic sealant prior to dry-lining.
 - k) Phase 3 alterations to intermediate floor construction, applying the flooring after frame construction rather than having chipboard pre-attached to flooring cassettes, eliminated the problem of gaps in the intermediate floor.
 - l) On D76, gaps around the cavity tray at the intermediate floor perimeter were sealed with tape. Where possible the cavity tray was omitted to allow the ground and first floor insulation panels to be taped together as in Table 5.
 - m) Tears and punctures to the outer foil surface of the wall insulation (the primary air barrier) were sealed with tape in D75, D76 and D96, a practice not observed during Phase 1 or on D73 and D74.
 - n) In D76 and D96, intermediate floor service penetrations for soil stacks were drilled with some precision, rather than smashed through as observed elsewhere on site.
 - o) At all openings in D76 tape was applied to return the air barrier in to the steel frame as in Table 5.
 - p) At window jambs in D76 tape was used to link the window frames to the air barrier.
 - q) In D76 at the loft/ceiling interface, the holes in the top of the internal partitioning were taped over and all gaps around the plasterboard ceilings were sealed using expanding foam.

Detail	Site Observations
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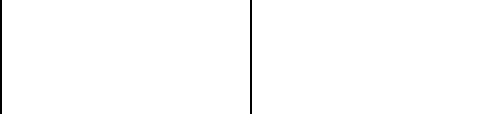
<p>Ground Floor Slab Perimeter</p>				
	<p>Phase 1 slab construction, with slab extensions at thresholds often misplaced leaving gaps into the cavity.</p>		<p>Phase 3 potential air paths from the wall void into the retrospective sealed cavity and around the slab perimeter</p>	
<p>Intermediate Floor Perimeter</p>				
	<p>Gaps around the intermediate floor cavity tray in both Phase 1 and 3, creating a break in the primary air barrier.</p>		<p>D76, where continuity of the air barrier at this junction is achieved by taping to both sides of the cavity tray or by omission of the cavity tray and taping.</p>	
<p>Openings</p>				
	<p>The airtightness around openings relies on the plasterboard lining linking the steel frame to the window or door frame, not a continuation of the air barrier.</p>		<p>For D76, the air barrier is returned inward to the steel frame and extended outward to meet the window frame using tape.</p>	
<p>Loft Boundary</p>				
	<p>Holes linking the internal partitioning voids directly to the ventilated loft-space.</p>		<p>D76, with ceilings and service penetrations into the loft sealed around.</p>	

Table 5 Selected alterations to detailing adopted by developer D.

Developer E

- 25 The general approach taken by this developer has been to tighten up the existing detailed design, by concentrating effort on a number of areas that contributed to air leakage during Phase 1 of the project. For instance, in all of the plots increased attention (initially by site management) will be paid to soil stack risers and window/door jambs, sills and thresholds. In apartments EA301 and EA302 (top-floor apartments) additional attention will also be paid to loft-space junctions, particularly around the mezzanine storage deck.
- 26 Initial observations from site for Phase 3 indicate that the high quality of construction observed throughout Phase 1 is being maintained. Construction on site is currently at the superstructure stage and the potential airtightness issues raised during Phase 1 relate to details which are expected to be constructed between November 2005 and February 2006.

Results of the Pressurisation Tests

- 27 Pressurisation tests have so far been undertaken on 11 of the 26 selected dwellings. All of these tests were carried out by Leeds Metropolitan University using an Energy Conservatory Minneapolis Model 3 Blower Door. The internal volumes and exposed external areas of the tested dwellings are listed in Table 6.

Dwelling	Volume (m³)	Exposed internal surface area (m²)
B14	398	364
B16	338	296
B17	338	296
B21	338	296
B22	338	296
C194	264	268
D73	283	296
D74	231	232
D75	295	309
D76	308	296
D96	252	267

Table 6 Details of the tested dwellings

- 28 In addition to the pressurisation tests, the main air leakage paths within each of the dwellings were identified by pressurising the building, and locating the main areas of air leakage using hand held smoke generators. However, quantifying exactly what contribution each leakage path made to each dwelling's overall air leakage was not possible. Determination of major and minor leakage paths contained within this reports rely upon the experience of the researchers carrying out the leakage detection; by using a standard procedure for the leakage detection, comparative flow rates of smoke escaping from the building envelope were used.
- 29 All of the pressurisation tests and the air leakage paths associated with each dwelling were photographed and in many cases video recorded. The air permeability data and leakage path information was also fed back to each of the developers (see task 2.3.3 of the project proposal) to assist the developers in identifying problems areas and to improve the airtightness performance of their future dwellings.
- 30 Detailed pressurisation reports relating to each of the developers are available on request.

Air permeability

31 The results of all the individual air permeability tests are shown in Table 7 and Figure 1.

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability (m ³ /(h.m ²))
	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	Permeability (m ³ /(h.m ²))	r ² coefficient of determination	
B14	9.33	0.996	8.15	0.980	8.74
B16	5.50	0.987	5.69	0.993	5.59
B17	5.61	0.990	5.76	0.991	5.69
B21	7.31	0.996	7.27	0.997	7.29
B22	7.44	0.995	7.31	0.991	7.37
C194	15.90	0.996	14.02	0.992	14.96
D73	13.39	0.991	13.22	0.991	13.31
D74	12.62	0.970	12.80	0.949	12.71
D75	10.97	0.979	10.22	0.990	10.60
D76	9.23	0.982	8.56	1.000	8.89
D96	11.52	0.995	10.77	0.999	11.14

Table 7 Mean air permeability of the tested dwellings.

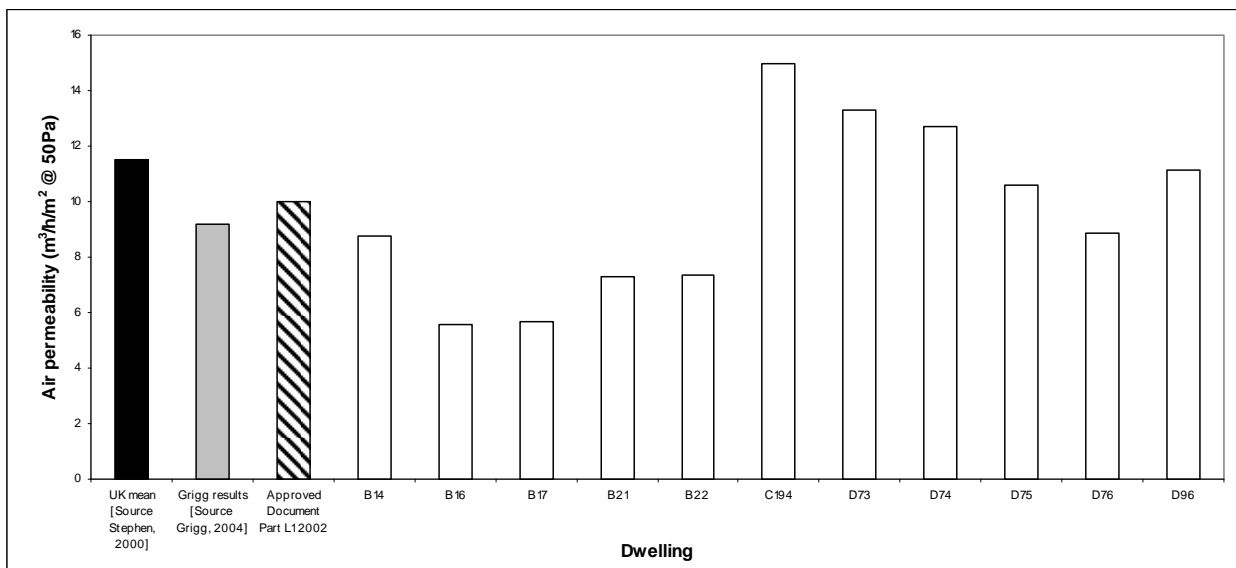


Figure 1 Mean air permeability of the tested dwellings.

32 Figure 1 illustrates the air permeability of the 11 tested dwellings compared with the UK mean,¹ the recommended maximum level set in the 2002 edition of the Building Regulations Approved Document Part L1 of 10 m³/(h.m²) @ 50Pa (ODPM, 2001) and some recent measurement

¹ The UK mean has been derived from the Building Research Establishment's (BRE's) air leakage database, which is the largest and most comprehensive source of information on the airtightness of UK dwellings (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. However, despite its size, this database is not the result of random sampling and cannot claim to be unequivocally representative of the UK housing stock.

undertaken by Grigg (2004).² The data show that a relatively wide range of airtightness was measured for the tested dwellings. The air permeability of the dwellings ranged from 5.6 to 15.0 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa, with a mean of 9.7 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ and standard deviation of 3.1 $\text{m}^3/(\text{h}\cdot\text{m}^2)$. Although the range of air permeability that was measured within the tested dwellings is consistent the work undertaken by Grigg (2004), the mean for the dwellings tested in this project is slightly higher (9.7 as opposed to Grigg's $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa). This may be a result of the inclusion of large proportion of apartments³ (36%) in the sample tested by Grigg (2004) compared with our sample (to date, no apartments have been included in our sample). Only three of the 11 dwellings (27%) had an air permeability that was higher than or equal to the UK mean of 11.5 $\text{m}^3/(\text{h}\cdot\text{m}^2)$. The mean of all 11 results (9.7 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa) suggests that these dwellings are more airtight than the average for the UK stock as a whole (11.5 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa). However, given the number of dwellings tested and the range of values measured, there is not a statistically significant difference between the sample and the UK mean.

- 33 Perhaps of most importance is that only six of the 11 dwellings tested to date have achieved air leakage values that are lower than the maximum specified level of 10 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa set in the 2002 edition of the Approved Document Part L1 (ODPM, 2001). As in Phase 1 of the project, all of the dwellings that have been tested to date were using Part L Robust Details (see DEFRA, 2001) as the basis of the application for regulatory approval. In addition to this, each developer also received detailed and targeted feedback from the Leeds Met research team on any potential areas or issues that may have an influence on the eventual airtightness performance of the selected dwellings.
- 34 The data also show that the tightest dwellings tested were those constructed by developer B. All of the dwellings constructed by this developer achieved air leakage values less than the target of 10 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa that is specified within ADL1 2002. The leakiest dwelling tested to date was constructed by developer C, which was built as per their standard Phase 1 construction. Only one of the five dwellings constructed by developer D achieved an air leakage rate of less than 10 $\text{m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa.
- 35 The air permeability of the 11 tested dwellings has also been compared against the air permeability results that were achieved during Phase 1 of the project. The results of this are shown in Figure 2.

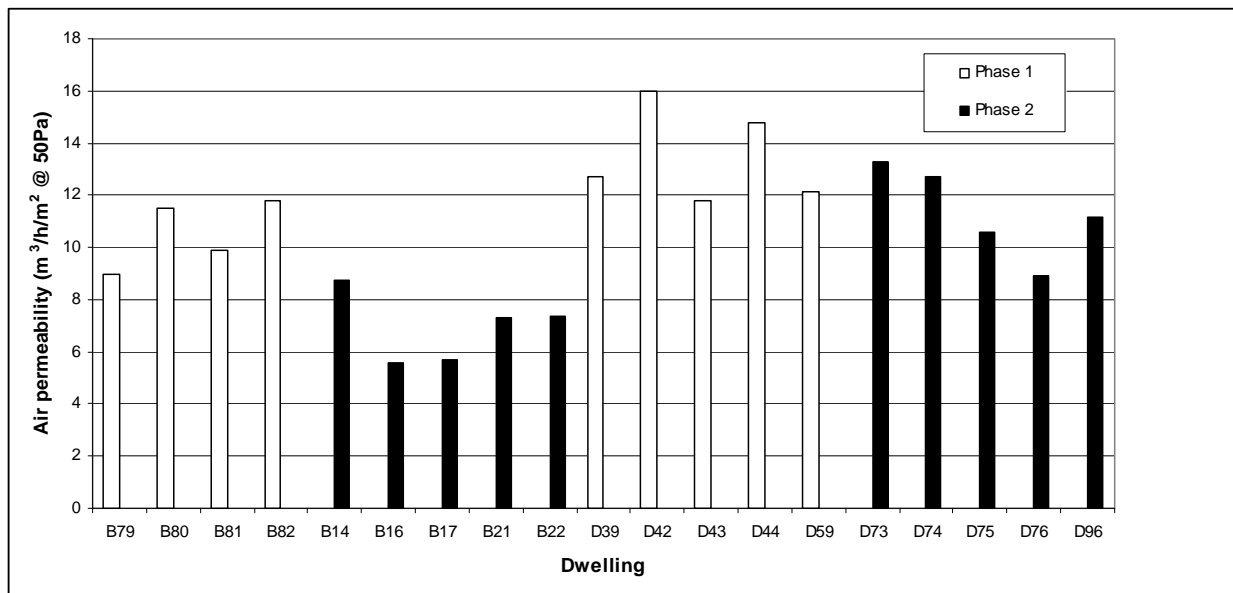


Figure 2 Mean air permeability of the tested Phase 1 and Phase 3 dwellings.

- 36 Figure 2 illustrates that in the majority of cases, the dwellings that have been tested during Phase 3 of the project are more airtight than the corresponding dwellings that were tested during Phase

² The measurements undertaken by Grigg (2004) are based upon a non-random sample of 99 dwellings that were constructed to the provisions contained within the 2002 edition of the Building Regulations Approved Document Part L1.

³ Apartments tend to be more airtight than other dwelling forms of equivalent area as they are more likely to have solid intermediate floors, fewer door and window openings and fewer service penetrations.

1. This suggests that the combination of feedback from the Leeds Met research team coupled with the various approaches adopted by the developers has had a positive impact on the airtightness of the dwellings tested.

37 In order to establish the scale of the reductions that have been achieved by undertaking various airtightness measures and acting upon the feedback from the Leeds Met research team, the air permeability results have been analysed for each individual developer. The results of this analysis are set out below:

Developer B

38 A summary of the Phase 3 air permeability test results and measures that were undertaken on the dwellings constructed by this developer are contained within Table 8 and Figure 3.

Dwelling	Measures undertaken	Air permeability (m ³ /(h.m ²))
B14	Built as standard, taking on board the feedback from Phase 1.	8.74
B16	As B21, plus pointing to all joints and apertures prior to dry-lining.	5.59
B17	As B21, plus the application of a parging layer to all external walls.	5.69
B21	Built as B14, plus acting upon the on-site feedback from Leeds Met research team where applicable.	7.29
B22	As B21, plus all of the light fittings, radiator and electrical pattrass boxes have been sealed to the plasterboard dry-lining.	7.37

Table 8 Air permeability of the dwellings tested for developer B.

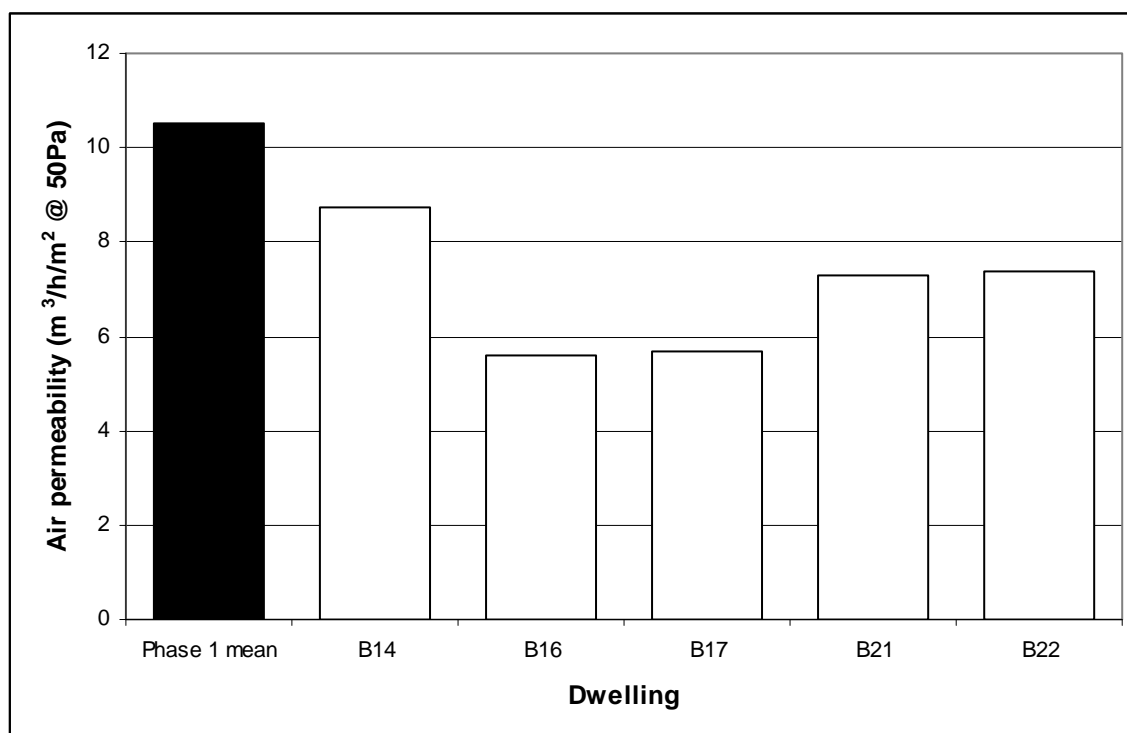


Figure 3 Air permeability of the dwellings tested for developer B.

39 Given the small sample size the results for developer B cannot provide absolute certainty of the success of each measure taken in this staged approach. However, this initial sample would suggest that the most important measures undertaken by this developer during Phase 3 of the project involved pointing all of the joints and apertures prior to the application of the dry-lining (B16) and parging all of the external walls prior to dry-lining (B17). Both of these measures reduced the air leakage rate of the dwellings constructed by this developer, from a mean of 10.5 m³/(h.m²) @

50Pa during Phase 1, to 5.6 and 5.7 m³/(h.m²) @ 50Pa, respectively in Phase 3. This represents a reduction in air leakage of almost 50% from the Phase 1 mean. In addition, these results also suggest that pointing and parging can have a similar impact on the overall reduction in air leakage rate.

- 40 Next in importance would appear to be acting upon the on-site feedback from the Leeds Met research team where applicable (B21), which resulted in a reduction in the mean air leakage rate of around 3 mh⁻¹ @ 50Pa (a 30% improvement from the Phase 1 mean). Sealing all of the light fittings, radiator and electrical pattress boxes (B22) appeared to have little additional effect on air leakage and gave a similar reduction to acting upon the on-site feedback from the Leeds Met research team. Finally, the least effective measure was to build the dwellings as standard and only taking on board the feedback from Phase 1 of the project (B14), although the sample size of 1 once again prevents accurate statistical analysis. Nevertheless, this still resulted in a reduction in the air permeability by around 2 m³/(h.m²) @ 50Pa (a 17% improvement from the Phase 1 mean).
- 41 In terms of leakage identification, all of the dwellings were found to have a number of common air leakage paths. These are identified within Table 9 below.

Elements and junctions	Fixtures and fittings	Service penetrations
Between the skirting board and ground floor. Around thresholds. Around the stairs. Between the skirting board and intermediate floors.	Around kitchen units. Around trickle vents. Around bath panels and shower trays.	Service penetrations in the kitchen and utility room. Service penetrations in downstairs toilet. Pipe-work penetrations behind the radiators. Service penetrations in the bathrooms and en-suites. Service penetrations below the CPSU.

Table 9 Main air leakage paths associated with developer B.

- 42 In addition the common air leakage paths listed in Table 9, leakage paths were also identified that were particular to specific dwellings. These were as follows:
- Around extract fans in dwellings B14, B16 and B21.
 - Through TV aerial and electrical sockets in dwellings B14, B16.
 - Around internal door frames in dwellings B14, B21 and B22.
 - Around rooflight in dwelling B14.
 - Around loft hatch in dwellings B14, B16 and B22.
 - Around rear door in dwellings B16, B17 and B21.
 - Around fireplace in dwellings B16 and B21.
 - Around window casement in dwellings B17 and B21.
 - Hole in intermediate floor in dwelling B17.
- 43 Most of the leakage paths are common to a number of dwellings. Leakage detection performed during the pressurisation tests provided observational data that the amount of smoke escaping through these gaps varied considerably between dwellings, unfortunately no method of measuring this quantitatively was available. An example being the significantly reduced flow of smoke observed through the junctions of intermediate floors and walls in both B16 and B17, and through the ground floor/external wall junction in B17. Also the treatment of certain details was not common throughout this site, for example dwellings B21 and B22 had boiler flue pipes which were fully sealed around and no leakage detected, whereas this appeared to be a major direct source of air leakage detected in all of the other three dwellings constructed by developer B.
- 44 Photographs of all of these leakage paths can be found within the relevant pressurisation test reports.

Developer C

- 45 The Phase 3 air permeability test results for developer C indicate that plot C194 achieved an air leakage rate of 15.0 m³/(h.m²) @ 50Pa, which is comparable to the leakage rates achieved for the two worst performing dwellings constructed during Phase 1 (Plots C236 and C237 which achieved

air leakage rates of 16.5 m³/(h.m²) and 14.0 m³/(h.m²) @ 50Pa, respectively), both of which were mid-terraced properties where the intermediate floor void continued across an alleyway. This floor void was identified as a potentially significant source of air leakage within both of these dwellings. The performance of the two mid-terraced dwellings was around 3 to 4 m³/(h.m²) @ 50Pa higher than the air leakage rates measured in the end-terraced (Plot C238) and the semi-detached dwellings (Plots C239 & C240) constructed during Phase 1. The relatively poor air leakage performance of C194 may be attributable to a number of complex details that are contained within the dwelling, such as an integral garage and ventilated roof void between the ground floor and first floor bay windows (the latter also an issue on the mid-terraced dwellings), where the continuity of the primary air barrier was disrupted.

- 46 In terms of leakage identification, the main air leakage paths associated with dwelling C194 are identified within Table 10 below.

Elements and junctions	Fixtures and fittings	Service penetrations
Between the skirting board and ground floor. Around the stairs. Between the skirting board and intermediate floor. At French door threshold. Through holes in cylinder cupboard floor.	Around kitchen units. Through and around trickle vents. Through French doors. Around bath panel. Around bay window head. Around internal door frames. Around loft hatch.	Service penetrations in the kitchen. Service penetrations in the downstairs toilet. TV aerial and electrical sockets. Service penetrations in the bathroom. Around central light fittings. Service penetrations in the cylinder cupboard.

Table 10 Main air leakage paths for dwelling C194.

- 47 No specific measures were taken to increase the airtightness of dwelling C194 over the standard construction in Phase 1. This suggests that the more complex design issues affecting the detached and mid-terrace dwellings, which are absent on the semi-detached and end-terrace dwellings, have a detrimental effect on the airtightness of the dwellings from developer C; although the small sample size prevents accurate statistical analysis.
- 48 Photographs of all of these leakage paths can be found within the relevant pressurisation test report.

Developer D

- 49 A summary of the Phase 3 air permeability results and measures that were undertaken on the dwellings constructed by this developer are contained within Table 11 and Figure 4.

Dwelling	Measures undertaken	Air permeability (m ³ /(h.m ²) @ 50Pa)
D73	Built as standard to new design.	13.31
D74	Built as standard to new design.	12.71
D75	As D73 and D74 with greater care being taken to seal around the primary air barrier.	10.60
D76	As D73 and D74 plus the incorporation of a number of design changes that have not incurred significant costs.	8.89
D96	As D73 and D74 with greater care being taken to seal around the primary air barrier.	11.14

Table 11 Air permeability of the dwellings tested for developer D.

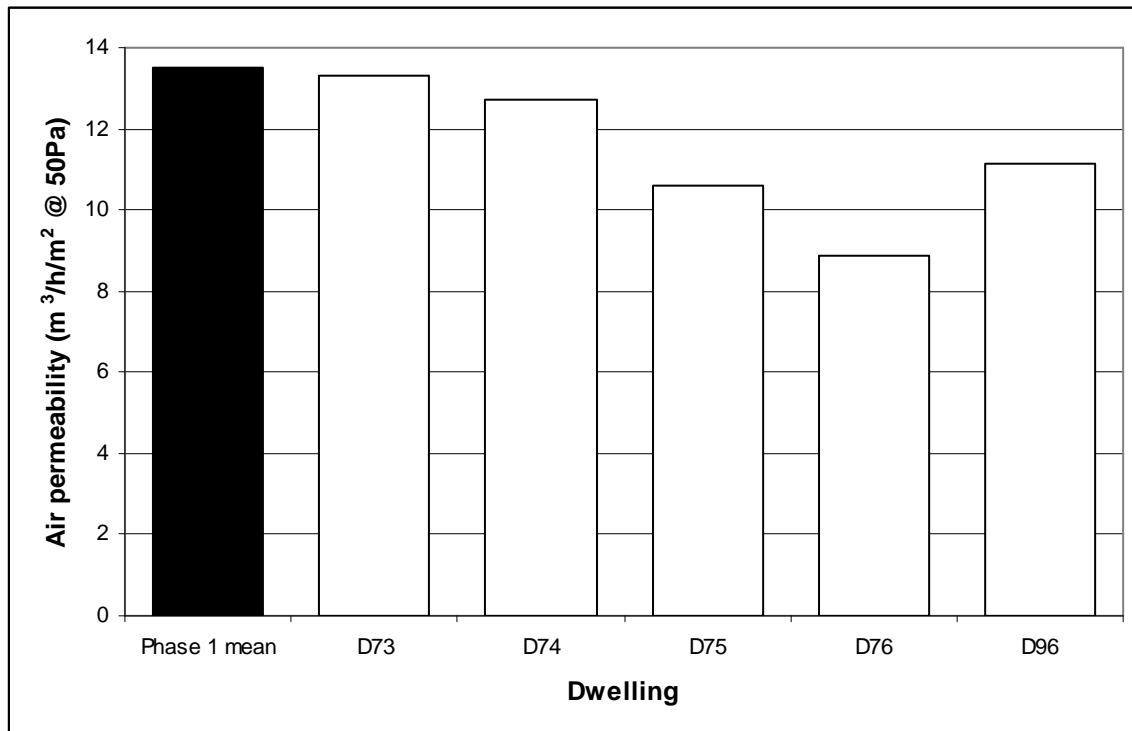


Figure 4 Air permeability of the dwellings tested for developer D.

- 50 The results for developer D indicate that in those dwellings that were built as standard using the new designs, and where no additional measures were undertaken to improve the airtightness of the dwellings (plots D73 and D74), the air leakage rates obtained were 13.3 m³/(h.m²) and 12.7 m³/(h.m²) @ 50Pa, respectively. These rates are comparable to those obtained during Phase 1 of the project, where the mean air leakage rate for developer D was 13.5 m³/(h.m²) @ 50Pa. This suggests that in terms of airtightness, the new dwelling designs do not perform significantly better than the old dwelling designs. In those dwellings where more care was taken to seal around the primary air barrier (Plots D75 and D96), the air leakage rate reduced to 11.1 and 10.6 m³/(h.m²) @ 50Pa, respectively. This represents a reduction in air leakage from Phase 1 of around 20%. The tightest dwelling constructed by developer D was Plot D76, where considerable effort was made by the construction team to make the dwelling airtight. The air leakage rate measured for this dwelling was 8.9 m³/(h.m²) @ 50Pa, resulting in a reduction in the mean air leakage rate of 34%. Dwelling D76 was also the only dwelling constructed by developer D to achieve an air leakage rate lower than the target of 10 m³/(h.m²) @ 50Pa that is specified within ADL1 2002.
- 51 The light steel frame method of construction adopted by developer D uses the outer foil coating of the polyurethane foam insulation as the primary air barrier, with a reliance on the use of a metallic tape to ensure continuity of this air barrier. The site assessments and on-site feedback from the Leeds Met research team give an indication of the comparative fragility of this air barrier, which would appear to be reinforced by the test results obtained. Where increased attention was given to this air barrier (D75 and D96) airtightness performance was increased; where further consideration to the air barrier was introduced the dwelling air permeability was reduced further. Once again the small sample size precludes certainty.
- 52 In terms of leakage identification, all of the dwellings were found to have a number of common air leakage paths. These are identified within Table 12 below.

Elements and junctions	Fixtures and fittings	Service penetrations
Gaps between skirting board and ground floor. Gaps between skirting board and	Around kitchen units. Around trickle vents. Patio doors.	Service penetrations in the kitchen and utility room. Service penetrations in downstairs toilet.

first floor. Leakage around all thresholds. Gaps around the stairs.	Around loft hatch. Gaps around the bath panel and the shower tray.	Around electrical fuse box and electrical sockets. Pipework penetrations behind the radiators. Service penetrations in the bathrooms, en-suites and cylinder cupboards Around extract fans.
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Table 12 Main air leakage paths.

- 53 In addition the common air leakage paths listed in Table 12, leakage paths were also identified that were particular to specific dwellings. These were as follows:
- a) Hole at the junction between the wall and the ceiling in dwelling D73.
 - b) At the window sill/wall junction in dwelling D73.
 - c) Around the rear doors in dwellings D73, D74 and D96.
 - d) At the window head in dwellings D75 and D76.
 - e) Around window casements in dwellings D76 and D96.
- 54 Photographs of all of these leakage paths can be found within the relevant pressurisation test reports.

Conclusions

- 55 This report presents the progress that has been made in assessing the site survey data that have been collated for Phase 3 and presents the interim results of the Phase 3 pressurisation tests performed to date.
- 56 During Phase 3 of this project a number of different approaches have been adopted by the participating developers. Developer A is concentrating efforts on existing detailed design, with a possible review for the final two dwellings dependent upon the interim pressurisation results obtained for the initial three dwellings. Developer E is also concentrating efforts on existing detailed design as discussed in their Phase 2 feedback session, and will introduce the agreed measures when construction reaches that stage. Developers B, C and D, on the other hand, have adopted a staged approach enabling some general comparisons between different airtightness measures to be made, with developer C currently reviewing their strategy as a direct result of feedback from the Leeds Met research team following the initial Phase 3 site surveys.
- 57 An analysis of the site observations indicates that all of the developers have acted upon the feedback from Phase 1 of the project and have actively participated in a two-way dialogue with the Leeds Met research team. The observations obtained from site have illustrated the variety of approaches that have been adopted by the developers for Phase 3 of the project, ranging from the tightening up of the existing detailed design approach and addressing supervision and workmanship issues to design amendments such as the application of a parging layer to all external walls. The observations also indicate that the feedback from the Leeds Met research team coupled with the approach undertaken by each developer has resulted in the majority of the airtightness issues identified during Phase 1 of the project being addressed. However, other measures that tend to require design changes or are perceived to incur significant costs, remain unaddressed and are likely to contribute to air leakage within the selected dwellings. For instance, significant modifications to the loft/ceiling junctions have only been attempted on one dwelling in Phase 3 (dwelling D76); as this is presumed to either require extra labour and material costs or require new design drawings being created which is even more costly. In none of the participating sites has a specific budget been introduced to increase the airtightness performance of the dwellings, but this may change for developer A, subject to the outcome of pressurisation tests for Plots A64, A65 and A66.
- 58 Results from both developers B and D would suggest that the maximum specified air permeability of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ set in Part L1 2002 is not unrealistic for either of these two different construction methods, and in the case of developer B substantially lower levels of infiltration are achievable with relatively little extra cost incurred. The results from developer B indicate that investing efforts into the primary air barrier in full fill masonry cavity construction, by pointing up or parging the external walls prior to dry-lining, provided the most noticeable improvements in

airtightness of the dwellings, and air permeabilities of less than $6 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ are genuinely achievable. However, the very small data set precludes certainty. With the light steel frame construction used by developer D, increased awareness of airtightness issues by site supervisors improved the airtightness of the dwellings but design changes (predominantly to the primary air barrier) were necessary for the air permeability of the dwelling to be reduced below the target figure of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$.

- 59 A number of common air leakage paths were observed in all 11 dwellings tested, all of which were also detected in Phase 1. However, although many of these observed points of entry detected under pressurisation exist, their individual contribution to overall dwelling leakage is less obvious, as the point of entry rarely relates directly to the actual point of leakage from the building envelope. The sealing of all wall, ceiling and floor penetrations through the primary air barrier at any earlier stage of construction was highlighted to all developers in the Phase 1 feedback sessions, to prevent subsequent building work obstructing any sealing to be carried out at a later date. These sequencing issues, coupled with certain specific design changes adopted, have been reflected by some of the initial improvements seen in the Phase 3 air permeability test results. The two-way dialogue established between the Leeds Met research team and the developers in Phase 3 has ensured that all involved personnel, particularly site management, are gaining an increasing awareness of airtightness issues, and are able to make advancements in the reduction of the air permeability of their respective dwellings.

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Appendix

Phase 3 - Site observations and developer feedback

Site A A1
Site B A10
Site C A25
Site D A32
Site E A39

Airtightness of buildings – towards higher performance

Site A

Visit date: 28-Sep-2005

Observations:

Site Overview

A64 and A65 currently in pre-plaster stage and yet to undergo final pre-plaster check.
 A66 currently being dry lined
 A79 and A80 yet to commence ground floor construction.

General Observations

There continues to be a marked improvement in these plots over those observed in Phase 1 in terms of expected airtightness of the dwellings. As well as the previously mentioned general improvements in quality and workmanship, additional specific measures have also been taken. These actions will have a positive effect on the airtightness of the dwellings. However, whether this is enough to reliably reduce the air permeability from the average $14.2 \text{ mh}^{-1}@50\text{Pa}$ achieved in Phase 1 to the target of below $10 \text{ mh}^{-1}@50\text{Pa}$, or whether further measures need to be taken, remains to be seen.

A64

2-Storey, 3-bedroom, mid-terrace dwelling.
 Partial-fill cavity-masonry, standard build to completion.

Currently in pre-plaster stage and yet to undergo final pre-plaster check.

Openings

The taping of perforations in the lintels should reduce air leakage. At the jambs plasterboard adhesive for the lining will be used to seal any small gaps around the closers, similarly a mortar bedding for sill boards should ensure that air leakage through this detail is minimised.



Service Penetrations – External Walls

Some service penetrations through the external walls have already been sealed effectively (gas pipe), others (boiler flue) have neat, suitably-sized holes bored which will simplify sealing after installation. The hole for the cooker hood extract duct, which was observed on the previous visit, has been loosely packed with mineral wool; this will get compacted and sealed with either mortar or expanding foam prior to the plasterboard ceiling being fitted.



Service Penetrations – Intermediate Floor

Although air will not escape directly to outside the building envelope through these penetrations, they allow air to move more freely throughout the dwelling generating 'hidden' leakage paths. Some penetrations through the intermediate floor are larger than necessary and will take more time and effort to seal; if penetrations through the cylinder cupboard floor are to be sealed effectively this will require doing so before the tank is positioned and access is restricted.



Built-In Joists

All the joists built in to the external walls have been successfully sealed around using mortar and mastic, with the exception of those where the close proximity of an adjacent wall has made access to the junction difficult. If necessary, additional work could be done to seal these awkward joints but would incur extra time and costs, efforts which may be better spent elsewhere in the dwelling.



Loft/Ceiling Junction

An unaddressed cause of air leakage; air movement into the ventilated loft-space through holes in the top of the metal studwork for internal partition walls. Loft insulation will be placed over the top of these holes, but will have very little effect in reducing the amount of air movement through them.

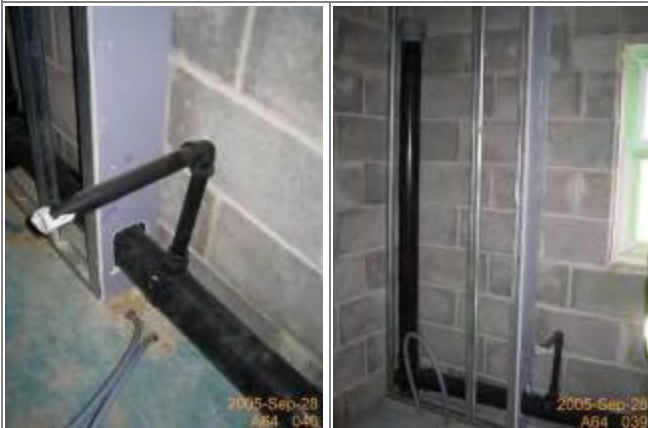


Bathroom Boxing & Soil Stack

Both the boxing-in of the pipe-work and the soil stack have penetrations directly into the ventilated loft-space. These will be filled with mineral wool which will reduce smoke spread, but will still allow air to move between the void behind the boxing and the loft-space.

In both cases, air may be able to enter the boxing void from other voids. In the bathroom the void behind the boxing may be linked to voids behind the dry-lining and under the bath; in the case of the soil stack the boxing void is also linked to the intermediate floor void.

With air able to move throughout the dwelling due to these interconnected voids, complex 'hidden' air-leakage paths are created. A leakage path where air enters one void and escapes the building envelope via a different one may not only be difficult to identify and detect, but equally awkward to seal; particularly if the sealing is required to be done retrospectively.





A65



2-Storey, 3-bedroom, mid-terrace dwelling.
Partial-fill cavity-masonry, standard build to completion.

Currently in pre-plaster stage and yet to undergo final pre-plaster check.

Openings

As in A64, the small gaps around the closers at the jambs will be sealed using plasterboard adhesive as the lining is positioned. The gaps at the tops of the closers have been sealed with mastic, and the perforations in the lintels sealed with tape.

**Service Penetrations – External Walls**

As in A64 service penetrations through the external walls have neat, suitably-sized holes which be easily sealed around after installation. The cooker hood extract duct and electrical consumer unit penetrations will again be plugged with compacted mineral wool and sealed with either mortar or expanding foam prior to dry-lining.



Service Penetrations - Intermediate Floor

Holes made in the intermediate floor are more appropriately sized for the penetrations than in A64, which will prove either easier to seal or may restrict the air flow around them. As in A64, if services to the cylinder cupboard are to be sealed, this needs doing so before access is limited.



Built-In Joists

As in the previous plot, all the joists built in to external walls have been well sealed with mortar and then mastic wherever possible.



Steel Studwork

Apertures in the steel studwork allow air to circulate throughout internal partitions and, when fitted on the first floor, directly into the loft-space. When grommets are fitted to prevent abrasion to cables these gaps are reduced but will still allow air movement.

The shower is typically an area where air leakage through this path occurs. Air can enter the void beneath the shower tray from around the flexible plastic front panel (or via intermediate floor penetrations) and move directly into the ventilated loft-space through gaps in the steel studwork. Mineral wool placed in these voids for acoustic purposes may impede the air flow to some degree but will not stop air movement through this partitioning.

A6



Connected voids

As in A64, the boxing-in of pipe-work in the bathroom links a number of voids (including voids in the partition wall, beneath the bath, behind the dry-lining, etc.) directly to the loft-space creating increasingly complex 'hidden' air leakage paths.

The voids around the stairs also link together various other voids which, although not leaking directly to outside of the building envelope, allow air to circulate more freely throughout the dwelling.



A66



2-Storey, 3-bedroom, end-terrace dwelling.
Partial-fill cavity-masonry, standard build to completion.

Currently in initial stages of dry-lining.

Openings

All gaps previously observed around openings have been successfully filled. The use of propriety cavity closers at thresholds, taping of lintel perforations and mastic sealing of junctions will minimise leakage at these details. Ribbons of plasterboard adhesive running the full length of the jambs are to be used to ensure that they are also made as airtight as possible.



Service Penetrations – External Walls

Small penetrations for cables have been sealed around using mastic. The hole for the boiler flue is not excessively large and will be filled with expanding foam where it penetrates the blockwork once the boiler is installed. The mineral wool surrounding the cables to the electrical consumer unit is to be compacted and sealed using expanding foam prior to dry-lining.



Cylinder Cupboard

Penetrations beneath the cylinder cupboard floor link various voids and may help create hidden leakage paths. As mentioned previously, penetrations through the cylinder cupboard floor will require sealing around prior to the tank being positioned.



Loft-space junction

Some possible air leakage paths may remain after dry lining. Holes in the top of the steel studwork will allow air to move between the void in the partitioning and the loft. Gaps around the edges of the first floor ceiling and gaps at the ends of the wall plate may both allow air from behind the plasterboard on the walls to move into the loft, if continuous ribbons of plasterboard adhesive are not used at this junction.



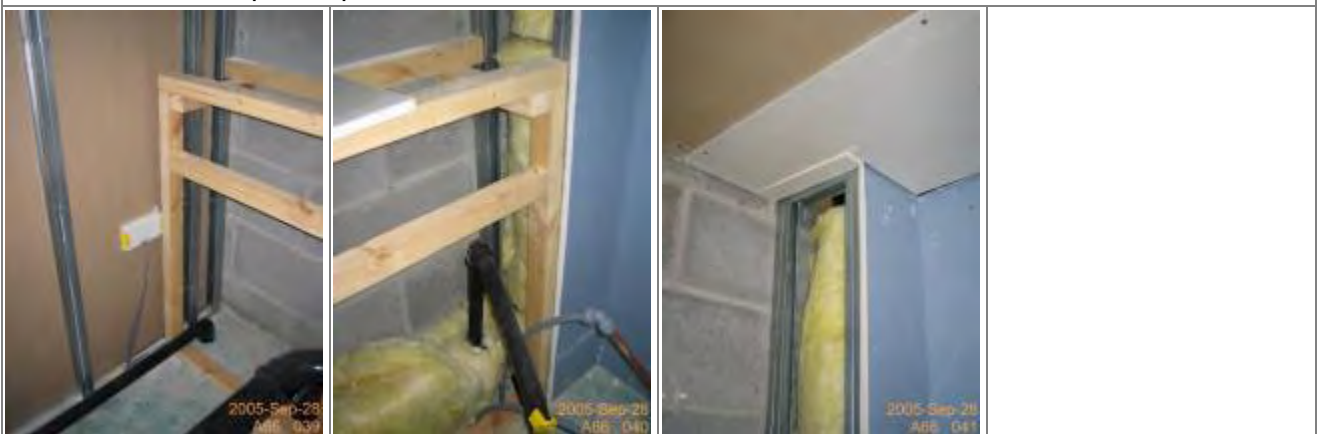
Shower

As mentioned in A65, the shower is an area where air moving through the steel studwork may be a major source of air leakage, as air entering the void under the shower tray (form around the panel, from the intermediate floor and through adjacent studwork voids) may move relatively freely into the loft-space.



Bathroom Boxing and Soil Stack

As described for A64, the dual problem of inter-linked voids and possible air-paths directly into the loft-space are apparent at both these details. These details have been constructed 'as designed', and it would appear that the issue of airtightness of these details is an issue of design rather than one of workmanship or supervision.



A9



Airtightness of buildings – towards higher performance

Site B

Visit date: 05-Aug-2005

Observations and comments:

B16

Full-fill cavity masonry, 3-storey, 3-bed, semi-detached dwelling.
Standard build – plus party walls and fill apertures to all external walls.

Pressure Test Result:**Air permeability****5.60 m³/(h.m²) @ 50Pa**

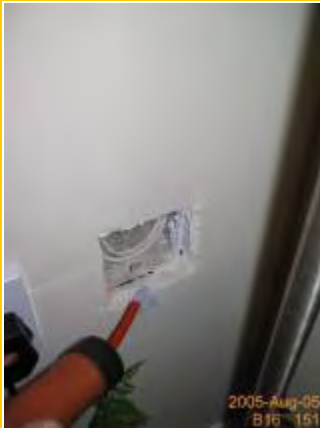
Air permeability – depressurisation only

5.69 m³/(h.m²) @ 50Pa

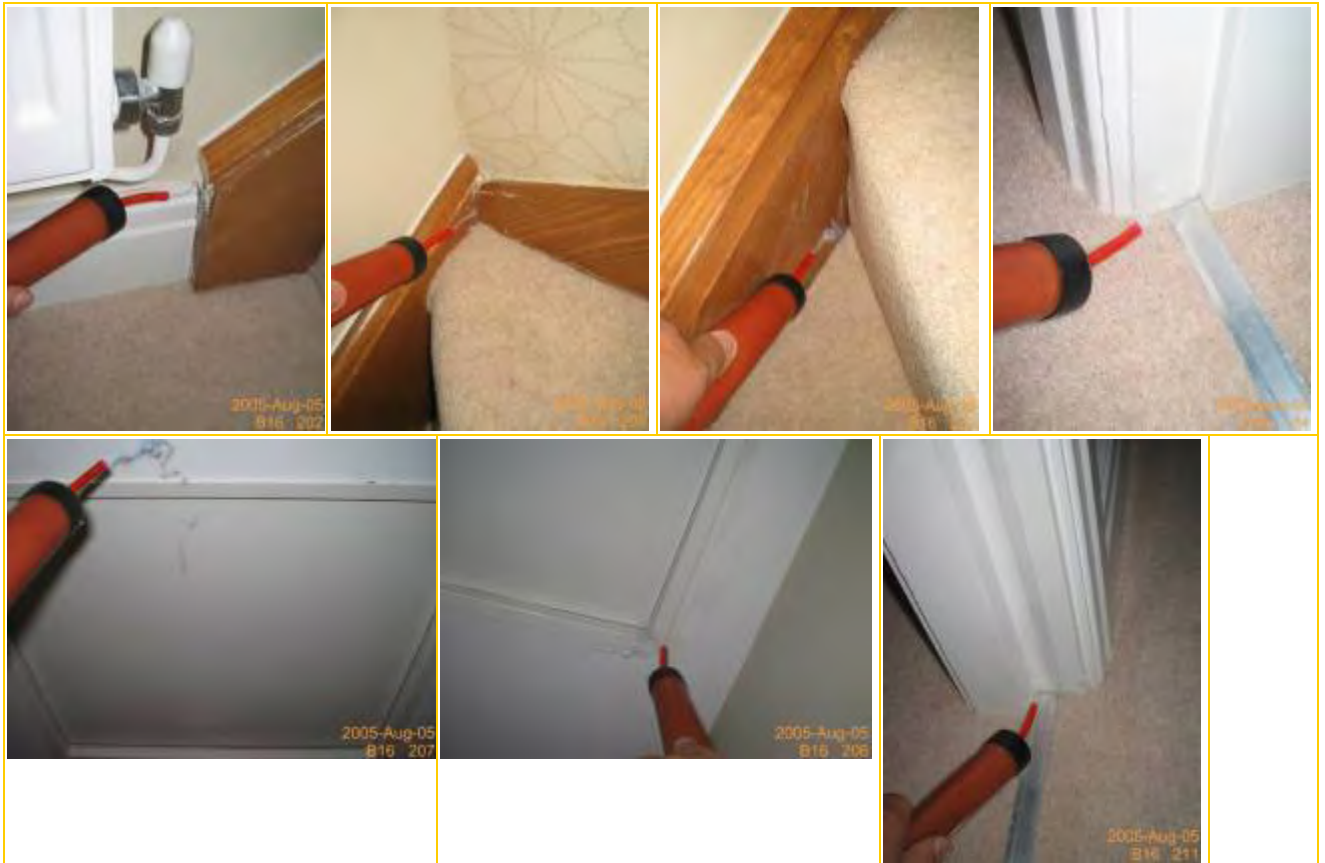
Air permeability – pressurisation only

5.50 m³/(h.m²) @ 50Pa**Hall, stairs and landings**

- Air leakage through an unfinished pattrass box in the hallway.
- Various points of leakage through and around both sets of stairs.
- Leakage into some junctions of door frames and intermediate floors.
- Slight air movement around the loft-hatch and its housing.

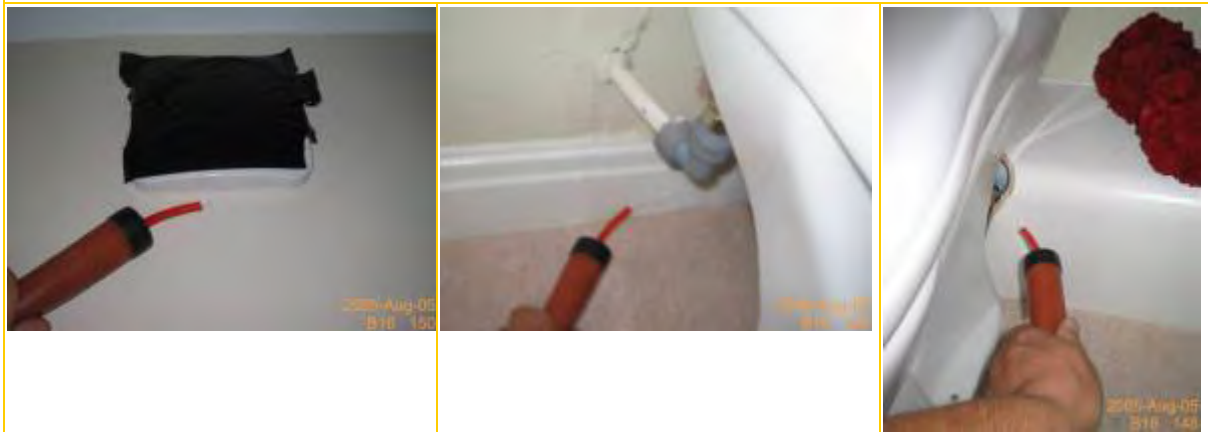


A11



Downstairs closet

- Air leakage around the extraction fan housing.
- More significant air movement into the open-ended boxing around the soil pipe.



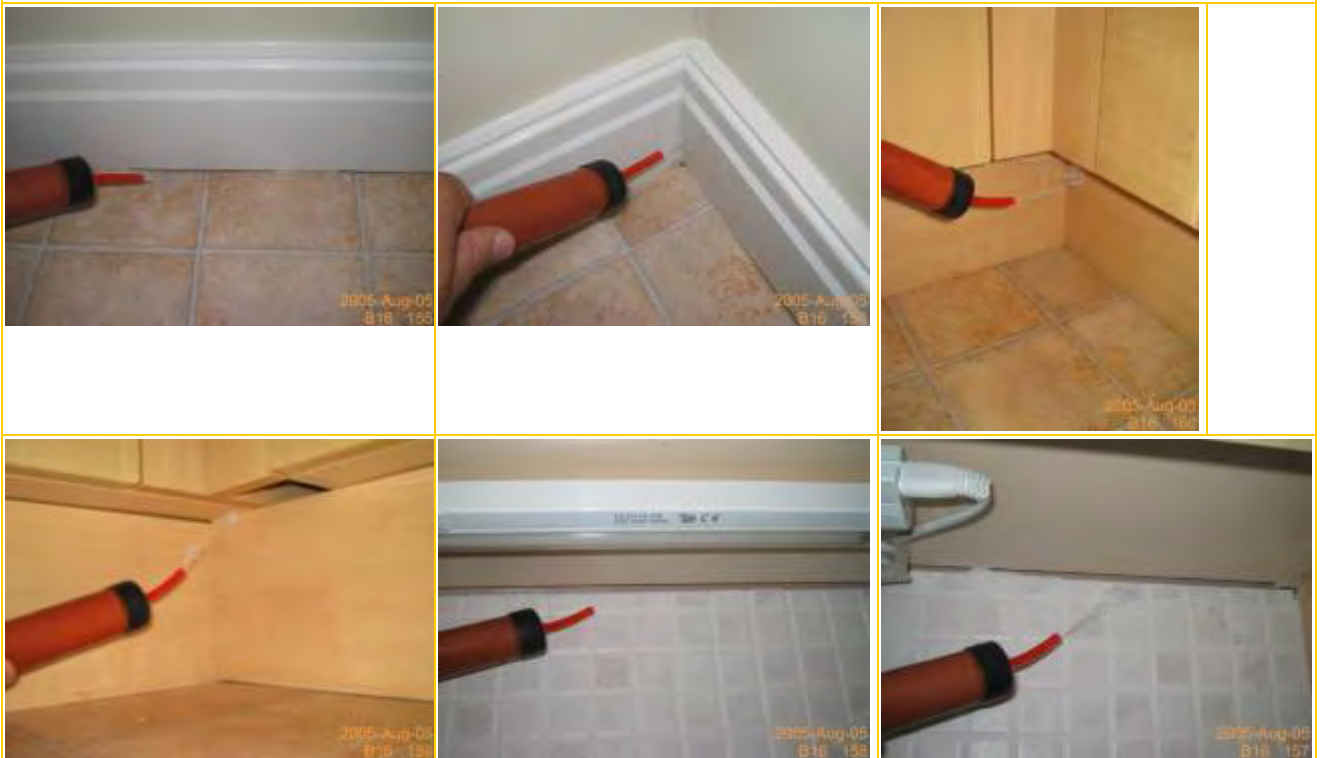
Dining room

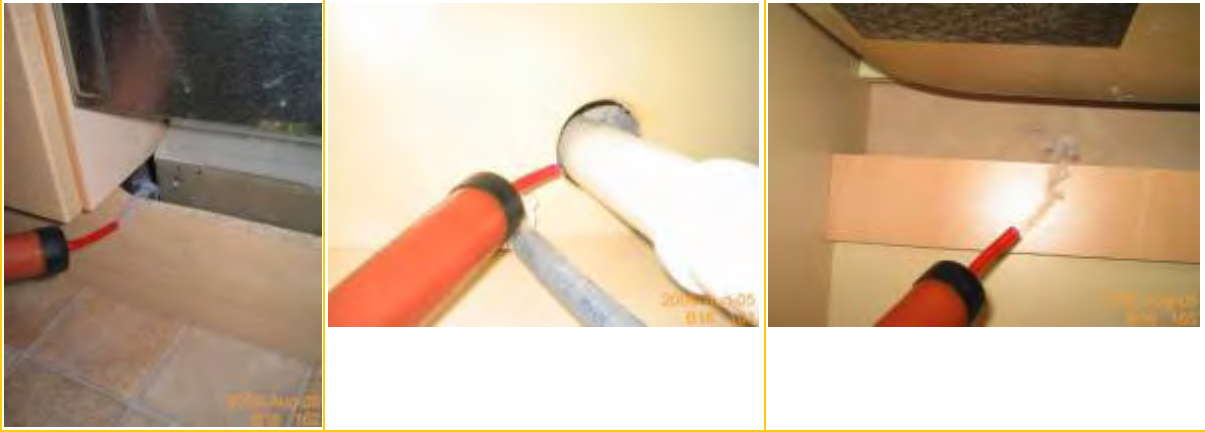
- Air leakage at the junction of ground floor/party wall/external wall.
- Leakage around the electrical socket on the party wall.



Kitchen

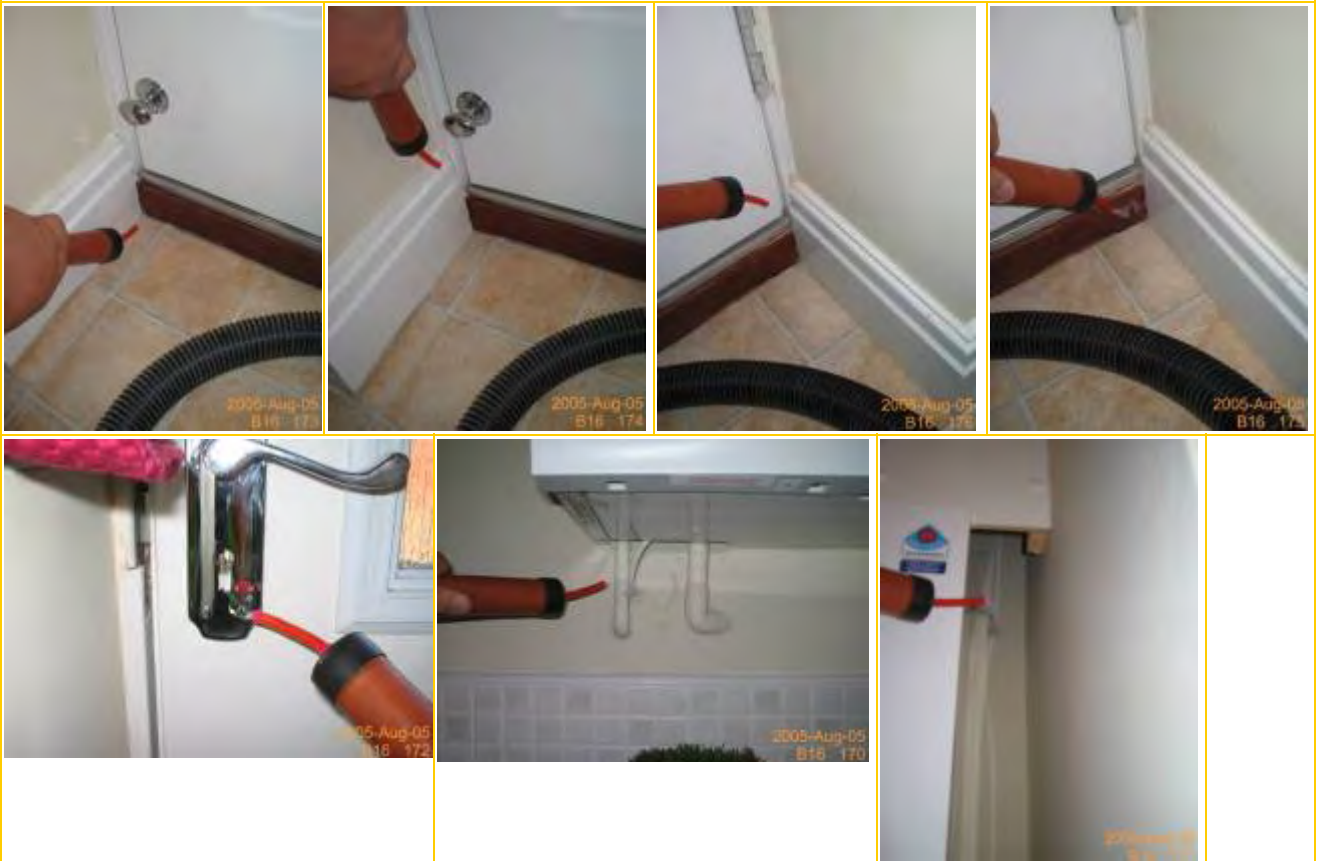
- Leakage along the ground floor/wall junctions, most severe in the corners.
- Significant air movement over the plinth into the void beneath the kitchen units through the gap observed under the corner unit.
- Air leakage into the space behind the wall units along the party wall.
- Significant air movement into the void beneath the kitchen units around the dishwasher.
- Inside the unit under the sink, significant leakage detected around the service penetrations and over the back of the unit.

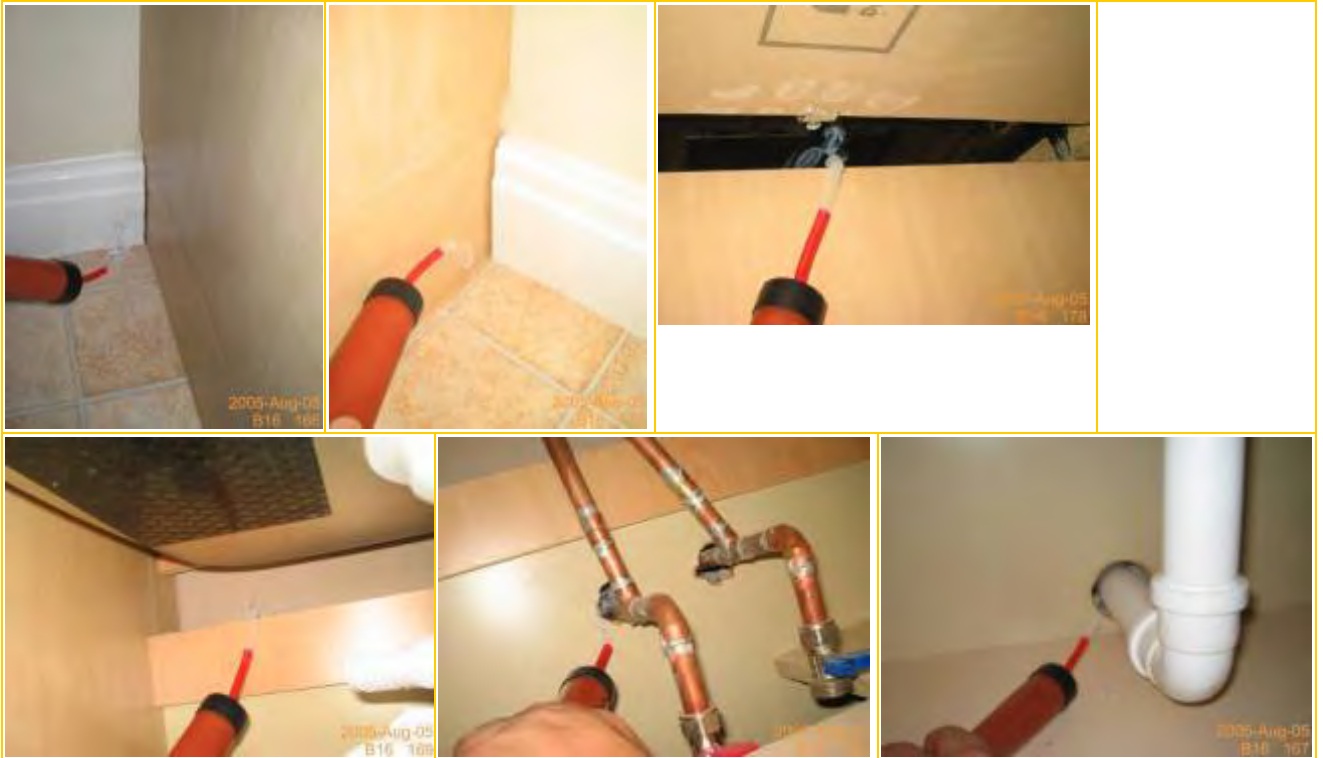




Utility room

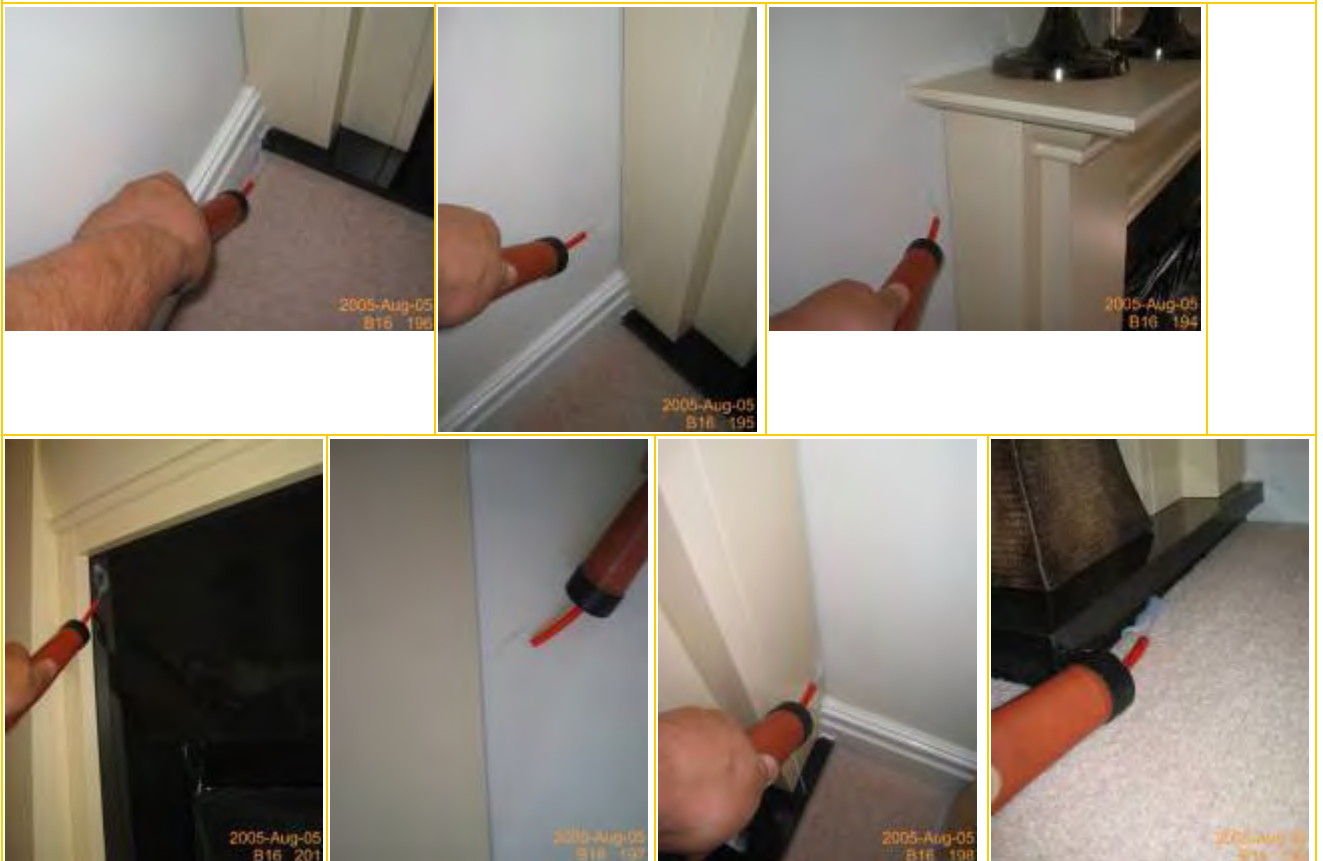
- Air movement around both sides of the threshold and bottom of the back door, and through the keyhole.
- Leakage detected around the boiler.
- As in the kitchen, air movement was observed around the base of the units, over the unit back under the sink and through service penetrations.





Lounge

- Air movement was detected all around the fireplace surround.



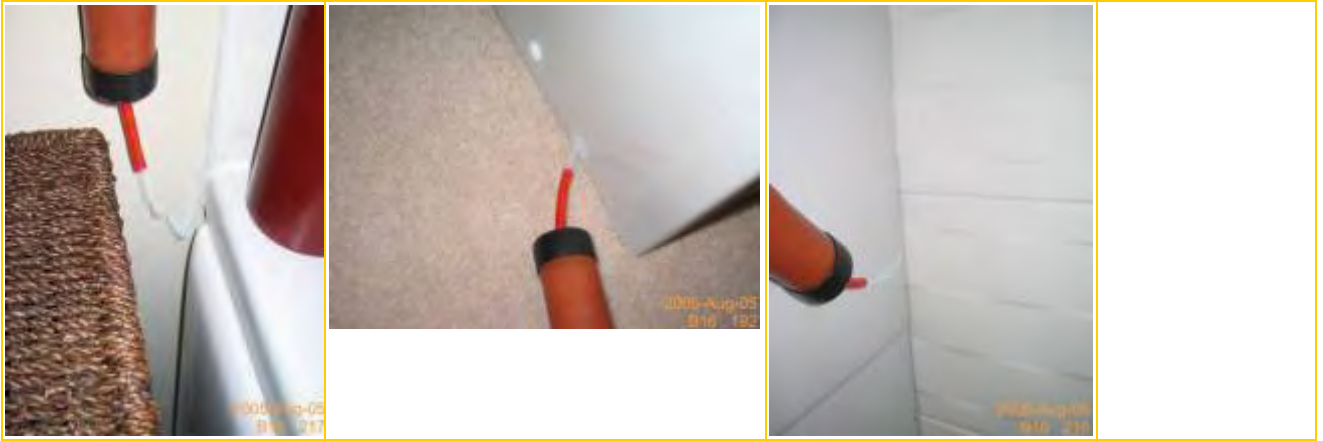
Bathrooms

- Air movement around extraction and trickle vents, and through poorly closing trickle vents.
- Significant leakage around soil pipes in both bathrooms.
- Leakage into both intermediate floors around the water supply pipe-work to wash basins, and into the external wall around both waste pipes.

- Leakage around all edges of the bath panels.

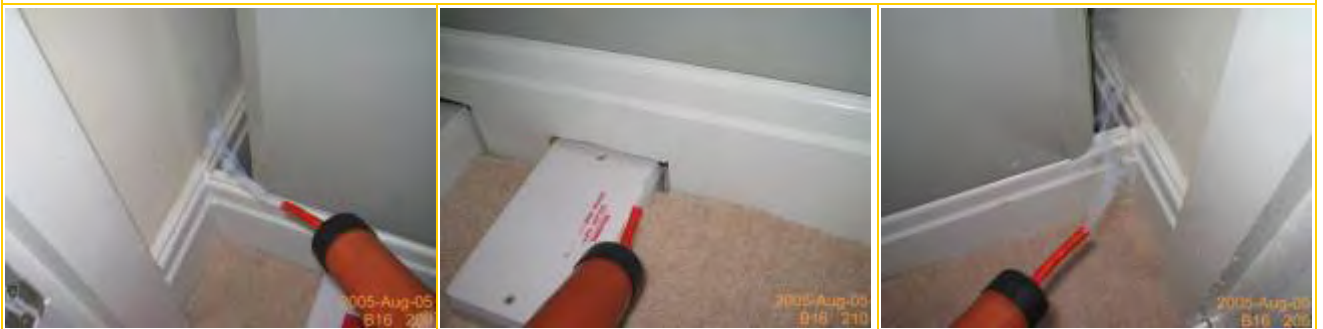


A16



CPSU cupboard

- Significant air movement around both sides of the water storage unit, and through gaps in the skirting board placed in front of it.



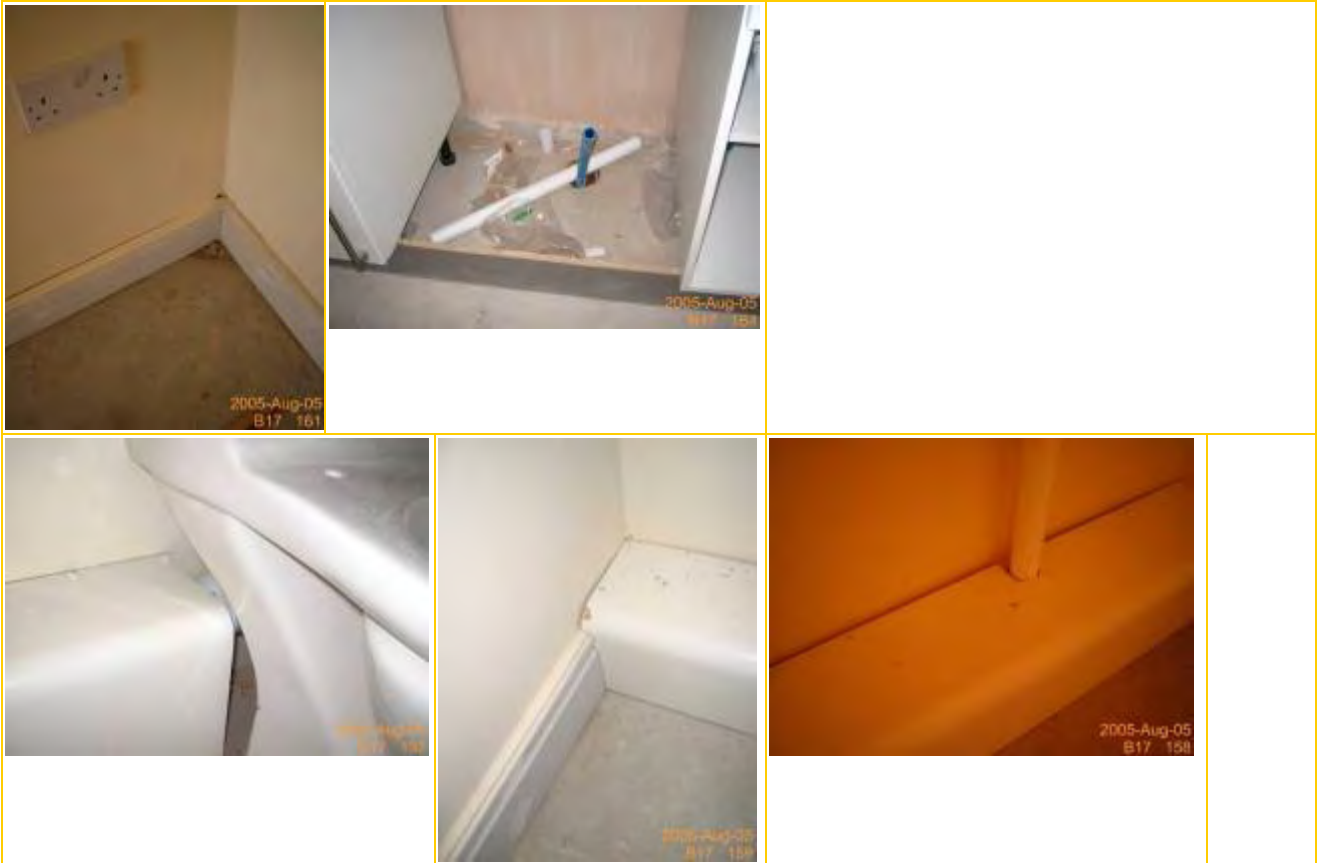
B17



Full-fill cavity masonry, 3-storey, 3-bed, semi-detached dwelling. Standard build – plus parging to all external walls prior to dot and dab plastering.

Ground floor

Gaps observed under the skirting, particularly at the corners of room. Where penetrations into the ground floor existed, these are hidden by units or boxing so may well remain unsealed and provide potential leakage paths – as observed in B16.



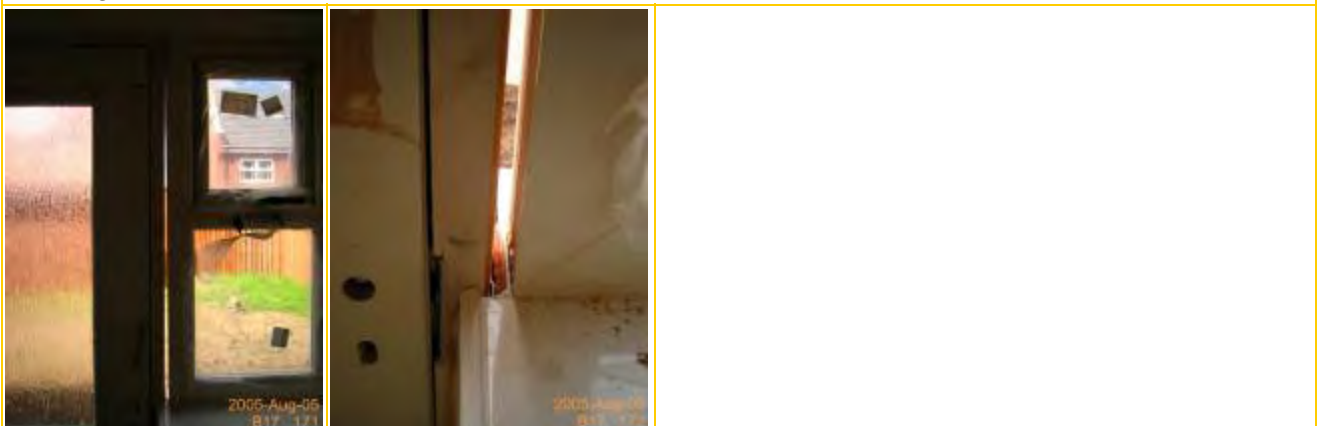
Thresholds

This was another area of air leakage in B16, and it would appear that this is likely to also provide potential leakage paths at both front and back door in this dwelling.



Back door/window frame

Although it is envisaged that this gap will be sealed where visible it is the part of this gap hidden below sill level that may remain, linking the void behind the plasterboard directly with the cavity and allowing unrestricted air movement between the two.

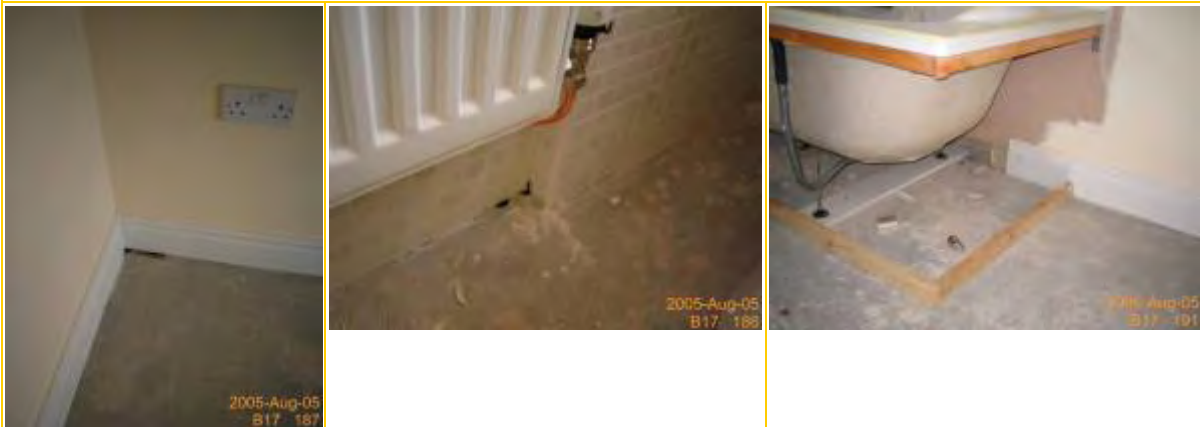


Intermediate floor

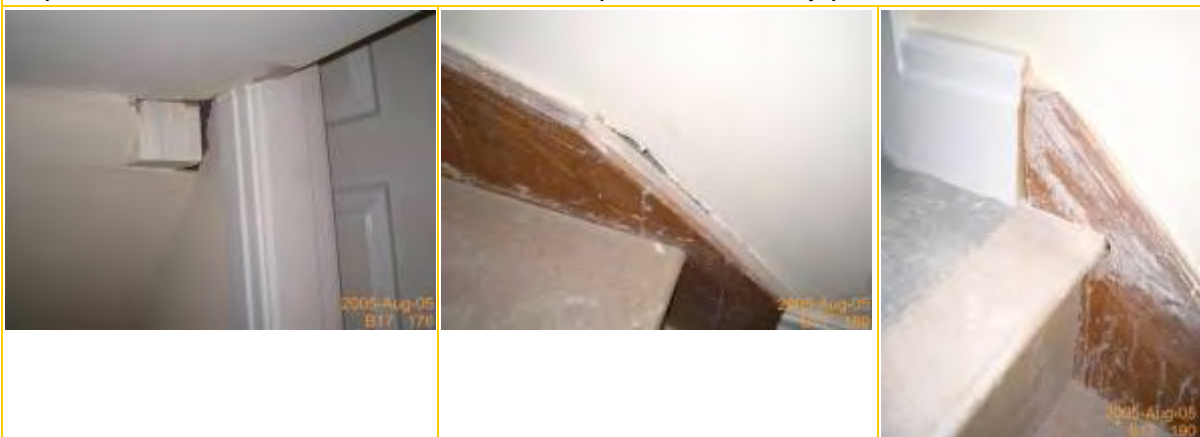
Slices have been made into both intermediate floors, presumably for access after the ceilings have been fitted. These may leave gaps allowing air to move into the floor void if not sealed.

**Intermediate floor/wall junction**

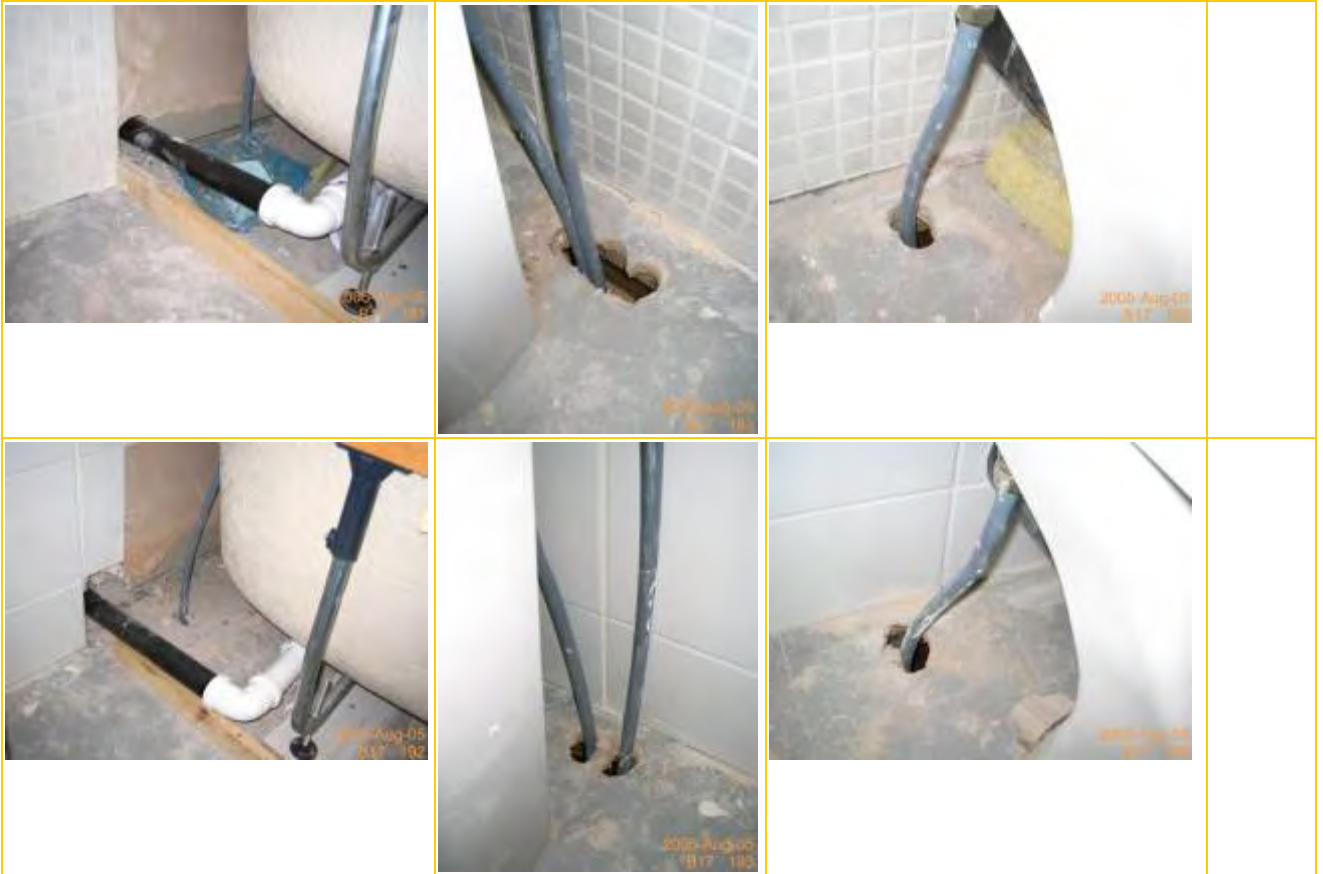
Some gaps were observed around the intermediate floor perimeter, enabling movement of air into the floor and wall voids. Behind the bath, where no skirting board is applied and the wall/floor junction is not finished-off, any air movement around the bath panel will be able to travel directly into these voids.

**Stairs**

Gaps observed around the base of the newel post and in many places around both sets of stairs.

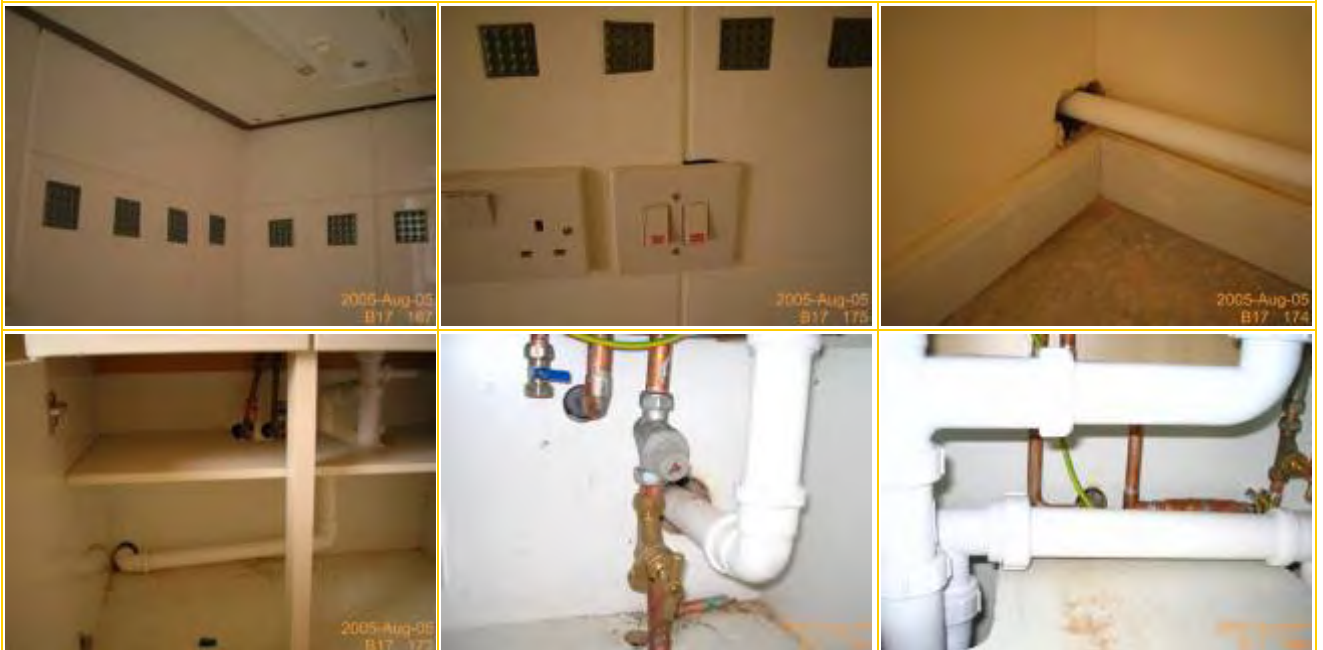
**Bathroom service penetrations**

Both bathrooms suffered from the same problems, with unsealed service penetrations through both external walls and intermediate floors, often with much larger holes than necessary made for pipes.



Kitchen/Utility room

Gaps observed similarly to where leakage occurred in B16 around units and service penetrations.



Other heating and plumbing penetrations

Potential leakage paths again exist at; radiator pattresses, where excessively large holes have been made in the intermediate floor beneath the water storage unit and where pipe-work runs from the CPSU directly into the ventilated loft-space.

A20



B21



Full-fill cavity masonry, 3-storey, 3-bed, semi-detached dwelling. Standard build to completion.

Ground floor

Without continuous ribbons of plasterboard adhesive, air may well be able to move directly into the void behind the plasterboard dry-lining from under the skirting board. The service penetrations through the ground floor situated extremely close to the walls may also cause both similar and added difficulties, as observations in previous plots have indicated.



Thresholds

Possible leakage paths at both front and rear thresholds, as previously noted.



Intermediate floor

As in previous plots, slits can be seen cut into the intermediate floors that provide potential leakage

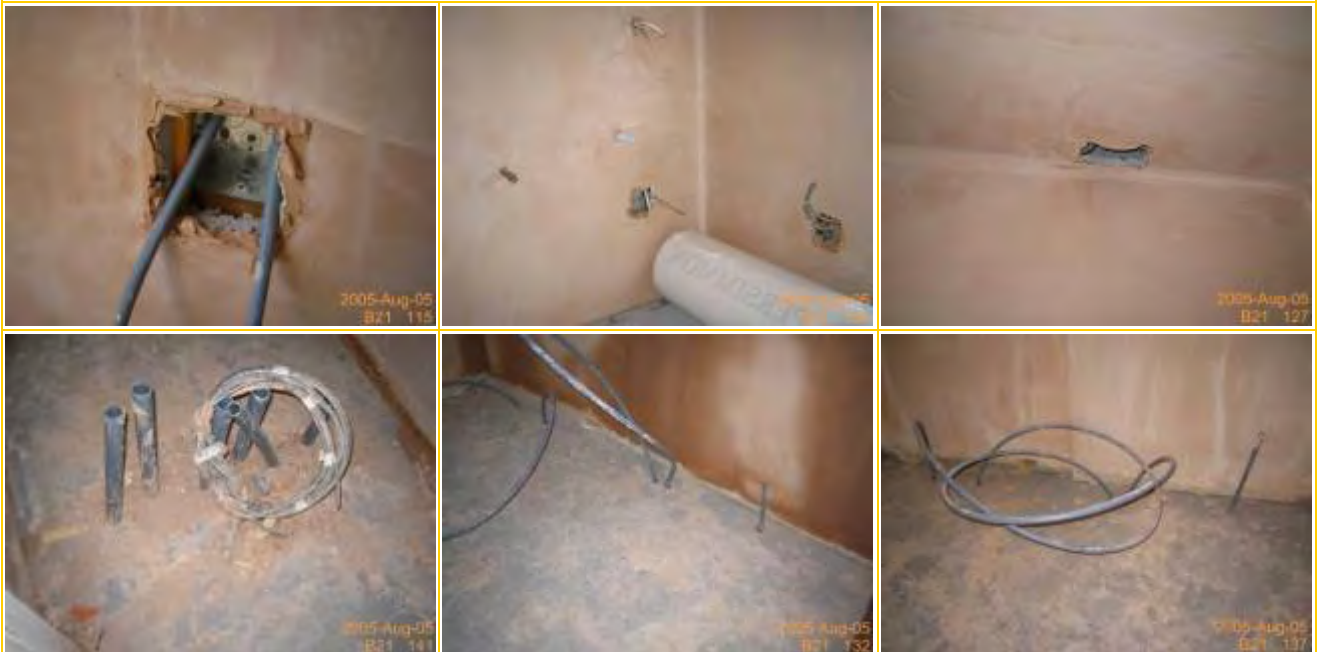
A21

paths. At the floor perimeter air leakage may also occur under the skirting into the wall and floor voids, which are linked due to dabs of plasterboard adhesive (rather than continuous ribbons) being applied.



Service penetrations

Potential for air leakage around the radiator pattress boxes exists as in previous plots. Penetrations for the boiler and electrical sockets/switches appear to have reduced gaps around them compared with previous dwellings, but it is around plumbing penetrations through the intermediate floor where this improvement is most noticeable, with little or no air-gap surrounding most of the pipe-work.



B22



Full-fill cavity masonry, 3-storey, 3-bed, semi-detached dwelling. Standard build plus parge party wall, light fitting cables through pattresses, switch boxes and heating cable boxes sealed at plaster stage, all pipes penetrating external walls to be sealed.

Thresholds

At both front and rear these have the potential to be far more airtight than in previous dwellings, with

the few small gaps around the closers generally effectively sealed with mastic at both jambs and thresholds.



Windows

Similar to the treatment of door jambs, heads and thresholds in this plot, the treatment around the windows shows a marked improvement for airtightness. No gaps were observed around the cavity closers at the sills or jambs. At the jamb/head junctions most previously observed gaps had been filled with expanding foam or mastic, with only very small amounts of non-airtight mineral fibre stuffing remaining visible.



Built-in joists

At party walls mastic sealant had been applied around all built-in joists increasing their airtightness, except those so close to the walls that access was seriously impeded. It is assumed this was done for acoustic purposes rather than for airtightness, as only occasional examples were observed of mastic sealant being applied around joists built into the external walls.



Loft/ceiling junction

Gaps around the perimeter of the plasterboard ceiling will allow air to move directly from the void behind the dry-lining on the walls directly into the ventilated loft-space; unless they are adequately

sealed or continuous ribbons of plasterboard adhesive are applied along this junction.



Service penetrations – external walls

At the penetrations through the external wall for both gas and electricity, the holes had been plugged using mortar and a mastic sealant applied. This should provide a far more airtight seal than the mineral wool alone which had been observed in previous plots.



Service penetrations – intermediate floor

A mastic sealant had been used to seal unnecessary holes made in the intermediate floor, and to seal around most of the plumbing penetrations. Where no mastic had been applied, the holes bored for the pipe-work were of a suitable size with little space around them.



Service penetrations – pattress boxes

Mastic sealant has been applied to all electrical pattresses where cables pass into them; however, many gaps remain around the junctions of these pattress boxes and the plasterboard dry-lining, allowing air movement into the dry-lining void if they are not sealed effectively.

A24



Airtightness of buildings – towards higher performance

Site C

Visit date: 16-Sep-2005

Observations:

C17

Masonry cavity, full-fill blown-fibre insulation, 2-storey, 2-bedroom, semi-detached dwelling.
Standard build to completion, parging layer to be applied to party wall only.

Ground floor

Potential for leakage into the floor void around penetrations. If mineral wool is used as a packing material to fill gaps it will reduce air flow, but will not make the penetration airtight.

**Patio door**

Possible leakage path at the threshold, particularly as the patio door frames are fitted in-line with the external brickwork rather than over the cavity. If the cavity is not sealed prior to dry-lining an air path from behind the reveal lining directly into the cavity remains. The blocked-in reveals may not be in accordance with Robust Details, but should provide a relatively airtight jamb/head junction.



Bay window

The bay wall provides a more complex detail which may provide potential leakage paths at the jamb/sill junction and at the angles of the bay where the perpend are not completely filled through the whole thickness of the wall.

**Built-in joists**

A mixture of good and bad examples. In some cases the joints around the joists have been completely filled with mortar which will assist in airtightness and the potential problem areas where joists are fitted closely parallel to walls have been well constructed. However, in some cases there are gaps around and between joists large enough to make the external brickwork visible, these may prove difficult to seal with mastic and could contribute to the leakiness of the dwelling.



C18



Masonry cavity, full-fill blown-fibre insulation, 2-storey, 2-bedroom, mid-terraced dwelling.
Standard build to completion, parging layer to be applied to party walls only.

Ground floor

As previously mentioned for ground floor penetrations and the patio door threshold. At the front door a propriety cavity closer has been fixed at the threshold, which should assist in reducing any air leakage at this detail.

**Openings**

At door, window and patio door heads only small gaps exist which should easily be sealed with a suitable sealant.

**Steelwork**

Gaps exist between the RSJs and between the joist and the steelwork, both of which may provide potential leakage paths if left unsealed.



Built-in joists

Again, some joists are fully mortared in whilst others have gaps around, these gaps may get filled in when the party walls are rendered. A more complex detail, and potentially serious problem, occurs above the ginnel; where there is uncertainty over what constitutes the primary air barrier. Here the intermediate floor void extends over the ginnel underneath the bathroom, the drawings suggest the top of this wall is sealed by pushing in the 200mm mineral wool quilt placed in the floor void above the ginnel, this is not regarded as a satisfactorily airtight seal and further consideration of this detail is suggested before further construction work restricts access.



C19



Masonry cavity, full-fill blown-fibre insulation, 2-storey, 2-bedroom, mid-terraced dwelling.
Standard build to completion plus parging layer to be applied to all external and party walls.

Ground floor

Potential problems as mentioned in previous plots.



Openings

Small gaps at the sills and jambs should get filled by the parging layer. At the jamb/head junction the gaps are small enough to be filled easily with a suitable sealant.



Blockwork

The application of the parging layer should seal gaps such as these, which otherwise would allow air to move directly between the void behind the plasterboard dry-lining and the cavity.



Steelwork

As with C18, there are concerns that air might be able to move from behind the plasterboard fixed on dabs up into the cavity between the RSJs if it is not effectively sealed.

A30



Built-in joists

As with C18, there are concerns where the intermediate floor extends over the ginnel.



C20



Masonry cavity, full-fill blown-fibre insulation, 2-storey, 2-bedroom, semi-detached dwelling.
Standard build to completion plus parking layer to be applied to all external and party walls.

Ground floor

As mentioned for previous plots.



Blockwork

As with C19, unfilled perpend and gaps in bedding layers should not be a problem as they will be filled when the walls are parged.



Built-in joists

Once again, some gaps have been effectively sealed (in the 1st example using a facing brick) and others not. Providing that the parging layer extends throughout the intermediate floor void, and right up to the joists, this should not cause a problem.



Airtightness of buildings – towards higher performance

Site D

Visit date: 05-May-2005

Observations and comments:

D73**Threshold & cylinder cupboard**

Continuing potential leakage paths at thresholds, particularly where cavity-fill may not extend fully into base of reveal, allowing a direct air path from the wall void into the cavity.

Roof of cylinder cupboard still a potential problem due to service penetrations and non-airtight seals at junctions.

**Integral garage**

The intermediate floor and wall voids of the main house are linked directly to the wall voids of the garage, allowing free movement of air between the two.

Unsealed holes in the structural steelwork allow air leakage directly from the intermediate floor void into the roof-space above the garage.

**D74****Ground floor**

Potential leakage paths where service penetrations are hidden (e.g. behind kitchen units) and where shrinkage of filling materials may occur.



Threshold & boxed-in pipe-work

As previously mentioned, at thresholds, concerns over the treatment of reveal bases and shrinkage of filling material.

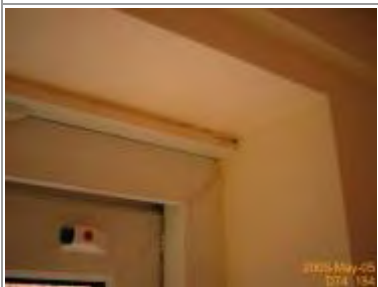
Unsealed ends of boxing-in of pipe-work allow unrestricted air leakage (via soil pipe stack).



Window heads

Apparently unresolved potential leakage path at the window heads, with small holes in the corners allowing direct passage of air from inside the building into the cavity.

These holes are only small, but do have a cumulative effect on the overall air leakage of the dwelling.



Boiler

Access to the boiler flue, to seal the air barrier around it, is becoming increasingly limited as construction progresses. Our initial concerns that this will only get sealed at the plasterboard and externally still apply, and there is a very distinct possibility that the substantial hole in the air barrier caused here will remain inadequately sealed at the insulation (air barrier) layer.

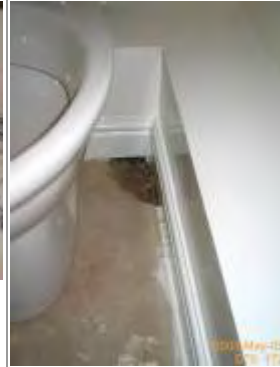


D75

Ground floor

Concerns in the kitchen with service penetrations through ground floor that are yet to

be sealed; also the junction between floor and wall presents an increased risk behind the units where it is more likely to remain unfinished/unsealed.
Service penetration in downstairs WC may provide path to unsealed area behind boxing-in of pipe-work.



Thresholds

Potential risks as mentioned for both previous plots. Concerns over air leakage at both front door and at rear patio doors, due to air movement around base of reveals and potential leakage paths through joints and cracks caused by shrinkage of the filler material.



Boiler

As mentioned with previous plot, sealing at the air barrier becomes increasingly difficult (and more likely to get omitted) as further work is carried out.



Pipe-work & cylinder cupboard

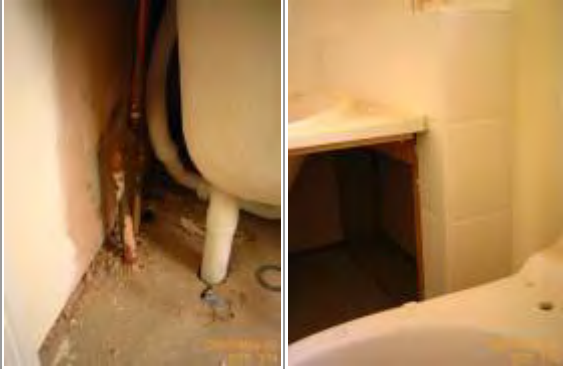
Gaps at the top of the boxing and in the cylinder cupboard roof; both providing potentially serious air leakage paths; via the soil pipe void and loft space, respectively.



Bath

Service penetrations through the intermediate floor are likely to remain unsealed as they will soon be hidden behind the bath panel; similarly the wall floor junction is also

likely to remain unfinished.



Shower

The problems noted for the bath are increased here as there is no facing on the partition walls beneath the shower tray. Air movement from underneath the tray, via the partition wall, to the loft space can be expected.



D76

Ground floor

Caulking of the ground floor junction with the external walls reduces the likelihood of air leakage under the steel frame, where shims have been used for levelling. Generally this was done very effectively, some minor points: an opportunity has been missed to seal between vertical gaps in plasterboard, some missed areas at the ground floor service penetrations and access to some junctions with internal walls was impeded due to the build sequence.



Threshold

As previously mentioned for all external doors



Insulation

Damage to insulation (and hence, air barrier) has been repaired successfully in most cases.

Problems still exist where the tape appears to be losing its adhesion, particularly at internal corners and where wall-tie channels are close to joints between insulation boards.



Service penetrations

Externally and internally, penetrations are still being created larger than necessary and rarely sealed by the trades creating them.

Areas illustrated here are penetrations which are more likely to remain unsealed (covered by the meter box and by kitchen units, respectively).



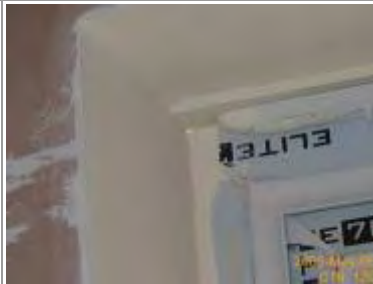
Windows – continuation of air barrier

Valiant attempts made to continue the air barrier between the insulation and the window frames using tape – to varying degrees of success.



Window heads

Small gaps are again common at the window heads.

**Pipe-work & cylinder cupboard**

As mentioned for previous plots.

**Bath & shower**

As mentioned for previous plots.

**Loft hatch**

Hinges are not fitted in the loft hatch where spaces are provided for them. Resulting in gaps at the end opposite the catch, and a lack of compression of the draught-stripping at that end.

Small gaps also exist around the loft hatch framing.

**D96****Ground floor**

Potential for air leakage exists around the ground floor service penetrations, particularly where these lie in close proximity to external walls and access to sealing around them is limited.



Insulation

Some damage caused to the insulation by scaffolding during the roof construction. Noticeable lack of care taken when puncturing the insulation for services.



Airtightness of buildings – towards higher performance

Site E

Visit date: 17-Aug-2005

Observations:

Phase 3 – Site Overview

4-Storey apartment block, 8 apartments per floor, mix of 1 and 2 bedroom apartments.
Masonry cavity, partial-fill insulation; concrete intermediate floors, solid party walls, wet plastered throughout.

**General Comments:**

On initial inspection there appear to be no obvious differences in quality of both materials and workmanship from those observed in Phase 1; the taping of insulation joints is maintained and blockwork is to an equally high quality throughout.

However, due to problems caused by moisture infiltration during the construction of Phase 1, plastering and fitting of internal fixtures of this block is not due to commence until the roof construction is complete and each section is made weather-tight.

EAG01

Ground floor, 2-bed apartment

Service Penetrations

Noted as a potential leakage path in Phase 1, penetrations here have been cut neatly, square and not excessively large, so they should prove easier to make airtight.



Wall/Floor Junctions

Possible slight gaps around the ground floor/wall junctions which should become airtight once the screed and plaster are applied. The intermediate floor/wall junction has been pointed up around the balcony supports, but nowhere else as yet. This junction is more likely to be a source of air leakage unless it is sealed before the suspended ceiling is fitted.



Balcony Door

Gaps exist between the cavity closer and lintel at the jamb/head junction, which may allow air to escape into the cavity if not sealed. Perforations in the lintel itself may also allow infiltration if not sealed (or sealed around). At the jambs, any gaps around the closers should be sealed when plastering except for the small gap at the threshold where the plaster may not be applied right down to the floor. At the thresholds, air was observed escaping into the cavity in Phase 1, this may again be the case here if the frame/floor junction is not effectively sealed.



Windows

Potential problems at heads, jambs and sills as described above.



EAG02



Ground floor, 1-bedroom apartment.

Service Penetrations

Larger than necessary holes for service penetrations requiring more effort to seal to an airtight standard at a later date, so increasing the likelihood of air paths remaining on completion. Mineral wool packing required around penetrations through intermediate floors (at min. 10 Kg/m³ as specified in the design drawings) for acoustics purposes will not make it airtight, and air may still move between storeys and into the holes running through the concrete planks.



Wall/Floor Junction

Again, concerns over the intermediate floor/wall junctions, which will be hidden by the suspended ceiling. Any air coming through the ceiling (e.g. through recessed light fixings and through partition

walls) will rely on this junction being sealed to maintain the airtightness of the apartment.



Wall/Wall Junction

It is expected that these junctions will get pointed up and then made airtight by plastering. The slight concern is the treatment at the very tops and bottoms of these junctions which will not be plastered over, and are hidden by the suspended ceiling and by skirting boards respectively.



Balcony Door

As discussed for EAG01.



Window

As discussed for EAG01.



EA201



2nd floor, 2-bedroom apartment

Service Penetrations

As with EAG01, the holes made for service penetrations are suitably small and should result in more effective sealing around than when larger holes are made. Again, packing/plugging with a minimum density 10 Kg/m³ mineral wool will reduce the air flow through these penetrations but will not make them airtight.



Balcony Door

Possible leakage paths around the brackets and through the blockwork should get sealed when the floor is screeded.



EA202



2nd floor, 1-bedroom apartment

Service Penetration

As observed for previous plots.



Balcony Door

As observed for previous plots.



Appendix 9

Airtightness of buildings — towards higher performance Milestone Number: D9 (Revised)

Discussion Paper 1 — Performance and Implementation

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This paper discusses the results obtained on this project, identifying the levels of air permeability currently being achieved within new UK dwellings meeting the requirements of Approved Document Part L1 (2001) and investigating practical ways of achieving the higher levels of airtightness performance described in Approved Document L1A (2006). The paper addresses those issues relating to airtightness in the domestic sector.
- 2 Following a preliminary literature review, Phase 1 of this project considered the design and construction of a selection of UK domestic dwellings through drawing assessments, extensive site surveys and dwelling pressurisation tests and leakage detection. Of the 25 dwellings observed in Phase 1, only eight achieved a mean air permeability of below the ADL1 recommended limit of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, six of these being apartments. Phase 2 involved presenting these results to each developer by way of individual feedback sessions, where general information on airtightness of dwellings and site-specific guidance was presented and possible methods of increasing the airtight performance of the developers' properties was discussed. Phase 3 repeated the procedure adopted in Phase 1, but with the Leeds Met research team establishing a two-way dialogue with the developers throughout the construction of the Phase 3 dwellings, offering further guidance and on-site quality control. Whereas site surveys conducted in Phase 1 were purely observational, in Phase 3 observations were reported back to the developers immediately allowing on-site alterations and remedial action (where necessary) to take place before construction progressed much further.
- 3 The project results highlight a number of issues that require consideration when constructing dwellings to meet any particular airtightness target.
 - a) Certain construction types are intrinsically more airtight than others. The results from the project overall suggest that wet plastering and quasi-wet plastering (parging) of masonry cavity construction can default to a reasonable level of airtightness by UK standards. Other construction types, such as dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to achieve an air permeability below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. The construction type that presented the greatest difficulty was light steel frame. Air permeability values of below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ are possible with this type of construction, but are likely to require considerable additional attention to detail on site and changes to the design to ensure that continuity of the primary air barrier is maintained. In fact it is difficult to see how it would be possible to achieve an air permeability consistently less than $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ without a fundamental rethink of airtightness design in this form of construction.
 - b) Complexity can have a significant effect on airtightness. Results illustrate that significant variations in air permeability can be observed in dwellings of the same form, constructed by the same site team, where the only observed difference was the number of complex details associated with these dwellings. These disparities were most common where certain design features required the primary air barrier to cope with complex changes in plane, negotiate structural members and accommodate changes in material. Such details included ground floor projections, rooms adjacent to semi-exposed areas, timber bays in masonry construction and complex junctions with ventilated cold roof loft-spaces.
 - c) The approach adopted to increase airtightness can influence the potential level of air permeability achievable. The lowest levels of air permeability were achieved where attention was given to design modifications in which the primary air barrier was designed and made explicit as well as ensuring that the design was executed successfully on site.
 - d) The level and consistency of feedback and guidance is important. Results suggest that providing general feedback and guidance on airtightness may have little effect on the air permeability of dwellings constructed. Feedback and guidance should therefore be continuous and targeted. However, providing this sort of feedback and guidance on a site by site, or even dwelling by dwelling basis can be onerous and labour intensive. Although during any learning phase the need for such intensive feedback will be inevitable, in the long term, ensuring that airtight design is built into the routine quality control culture of design and site teams (including an element of testing) will be critical.
 - e) The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on secondary sealing measures (such as many of those implied in the current edition of Part L

Robust Details — DEFRA, 2001) are likely to be much less robust than those approaches that concentrate on ensuring that there is an effective and continuous primary air barrier. Approaches that are easy to build and are most amenable to simple and effective quality procedures are also likely to be more robust.

- f) Anecdotal observations of non-test dwellings on the sites involved would suggest that on-site knowledge and experience gained through feedback with respect to the test dwellings does not always appear to be utilised more generally. Although the team were not able to carry out any random tests on non-test dwellings visual inspections suggest that it is unlikely that the other dwellings on-site will achieve around the same levels of airtightness as the dwellings featured in this project. The results also suggest that achieving consistent levels of airtightness in dwellings of the same size, construction type and form may be difficult within existing design and construction cultures.
- 4 The results obtained from Phase 1 of this project suggest that the impact of the 2002 edition of Approved Document Part L1 on airtightness has not been as successful as anticipated. The failure of the majority of the dry-lined masonry cavity and steel framed dwellings in Phase 1 to achieve the ADL1 2002 airtightness target also suggests that the adoption of Robust Construction Details, at least in the current form, provides no guarantee that the current regulatory standard is achieved with any degree of consistency. The results from Phase 3 of the project suggest that an air permeability of less than $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ is achievable within mass-produced housing in the UK using existing techniques, materials and practices, and without incurring significant cost. However ensuring consistency and robustness is likely to present the greatest challenge. To reliably reduce the air permeability to much lower levels ($5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ and below) will require more significant changes to the design and the approach to construction.

Introduction

- 5 This paper constitutes milestone D9 (Performance and Implementation of the Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). The purpose of this paper is to discuss the results obtained to date on this project with a view to identifying the levels of air permeability that could be achieved within new UK dwellings within the context of existing mainstream practice and readily available techniques. It is anticipated that this discussion paper will form one of the inputs into the Forward Thinking Paper on energy conservation which is due to be updated in 2006. It is also intended that the findings of this work will be used to inform future revisions to Part L of the Building Regulations.

Airtightness and Building Regulations: ADL1 2002 and ADL1A 2006

- 6 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 $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. for both domestic and non-domestic buildings. In April 2002, the amended editions of the Approved Document came into effect; Part L1 for dwellings (DTLR, 2001a) and Part L2 for buildings other than dwellings (DTLR, 2001b). These amendments were 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 currently taking place (see DTI, 2003). The 2002 amended edition of the Approved Document L1 (ADL1) required that reasonable provision should be made to reduce unwanted air leakage, and suggested that this can be achieved by adopting the guidance given in the report on Robust Construction Details (see DEFRA, 2001), or by pressure testing.²⁸ The consultation document that was published in July 2004 for the 2005 review of Part L required the inclusion of airtightness as part of the calculation of the total carbon emission rate for a particular dwelling design (ODPM, 2004).
- 7 The final version of the approved document, *L1A Work in New Dwellings*, was published in April 2006 and defines three specific concepts:
- a) TER — Target CO2 Emission Rate: the minimum energy performance requirement as defined using the SAP200529 calculation tool and expressed in kg of CO2 per m2 of floor area per year. The target is defined in terms of a 20% reduction in carbon emissions from space and water heating and lighting compared to a notional gas heated dwelling built in accordance with the guidance given in ADL1 2002.
 - b) DAP — Design Air Permeability is included in the SAP2005 calculation tool. The expected overall limit to permeability is $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ but designers are free to specify a lower value in order to achieve the required TER. However, a verification and testing regime is incorporated in the regulations to ensure that actual construction is commensurate with the values required to ensure that the regulatory requirement is achieved. This means that designers and developers need to be able to specify air permeability levels with a high degree of confidence that they can be achieved in practice.
 - c) DER — Dwelling CO2 Emission Rate, as determined by the SAP30 software, must be equal to or better than the TER.
- 8 For buildings containing multiple dwellings, both the TER and DER for individual dwellings can be calculated using floor area weighted averages based on the whole building TER and DER; with each block of flats being regarded as a separate development, regardless of the number of blocks on the site.
- 9 Compliance with regulation will usually be achieved either by using accredited construction details and satisfying the above requirements, or by a more rigorous pre-completion testing regime, as

²⁸The method for pressure testing of dwellings is currently outlined in CIBSE technical memorandum TM23 (CIBSE, 2000). The recommended good practice air permeability for naturally ventilated dwellings is therein given as $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, and $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ for dwellings with balanced whole house mechanical ventilation.

²⁹ SAP2005 to be used for individual dwellings of 450 m^2 total floor area or less; larger individual dwellings will be calculated using the Simplified Building Energy Model (SBEM).

³⁰ For dwellings over 450 m^2 SAP is not appropriate and in such cases the Simplified Building Model or other approved calculation tool must be used.

described in L1A, Section 2: Criterion 4. Whichever approach is adopted by the developer, it is therefore expected that all dwellings will have to achieve a maximum value of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ irrespective of the TER and DER realized.³¹ However, in order to achieve an acceptable TER/DER, the airtightness specification of many dwelling designs (particularly where fuels with a higher carbon intensity than gas are to be used) may have to be much lower than this and $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ or less may become a common design requirement.

- 10 When using accredited construction details as a method of compliance, one example of each dwelling type will require pressure testing. Dwelling type is defined in L1A (2006) as a dwelling of the same generic form; e.g. detached, semi-detached, end-terrace, mid-terrace, ground-floor flat, mid-floor flat, top-floor flat, with no further reference to building form. However, they may vary in complexity. When compliance is sought without using accredited construction details, on each development a minimum of either two units or 5% of each dwelling type will require testing, whichever is the greater. This number may be reduced if the first five dwellings tested all perform within their respective DAPs. For developments of one or two dwellings, the developer has the option to adopt a DER based upon an air permeability of $15 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ and dispense with any obligation for a pressure test to be performed, this would have to be off-set against substantial improvements in energy efficiency elsewhere in the dwelling(s). Compliance through a third-party accreditation scheme is provided for, subject to approval by the Secretary of State.
- 11 L1A (2006) also introduces new guidelines over who should perform the obligatory pressure testing of dwellings and the procedures to be followed. ADL1A 2006 states that local authorities are authorised to accept as evidence a certificate from a person who is registered by the British Institute of Non-Destructive Testing (BINDT) in respect of pressure testing for the airtightness of buildings. In addition, tests are to be performed using the procedure approved by the Secretary of State for air pressure testing, which is set out in the Airtightness Testing and Measurement Association (ATTMA) publication *Technical Standard 1* (TS1) ATTMA's TS1 is based on techniques and methodologies outlined in CIBSE Technical Memorandum TM23 (CIBSE, 2000) and BS EN Standard 13829:2001 (British Standards Institute, 2001).

Airtightness of New UK Housing

- 12 There is a commonly held perception that new dwellings in the UK are built to a high standard of airtightness (Olivier, 1999). This is not generally found to be the case. Cohort data contained within the Building Research Establishment's (BRE's) air leakage database³² suggest that dwellings built between 1980 and 1994 are, on average, as airtight as those built at the beginning of the twentieth century (see Figure 1). 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.

³¹ An adjustment period of up to 31 October 2007 is included to allow for dwellings failing to achieve the target figure to temporarily be subject to less stringent re-test targets.

³² The BRE's database of air leakage is the largest and most comprehensive source of information on the airtightness of UK dwellings (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. However, despite its size, this database is not the result of random sampling and cannot claim to be unequivocally representative of the UK housing stock.

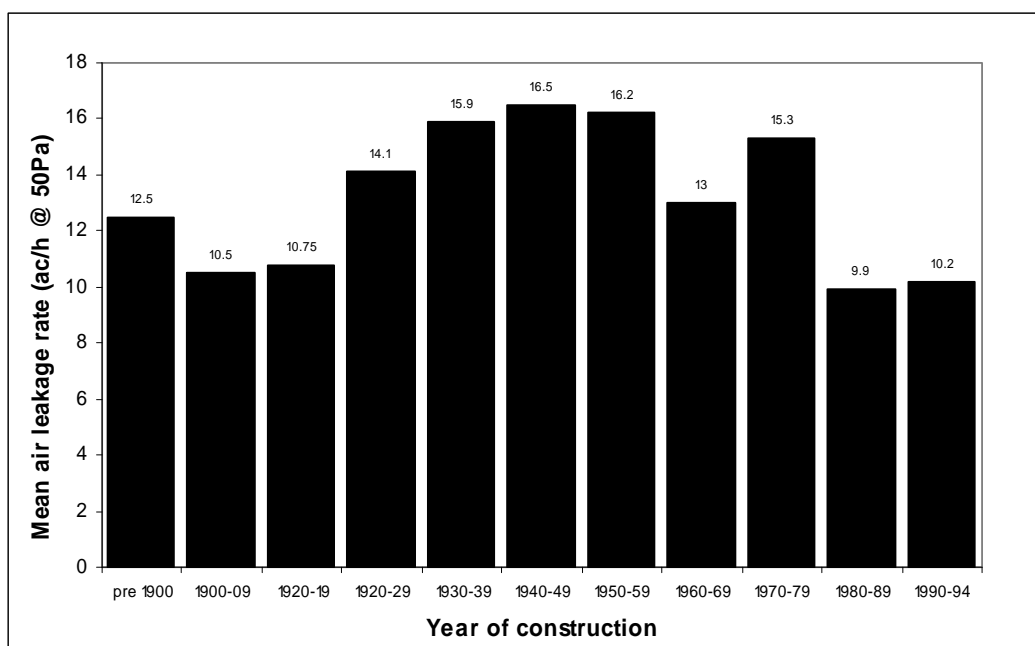


Figure 1 Relationship between dwelling age and air leakage. After Stephen (2000).

- 13 Air leakage data on dwellings built from 1995 onwards remain somewhat limited. 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 m³/(h.m²) @ 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 m³/(h.m²) @ 50Pa as opposed to 11.5 m³/(h.m²) @ 50Pa). This difference is very small and given the non-random nature and size of the sample cannot be considered to be even remotely significant. This suggests that there has been no real improvement in the airtightness of dwellings built post 1995.
- 14 A limited amount of air leakage data is available on dwellings that have been built to conform to the requirements set out in the 2002 edition of the Approved Document Part L1 (DTLR, 2001). Early work undertaken by the BRE for the Office of the Deputy Prime Minister (ODPM) on a small number of dwellings built to Part L1 2002 indicated that about two-thirds of the dwellings failed to achieve an air permeability of 10 m³/(h.m²) @ 50Pa (cited in Grigg, 2004). In 2004, the BRE undertook airtightness measurements on a much larger non-random sample of 99 dwellings that had been built to Part L1 2002 (see Grigg, 2004). The sample included a range of dwelling types,³³ of both masonry and framed construction, which were located in various geographical locations and were from both the private and social housing sectors. The results showed that a relatively wide range of airtightness was observed within the sample (see Figure 2). The air permeability of the dwellings ranged from 3.2 to 16.9 m³/(h.m²) @ 50Pa, with a mean of 9.2 m³/(h.m²) @ 50Pa and a standard deviation of 2.8 m³/(h.m²). In addition, approximately two-thirds of the sample (68%) achieved an air permeability that was lower than or equal to the maximum specified level of 10 m³/(h.m²) @ 50Pa set in the 2002 edition of the Approved Document L1 (DTLR, 2001a). These results contrast with the earlier much smaller BRE sample where two-thirds of the sample failed to achieve an air permeability of 10 m³/(h.m²) @ 50Pa.
- 15 The results for the apartments and the other dwelling types in the BRE sample were also analysed separately (see Figures 3 and 4) as apartments had been under-represented in the earlier study and may have skewed the results.³⁴ The analysis indicated that the air permeability of the apartments ranged from 3.2 m³/(h.m²) @ 50Pa to 12.4 m³/(h.m²) @ 50Pa, with a mean of 8.0 m³/(h.m²) @ 50Pa. This compared with the other dwelling forms which achieved an air permeability

³³ The sample comprised 36 apartments, 21 mid-terrace houses, 10 end terrace houses, 19 semi-detached houses, 10 detached houses, 2 semi-detached bungalows and 1 detached bungalow.

³⁴ The reason for this is that apartments tend to be more airtight than other dwelling forms of equivalent area, as they are more likely to have solid intermediate floors, fewer external door and window openings and fewer service penetrations.

of between $5.6 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ and $16.7 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, with a mean of $9.8 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. The results also showed that 83% of the apartments achieved $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ or better compared with 57% of the other dwelling forms. The results of this analysis suggest that the high rate of compliance for the tested dwellings (68%) is likely to be due, in part, to the number of apartments in the sample. However, the overall rate of compliance in new dwellings may be slightly higher than that indicated by Grigg since the proportion of flats within the annual new-build total is some 5% higher than the 36% in the Grigg sample.³⁵

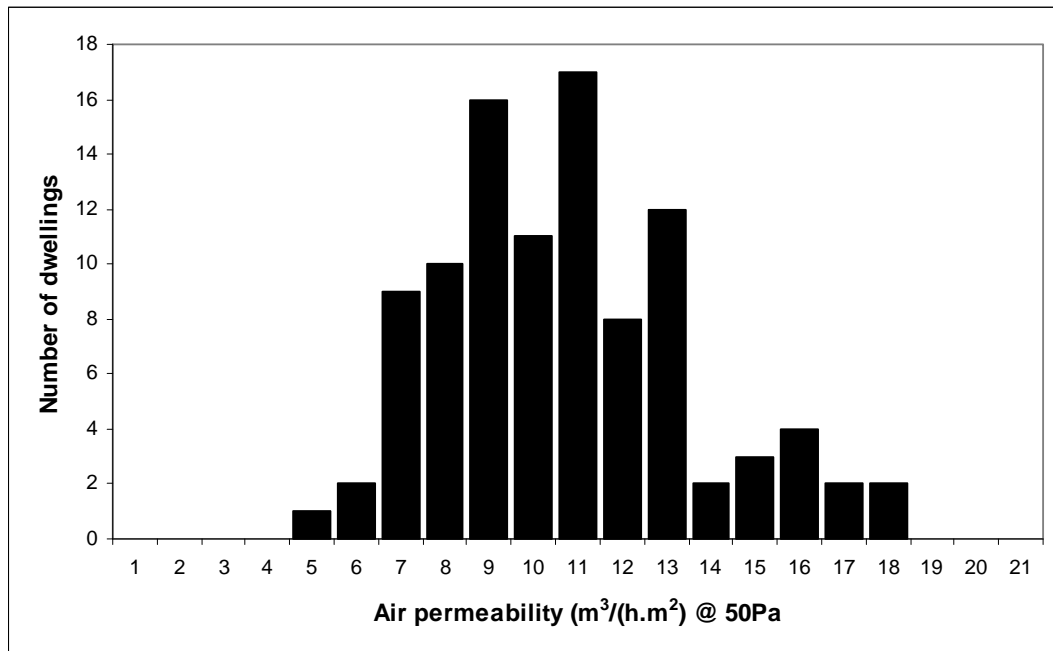


Figure 2 Mean air permeability of dwellings built to Part L1 2002. After Grigg (2004).

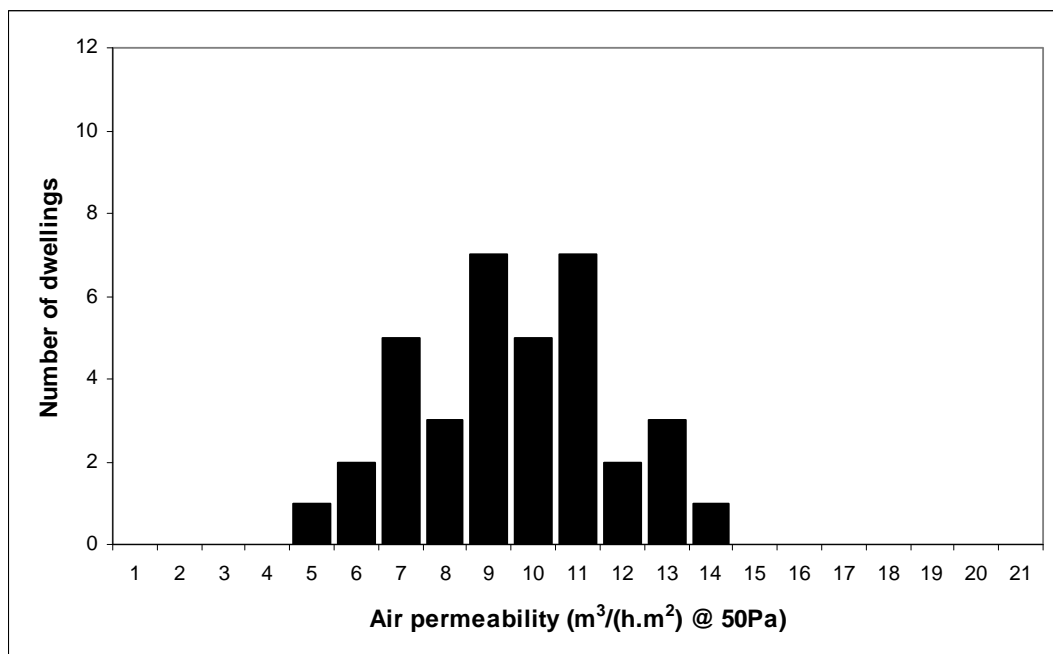


Figure 3 Mean air permeability of flats built to Part L1 2002. After Grigg (2004).

³⁵ Recent housebuilding statistics from Communities and Local Government indicate that flats represented 41% of all new dwellings completed in England in the financial year 2004/5.

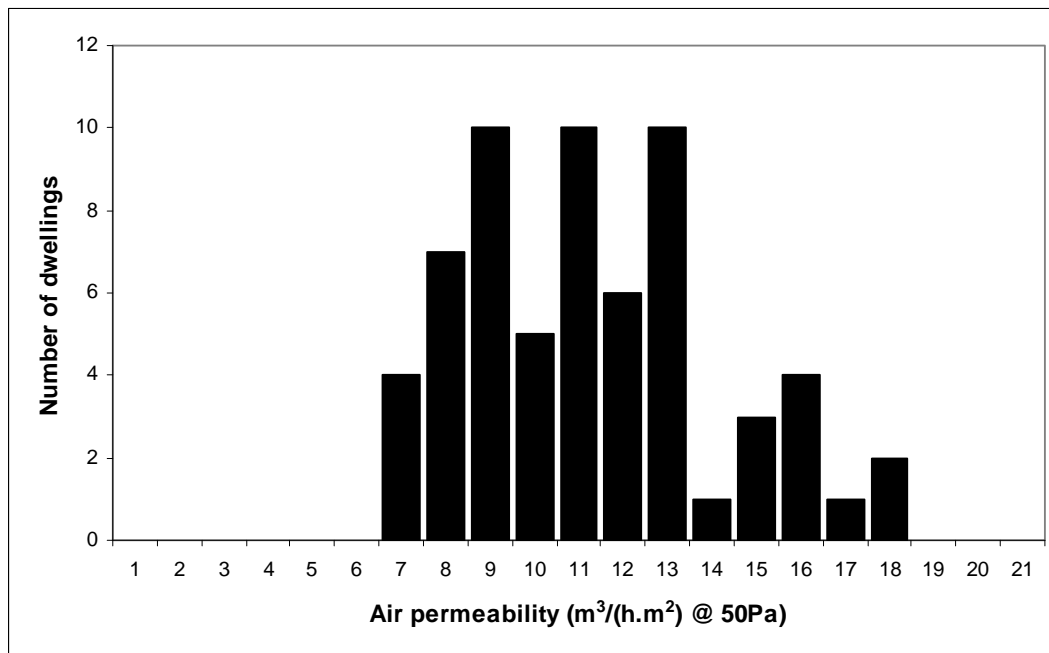


Figure 4 Mean air permeability of other dwelling types built to Part L1 2002. After Grigg (2004).

Project Summary

- 16 The overall aim of this project is to investigate practical ways of achieving higher levels of airtightness performance than the current requirements of Approved Document Part L1 and L2. This report addresses those issues relating to the domestic sector. Work is being undertaken in parallel on the airtightness of buildings in the non-domestic sector.
- 17 The project was undertaken in two parts:
- a) Literature review — A conventional literature review was undertaken, 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 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.
 - b) Participatory action research — This part of the project was undertaken in three distinct phases and involved five developers from the commercial and social housing sectors.
 - Phase 1 — In this phase the design and construction of 25 dwellings, selected from five developments (five dwellings per developer) were monitored in detail.³⁶ This was done based on detailed reviews of design drawings, and extensive site survey work carried out as dwellings were constructed. Upon completion each dwelling was pressure tested and the main air leakage paths were investigated using smoke tests.³⁷ The objective of this phase was to establish those factors of design and construction that are likely to influence the eventual airtightness of the dwellings.
 - Phase 2 — The results from Phase 1 were fed back in a participatory seminar (one per developer) and ways of improving airtightness were discussed with the developer and their design and construction teams. The developer was encouraged to set an airtightness standard (commensurate with existing ventilation strategies) for the design and construction of a further set of dwellings that would be assessed and tested in Phase 3.

³⁶ As one dwelling (B85) was handed over to the customer prior to completion, an additional dwelling from developer E was included in the project to maintain the total number of dwellings at 25.

³⁷ Smoke tests were performed from inside the dwelling using hand held smoke puffers, with the dwellings pressurised to 75–80Pa. The direction and rate at which smoke flowed into the building structure provided indications of internal points of air leakage and their comparative significance; however, this method alone cannot identify or quantify many of the more complex air leakage paths.

- Phase 3 — This phase mirrors Phase 1 in which the design and construction of a further set of dwellings (five from developers A, B, C and D, and six from developer E) were monitored following the feedback and enhanced understanding gained during Phase 2. Two further dwellings were subsequently included for developer C to include an additional dwelling type. Upon completion and testing, a feedback seminar will be held to review the design and construction experience from the developer's point of view.

18 Details of the dwellings that were selected to participate in Phases 1 and 3 of the action research project are contained within Tables 1 and 2.

Developer	Type of construction	Dwelling	Built form	Internal floor area (m ²)
A	Dry-lined masonry cavity, partial fill.	A09	Mid-terrace	83
		A11	Mid-terrace	117
		A12	End terrace	117
		A13	Detached	117
		A14	Semi-detached	80
B	Dry-lined masonry cavity, full fill.	B79	Detached	129
		B80	Detached	164
		B81	Detached	149
		B82	Detached	149
C	Dry-lined masonry cavity, full fill.	C236	Mid-terrace	72
		C237	Mid-terrace	71
		C238	End terrace	61
		C239	Semi-detached	69
		C240	Semi-detached	68
D	Light steel frame.	D39	Semi-detached	72
		D42	Detached	91
		D43	Detached	84
		D44	Detached	91
		D59	Detached	102
E	Mechanically/ manually wet plastered ³⁸ masonry cavity, partial fill.	ECG01	Ground-floor apartment	57
		ECG02	Ground-floor apartment	43
		EC201	Mid-floor apartment	58
		EC202	Mid-floor apartment	44
		EC301	Top-floor apartment	59
		EC302	Top-floor apartment	44

Table 1 Size, built form and construction type of the dwellings selected for Phase 1.

Developer	Type of construction	Dwelling	Built form	Internal floor area (m ²)
A	Dry-lined masonry cavity, partial fill.	A64	Mid-terrace	113
		A65	Mid-terrace	113
		A66	End terrace	117
		A79	Mid-terrace	117
		A80	End terrace	117

³⁸ All of the plots were originally intended to be mechanically plastered. However, due to delays in the construction and the drying out times associated with the mechanical plastering system that was being applied, Plots C301 and C302 were manually wet-plastered.

B	Dry-lined masonry cavity, full fill.	B14	Detached	164
		B16	Semi-detached	132
		B17	Semi-detached	132
		B21	Semi-detached	132
		B22	Semi-detached	132
C	Dry-lined masonry cavity, full fill.	C17	End terrace	61
		C18	Mid-terrace	72
		C19	Mid-terrace	71
		C20	End terrace	61
		C21	End terrace	61
		C193	Detached	106
		C194	Detached	106
D	Light steel frame.	D73	Detached	119
		D74	Detached	94
		D75	Detached	118
		D76	Detached	125
		D96	Detached	100
E	Wet plastered masonry cavity, partial fill.	EAG01	Ground-floor apartment	57
		EAG02	Ground-floor apartment	43
		EA201	Mid-floor apartment	58
		EA202	Mid-floor apartment	44
		EA301	Top-floor apartment	59
		EA302	Top-floor apartment	44

Table 2 Size, built form and construction type of the dwellings selected for Phase 3.

Project Results

- 19 The results from Phase 1 and those obtained to date for Phase 3 of the project are detailed within Tables 3 and 4 and Figures 5 and 6. A more detailed analysis of these results can be found in Johnston, Miles-Shenton and Bell (2004 and 2005c).

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability (m ³ /(h.m ²) @ 50Pa)
	Permeability (m ³ /(h.m ²) @ 50Pa)	r ² coefficient of determination	Permeability (m ³ /(h.m ²) @ 50Pa)	r ² coefficient of determination	
A9	13.95	0.999	13.86	0.999	13.91
A11	15.46	0.996	14.66	0.997	15.06
A12	12.12	0.990	12.49	0.999	12.31
A13	14.51	0.999	14.16	0.999	14.33
A14	15.33	0.993	15.71	0.994	15.52
B79	8.96	1.000	9.02	0.983	8.99
B80	11.76	0.992	11.20	0.990	11.48
B81	10.11	0.999	9.66	0.993	9.89
B82	12.04	0.996	11.53	0.999	11.79
C236	16.81	1.000	16.26	1.000	16.53
C237	14.08	1.000	13.98	1.000	14.03
C238	11.17	0.998	11.02	1.000	11.09
C239	12.46	0.997	11.90	0.986	12.18
C240	12.11	0.971	11.40	0.981	11.76
D39	12.82	0.992	12.61	0.984	12.72
D42	15.55	1.000	16.37	0.999	15.96
D43	12.10	0.997	11.44	0.999	11.77
D44	14.58	1.000	14.94	1.000	14.76
D59	12.50	0.990	11.76	0.984	12.13
ECG01	5.13	0.999	4.90	0.996	5.01
ECG02	4.37	0.998	4.32	0.997	4.35
EC201	4.79	1.000	4.43	0.997	4.61
EC202	3.94	0.999	3.96	1.000	3.95
EC301	7.46	0.995	7.38	0.997	7.42
EC302	5.53	0.999	4.98	0.995	5.25

Table 3 Mean air permeability of the dwellings tested during Phase 1.

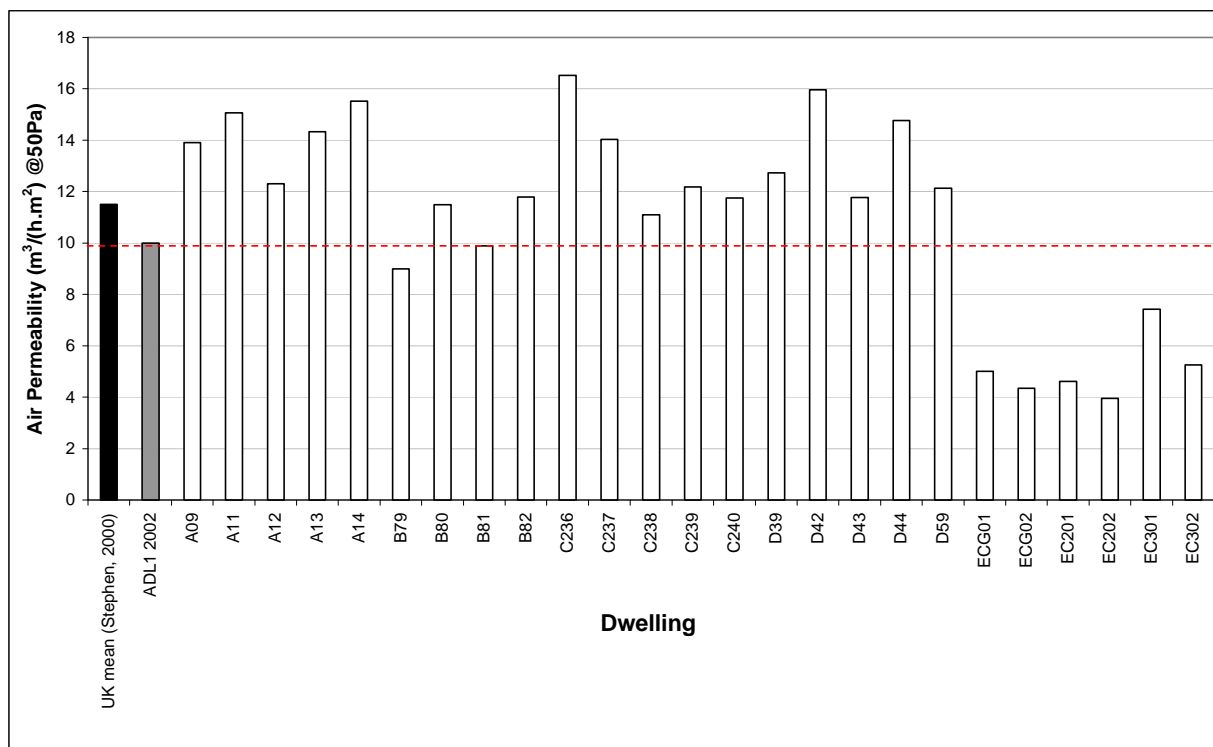


Figure 5 Mean air permeability of the dwellings tested during Phase 1.

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability (m³/(h.m²) @ 50Pa)
	Permeability (m³/(h.m²) @ 50Pa)	r ² coefficient of determination	Permeability (m³/(h.m²) @ 50Pa)	r ² coefficient of determination	
A64	10.68	0.996	10.19	0.999	10.44
A65	8.44	0.998	7.67	0.997	8.06
A66	8.01	0.999	7.96	0.999	7.98
A79	6.45	0.998	6.59	0.999	6.52
A80	5.54	1.000	5.65	1.000	5.59
B14	9.33	0.996	8.15	0.980	8.74
B16	5.50	0.987	5.69	0.993	5.59
B17	5.61	0.990	5.76	0.991	5.69
B21	7.31	0.996	7.27	0.997	7.29
B22	7.44	0.995	7.31	0.991	7.37
C17	6.17	1.000	5.95	1.000	6.06
C18	9.13	0.987	9.69	0.992	9.41
C19	7.32	0.999	7.29	0.985	7.30
C20	10.77	0.991	10.12	0.993	10.45
C21	10.40	0.990	9.60	0.994	10.00
C193	9.82	0.987	9.45	0.996	9.64
C194	15.90	0.996	14.02	0.992	14.96

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability (m ³ /(h.m ²) @ 50Pa)
	Permeability (m ³ /(h.m ²) @ 50Pa)	r ² coefficient of determination	Permeability (m ³ /(h.m ²) @ 50Pa)	r ² coefficient of determination	
D73	13.39	0.991	13.22	0.991	13.31
D74	12.62	0.970	12.80	0.949	12.71
D75	10.97	0.979	10.22	0.990	10.60
D76	9.23	0.982	8.56	1.000	8.89
D96	11.52	0.995	10.77	0.999	11.14
EAG01	6.56	0.999	6.57	0.997	6.56
EAG02	4.98	0.989	4.74	0.997	4.86
EA201	7.11	0.991	6.89	0.995	7.00
EA202	5.47	0.978	5.36	0.992	5.41
EA301	6.24	0.990	6.05	0.998	6.15
EA302	4.92	0.995	4.96	0.975	4.95

Table 4 Mean air permeability of the dwellings tested during Phase 3.

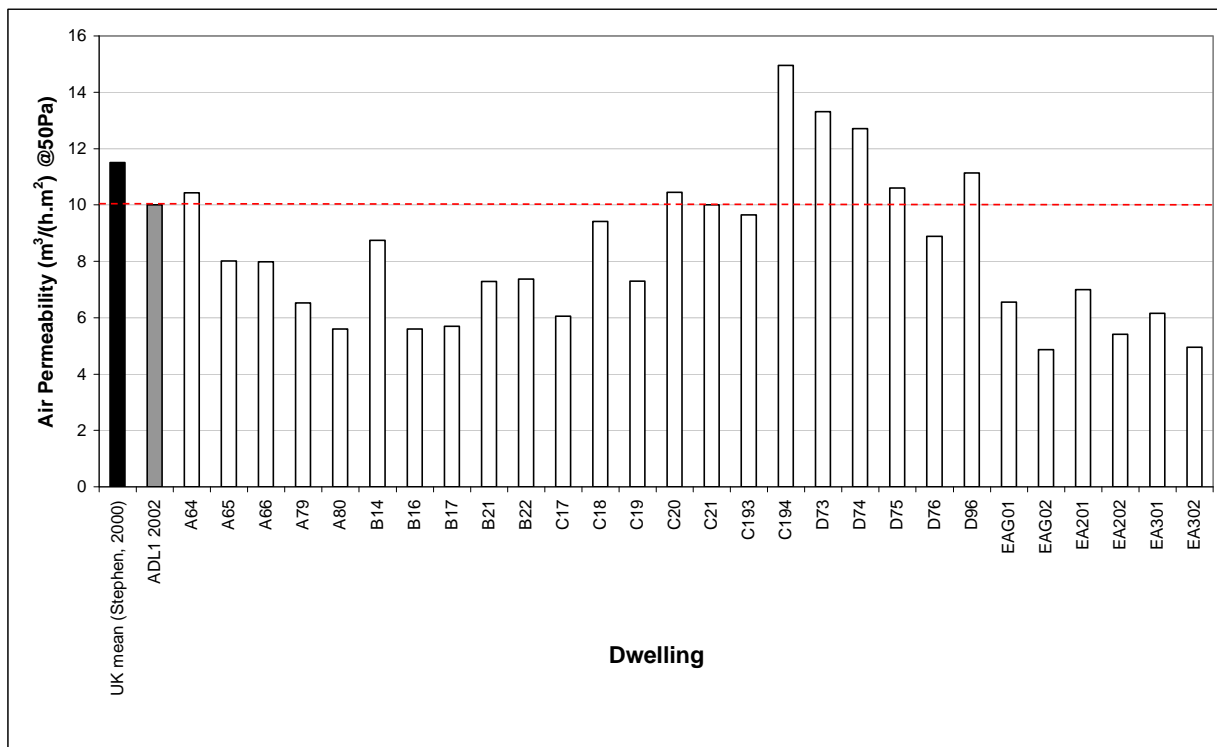


Figure 6 Mean air permeability of the dwellings tested during Phase 3.

20 It is important to realise that the results obtained from this project are based upon a non-random sample of dwellings. In addition, the sample sizes for both phases of the project are small, precluding absolute certainty when comparing the data. Consequently, conclusions drawn from the study are essentially qualitative in nature; future work would be required to establish whether the results reported are truly indicative of the UK house building industry as a whole.

Discussion of the Project Results

- 21 The measurements undertaken during Phase one of the project³⁹ showed that a relatively wide range of air permeability was measured for the tested dwellings. The air permeability of the dwellings ranged from 4.0 to 16.5 m³/(h.m²) @ 50Pa, with a mean of 11.1 m³/(h.m²) @ 50Pa and standard deviation of 3.8 m³/(h.m²). Although the range of air permeability measured within these dwellings was consistent with the recent measurements undertaken by the BRE (see Grigg, 2004), the mean for these dwellings was higher (11.1 as opposed to the BRE's 9.2 m³/(h.m²) @ 50Pa). This is probably a result of the larger proportion of apartments (36%) included in the BRE sample compared with this sample (24%). The data also indicated that only 10 of the 25 dwellings (40%) had an air permeability that was lower than or equal to the UK mean of 11.5 m³/(h.m²) @ 50Pa. The mean of all 25 results (11.1 m³/(h.m²) @ 50Pa) suggests that these dwellings are broadly in line with existing data on the UK stock as a whole and that, at least in these cases, the impact of the 2002 edition of ADL1 has been minimal. Given the qualitative nature of the project it is not possible to extrapolate to the post 2002 new build stock with any confidence but the Grigg data would suggest that the results obtained are not untypical.
- 22 The results obtained from Phase 1 also suggest that despite all of the developers using Robust Construction Details – Part L (DEFRA, 2001) as the basis of the application for regulatory approval, only eight of the tested dwellings (six flats and two houses) (32%) had air leakage values that were lower than the maximum specified level of 10 m³/(h.m²) @ 50Pa set in the 2002 edition of the Approved Document Part L1 (DTLR, 2001a). If the six flats tested are excluded (flats tend to be a more airtight dwelling form), only two out of 19 houses achieved a level below the value given in ADL1. In addition, only one of the developers (developer E — flats) managed to satisfy the air leakage criterion with all of their tested dwellings. The other four developers were unable to achieve the airtightness target in the majority of cases. This suggests that simply adopting Robust Construction Details, at least in their current form,⁴⁰ provides no guarantee that the current regulatory standard will be achieved with any degree of consistency.
- 23 A review of available literature (see Johnston, Wingfield and Bell, 2004) has revealed that it is possible to construct relatively airtight dwellings in the UK using a variety of different construction techniques. Such dwellings include the Autonomous Urban House (masonry cavity, 4.4 m³/(h.m²) @ 50Pa; Johnston, 2004), the Hockerton Housing Project (earth-sheltered, 1.1 m³/(h.m²) @ 50Pa; Johnston, 2004) and the Low Energy House at Stenness (timber-frame, ~1.0 m³/(h.m²) @ 50Pa; Bullen, 2000). Despite this, there is a still significant gap in airtightness between the best performing dwellings constructed in the UK (around 1 m³/(h.m²) @ 50Pa) and the most airtight dwellings constructed abroad (mean of less than 0.3 m³/(h.m²) @ 50Pa for the CEPHEUS houses; Feist, Peper and Gorg, 2001). Another issue associated with the dwellings that have been constructed in the UK is that these dwellings tend to be one-off 'specials' that have been designed and constructed to be very airtight by concerned individuals. Although these dwellings illustrate the levels of airtightness performance that could be achieved in the UK, they are not representative of the systems that produce the vast majority of new dwellings in the UK.
- 24 An indication of the levels of airtightness that could potentially be achieved within the current system of mass-produced housing in the UK has been obtained from the results of Phase 3 of the project. During this phase of the project, each of the developers identified a range of measures⁴¹ that they would incorporate within their dwellings, in order to improve their airtightness performance. The results obtained from this phase of the project indicate that in the majority of the dwellings where measures were identified and applied, reductions in air permeability from the Phase 1 mean were achieved. The only instance where this was not the case was with developer

³⁹ Further details of the Phase 1 results can be found within Johnston, Miles-Shenton and Bell (2005a)

⁴⁰ It is worth observing that the apparent failure of the adoption of Robust Details in these cases could be due to a wide range of causes relating not only to the intrinsic nature of the details themselves and the general level of guidance provided but also to the general quality control system into which they are embedded. In fact evidence from elsewhere (Bell, Smith and Miles-Shenton 2005) would suggest that levels of awareness of the details themselves among designers and constructors are low and that their adoption is rarely seen in the context of a design and construction quality control system. This contrasts with the separate system of Robust Detail accreditation used by many developers in support of achieving the performance requirements of Part E (sound).

⁴¹ Details of the individual measures incorporated by each developer are detailed within Johnston, Miles-Shenton and Bell (2005c).

E, where the air permeability of four⁴² of the Phase 3 apartments (Plots EAG01, EAG02, EA201 and EA202) were on average $1.5 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa (33%) higher than the corresponding apartments constructed during Phase 1 of the project. The reasons for the increase in air permeability was felt to be attributable to differences in the way in which these dwellings were tested⁴³ and the use of liner boards on dabs at the window reveals in these apartments, instead of wet plaster.

- 25 The scale of the reductions in air permeability that were achieved also varied considerably, as did the absolute levels of air permeability. Despite this, the results suggest that mass-produced housing in the UK can be constructed to be relatively airtight by UK standards, with an air permeability as low as 5 or $6 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa being obtainable with relatively small changes in design and approach to construction.
- 26 Given the level of feedback provided in Phase 3 it is, perhaps, surprising that only 21 of the 28 houses tested have achieved air leakage values meeting the $10 \text{ m}^3/(\text{h.m}^2)$ target level, although three of the 28 houses (Plots C194, D73 and D74) were built without taking the feedback on board in order that the developer could compare alternative dwelling types or new designs that had been built by the same construction team at the same time.⁴⁴ As in Phase 1 of the project, all of the dwellings to date were using Part L Robust Details (DEFRA, 2001) as the basis of the application for regulatory approval. In addition to this, each developer also received detailed and targeted feedback from the Leeds Met research team on any potential areas or issues that may have an influence on the eventual airtightness performance of the selected dwellings.
- 27 The data also show that the tightest dwelling tested was constructed by developer E. All of the dwellings constructed by this developer achieved air leakage values less than the target of $10 \text{ m}^3/(\text{h.m}^2)$. The leakiest dwelling tested was constructed by developer C, which was built as per their standard Phase 1 construction. Only one of the five dwellings constructed by developer D achieved an air leakage rate of less than $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa.
- 28 Further analysis of the results obtained for both phases of this project has highlighted a number of factors that are likely to influence the airtightness performance of new UK dwellings. These factors are as follows:
 - The type of construction.
 - The complexity of design.
 - The approach adopted to improve the airtightness performance of the dwelling.
 - The use of feedback and guidance.
 - Robustness of approach.
 - Repeatability.

Type of construction

- 29 Construction type is known to have an influence on airtightness (see Stephen, 1998 and 2000). This is illustrated in the results from both phases which appear to show a difference in permeability between the different types of construction method used by the various developers (see Figures 7 and 8 and Tables 5 and 6). The tightest dwellings were the apartments built using wet plastered masonry cavity construction. These dwellings were on average a factor 2 more airtight than all of the other construction types. The reasons for this are two-fold. First of all, wet plastered masonry dwellings tend to be intrinsically more airtight than comparable dry-lined masonry or steel frame construction (Olivier, 1999). Secondly, apartments tend to be more airtight than comparable

⁴² The other two Phase 3 apartments constructed by developer E (Plots EA301 and EA302) showed a reduction in air permeability from the corresponding Phase 1 apartments of around 12%.

⁴³ In Phase 1, the apartments were pressure tested by placing the blower door in the front door frame of each apartment. In Phase 3, the blower door was positioned in the patio door of the apartments, as the closer mechanism for the front door prevented the blower door frame from being installed correctly. Air leakage was subsequently detected around the front door and its fixings that had not been possible to detect in Phase 1.

⁴⁴ In the case of developer C, Plot C194 was included to explore the issues associated with constructing a different house type (in this case a detached dwelling as opposed to a semi-detached or terraced dwelling). Plots D73 and D74 were included by developer D so that they could examine the effect of new house designs and detailing that had been introduced in response to the introduction of the 2002 Building Regulations (the Phase 1 dwellings adopted an older design that had been adapted for 2002 compliance).

dwellings of different built form. The least airtight dwellings were those constructed using light steel frame, although these were only marginally leakier than the dry-lined masonry cavity dwellings in Phase 1 (see Figure 7). A more significant difference was displayed in Phase 3 (see Figure 8). However, type of construction should not be considered in isolation when analysing either set of results, as the other variable factors listed previously also need to be taken into consideration.

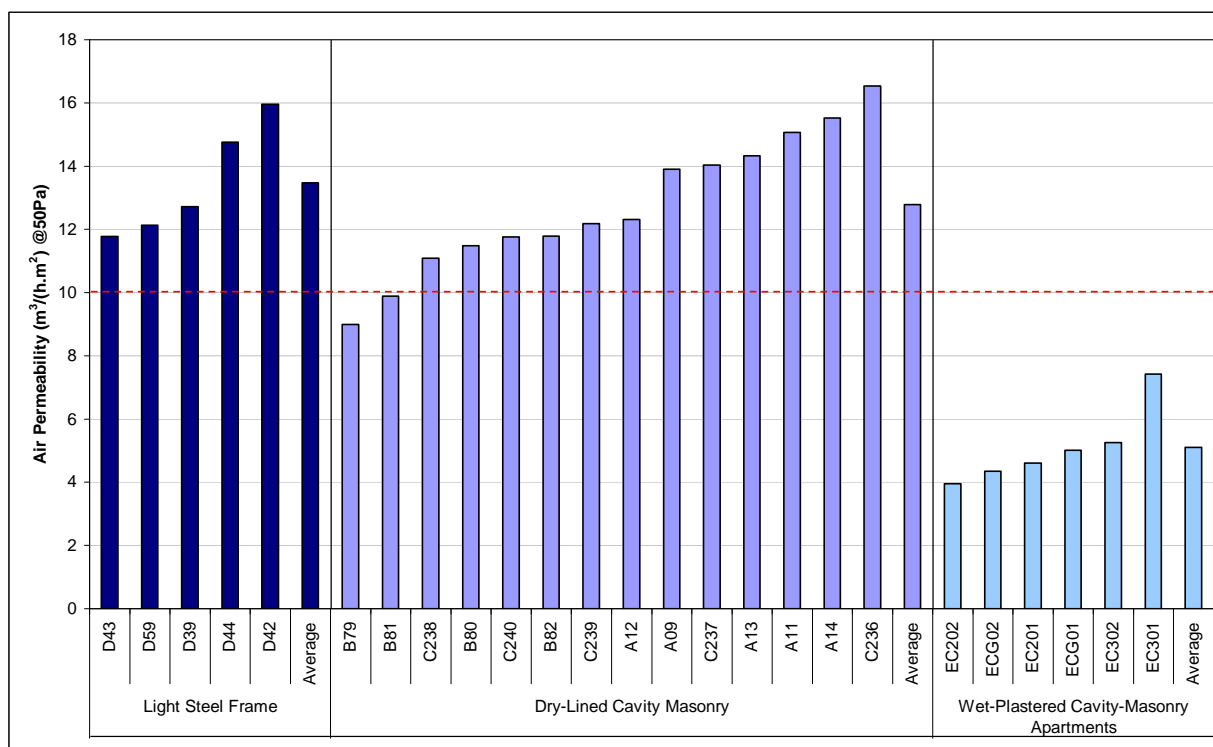


Figure 7 Mean air permeability of the Phase 1 dwellings by construction type.

Construction type	Mean air permeability (m³/(h.m²) @ 50Pa)
Dry-lined masonry cavity (Developers A, B and C)	12.6
Light steel frame (Developer D)	13.5
Mechanically/manually wet plastered masonry cavity (Developer E)	5.1

Table 5 Mean air permeability of the Phase 1 dwellings by construction type.

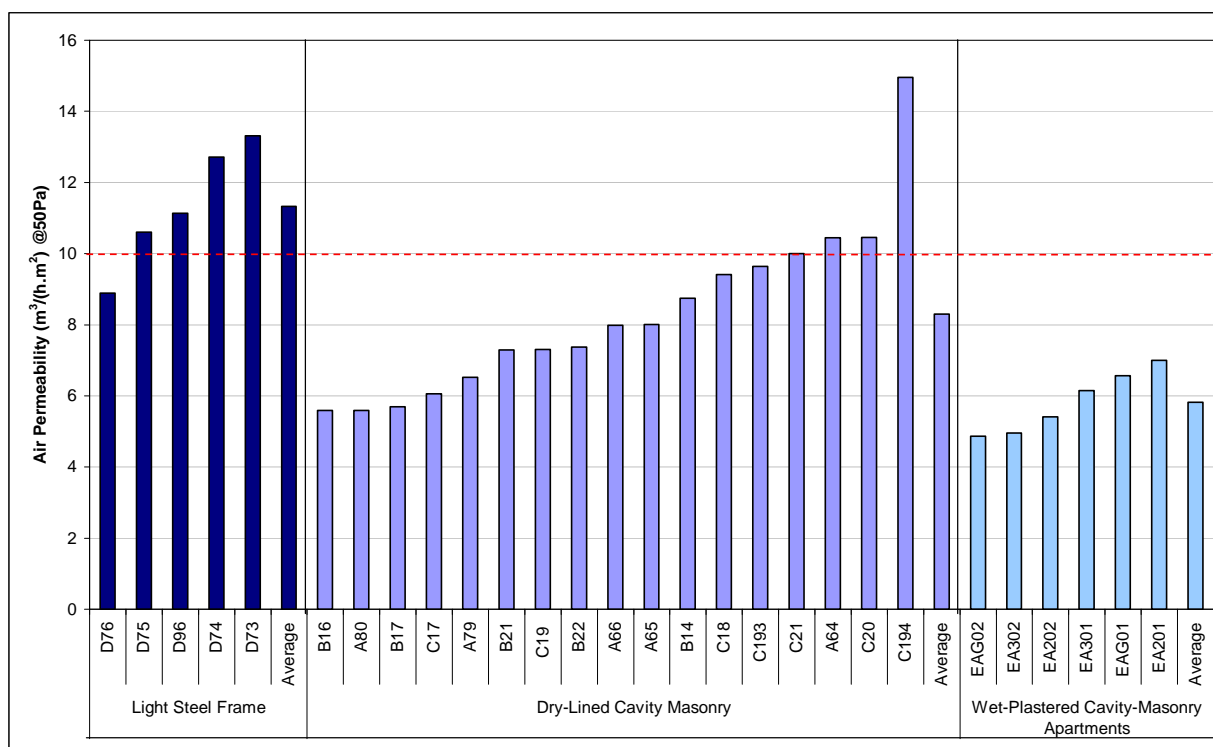


Figure 8 Mean air permeability of the Phase 3 dwellings by construction type.

Construction type	Mean air permeability (m³/(h.m²) @ 50Pa)
Dry-lined masonry cavity houses (Developers A, B and C)	8.3
Light steel frame houses (Developer D)	11.3
Wet plastered masonry cavity apartments (Developer E)	5.8

Table 6 Mean air permeability of the Phase 3 dwellings by construction type.

- 30 The results from Phase 3 (Figure 8) indicate that light steel frame is presenting greater difficulties in terms of airtightness than masonry cavity construction. To what extent this is a function of the current level of experience with this construction form or of a greater level of technical difficulty is uncertain. However, the results indicate that much more thought is required to the airtightness aspects of design and construction if reliably airtight steel frame dwellings are to be constructed. Only one of the steel frame dwellings achieved an air permeability of less than 10 m³/(h.m²) @ 50Pa and this result was only obtained after considerable efforts had been made on site to ensure that the primary air barrier (in this case the wall insulation fixed to the exterior of the frame) was made as airtight as possible. This involved extra taping around all junctions and openings, and sealing around the ground floor slab/external wall junction. Indeed, the best performing steel frame dwelling tested in Phase 3 was still less airtight than 11 out of the 17 masonry cavity dwellings tested in this phase of the project.
- 31 As the light steel frame dwellings for both phases were built using accredited construction details as a means for Part L compliance, the primary air barrier consisted of rigid insulation panels butt-jointed and sealed with an approved tape as recommended in the Robust Details document (DEFRA, 2001). These results suggest that with considerable additional attention to detail, a number of minor design alterations, and extreme care on site, an air permeability of below 10 m³/(h.m²) @ 50Pa can be achieved with this type of construction, but the achievement of levels of

airtightness significantly below $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa may be difficult to achieve without a fundamental rethink of the airtightness aspects of this form of construction.

Complexity of design

- 32 Complexity of design is also known to influence airtightness. All things being equal, the more complex the form and the techniques used to construct a building, the greater the potential for air leakage (see Johnston, Wingfield and Bell, 2004). The effect that complex designs can have on air permeability was observed in the Phase 1 dwellings constructed by developer C. In this phase, the results for the end-terraced and semi-detached dwellings tested returned lower air permeability than the mid-terraced dwellings by some 3 to 4 $\text{m}^3/(\text{h.m}^2)$ (see Figure 8). Despite differences in dwelling form, notable differences in the complexity of detailing were observed and this was thought likely to have been a significant factor in the results.
- 33 Three of the dwellings (C238, C239 and C240) were similar in size and design, only differing in form (one was an end-terrace whilst the other two were semi-detached), the two remaining dwellings (C236 and C237) were virtually identical mid-terraced dwellings; all were constructed by the same team on site (Figure 9). The measured air permeability of the mid-terraced dwellings was 16.5 and 14.0 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa, and 11.1, 12.2 and 11.7 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa for the end-terrace/semi-detached dwellings. The higher air permeability of the mid-terraced dwellings could be partly attributable to the fact that mid-terraced properties tend to have low exposed internal surface areas and a greater proportion of openings on the external walls than other dwelling forms of equivalent floor area. Although this may explain some of the difference in air permeability between the dwellings, a greater part of the difference is likely to be attributable to a number of complex details that had been incorporated within the mid-terraced properties in particular the extending of the first floor bathrooms over the ground floor passage way (see Figure 10).



Figure 9 Front elevations of developer C mid-terrace and end-terrace properties.

- 34 As a direct result of the Phase 2 feedback session held with developer C it was decided to explore the issue of complexity a little further.⁴⁵ In order to do this a detached dwelling on the same site containing many of the more complex design detailing issues as in the mid-terrace dwellings was selected (C194 — Figure 11) and constructed by the same site team using the same standard-build approach as in Phase 1 and its construction observed. The pressure test result of this detached property was 14.96 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa, which was similar to the mid-terrace dwellings in Phase 1. Figure 12 compares the pressure test results for the Phase 1 dwellings with that obtained for the detached dwelling.

⁴⁵ We are of course aware that this trial cannot be seen as having any statistical significance but in a qualitative and exploratory study such as the one being reported it was considered a useful exercise for the insights and explanatory power it provides. To address this issue directly would require a much more complex and expensive study involving many more dwellings and a complex control framework.

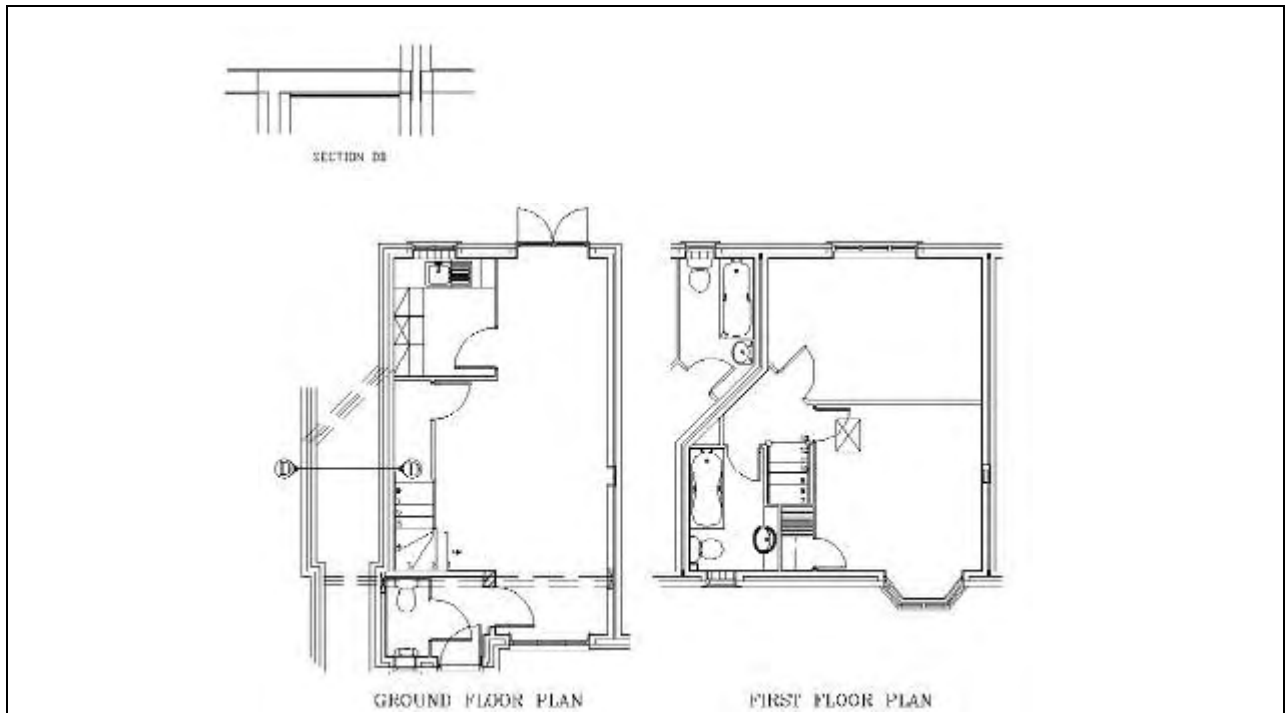


Figure 10 Ground and first floor plans of developer C's mid-terrace property.



Figure 11 Developer C's detached property, C194, and internal view of partially constructed first floor bay.

- 35 Complexity of geometry and structure tend to add a degree of uncertainty as to what actually constitutes the primary air barrier, and how its continuity was maintained. In the end-terraced/semi-detached dwellings some uncertainty occurred around the roof of the front porch, but the mid-terrace properties displayed a greater degree of complexity with significant changes in the plane of the primary air barrier, including extended ground floors, timber framed first floor bay windows, angled separating wall junctions and bathrooms constructed over passageways (see Figures 9 and 10). The detached property (C194 — Figure 11) displayed similar complex detailing to the mid-terrace housing; in both house types there appeared to be confusion over what constituted the air barrier directly above semi-exposed areas (in the cases of the integral garage in C194, and the bathrooms over the passageway in C236/C237). Also substantial air leakage into areas around the roof space over the extended ground floor was observed in both house types particularly around the first floor bays (Figure 11). Since site observations indicated that the quality of materials, workmanship and supervision were constant throughout this site, these results suggest that the additional complex detailing in C194, C236 and C237 was likely to have been influential in the different air permeability test results obtained.

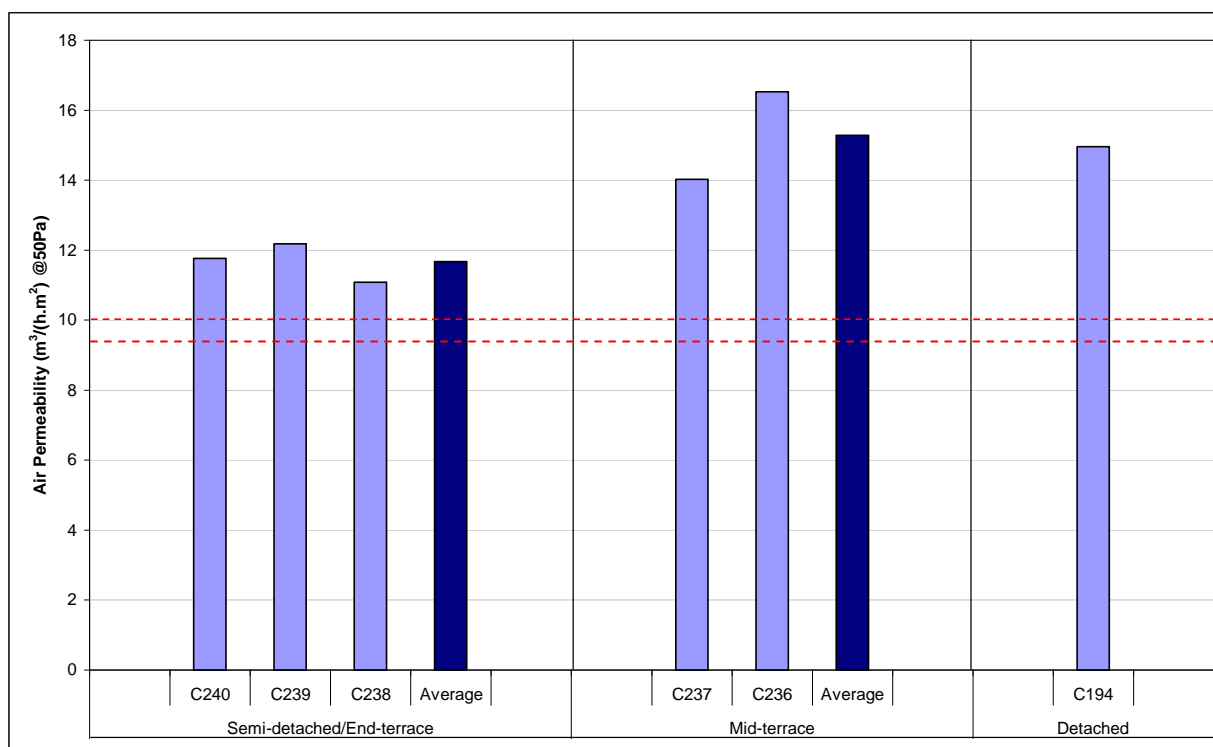


Figure 12 Developer C's test results for Phase 1 dwellings and C194 (Phase 3).

36 In multi-dwelling buildings, different dwellings within the same block may contain varying degrees of complexity and even different construction types. The summary of the Phase 1 air permeability test results for developer E, contained within Table 7 and Figure 13, indicate the variation in dwelling performance based on the boundary conditions for these apartments. The L1A (2006) definition of dwelling type distinguishes between ground, mid and top-floor apartments. The results obtained for developer E support this approach, with the two top-floor apartments producing higher air permeability test results than the ground and mid-floor apartments. Another factor that appeared to have an effect on the air permeability was that of location of the apartment on its specific floor (Figure 14), with the three apartments situated on the external edge of the apartment block being less airtight than their internal equivalents. The traditional timber roof construction of the top-floor apartments (EC301 and EC302) contained loft hatches and had recessed lights backing into a ventilated loft void rather than the enclosed suspended void observed in the other apartments; apartments with a greater number of external walls (ECG01, EC201 and EC301) also had at least two additional windows.

Dwelling	Boundary condition	Air permeability (m³/(h.m²))
ECG01	Concrete ground and intermediate floors, 3 external walls	5.01
ECG02	Concrete ground and intermediate floors, 2 external walls	4.35
EC201	Concrete intermediate floors, 3 external walls	4.61
EC202	Concrete intermediate floors, 2 external walls	3.95
EC301	Concrete intermediate floor, traditional timber roof, 3 external walls	7.42
EC302	Concrete intermediate floor, traditional timber roof, 2 external walls	5.25

Table 7 Air permeability of the dwellings tested for developer E.

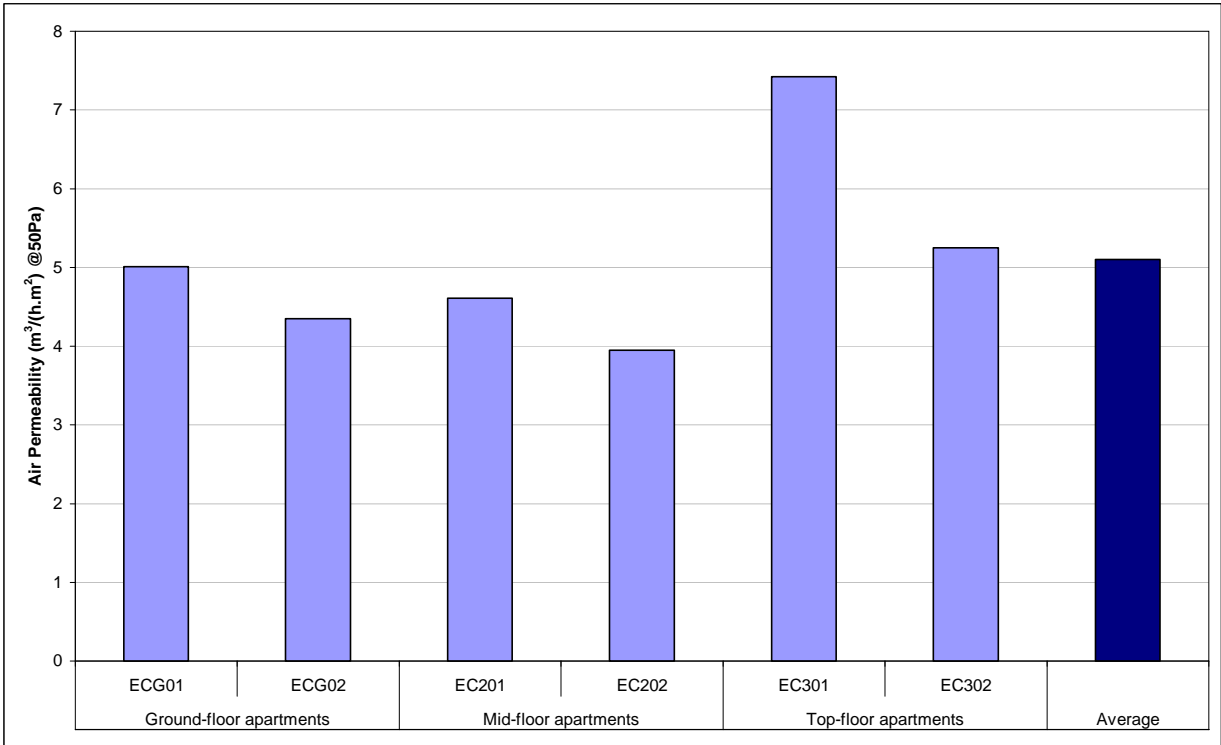


Figure 13 Developer E, Phase 1 pressure test results.

37 The test result for EC301 still exceeds what would be expected for the slight increases in complexity outlined above, this can be explained by the introduction of a mezzanine storage deck across the entire width of the apartment (Figure 14) and an additional high-level window, neither of which is present in EC302 or in any of the other apartments tested. Leakage detection performed in conjunction with the pressure tests showed similar leakage paths present in all the apartments but in the case of EC301 an additional and significant amount of air leakage was observed in the area of the mezzanine storage deck, indicating the influence of the more complicated detailing around this feature.

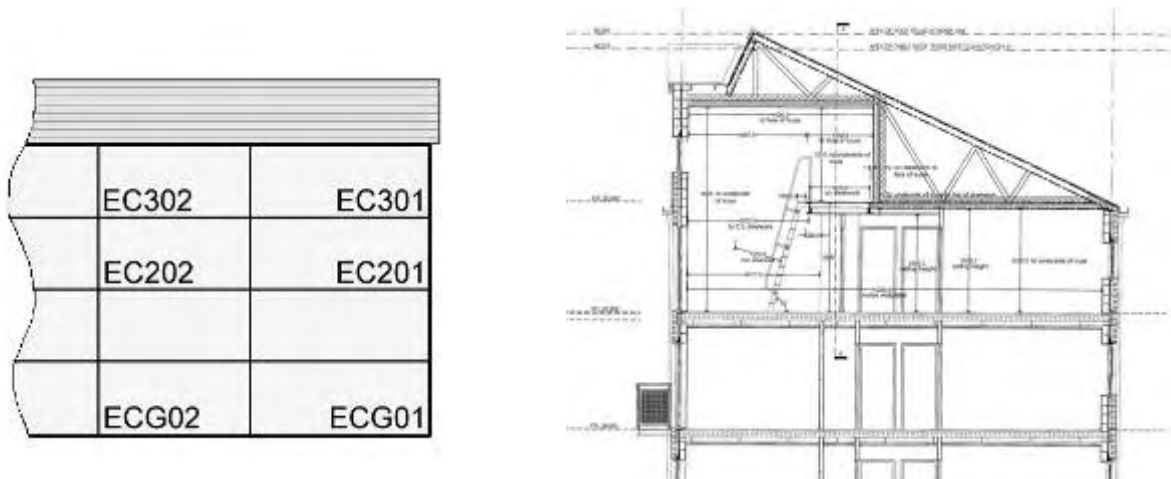


Figure 14 Developer E's apartment locations within the block, and the mezzanine storage deck in EC301.

38 The discussion of complexity is not intended to imply that such complexity should be avoided as a matter of principle. Clearly where complexity serves no purpose there are benefits to be gained in

all aspects of design by simplification, but where there are clear aesthetic or other reasons we do not advocate the avoidance of complex details. However, designers and constructors need to understand the airtightness problems that are introduced and devise robust solutions.

Approach

39 The Phase 3 results have been analysed in terms of the different approaches to improving performance taken by each developer. Table 8 and Figures 15 and 16 show, for the three general approaches adopted, the percentage improvement (on a plot by plot comparison) together with the Phase 3 test result. This provides an indication of the sort of reductions that can be achieved by the different strategies.

Action taken	Plot	Construction type	Test result (m ³ /(h.m ²) @ 50Pa)	Developer Phase 1 equivalent (m ³ /(h.m ²) @ 50Pa)	Plot % improvement over Phase 1 equivalent
1: General feedback only	C194	Full-Fill Masonry	14.96	15.28	2.1
	D73	Light Steel Frame	13.31	13.47	1.2
	D74	Light Steel Frame	12.71	13.47	5.6
	Average		13.66		2.97
2: Detailed site quality control and feedback from Leeds Met research team	A64	Partial-Fill Masonry	10.44	14.23	26.6
	A65	Partial-Fill Masonry	8.01	14.23	43.7
	A66	Partial-Fill Masonry	7.98	14.23	43.9
	B14	Full-Fill Masonry	8.74	10.54	17.1
	B21	Full-Fill Masonry	7.29	10.54	30.8
	B22	Full-Fill Masonry	7.37	10.54	30.1
	C18	Full-Fill Masonry	9.41	14.28	47.0
	C20	Full-Fill Masonry	10.45	11.68	10.5
	C21	Full-Fill Masonry	10.00	11.68	14.4
	C193	Full-Fill Masonry	9.64	15.28	36.9
	D75	Light Steel Frame	10.6	13.47	21.3
	D96	Light Steel Frame	11.14	13.47	17.3
	Average		9.26		28.3
3: Additional sealing to primary air barrier	A79	Partial-Fill Masonry	6.62	14.32	54.5
	A80	Partial-Fill Masonry	5.59	11.79	52.6
	B16	Full-Fill Masonry	5.59	10.54	47
	B17	Full-Fill Masonry	5.69	10.54	46
	C17	Full-Fill Masonry	6.06	11.68	48.1
	C19	Full-Fill Masonry	7.30	14.28	48.9
	D76	Light Steel Frame	8.89	13.47	34
	Average		6.52		47.3

Table 8 Phase 3 results by approach, showing improvement over Phase 1 mean.

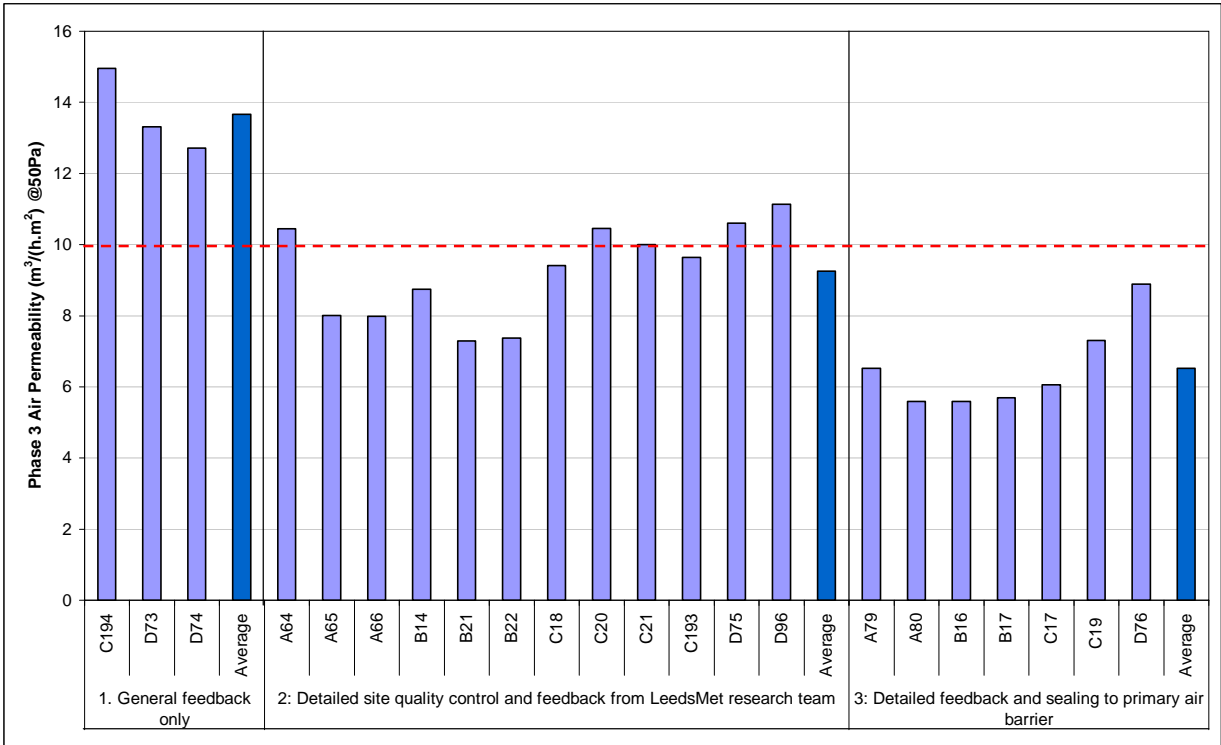


Figure 15 Phase 3 air permeability test results.

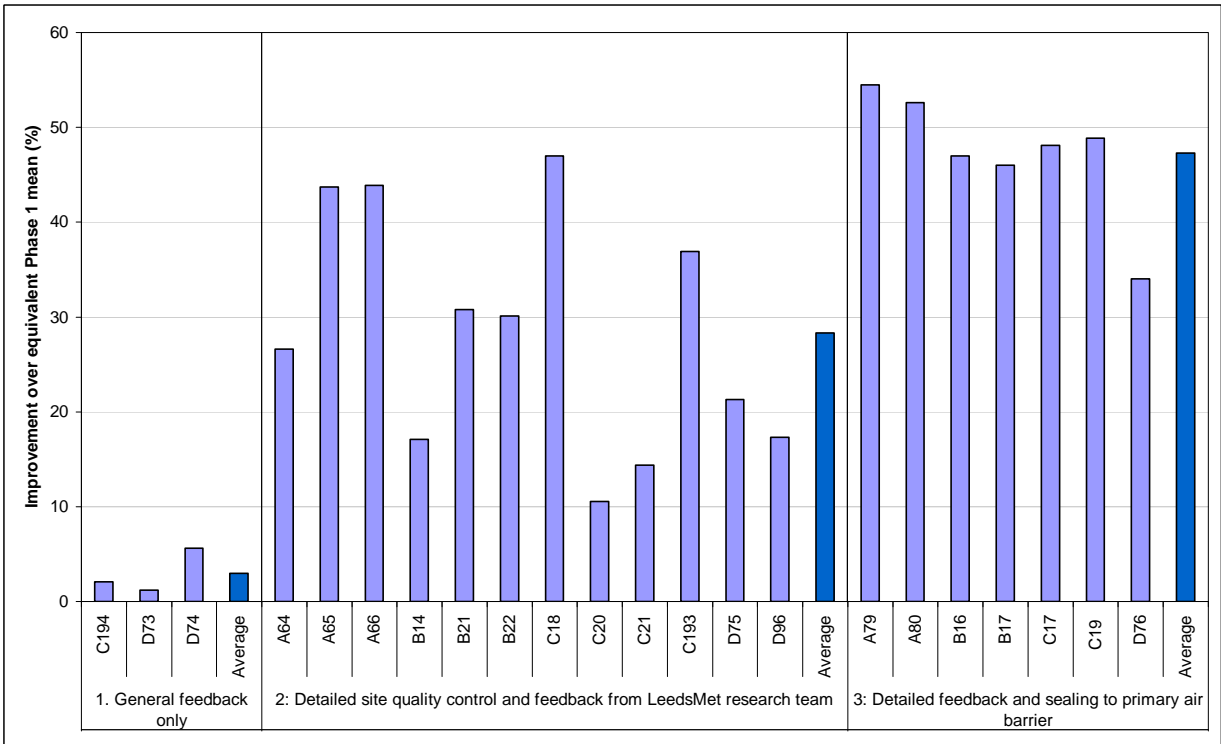


Figure 16 Improvement of Phase 3 air permeability test results over equivalent Phase 1 mean.

40 As Figures 15 and 16 illustrate, the least effective approach was to seek to respond to the general feedback provided in Phase 2 by tightening up in a general way, but with no specific design measures or any detailed site control measures. This resulted in a negligible reduction in the mean air permeability of the dwellings constructed. The second approach was to maintain existing detailed design, but to seek to address the site quality issues. An approach that could be labelled 'doing what we do now but with improved and detailed quality control'. This approach also entailed

responding to detailed feedback from the Leeds Met research team following each site visit. Typically this would result in additional sealing and rectification works done as construction progressed. Adopting this measure produced air permeability values ranging from 7.3 to 11.1 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa (with an average of 9.3 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa) with reductions of between 11% and 47%. The greatest reductions in air permeability were observed when design-led changes were introduced focusing attention on the air barrier, its identification and its continuity. This approach resulted in air permeabilities of between 5.6 and 8.9 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa (average 6.5 $\text{m}^3/(\text{h.m}^2)$ @ 50Pa), with reductions over the equivalent Phase 1 dwellings of between 34% and 55%.

- 41 As indicated above, where no specific action had been taken to improve the airtightness of the dwellings for Phase 3, besides the general Phase 2 feedback, no significant improvement in airtightness was observed. In the case of C194 this was expected, as it was only chosen for Phase 3 to provide a comparison with developer C's different house types included in Phase 1. However in the cases of D73 and D74 (light steel frame), the developer had introduced new house designs and detailing to comply with the 2002 Building Regulations, their dwellings examined in Phase 1 had been manufactured to older designs adapted for 2002 compliance. The design assessments carried out on D73 and D74 (Johnston, Miles-Shenton and Bell 2005b) indicated only one airtightness modification was made for these Phase 3 dwellings; the use of a temporary course of blockwork as a sacrificial slab former, to improve the junction of the slab, frame and insulation (see Figures 17 and 18). The remaining Phase 3 dwellings (D75, 96 and 76) built by developer D received much more attention with commensurate improvements in airtightness.



Figure 17 Developer D, Phase 1, the use of removable polystyrene formers created an inconsistent and uneven slab edge, with potential for air leakage at the junction of slab, steel frame and insulation.

- 42 Developers A, B, C and D have all had Phase 3 properties tested where secondary sealing measures have occurred as a result of detailed feedback from the Leeds Met research team. This has involved tightening up on existing detailing due to information received in the Phase 2 individual developer feedback sessions and additional measures taken as a reaction to continuous on-site feedback from the research team, who visited the sites at critical stages throughout the Phase 3 construction programme. In all cases this resulted in improved supervision of operatives via a more informed site management team and many minor changes were introduced which did not incur any significant additional cost; this has been reflected in the results.



Figure 18 Developer D, Phase 3, using sacrificial blockwork to form the slab; after the blockwork is removed a straightener and more uniform slab edge reduces the potential for air leakage at this junction.

- 43 Three of developer A's Phase 3 dwellings (A64, A65 and A66) displayed no apparent difference in quality or methodology between their construction process and level of feedback received, yet the pressure tests yielded results of $8 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa for two of the Phase 3 properties (A66 and A65) and $10.4 \text{ m}^3/(\text{h.m}^2)$ for the other one (A64). Leakage identification performed with the pressure tests revealed similar leakage paths in all three dwellings. These Phase 3 results for developer A suggest that this approach of improved supervision and site feedback can reduce air leakage in traditional-build cavity masonry partial fill dwellings, but this alone cannot be relied upon to guarantee compliance with the new Part L limit of $10 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa. The two dwellings where developer A introduced additional sealing to the primary air barrier (A79 and A80) both provided test results well below this limit, at 6.5 and $5.6 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa.
- 44 The Phase 3 results for developer B suggest that increased knowledge and awareness of airtightness issues alone can reduce air permeability, as shown with Plot B14. With the additional on-site feedback from the Leeds Met research team the airtightness was reduced further, with both Plots B21 and B22 producing test results of below $7.5 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa. The additional internal secondary sealing performed on B22 (e.g. mastic sealant around electrical pattress boxes and light fixings), but not on B21, did not appear to have any significant additional effect as the test results for both properties were very similar (7.4 and $7.3 \text{ m}^3/(\text{h.m}^2)$ @ 50Pa, respectively).
- 45 The most significant reductions in air permeability, and lowest test results for each developer, occurred where improvements to the primary air barrier were introduced. Establishing exactly what constituted the primary air barrier was essential in this approach. The solid ground floor and top-floor ceiling were identified as the primary air barrier in all dwellings. In the cavity masonry construction of developers A, B and C the primary air barrier for walls was identified as the inner leaf blockwork, whilst for developer D's light steel frame dwellings it was the polyurethane foam external insulation system. Developer A introduced additional sealing to the primary air barrier in dwellings A79 and A80. This was achieved using tape, mastic and expanding foam to seal junctions, penetrations and the loft boundary at a pre-plaster stage, and was coupled with increased site supervision and quality control. Developer B sought to test two approaches to improving the airtightness of the inner leaf. In the case of B16 all internal blockwork and junctions were inspected at the pre-plaster dry-lining stage and additional pointing work undertaken to remedy any defects. In contrast, B17 had a 3~6 mm thick full parging layer applied to the blockwork prior to dry-lining. Developer C adopted a similar approach in the case of C17, with a 6~12 mm coarse render applied to party walls (for Part E compliance) also being applied to all external walls. Developer D improved their primary air barrier with a combination of additional sealing (with tape, mastic and expanding polyurethane foam) and a minor design change at the intermediate floor perimeter. For developers B, C and D the cost of this action was approximately one man-day per dwelling plus marginal material costs. In the case of developer A, the work undertaken was more

labour intensive, approximately 2 man-days per dwelling, and involved much greater material costs (approximately £500 per dwelling). Of the design-led approaches, the most significant reductions were achieved by developer A in dwellings A79 and A80, which achieved an air permeability of 5.6 and 6.5 m³/(h.m²) @ 50Pa, respectively, representing a reduction in excess of 50% compared with their equivalent Phase 1 dwellings. However, the approach used to achieve these reductions was not only labour and material intensive but relied on assiduous site supervision and sealing of the loft boundary junction. However, the effort involved is likely to make such an approach unsustainable in the long term. Similar and more robust reductions in air permeability are likely to be achievable by adopting an alternative approach to providing continuity of the air barrier at the loft boundary junction, such as the use of membrane materials. B16 and B17 achieved similar figures for air permeability of 5.6 and 5.7 m³/(h.m²) @ 50Pa, representing reductions of 47% and 46% from the Phase 1 equivalent. Plots C17 and C19 displayed pressurisation test results of 6.1 and 7.3 m³/(h.m²) @ 50Pa when tested on completion, representing 48% and 49% reductions on their equivalent Phase 1 mean. The smallest reduction of the design-led approach was seen in the case of steel frame construction, with D76 providing a final air permeability measured at 8.9 m³/(h.m²) @ 50Pa, a reduction of 34%. This was only achieved after considerable effort by both the site staff and the Leeds Met research team to identify potential leakage paths and perform the necessary remedial action, suggesting that much more thought is required in the design of the air barrier for light steel frame designs (warm frame) that rely on the external insulation layer as an air barrier.⁴⁶

Feedback and guidance

- 46 An important aspect of the project was the feedback and guidance given by the Leeds Met research team. During Phase 1 of the project, the research team's role was purely observational and no feedback or guidance on airtightness was given to the developers during the construction of the Phase 1 dwellings. Following completion of these dwellings, a feedback seminar was organised with each of the developers where the observations from site, the air permeability results and the leakage identification work was presented to the developers and general advice and guidance was given on airtightness. Further details of these seminars can be found within Johnston, Miles-Shenton and Bell (2005a).
- 47 A two-way dialogue was then facilitated between the Leeds Met research team and the developers during Phase 3, enabling any observations from site on the airtightness performance of each of the selected dwellings to be fed back to the developers. In practice, the feedback took the form of a short written report, supplemented by photographs, highlighting any potential areas or issues that may have an influence on the eventual airtightness performance of the dwellings in question. These reports were sent to the respective sites by mail or electronically to allow action to be taken as soon as possible, and in most cases were supplemented with discussions with the site team prior to the next site visit. By providing continuous detailed (site specific) feedback to the developers, it gave them the opportunity to identify and rectify any issues relating to airtightness on site, prior to the dwellings being completed and tested. The provision of such feedback also raised the awareness levels of airtightness on site.
- 48 With respect to the effect of feedback and guidance on airtightness, the Phase 3 results suggest that for those dwellings where the only difference between Phases 1 and 3 was the general feedback provided at the Phase 2 seminar (C194, D73 and D74), very little reduction in air permeability was observed. This suggests that there appears to be little immediate benefit in providing general feedback on airtightness to developers. Although how much information from the Phase 2 seminar had filtered down to site operative level at the time of completion of these dwellings is unclear. The results would suggest that very little had reached site level.
- 49 It has not been possible to separate out the effect that the detailed feedback alone had on the Phase 3 results. Nevertheless, in those dwellings where constant detailed feedback was given to the developers, reductions in air permeability from the Phase 1 mean were observed. Although it is difficult to say how much of this reduction was attributable to the detailed feedback and how much was attributable to the measures that were adopted, it is felt that feedback alone is unlikely to result in significant reductions in air permeability.

⁴⁶ The adoption of a hybrid form of steel frame (see DEFRA, 2001 section 7) in which insulation is placed between studs as well as externally together with an internal vapour control layer (as is common in timber frame) may present fewer airtightness problems.

- 50 It is also important to note that providing continuous detailed feedback on airtightness during the construction of a dwelling, at the same level as discussed above, is onerous and labour intensive.

Robustness of approach

- 51 Observations from site suggest that there are likely to be differences in the robustness of the approach adopted to improve airtightness. The observations from this project suggest that the adoption of an approach which involves no change to design relying instead on assiduous site supervision and remedial sealing where necessary is unlikely to be robust. In most cases such an approach tends to rely upon the sealing of gaps, such as service penetrations through intermediate floors, skirting boards at floor/wall junctions and the sealing of entries into internal service ducts. Practically, it is almost impossible to seal all of these gaps. The difficulties are compounded by the fact that many of the spaces within the construction communicate with each other resulting in a very complex pattern of air flows both within and through the building envelope. Thus to concentrate on this type of sealing works, which often takes place after key areas have been covered up, is not a very efficient approach. To ensure acceptable airtightness through this route requires a very high level of workmanship and site supervision to ensure that all of the gaps are properly sealed. A much more robust approach would be to adopt a design-led primary sealing approach, where the effort in both design and construction is concentrated on ensuring that there is an effective and continuous air barrier.
- 52 The results for dwellings B16 and B17 also highlight another aspect of robustness. Although both dwellings adopted a primary sealing approach for Phase 3, the measures that were incorporated within each dwelling were quite different. Both dwellings achieved similar air permeability results ($5.6 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$), suggesting that pointing and parging can have a similar impact on airtightness. However, from a quality control perspective, it is much simpler and quicker to check that the parging layer has been applied correctly rather than checking to see if all of the apertures and joints have been pointed. Although both methods achieved similar results, it is felt that parging is likely to provide greater consistency.

Repeatability

- 53 During the inspection work on the individual dwellings, attempts were made, in some cases, to observe in a general way the construction of other dwellings not featured in the research project. Casual observations from the sites suggest that the knowledge and experience of airtightness gained throughout this project does not appear to be filtering through to the construction of other dwellings on site. A way of establishing whether this is actually the case would be to measure the air permeability of a number of other dwellings, from the same production phase as the test dwellings, that were not directly involved in this project. Although a number of the developers have been approached regarding this, to date, no agreements have been given by the developers to test such dwellings on site.
- 54 A possible explanation for why this knowledge and experience may not be filtering through may simply be that there is no current requirement to do so, as all of the dwellings currently under construction are meeting the airtightness requirements by the adoption of Robust Construction Details. This situation is unlikely to change significantly, even after the introduction of Part L1A 2006 (ODPM, 2006a), as the current pressure testing regime only requires a limited number of dwelling types⁴⁷ to be tested per development. It is also difficult to say how the experience of airtightness gained from one particular site will transfer to other sites that are being constructed by the same developer.
- 55 The results from developer A highlight that it is also likely to be difficult to achieve consistent air permeability results even when dwellings of the same size, construction type and form are being constructed on the same site by the same workforce. As previously mentioned, the Phase 3 dwellings constructed by developer A displayed no apparent difference in quality or methodology between the dwellings. Despite this, the air permeability of the two identical mid-terraced dwellings (A64 and A65) varied by over $2 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, with dwelling A64 achieving an air permeability of $10.4 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ whilst dwelling A65 achieved an air permeability of $8.0 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$.

⁴⁷ Dwelling type is defined in Part L1A (2006) as a dwelling of the same generic form, e.g. detached, semi-detached, end-terrace, mid-terrace, ground-floor flat, mid-floor flat, top-floor flat.

- 56 Another issue that is likely to influence repeatability is the level and consistency of the feedback and guidance that is given on airtightness. The results from Phase 3 suggest that any feedback and guidance given on airtightness should be continuous, detailed, targeted and an integral part of a consistent quality control system if it is to result in a reduction in air permeability. Although general feedback and awareness raising is important, on its own, it is unlikely to result in any improvement in performance. It is also critical that design and construction quality control systems take into account construction processes and sequences since once the dwelling or a particular part of the dwelling is complete, it becomes extremely difficult and expensive to improve airtightness through secondary sealing measures.

Conclusions

- 57 This paper discusses the results that have been obtained on this project and identifies the levels of air permeability that could be achieved within new UK dwellings using existing technology and construction techniques.
- 58 Although the size, structure and non-random nature of the sample preclude it being taken as representative, the results obtained from Phase 1 suggest that the impact of the 2002 edition of Approved Document Part L1 on airtightness has been minimal. The failure of the majority of the dry-lined masonry cavity and steel framed dwellings included within this phase to achieve the ADL1 2002 airtightness target also suggests that the adoption of Robust Construction Details, at least in their current form, provides no guarantee that the current regulatory standard will be achieved with any degree of consistency. The results from Phase 3 of the project suggest that an air permeability of less than $6 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ is genuinely achievable within mass-produced housing in the UK using existing techniques, materials and practices, and without incurring significant cost.⁴⁸ However, to achieve such a standard in a consistent and robust way will require a mix of relatively minor modifications to design and a committed and targeted approach to quality control.
- 59 The results from both phases of the project have highlighted a number of issues that need to be considered when constructing dwellings to meet a particular airtightness target. These issues relate to:

Type of construction — Certain construction types are intrinsically more airtight than others. The results illustrate that wet/mechanically plastered masonry cavity construction can default to a reasonable level of airtightness by UK standards without much additional attention being given to airtightness. Other construction types, such as dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to achieve an air permeability below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. In the case of masonry the required design changes may be relatively minor. The construction type that presented the greatest difficulty was steel frame construction (warm frame). Air permeability values of below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ are possible with this type of construction, but with existing design and detailing the effort involved, particularly at site level, is considerable. Given the observations in this project it is difficult to see how an air permeability consistently below $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ can be achieved without a fundamental rethink of airtightness design in this form of construction.

Complexity of design — Complexity of design is likely to have a significant impact on airtightness. Differences in air permeability of up to $4 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ from the mean were observed in dwellings of similar size, construction and form that had been constructed with comparable levels of workmanship and site supervision. The main difference observed between the dwellings was the complexity of the detailing. Higher levels of air permeability were consistently observed in those dwellings that contained the most complex detailing. In some instances, this detailing also added a degree of uncertainty as to what actually constituted the primary air barrier. Examples of such detailing included: extended ground floors, timber frame first floor bay windows, angled separating wall junctions, habitable rooms constructed over passageways and mezzanine storage decks.

Airtightness approach adopted — The approach that is adopted to improve airtightness can influence the eventual levels of air permeability that are achieved. The greatest reductions in air permeability were achieved where improved construction was undertaken in the form of designed changes with respect to the primary air barrier.

⁴⁸ The exception is light steel frame where much more thought at the design stage is likely to be required.

Feedback and guidance — The level and consistency of any feedback and guidance that is provided on airtightness is important. The results obtained from this project suggest that the provision of general feedback and guidance to the developer on airtightness, prior to the dwellings construction, is likely to have little or no immediate effect on airtightness. Such guidance does little more than raise awareness and, although a necessary first step, it must lead to a system of quality control that provides continuous detailed feedback and guidance during construction. However, providing this sort of feedback and guidance on a dwelling by dwelling basis is onerous and labour intensive.

Robustness of approach — The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on basic workmanship coupled with secondary, remedial, sealing measures during construction are likely to be much less robust than those approaches that are based on an explicit attempt at the design stage to concentrate on ensuring that there is an effective and continuous air barrier. Detail design that recognises the importance of buildability and simplifies the construction process are also likely to be more robust.

Repeatability — Observations from site suggest that the knowledge and experience gained on airtightness does not appear to be filtering through to other dwellings on the same site. There are concerns that the other dwellings will not achieve the same sorts of levels of airtightness as the dwellings featured in this project. Clearly there remains a considerable amount of training and development work to be done to ensure that the house building industry is capable of producing a consistent standard of airtightness. This will not be a trivial task.

- 60 All of the above issues will have implications for the development of future regulations and testing regimes. These implications are discussed in detail in milestone D10 of this project (*Discussion Paper 2 — Impacts of Pressure Testing*).

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Appendix 10

Airtightness of buildings — towards higher performance

Milestone Number: D10 (Revised)

Discussion Paper 2 — Impacts of Pressure Testing

Dr David Johnston, Centre for the Built Environment, Leeds Metropolitan University

Dominic Miles-Shenton, Centre for the Built Environment, Leeds Metropolitan University

Prof. Malcolm Bell, Centre for the Built Environment, Leeds Metropolitan University

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Executive Summary

- 1 This paper reviews the pressure testing regime incorporated within Part L1A 2006 of the Building Regulations, analyses the logistics associated with compulsory pressure testing and discusses the effect that the testing regime is likely to have on new dwellings.
- 2 The review highlighted a number of issues associated with the pressure testing regime incorporated within Part L1A 2006.
 - a) The testing regime incorporated within ADL1A 2006 involves categorising dwellings by their generic form. Such a categorisation is unlikely to capture a number of important house type issues that influence airtightness. The results obtained from this project, and supported by parallel research, suggest that the issues associated with the geometry and complexity of the construction may have a much greater influence on the eventual airtightness of a dwelling than generic form.
 - b) There is little guidance given within ADL1A 2006 relating to dwelling selection. Depending upon when developers are notified of the dwellings to be tested, there may be scope for additional measures to be undertaken on the selected dwellings to ensure that they meet the required airtightness target. In addition, ADL1A 2006 suggests that a significant proportion of the dwellings should be tested early on in the construction programme to enable any lessons learnt to be fed back into the construction and design process. Anecdotal evidence obtained from Phase 3 of the project suggests that this is unlikely to be the case as there was a noticeable difference in the quality of workmanship in relation to airtightness in those dwellings that were participating in the project and those that were not. Although the response of developers to Part L1A 2006 is uncertain, the experience obtained from this project would suggest a risk that the airtightness of those dwellings that are selected to be tested may not be representative of the performance of other dwellings of the same type on the same development.
 - c) Local authorities are authorised to accept a certificate from a person who is registered by BINDT in respect of pressure testing for the airtightness of dwellings. However, there is no clear guidance given about who else can undertake the tests and issue certificates. It will therefore be up to individual BCBs to decide who is technically competent to undertake the tests and issue certificates. This may lead to issues relating to equity and fairness if BCBs adopt different practices and developers are treated differently in different parts of the country. Also the question of the independence of testing arises if developers are allowed to test and issue certificates for their own dwellings. Guidance on this issue may be necessary.
 - d) The sampling frequencies outlined in ADL1A 2006 are likely to result in a small non-random number of dwellings tested on each development. The sample sizes involved are also unlikely to be statistically significant; therefore, the results obtained may not be indicative of the airtightness performance of other dwellings on the development. The results obtained from this project suggest that the proportion of dwellings requiring testing is likely to vary considerably between developments (between 1% and 14%) and will be dependent upon the number of dwelling types and the method of compliance. In addition, where apartments are being constructed, a significantly greater proportion of apartments are likely to require testing than other dwelling types. This is despite the fact that apartments tend to be intrinsically more airtight than other dwelling forms of equivalent area.
 - e) Experience obtained from Phase 1 and Phase 3 of this project suggests that developers appear to be unaware of how to prepare a dwelling for a pressure test and, in some instances, tests have had to be abandoned as the dwelling was not in a finished state. The incidence of unprepared and unfinished dwellings being presented for testing is likely to reduce in the medium to long term as developers become accustomed to pressurisation testing and realise that they will have to pay for aborted tests where preparation is inadequate.
 - f) The design air permeability target for many dwelling designs is likely to be considerably lower than the maximum recommended level of 10 m³/(h.m²) @ 50Pa specified within ADL1A 2006, particularly where fuels with a higher carbon intensity than gas are to be used. Modelling work on statistical distributions suggests that an average air permeability of around 7, 5 and 3 m³/(h.m²) @ 50Pa would need to be achieved by a developer to meet a design air permeability target of 10, 7 and 5 m³/(h.m²) @ 50Pa, respectively, assuming a 10% initial failure rate. Reliably achieving an average air permeability of below 5 m³/(h.m²) @ 50Pa will be technically demanding, and such levels of air permeability are likely to require a fundamental rethink of airtightness design.

- g) The way in which the dwelling is tested can influence the eventual levels of air permeability achieved and bias the results. The approved procedure for pressure testing a dwelling, ATTMA Technical Standard 1 (ATTMA, 2006), states that valid test results can be achieved by: pressurising the dwelling; depressurising the dwelling; or pressurising and depressurising the dwelling and averaging the results. The results obtained from Phase 1 and Phase 3 of the project indicate that the difference between pressurisation and depressurisation can be as high as 14%, and the results obtained by depressurising the dwelling only are, in most cases, lower than the corresponding pressurisation test results. Consequently, more favourable test results could be achieved by selecting only depressurisation to obtain test results.
- 3 The number of new dwellings requiring testing each year will be dependent upon the strategy adopted for regulatory compliance by the developer, the size of the development and the variation in dwelling types across the developments. Based on construction statistics for 2004 and 2005, it is estimated that the number of dwellings that will require testing will fall in the range 25,000 to 42,000 per year. The figure is likely to lie towards the higher end of this range due to re-tests and the trend towards constructing more multi-dwelling buildings. This will place considerable strain on testing capacity and will have a disproportionate effect on small and medium size developers, many of whom may have to test a high proportion of their production. Although the number of tests would be high the impact in quality control terms will be statistically inefficient and unbalanced since sample sizes are unlikely to be well constructed.
- 4 Wind speed can have a significant effect on the accuracy of pressure tests. Assuming a working day from 8am to 6pm, an analysis of the CIBSE/Met Office weather data for a semi-empirical Test Reference Year suggests that the average maximum number of hours available for testing in a year would be reduced by over 7% due to unfavourable wind conditions. The number of hours available for testing is likely to reduce further when tests are undertaken in more exposed locations, increasing the incidence of less reliable test data. Time spent travelling between sites, in order to undertake tests in different locations on the same day, will also affect the number of tests that can be performed.
- 5 Taking into account seasonal trends in dwelling completions and the number of hours available for testing, the average number of tests that are required to be undertaken in a single day could exceed 200 or fall below 80, depending upon the month of the year. Assuming that an average of four tests could be undertaken by a single testing team each working day, a minimum of 20 testing teams would be required in January to cover the testing requirements, rising to a minimum of 50 testing teams in June and December. These figures would double if it was only possible for the testing team to undertake an average of two tests per day.
- 6 The commercial charge for undertaking a single pressure test is of the order of £500 excluding VAT plus travel and subsistence. Any additional tests at the same visit are of the order of £100 per dwelling excluding VAT.
- 7 The strategy adopted to ensure a desired level of airtightness can influence the eventual air permeability test results that are achieved, and costs will vary accordingly. In the case of all the houses constructed by developers A, B, C and D; in Phase 3 of the project where feedback was provided but no additional effort put in to quality control and no design changes were made, negligible improvements in performance were observed over equivalent dwellings constructed in Phase 1. By improving quality control systems, through increased and better informed inspection, a 29% improvement was observed and an average mean air permeability of below $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$ was achieved. The additional costs being related to the extra staff hours accrued. The greatest reductions in air permeability observed in Phase 3 were achieved where improved construction was undertaken in the form of design-led changes with respect to the primary air barrier, combined with the plot-specific quality control. This approach saw an average improvement of over 45%, with test results averaging $6.9 \text{ m}^3/\text{h}\cdot\text{m}^2 @ 50\text{Pa}$. This approach incurred direct costs per dwelling for labour and materials, in addition to the increased staff costs of the enhanced quality control. The apartments constructed by developer E saw an average 12% decrease in air permeability for the top-floor apartments where design changes surrounding the traditional roof construction had been introduced, but an overall increase in air leakage due in part to difference in the test procedures between the two phases, and partly due to alterations to the detailing adopted by the developer and the apartments not being fully completed at the time the tests were undertaken.

- 8 Limited data are available on the costs associated with undertaking remedial work in dwellings that have failed a pressure test. Experience obtained at Derwentside on existing dwellings suggests a cost in the region of £1,200 per dwelling (see Johnston and Lowe, 2006). However, we believe that this cost is likely to exceed the costs of undertaking remedial airtightness work in newly constructed dwellings.
- 9 Three separate approaches have been proposed to address a number of the limitations previously identified with the pressure testing regime that is currently contained within ADL1A 2006.
- a) Direct quality control — This approach involves making a number of amendments to the current edition of ADL1A 2006. These amendments concentrate on providing clearer and more detailed guidance on a range of factors such as dwelling type, dwelling selection, registered testers and dwelling preparation. In addition, it is also suggested that the current sampling frequency should be increased such that a representative sample of dwellings is tested on each development.
 - b) Indirect quality control — This quality control approach would be outside the regulatory loop along the lines of the Robust Details system used by many developers with respect to Part E. It involves putting in place a national airtightness quality control system as an alternative to compulsory pressure testing or a direct regulatory checking process. Within the context of the scheme a random sample of visual inspections and pressure tests of completed dwellings would then take place to ensure that the dwellings are built as designed and meet the airtightness requirements of the Approved Document. Care would need to be taken with such an approach to ensure that the sampling protocols ensure statistical validity.
 - c) Compulsory testing — This is the most radical of all three approaches and would involve the compulsory pressure testing of all new dwellings. Although this approach would be the most expensive, and the UK does not currently possess the necessary testing capacity to implement it, this is the only approach that would ensure that the air permeability of all new dwellings is as specified in the calculation of the Target Emission Rate.

Introduction

- 10 This paper constitutes milestone D10 — Impacts of Pressure Testing of Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). The overall aim of this project is to investigate practical ways of achieving higher levels of airtightness performance than the current requirements of Approved Document Parts L1 and L2. This project addresses those issues relating to the domestic sector. Work is being undertaken in parallel on the airtightness of buildings in the non-domestic sector.
- 11 The project was undertaken in two parts:
 - a) Literature review — A conventional literature review was undertaken, 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.
 - b) Participatory action research — This part of the project was undertaken in three distinct phases and involved five developers (A, B, C, D and E) from the commercial and social housing sectors. Phase 1 involved a detailed assessment of the design and construction of five dwellings per developer (total of 25 dwellings) and pressure tests. In Phase 2, the results from Phase 1 were fed back to each of the developers in a participatory seminar and ways of improving airtightness were discussed with the developer and their design and construction teams. Phase 3 mirrored Phase 1 in which the design and construction of a further set of dwellings (five from each developer) was monitored following the feedback and enhanced understanding gained during Phase 2.
- 12 The purpose of this paper is to review the pressure testing regime that has been incorporated within Part L1A 2006 of the Building Regulations and discuss the effect that it is likely to have on the testing of new dwellings. It is anticipated that this discussion paper will form one of the inputs into the Forward Thinking Paper on energy conservation which is due to be updated in 2006. It is also intended that the findings of this work will be used to inform future revisions to Part L of the Building Regulations.

Pressure Testing and the Building Regulations: ADL1 2002 and ADL1A 2006

- 13 The 2002 edition of the Approved Document Part L1 (DTLR, 2001) came into effect in April 2002. This document (ADL1) requires that reasonable provision should be made to reduce unwanted air leakage. Compliance can be achieved by adopting the guidance given in the report on Robust Construction Details (see DEFRA, 2001), or by pressure testing the building following the method outlined in CIBSE Technical Memorandum TM23 (CIBSE, 2000). If a pressure test is to be undertaken, the air permeability of the dwelling must not exceed $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$. Although two separate methods of compliance are identified within ADL1 2002, in the vast majority of cases Robust Construction Details have been used as the basis for regulatory approval as obligatory pressurisation testing was not required.
- 14 In 2005, a major review of Part L1 was undertaken following the publication of a consultation document in July 2004 (ODPM, 2004). The outcome of this review has been the publication of two revised versions of the Approved Document Part L1; L1A Work in New Dwellings and L1B Work in Existing Buildings. The brief outline in this section is based on the final version of Approved Document L1A Work in New Dwellings (ADL1A), which was published in March 2006 (ODPM, 2006a).
- 15 ADL1A 2006 requires that the building fabric should be constructed to a reasonable quality of construction so that the air permeability is within reasonable limits (ODPM, 2006a). Guidance on a reasonable limit for the design air permeability⁴⁹ is given as $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$. In the majority of cases, checking compliance with the regulation will require some degree of compulsory pressure testing.⁵⁰ The exception to this concerns small developments of no more than two dwellings. On

⁴⁹ Design air permeability is defined in ADL1A 2006 as the value of air permeability that is selected by the designer for use in the calculation of the DER.

⁵⁰ Details of the pressure testing requirements are contained within Regulation 20B of The Building Act 1984 (ODPM, 2006b).

such sites an alternative approach to pressure testing can be adopted. This requires the developer to show that in the preceding 12 month period, a dwelling of the same type constructed by the same builder has been pressure tested and has achieved the required Dwelling carbon dioxide Emission Rate (DER⁵¹). Alternatively, the developer can avoid the need for pressure testing altogether by using a value of 15 m³/(h.m²) @ 50Pa for the air permeability when calculating the DER. However, in order to achieve the Target carbon dioxide Emission Rate (TER) the high permeability would have to be offset against substantial improvements in energy efficiency elsewhere in the dwelling(s).

- 16 On developments of more than two dwellings, the degree of pressure testing varies depending upon whether the dwellings have adopted accredited construction details or not. The pressure testing regimes associated with each method of compliance are as follows:
 - a) Dwellings that have adopted accredited construction details – One example of each dwelling type selected by the Building Control Body (BCB) will require testing from the first completed batch of units from each dwelling type. Dwelling type is defined in ADL1A 2006 as a dwelling of the same generic form; e.g. detached, semi-detached, end-terrace, mid-terrace, ground-floor flat, mid-floor flat, top-floor flat, and where the same construction methods are used for the main elements (walls, floors, roofs, etc). Blocks of flats are to be treated as a separate development.
 - b) Dwellings that have not adopted accredited construction details – The number of tests required are dependent upon the number of dwellings of the same type that occur on the development. If four or less dwellings of the same type occur on the development then one test of each type is required to be undertaken. If more than four but less than 40 dwellings of the same type occur on the development then two tests of each type are required to be undertaken. If more than 40 dwellings of the same type occur on the development then at least 5% of each type are required to be tested. This number may be reduced to 2% if the first five dwellings tested all achieve their respective design air permeability. As with the adoption of Accredited Construction Details, blocks of flats are to be treated as a separate development. The dwellings to be tested may be selected by the BCB in consultation with the builder and should be selected such that about 50% of the tests for each dwelling type are undertaken during the construction of the first 25% of each dwelling type. This will enable any lessons learnt to be fed back to the builder before the majority of the dwellings are constructed.
- 17 For those dwellings that fail to achieve the required design air permeability, remedial works should be undertaken on the dwelling and the dwelling re-tested. The remedial works should ensure that when the dwelling is re-tested the measured air permeability is less than 10 m³/(h.m²) @ 50Pa and the DER calculated using the measured air permeability is no less than the TER.⁵² In addition to undertaking the remedial works, another additional dwelling of the same type is also required to be tested, resulting in an increase in the testing sample size. An adjustment period of up to 31 October 2007 is included to allow for dwellings failing to achieve the target design air permeability figure to be temporarily subject to less stringent re-test targets. The re-test targets allow an improvement of 75% of the difference between the initial test result and the design air permeability or if less demanding, a test result within 15% of the required design air permeability. Alternatively, the TER can be revised by substituting the measured air permeability obtained by following the above re-test procedure for the value set out in Appendix R of Sap2005, and demonstrate that the DER is not worse than the revised TER.
- 18 ADL1A 2006 also introduces new guidelines over who should perform the obligatory pressure testing of dwellings and the procedures to be followed. Local authorities are authorised to accept as evidence a certificate from a person who is registered by the British Institute of Non-Destructive Testing (BINDT) in respect of pressure testing for the airtightness of buildings. The tests are to be performed using the procedure approved by the Secretary of State for air pressure testing, which is set out in the Airtightness Testing and Measurement Association (ATTMA) publication Technical Standard 1: *Measuring Air Permeability of Building Envelopes* (ATTMA, 2006). This publication is broadly based on techniques and methodologies outlined in BS EN Standard 13829:2001 (British Standards Institute, 2001).

⁵¹ The DER is the predicted rate of carbon dioxide emissions from the dwelling.

⁵² The TER is the minimum energy performance requirement for new dwellings approved by the Secretary for State. It is expressed in terms of kgCO₂/m² per annum emitted as a result of the provision of heating, hot water, ventilation and internal fixed lighting for a standardised household when assessed using approved calculation tools.

Issues Associated with the Pressure Testing Regime in ADL1A

19 There are a number of issues associated with the pressure testing regime proposed for L1A 2006. These issues relate to the following:

- Dwelling type.
- Dwelling selection.
- Registered testers.
- Independence of the pressure testing.
- Sampling frequency.
- Practicalities of testing.
- Air permeability target.
- Test procedure.

Dwelling type

- 20 The current definition of dwelling type contained within ADL1A 2006 categorises dwellings into a number of generic forms. These forms comprise detached, semi-detached, end-terrace, mid-terrace, mid-floor flat, ground-floor flat and top-floor flat and assume that the dwellings are built using the same construction methods for each of the main elements. Such a categorisation significantly simplifies the issues surrounding geometric form and the complexity of construction that exists in new UK housing. For instance, such a categorisation may not enable a distinction to be made between a 2.5 and a 2-storey end-terraced dwelling⁵³ or between a detached dwelling that incorporates an integral garage and one that does not. Instead, they would both be treated as a generic end-terrace and detached dwelling, respectively. This has important implications for airtightness because, all other things being equal, the more complex the form and detailed design (particularly of junctions), the greater the potential for air leakage (see Johnston, Wingfield and Bell, 2004).
- 21 The air permeability results observed in Phase 1 for developers C and E illustrate the effect that complexity can have on airtightness. The results illustrate that significant variations in air permeability (up to $4 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa) can be observed in dwellings of similar size, construction and form that had been constructed with comparable levels of workmanship and site supervision and by the same site team. The only observed difference between the dwellings was the complexity of the detailing. Higher levels of air permeability were consistently observed in those dwellings that contained the most complex detailing. The disparities in detailing were most common where certain design features required the primary air barrier to cope with complex changes in plane, negotiate structural members and accommodate changes in material. Such details included ground floor projections, rooms adjacent to semi-exposed areas, timber bays in masonry construction and complex junctions with ventilated cold roof loft-spaces. A more detailed discussion of these results can be found in Johnston, Miles-Shenton and Bell (2006).
- 22 The effect that complexity can have on airtightness has also been observed in a number of field trial dwellings that have recently been constructed at Stamford Brook in Altrincham, Cheshire.⁵⁴ Pressure tests undertaken on 26 of the dwellings illustrate a noticeable difference in air permeability between the different dwellings (see Figure 1). Although the small sample size precludes certainty, the mean air permeability of the 2½-storey terraced dwellings (five of the 27 dwellings tested, 19%) were some $3 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa higher than that measured for all of the other dwellings and over $2 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa higher than the design air permeability for the dwellings ($5 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa). The higher air permeability of the 2½-storey terraced dwellings was felt to be attributable to the fact that these properties incorporate more complex detailing associated with a room-in-the-roof design.

⁵³ Some BCBs may interpret 2.5 and 2-storey dwellings as two separate dwelling types if the top floor is built using a different method of construction for the external walls.

⁵⁴ The maximum design air permeability target for the field trial dwellings was $5 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ @ 50Pa.

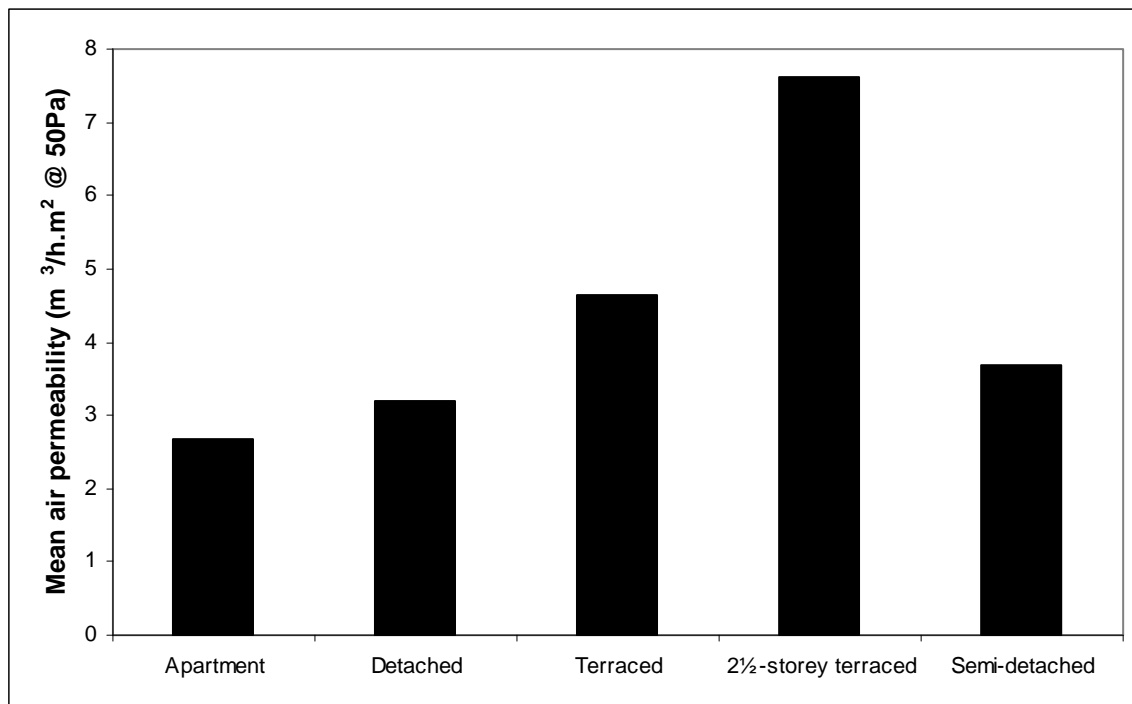


Figure 1 Mean air permeability of the field trial dwellings (adapted from: Wingfield and Bell, 2006).

- 23 Both results illustrate that the approach to testing set out in ADL1A 2006 is unlikely to capture the important house type issues that arise with respect to a viable testing regime. It is clear that dwellings of the same generic type will display considerable differences in geometric form and complexity of construction, characteristics which are likely to have a much greater influence on airtightness.

Dwelling selection

- 24 There are two issues relating to dwelling selection that are contained within ADL1A 2006. The first issue relates to the point at which the developer is notified of the dwellings that require testing and the second issue relates to the front loading of the testing requirement.
- 25 With respect to notification, ADL1A 2006 states that the BCB will select the dwellings to be tested and that these dwellings should come from the first completed batch of units of each dwelling type. However, no guidance is given within the document as to when the BCB should notify the developer of their selection. The point at which the developer is notified of the dwellings that are to be tested is crucial. If notification occurs either prior to the dwellings construction or early on in the construction process, then there may be an opportunity for the developer to make the dwelling more airtight than it would have otherwise been by undertaking 'additional measures' to the selected dwellings. These measures may include making changes to the dwelling's design, constructing the dwelling in a manner that would not normally be undertaken and placing a much greater emphasis on site supervision and workmanship. Consequently, the airtightness performance of the resulting dwelling may be much better than it would have normally been if it had been built as standard. However, if the developer is not notified of the selection until after the dwelling has been completed, say at the pre-handover inspection,⁵⁵ there will be no opportunity for the developer to undertake any 'additional measures' on the dwelling to improve its airtightness. Therefore, the airtightness performance of the constructed dwelling is more likely to be representative of the performance of other dwellings of the same type on that site.
- 26 In terms of when the selected dwellings should be tested, ADL1A 2006 states that when accredited construction details are being used all of the dwellings tested should be taken from the first completed batch of each type. If Accredited Construction Details are not being used, about 50% of

⁵⁵ Under the Council of Mortgage Lenders (CML) initiative lenders will not release the mortgage funds for new dwellings until the builder confirms that it has passed a pre-handover inspection by the NHBC or another warranty provider.

the required tests should be undertaken on the first 25% of each dwelling type constructed. The rationale for testing a significant proportion of the dwellings early on in the development is that it gives the developer sufficient time for any lessons learnt to be fed back into the design and construction process, enabling changes to be made before the majority of the dwellings are constructed. Although the rationale is sound, it is based upon a rather naïve view that once the developer demonstrates that the selected dwellings can be constructed to meet a particular airtightness target, the remaining dwellings on the development will also be constructed to the same standard of airtightness. This is unlikely to be the case as there will be little incentive for the developer to make sure that the remaining dwellings are constructed to the same level of airtightness. Consequently, those dwellings that are not required to be tested may have a higher air permeability than those that were tested.

- 27 Anecdotal evidence from the developments participating in Phase 3 of the project indicates that considerably greater care and attention to airtightness was being paid in those dwellings that were participating in the project. In those dwellings that did not participate in the project, there was a noticeable difference in the quality of workmanship in relation to airtightness. For instance, perpends were not fully filled, gaps were observed in the blockwork and there were gaps around built-in joists. This suggests that knowledge gained on airtightness from Phases 1 and 2 of the project may not have been disseminated to the workforce on site and are not featuring in standard quality control processes. Of course it must be acknowledged that this behaviour may be an artefact of the project since there was no requirement to achieve the same standard as the test dwellings across the development. Under the new regime the new regulatory context may make a difference but it cannot be assumed that it will.

Registered testers

- 28 With respect to who can undertake the pressure test, ADL1A 2006 states that local authorities are authorised to accept as evidence a certificate from a person who is registered by the British Institute of Non-Destructive Testing (BINDT) in respect of pressure testing for the airtightness of buildings. However, there is no requirement that the pressure tests must be undertaken by a BINDT registered person. The only requirement contained within ADL1A 2006 is that the results and data from the test are recorded based upon a manner approved by the Secretary of State and the results should be given to the local authority no later than seven days after the final test has been carried out. Since there is no requirement for the tests to be undertaken by a BINDT registered person, BCBs may accept test results from organisations that are not registered members of BINDT, as long as they can demonstrate that they are technically competent. Such a situation is likely to lead to issues relating to equity and fairness across the country, as some BCBs may prefer that the pressure test certificates are issued by a BINDT registered member, whilst others might not and there will be different interpretations of technically competent made by the various BCBs. It may also result in the same developer being treated differently in different regions of the country, due to variances in interpretation.
- 29 The requirements for becoming registered by BINDT in respect of pressure testing for the airtightness of buildings are laid down by the ODPM, as with all approved persons schemes. BINDT are currently in discussion with the ODPM over some of the requirements. The ATTMA is a special interest group within BINDT that are accredited to carrying out airtightness testing of buildings. At the time of writing, only six member organisations were listed on the ATTMA website, one of which is a national house builder. Due to issues surrounding commercial confidentiality, it is unlikely that other developers would allow this house builder to test their dwellings. In order to become a member of ATTMA the organisation must be accredited by UKAS to ISO/IEC 17025, with a scope covering airtightness testing to BS EN 13829:2001 (BSI, 2001) and CIBSE TM23 (CIBSE, 2000). At the time of writing, only nine organisations in the UK were UKAS accredited specifically to undertake building air leakage tests.

Independence of the testing

- 30 The 2004 consultation paper on Part L stated that any pressure tests should be carried out in an independent manner (ODPM, 2004). Interestingly, the guidance relating to the independence of pressure testing has been removed from ADL1A 2006. This implies that pressure tests could in theory be undertaken by the developer that constructed the dwellings or another organisation that has a vested interest in the outcome of the results. If this was to happen, it raises a concern relating to the quality and robustness of the tests and the procedures that would need to be in place to ensure an acceptable level of confidence in the results.

Sampling frequency

- 31 Under ADL1A 2006, the number of dwellings that are required to be tested are dependent upon the number of dwelling types on the particular development and the method that is being used to demonstrate compliance. In most instances, the sampling frequencies outlined in ADL1A 2006 are only likely to result in a small non-random sample of dwellings being tested on each particular development.
- 32 An analysis of the developments that were selected to participate in Phase 1 of the project was undertaken to determine the numbers of dwellings that are likely to be tested on a particular site if the dwellings were constructed in accordance with ADL1A 2006. Table 1 illustrates the results assuming that all of the developers adopt accredited construction details as the means of regulatory compliance. A detailed breakdown of each of the sites by dwelling type, and testing requirements if different compliance strategies are adopted, can be found in Appendix A. It should be noted that this analysis is merely illustrative and not necessarily representative of new UK developments as a whole.

Developer	Total number of units	Dwelling types	Total no of dwellings requiring testing	% of dwellings requiring testing
A	80	Mixture of apartments, terraced, detached and semi-detached properties.	11	14
B	86	Mixture of apartments, terraced, detached and semi-detached properties.	11	13
C	278	Mixture of terraced, detached and semi-detached properties.	4	1
D	143	Mixture of apartments, terraced, detached & semi-detached properties.	17	12
E	128	Apartments.	12	9

Table 1 Dwellings requiring testing assuming adoption of Accredited Construction Details.

- 33 The results illustrate that the proportion of dwellings requiring testing is likely to vary considerably between developments. In this particular instance there is over a ten-fold difference in the proportion of dwellings requiring testing, ranging from just over 1% for developer C to approximately 14% for developer A. The results also indicate that large developments with few dwelling types (developer C) will require a much smaller proportion of the dwellings to be tested than small developments with a large number of dwelling types (developer A). This issue is better addressed where non-accredited details are adopted, as the number of tests required on each dwelling type is dependent upon the number of instances in which that dwelling type occurs on the development.
- 34 The results for each developer have also been analysed further to determine the percentage of apartments and other dwelling types that are likely to require testing on each development (see Table 2). The analysis indicates that in all of the developments that incorporate apartments, a significantly greater proportion of the apartments require testing than the other dwelling types. This is despite that fact that apartments tend to be intrinsically more airtight than other dwelling forms of equivalent area.⁵⁶ The reason for the disparity in testing between the different dwelling types relates to the fact that under ADL1A 2006, each block of apartments has to be treated as a separate development. The results also illustrate that the smaller the apartment block, the greater the percentage of apartments that will require testing. In the case of developers A and B, 50% of the apartments will require testing as opposed to just over 9% of the apartments constructed by developer E.

⁵⁶ The reason for this is that apartments are more likely to have solid intermediate floors, fewer external door and window openings and fewer service penetrations.

Developer	Total number of units	Dwelling types	Total no of dwellings requiring testing	% of dwellings requiring testing
A	80	Apartments.	6	50
		Other dwellings	5	7
B	86	Apartments.	6	50
		Other dwellings.	5	7
C	278	Apartments.	0	-
		Other dwellings.	4	1
D	143	Apartments.	12	23
		Other dwellings.	5	6
E	128	Apartments.	12	9
		Other dwellings.	0	-

Table 2 Apartments and other dwellings requiring testing assuming adoption of Accredited Construction Details.

- 35 Another important implication of the analysis is that, in most cases, the sample sizes involved and the method of selection will result in samples that are not statistically significant. Therefore it will be very difficult for BCBs to be confident in the performance of those dwellings not tested. Further tests would need to be undertaken to establish whether the results obtained are likely to be truly indicative of the airtightness performance of the dwellings on the particular development as a whole. This could be achieved by undertaking tests on a randomly selected statistically significant sample of dwellings for each development.

Preparation for testing

- 36 ADL1A 2006 requires pressure tests to be performed using the procedure set out in the ATTMA Technical Standard 1: *Measuring Air Permeability of Building Envelopes* (ATTMA, 2006). This standard states that the building must be prepared prior to any tests being undertaken to allow effective pressurisation, and that the external envelope should be in its final completed state to enable representative results to be obtained. Responsibility for the preparation of the building is likely to vary depending upon the situation. If more than one test is to be undertaken, responsibility normally lies with the main contractor and/or client. However, if the test is a 'one-off', the testing organisation is likely to be responsible for preparing the building for the test. The standard also refers to BS EN 13829:2001 Method B – Test of the Building Envelope (BSI, 2001) as a method of preparing the building. Further guidance on preparing the building is also contained within the standard. However, since TS1 (ATTMA, 2006) encompasses procedures for both domestic and non-domestic building pressurisation testing, the guidelines contained within this standard tend to be generic, some of which are not particularly applicable to a large proportion of domestic buildings. For instance, the guidelines state that lift doors should be closed and reference is made to riser cupboards.
- 37 Experience suggests that it is not uncommon to arrive on site and find that the dwelling is unprepared for testing. In some instances the reason why the dwelling is unprepared relates to the fact that the developer is unaware of how to prepare the building for testing. For instance, during Phases 1 and 3 of the project it was not uncommon to find that the external envelope was complete but the drainage traps were not filled with water, external windows and doors were not closed, trickle ventilators were in the open position, the loft hatch was either missing or was open and the extract fans had not been turned off or temporarily sealed. These issues can easily be rectified on site and a test undertaken; however, this will increase the time taken to conduct the pressure test and may significantly decrease the number of tests one team could perform in a day. In time, it is expected that the occurrence of unprepared dwellings will diminish as developers gain more experience of pressure testing.

- 38 During this project It was not uncommon to arrive on site and find that the external envelope of the dwelling was in an unfinished state and various site operatives still working within the dwelling. This occurred in a number of instances during both Phases 1 and 3 of the project. In many cases, it would not have been possible to obtain representative results for the dwellings so the tests had to be abandoned. Experience from the non-domestic market does suggest that this occurs on a far less frequent basis when the contractor has to pay for this service.
- 39 It is also not uncommon to find that prior to the test, the developer has temporary sealed various elements of the building fabric in an attempt to achieve improved results. Any results obtained from testing such a dwelling will be unrepresentative and the dwelling will require to be re-tested at the developer's expense. Experience indicates that more direct guidance needs to be provided to developers prior to any testing that highlights their responsibilities and details how the building should be prepared.

Air permeability target

- 40 Although compliance with ADL1A 2006 will require all dwellings to achieve a maximum air permeability of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, the airtightness specification of many dwelling designs (particularly where fuels with a higher carbon intensity than gas are to be used) may have to be much lower than this. An air permeability of $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ or less may become a common design requirement, particularly post 2010. If this is the case, the average air permeability of the dwellings that are being constructed by the developer will need to reduce to a figure somewhere below the design air permeability target. The average figure will be dependent upon the failure rate that is acceptable by the construction industry and the shift in the distribution of air leakage that occurs as developers seek to achieve compliance. In order to establish what the average value may be for a given design air permeability, the existing distribution of air leakage⁵⁷ measured by Grigg (2004) has been scaled using a simple model⁵⁸ developed by Lowe, Johnston and Bell (2000). The model is as follows:

$$P_{(n50)} = aP_{0(n50)}$$

Where $P_{0(n50)}$ is the distribution of air leakage rates in current new dwellings, $P_{(n50)}$ is the distribution of air leakage rates following the introduction of ADL1A 2006, and a is a variable scaling parameter.

- 41 Figure 2 illustrates the resulting air leakage distribution assuming an initial failure rate of 10% and a design air permeability target of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. The resulting average air permeability rate that would need to be achieved by a developer would be around $7.0 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$. The results obtained from Phase 3 of the project illustrate that an average air permeability of around 7 can be achieved within new UK dwellings (see Johnston, Miles-Shenton and Bell, 2006). However, this requires the introduction of design-led improvements to the primary air barrier.
- 42 Figures 3 and 4 illustrate the resulting air permeability distribution if the design air permeability target is reduced to 7 and $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ with resulting average air permeabilities of 4.7 and $3.2 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, respectively. Recent results obtained from some field trial dwellings at Stamford Brook (see Wingfield and Bell, 2006) suggest that an average air permeability of around $4.7 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ can be achieved in practice by concentrating efforts on site supervision and workmanship and by maintaining continuity of the air barrier in the external walls by the application of a thin parging coat (3-4 mm) to all of the external walls prior to the application of the plasterboard dry-lining.
- 43 Achieving an average air permeability of around $3 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ is much more demanding as this level of air permeability is very tight by UK standards. Although an air permeability of less than $3 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ has been achieved in a number of dwellings constructed in the UK, for instance Stenness in Orkney (Scivyer, Perera and Webb, 1994), these dwellings tend to be one-off 'specials'. It is difficult to see how this level of air permeability could be consistently achieved in mass housing without there being a fundamental rethink of airtightness design in new UK dwellings.

⁵⁷ It is impossible to know what the distribution of air leakage would be following the adoption of a particular design air permeability.

⁵⁸ This model reduces the mean air leakage rate and the standard deviation of leakage rates in the same proportion. It is important to realise that this may not occur in practice and the adoption of a particular design air permeability rate may result in a very different distribution of air permeability.

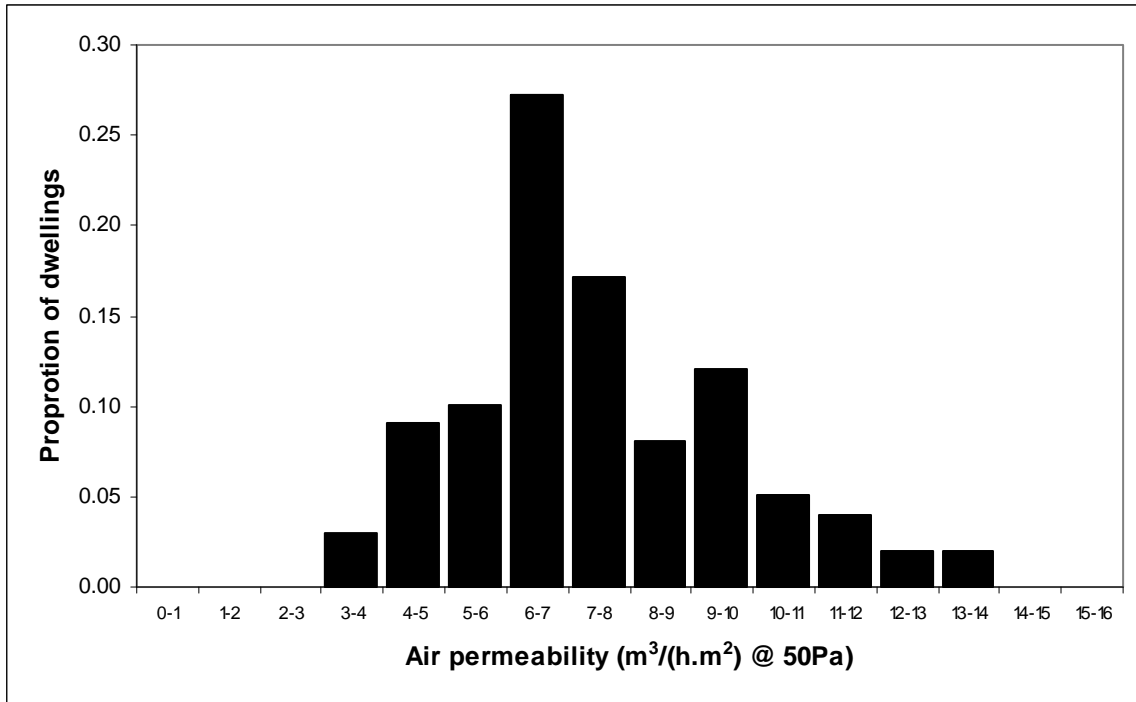


Figure 2 Distribution of air leakage rates assuming a design air permeability target of 10 m³/(h.m²) @ 50Pa and an initial failure rate of 10%.

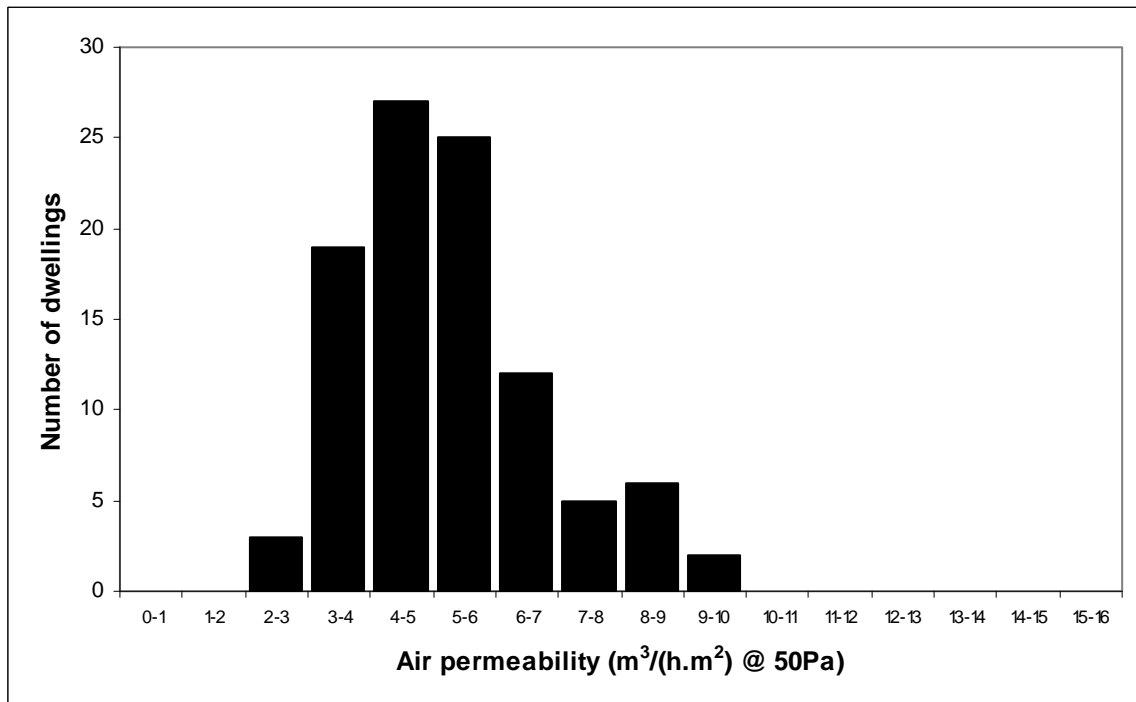


Figure 3 Distribution of air leakage rates assuming a design air permeability target of 7 m³/(h.m²) @ 50Pa and an initial failure rate of 10%.

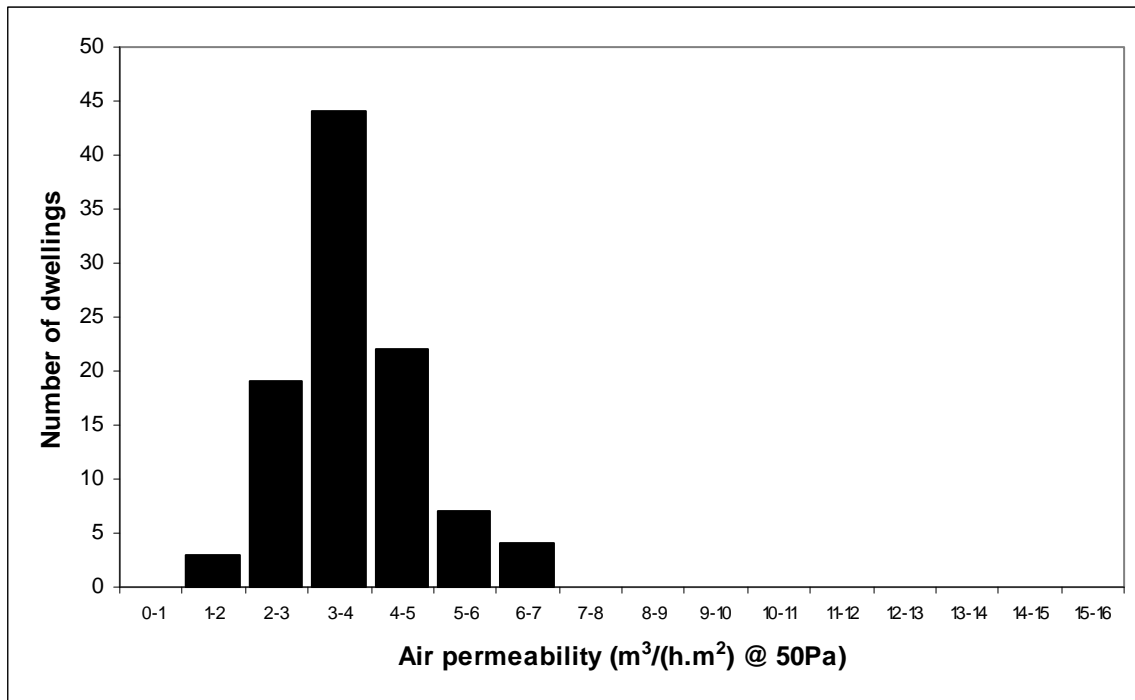


Figure 4 Distribution of air leakage rates assuming a design air permeability target of 5 m³/(h.m²) @ 50Pa and an initial failure rate of 10%.

- 44 Anecdotal evidence obtained from site, coupled with recent pressure test data from the field trial dwellings at Stamford Brook suggests that even when a demanding design air permeability target has been set (in this case 5 m³/(h.m²) @ 50Pa), there can be a deterioration in site workmanship and quality over time (Wingfield, Bell, Lowe and Bell, 2006). One of the first dwellings to be constructed on site was built to a high standard of workmanship and achieved an air permeability of 1.8 m³/(h.m²) @ 50Pa. This compares with the latest results obtained from site on a similar dwelling type where an air permeability of 3.6 m³/(h.m²) @ 50Pa was recorded. An analysis of the main air leakage points identified within both dwellings concluded that although air was leaking through the same points in both dwellings, it was leaking at a much greater rate in the leakier dwelling.
- 45 Another important point that is worthy of note is that airtightness tends to deteriorate over time (see Johnston, Wingfield and Bell, 2004). This effect has recently been observed in one of the dwellings participating in the field trial at Stamford Brook (see Figure 5). The dwelling was initially tested in February 2005 and achieved a mean air permeability of 3.3 m³/(h.m²) @ 50Pa. The dwelling was further tested in December 2005 and March 2006 and achieved a mean air permeability of 4.2 and 4.9 m³/(h.m²) @ 50Pa, respectively. This represents a deterioration in airtightness of almost 50% over the period of a year. The dwelling has been utilised as a show home and remained unoccupied over this time period; the increased leakage is presumed to be due to general shrinkage and other movement as the building envelope adjusts over time.

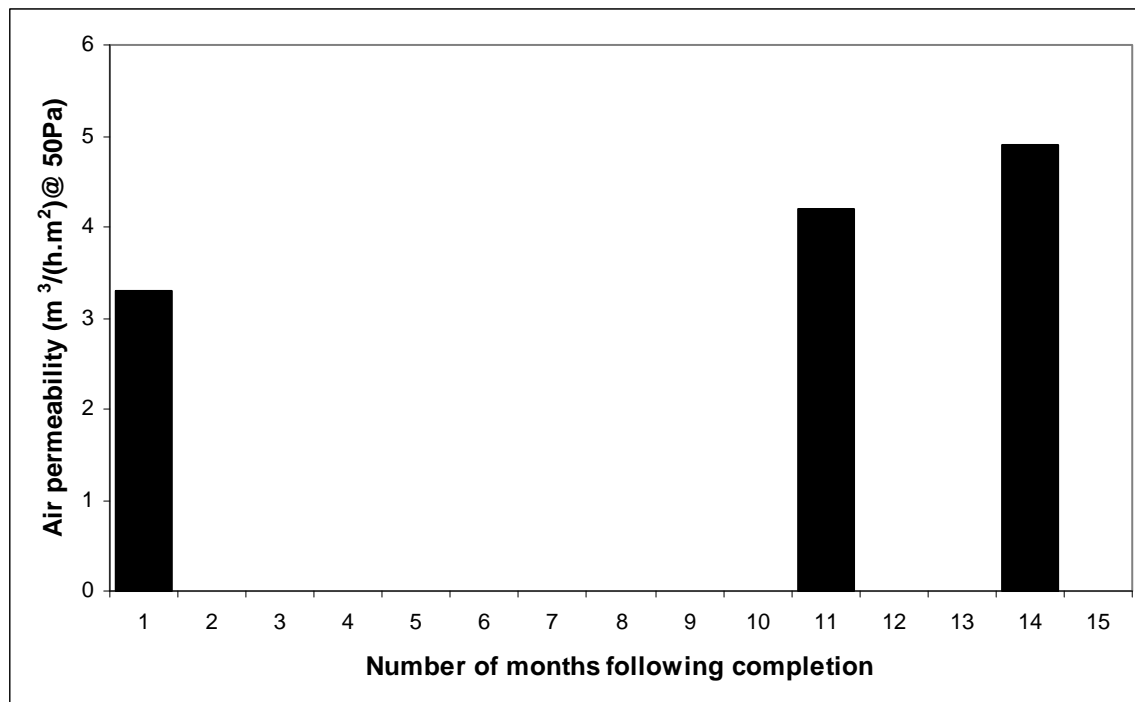


Figure 5 Effect of time on air permeability.

Test procedure

- 46 ADL1A 2006 states that the approved procedure for pressure testing a dwelling is given in ATTMA Technical Standard 1 — *Measuring Air Permeability of Building Envelopes* (ATTMA, 2006). This standard states that valid test results can be obtained by either pressurising or depressurising the building. Alternatively, the building can be pressurised and depressurised and the results averaged. This procedure is consistent with the advice given in CIBSE TM 23 (CIBSE, 2000). BS EN 13829:2001 (British Standard Institute, 2001), on the other hand, states that although compliance with the standard can be achieved by making only one set of measurements, it is recommended that two sets of measurements are made, one for pressurisation and one for depressurisation.
- 47 BS EN 13829: 2001 is not the only procedure to recommend that two sets of measurements are undertaken. The American Society for Testing and Materials (ASTM) standard E779-03 (ASTM, 2003) and the testing protocol devised by the BRE (see Stephen, 1998) both recommend that pressurisation and depressurisation tests are performed, and the results averaged.
- 48 There are valid reasons why two sets of measurements should be undertaken when pressure testing. All of the air leakage paths occurring within a dwelling will have particular aerodynamic characteristics that are dependent upon the direction in which the air is flowing. In addition, various elements of the building fabric, such as windows and doors, can either be pushed tight against their seals or pushed off, depending upon whether the dwelling is being pressurised or depressurised. Therefore, it is likely that more favourable results could be achieved by depressurising rather than pressurising the dwelling. By undertaking both sets of measurements and averaging the results, any aerodynamic effects cancel one another out and no preference is given to one set of results as opposed to the other.
- 49 Significant differences in the two sets of air permeability measurements can occur. For dwellings, CIBSE claim that it is common for the difference between the pressurisation and the depressurisation results to be more than 10% (CIBSE, 2000). Stephen (1998), on the other hand, suggests that the results can differ by as much as 20%. These sorts of differences in air permeability could make the difference between a dwelling complying with the requirements of ADL1A 2006 or not. Two examples in Phase 3 demonstrate this. In a pre-completion pressure test for Plot D76 constructed by developer D, the dwelling achieving an air permeability of 9.7 m³/(h.m²) @ 50Pa on depressurisation, whilst delivering an air permeability of 10.5 m³/(h.m²) @ 50Pa for pressurisation and a mean air permeability of 10.1 m³/(h.m²) @ 50Pa. A pressure test on Plot C21 built by developer C gave results of 9.6 m³/(h.m²) @ 50Pa on depressurisation, 10.4 m³/(h.m²) @ 50Pa on pressurisation and a mean of 10.0 m³/(h.m²) @ 50Pa. In both cases the choice of

depressurisation only, pressurisation only or mean permeability will determine whether a limit of $10 \text{ m}^3/(\text{h}\cdot\text{m}^2) @ 50\text{Pa}$ has been achieved or not.

- 50 An analysis of the results obtained for Phases 1 and 3 of the project was undertaken to determine the differences in air permeability that were measured when the dwellings were pressurised and depressurised. Tables 3 and 4 summarise the results. Details of the individual pressurisation and depressurisation results for each of these dwellings are contained in Appendix B.

Developer	Dwelling	Difference between pressurisation and depressurisation results (%)
A	9	0.6
	11	5.5
	12	3.1
	13	2.5
	14	2.5
B	79	0.7
	80 (pre-completion)	2.5
	80 (completed)	5.0
	81	4.7
	82	4.4
C	236	3.4
	237	0.7
	238	1.4
	239	4.7
	240	6.2
D	39	1.7
	42	5.3
	43	5.8
	44	2.5
	59	6.3
E	CG01	4.7
	CG02	1.2
	C201	8.1
	C202	0.5
	C301	11.3
	C302	1.1

Table 3 Difference in air permeability between pressurisation and depressurisation in Phase 1 dwellings.

Developer	Dwelling	Difference between pressurisation and depressurisation results (%)
A	64	4.8
	65	10.0
	66	0.6
	79	2.2
	80	2.0
B	14	14.5
	16	3.5
	17	1.2
	21	0.3
	22	0.8
C	193	3.9
	194	13.4
	17 (1 st fix)	1.2
	17 (2 nd fix)	3.7
	17 (completed)	3.7
	18	6.1
	19 (1 st fix)	0.3
	19 (2 nd fix)	1.7
	19 (completed)	0.4
	20	6.4
	21	8.3
D	73	1.3
	74	1.4
	75	7.3
	76 (pre-completion)	8.0
	76 (completed)	7.8
	96	7.0
E	AG01	0.2
	AG02	5.1
	A201	3.2
	A202	2.1
	A301	3.1
	A302	0.8

Table 4 Difference in air permeability between pressurisation and depressurisation in Phase 3 dwellings.

51 The results indicate that the difference between the two measurements can vary significantly. In the Phase 1 and Phase 3 dwellings this difference ranged from less than 1% to more than 14%, with an average of 4.1%. This difference is comparable to the figures stated by CIBSE (2000). In addition, in most instances, the depressurisation results obtained were lower than the corresponding pressurisation results.

Logistics of Compulsory Pressure Testing

52 In order to discuss the logistics for pressure testing a number of questions need to be addressed. These questions are as follows:

- How many new dwellings are likely to be tested per year?

- How many hours per year would you be able to test?
- How many blower doors are likely to be needed to meet testing demand?
- What are the costs involved in undertaking a pressurisation test?
- What are the likely remedial costs associated with failing a test?
- What are the likely costs in making new dwellings airtight?

Number of dwellings requiring testing

53 The number of new dwellings that will require testing each year will depend on the strategy adopted for regulatory compliance, the size of the development and the variation in dwelling types across each development. NHBC new house-building statistics (NHBC, 2006) show that in 2005, 16% of all NHBC registered new dwelling starts in Great Britain were by builders building less than 30 units per year (smaller developers), 24% by builders building between 31 and 499 units (medium size developers) and 60% by builders building over 500 units (large developers). The full breakdown is provided in figure 6. If these proportions are applied to the total number of UK dwelling completions for the year ending April 2005⁵⁹ it is estimated that some 124,000 dwellings were constructed by large developers, 49,000 by medium size developers and 33,000 by smaller developers.

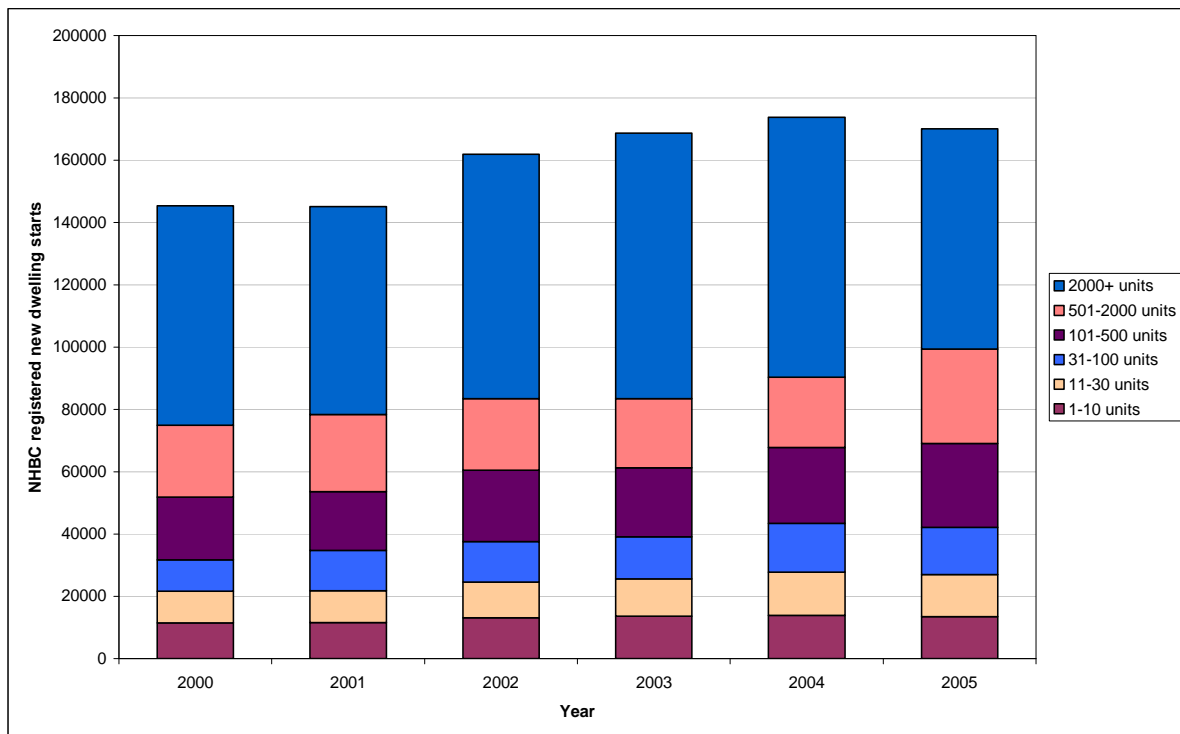


Figure 6 Number of NHBC registered dwelling starts by size of builder (Source: NHBC, 2006).

54 It is expected that the proportion of smaller developers relying on testing for Part L compliance will be high since they often operate from GA drawings and, at least in the short term, may not be in a position to develop a suitable set of details that follow generic accredited details. This is likely to contrast with large developers, who will be capable of supporting the technical infrastructure necessary to adapt designs and recalculate emission rates as required, in order to achieve compliance through an Accredited Construction Details route. In the case of large developers it is assumed that the testing requirement will be around 10%. This is broadly in line with the analysis of

⁵⁹ Figures for the proportion of output by size of builder were available for NHBC dwelling starts only (NHBC, 2006). In an ideal world a similar breakdown would be available for completions. However, given the relationships between starts and completions it is unlikely that the proportions would differ significantly and in calculating the likely number of tests the proportions have been applied to completions. Similarly, since NHBC statistics on completions represent about 84% of the UK total, the proportions have been applied to the national totals in deriving the estimates of test numbers. The ODPM Live Table 201 (Housebuilding: permanent dwellings started and completed — ODPM, 2006c) has been used for dwellings completed in 2004/5 (205,991).

the schemes studied as part of this project and set out in Table 1. For small developers, less inclined to use the Accredited Construction Details route, proportions of 25% and 50% have been adopted, based on an assessment of likely development size. The figures for medium sized developers are assumed to be somewhere between 10% and 25%. Using 2004/5 construction completions (ODPM, 2006c) as the base figure, and applying the different proportions, it is estimated that some 12,000 units will be tested for large developers, 5,000 to 12,000 for medium sized developers and 8,000 to 16,000 for small developers.

- 55 Using the above set of assumptions it can be estimated that the number of new dwellings that will require pressure testing, under the schedule specified in Section 2 of ADL1A, will initially fall within the range of 25,000 to 42,000 per year. Given that any dwellings that fail a pressure test will require a re-test and, where appropriate, another dwelling of the same dwelling type will be selected for testing; the actual number of pressure tests to be performed per year may fall towards the higher end of this range or even extend beyond it. Of course the numbers quoted are, to a large extent, speculative and are designed more to capture a likely range rather than be definitive. However the principal message is that a relatively large number of tests will be required and at least in the early phase of operation there will be considerable uncertainty
- 56 A general trend towards the construction of multi-dwelling buildings may also increase the number of dwellings that require testing. As indicated in Tables 1 and 2, developments containing a greater variety of dwelling types can result in a higher proportion of dwellings that require testing. With more new-build sites including small apartment blocks, to achieve desired population density levels, and each block being regarded as a separate development, the number of tests required under ADL1A 2006 may increase further. The current ODPM live tables, a selection from which is illustrated graphically in Appendix C, show the increasing number of apartments being constructed. In 2004/5 apartments constituted 41% of new dwellings in the United Kingdom, with fractions highest in the South East (47%) and London (83%). Recently published NHBC new house-building statistics (NHBC, 2006) further illustrate this trend. Figure 7 reveals that in the final quarter of 2005, 49% of all new dwelling starts in England were classified as 'flats and maisonettes'. How much of the increase in flat construction is due to the increasing trend for small blocks of flats included in larger developments is unclear; but with current market and political pressures to build more affordable housing and attain specific requirements for population density on many new developments, it is a trend that looks likely to continue in the near future,⁶⁰ with an increase in the number of dwellings to be tested.

⁶⁰ It must be acknowledged that the extent to which the current trend is set to continue is very difficult to predict in the medium term. The rate of increase is likely to slow but changes in household structure and other pressures may well continue to apply upward pressure or at least maintain the proportion at current levels.

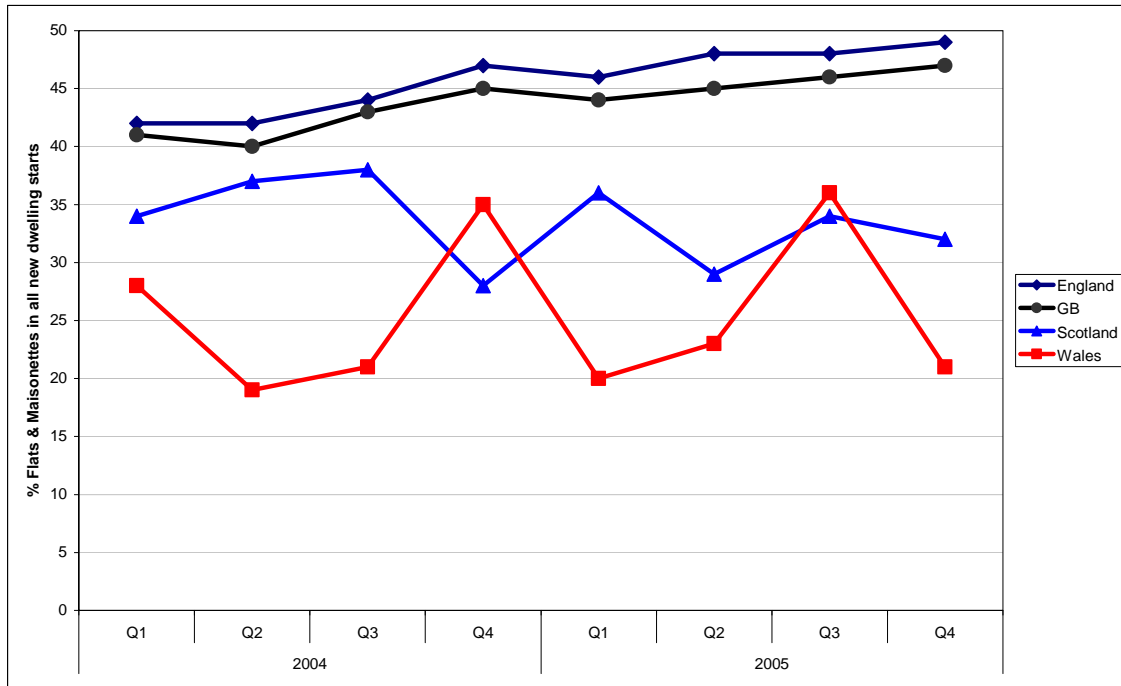


Figure 7 Proportion of flats and maisonettes, as a percentage of all NHBC registered dwelling starts, by quarter, for 2004 and 2005 (Source: NHBC 2006).

Number of hours available for testing

57 The approved procedure for pressure testing stated in ADL1A is ATTMA's Technical Standard 1 *Measuring Air Permeability of Building Envelopes* (ATTMA, 2006), which allows for a standard testing procedure to be carried out only when the following criteria have been met:

- Wind speeds are below 6 ms^{-1}
- Variations to the baseline pressure difference are below $\pm 5 \text{ Pa}$ (average over a 30 s period)
- The indoor/outdoor temperature difference multiplied by building height must not exceed 500 mK (for the purpose of dwellings, this only affects large apartment blocks)
- The r^2 correlation coefficient remains above 0.98

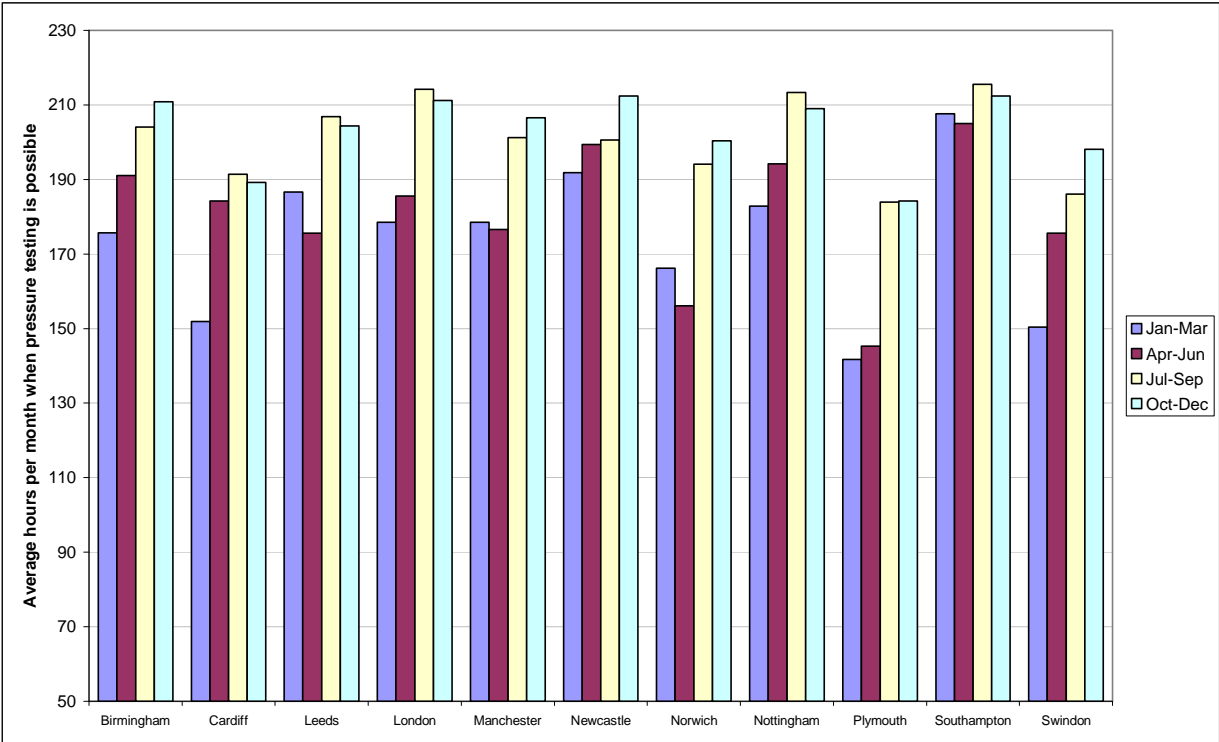
58 A testing regime is suggested for atmospheric conditions outside of these, by using increased pressure differentials and taking a greater number of readings. Appendix B Test Equipment Requirements of TS1 (ATTMA, 2006) is based primarily around BS EN 13829:2001 Thermal Performance of Buildings — Determination of *Air Permeability of Buildings — Fan Pressurisation Method* which notes:

"In calm conditions the overall uncertainty will be less than 15 % in most cases. In windy conditions the overall uncertainty can reach 40 %" (BSI, 2001 p15).

Our experience suggests that the air permeability measurements obtained using ADL1A's approved extended test procedure for more extreme meteorological conditions, contained in *Measuring Air Permeability of Building Envelopes* (ATTMA, 2006), will give the same mean air permeability (within experimental error) to that supplied by the standard test procedure under suitable conditions. However, the air permeability values calculated under pressurisation only or depressurisation only can vary considerably using the extended procedure (in excess of the values offered in Tables 3 and 4), as higher pressure differentials affect air movement, particularly around certain components such as doors, windows and loft hatches where the additional positive or negative pressure will force such components open or shut. There is also a higher likelihood under the extended test methodology that the r^2 correlation coefficient will display a greater level of inconsistency and fall below the 0.98 minimum, rendering the test results invalid. This is particularly the case when the wind is variable in both strength and direction. In such cases differential pressure and flow measurements can display large variations over very short periods of time and provide inconsistent results, hence wind conditions have a major effect on the number of hours when reliable pressure testing results are achievable.

59 In order to estimate the number of hours in which reliable pressure tests could be undertaken, an analysis of weather data obtained from CIBSE/Met Office for a semi-empirical Test Reference Year⁶¹ (CIBSE, 2005) was carried out. This weather data was corrected to a height of 2 m above ground level (the height at which wind speed measurements are taken on site) using the methodology outlined within CIBSE Guide J: *Weather, Solar and Illuminance Data* (CIBSE, 2002) and Terrain Category III (suburban or industrial areas). Assuming a working day from 8am to 6pm, for the 11 cities in England and Wales incorporated within the CIBSE/Met Office data set, meteorological conditions would be unsuitable for the standard tests to be carried out at five of the sites (Birmingham, Nottingham, Newcastle, London and Southampton) for less than 5% of the time, for another five (Cardiff, Leeds, Manchester, Norwich and Swindon) this could be expected to be 5–10% of the time, and over 10% of the time for one of the sites (Plymouth). In addition to this regional variation, there are also monthly and hourly trends which affect the time available for testing (see Appendix D). Conveniently, the most common occurrences of high wind speeds are in the first quarter of the year when the number of dwelling completions is traditionally at its lowest, with the least common occurrences in the third and fourth quarters. Daily, the general trend is for wind speeds to increase steadily throughout the morning, peaking in the early afternoon, with maximum wind speeds usually reached between 1pm and 4pm.

60 Using the above methodology, and assuming testing is not carried out at weekends and bank holidays, the average maximum number of hours available for testing per month is illustrated in Figure 8 for the 11 locations contained in the CIBSE/Met Office data set, based on wind speed alone. It must be stressed that the values represented in Figure 8 are an absolute maximum based on data from the test reference year, and may include individual hours within days when only a few hours had atmospheric conditions suitable for pressure testing. In addition, the use of quarterly figures smooth the monthly trends to some extent, with the monthly figures ranging between 120 and 222 hours per month for Plymouth in January and Southampton in July, respectively. The wind speed does not always need to exceed 6 ms⁻¹ to prevent an accurate test result being obtained. Although high wind speeds will produce significant pressure differences on various parts of the dwelling; variable gusting and changeable wind directions will also affect baseline pressure difference and may render any test results invalid, even if the extended procedure suggested in ATTMA TS1 is followed.



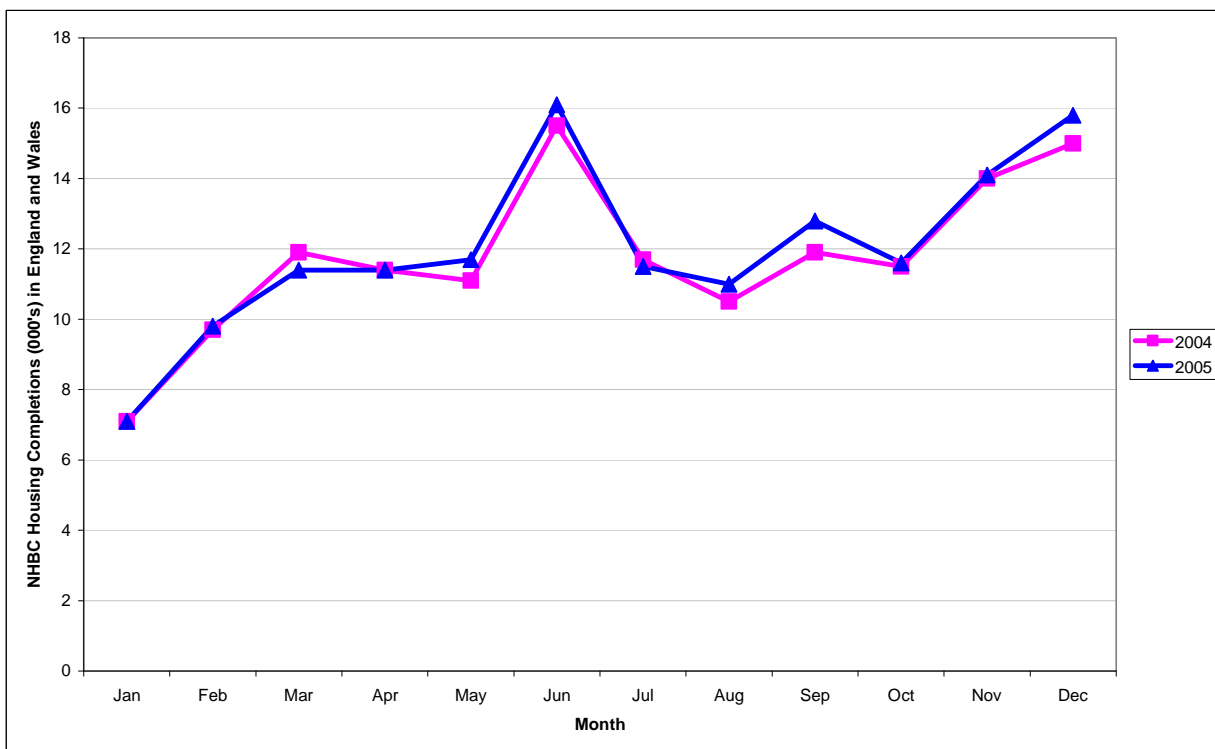
⁶¹ The CIBSE/Met Office Test Reference Year is comprised from hourly weather data for 12 typical months, selected from data sets recorded between 1983 and 2004, adapted to provide a continuous 12 months sequence of data. This is a purpose built data set to enable modelling and simulation under typical weather conditions.

Figure 8 Average hours per month when pressure testing is possible, based on wind speed $<6 \text{ ms}^{-1}$ at 2 m above ground level, terrain category III, between 8am and 6pm, working days only.

61 The number of available testing hours is likely to be reduced further by other factors. The above figures are adjusted to a terrain category III which simulates a suburban location. In more exposed areas the wind speed at 2 m above ground level will be greater, with fewer obstacles and a reduced surface roughness. The winter months present a potential problem with extreme differences in temperature inside and outside the dwelling resulting in less reliable test readings, particularly in larger apartment blocks, increasing the possibility of the correlation coefficient falling below the minimum acceptable level. Performing tests in a number of locations on the same day may also require substantial time spent travelling between sites, further limiting the time available for testing.

Meeting the demand for testing

62 House-building statistics for 2004 and 2005 (NHBC, 2006) show that the monthly number of dwelling completions, and hence the probable number of pressure tests required under ADL1A (ODPM, 2006a), can vary by over 100% as shown in Figure 9 and Table 5. With ADL1A recommending that 50% of initial tests for each dwelling type are carried out during construction of the first 25% of the development, the link between completions and pressure testing may not be straightforward. However, with any test failures requiring re-tests plus the selection of an additional dwelling for testing, and many construction phases of individual developments invariably grouping together certain dwelling types (as observed in sites B and D of this project⁶²); it is expected that the testing regime on many sites will not be completely front-loaded. On smaller sites where a higher sampling proportion is required, particularly where Part L compliance is not sought through the adoption of accredited details, the link between the number of completions per month and the number of pressure tests per month is likely to be strongest. With such a high variation in the anticipated requirement for testing throughout the year, the number of active teams necessary to carry out these pressurisation tests will also vary on a monthly basis. This is envisaged to reach peaks each June and December, when a high number of completions will require pressure testing. In December this is further compounded as the number of testing days available is reduced by annual holidays.



⁶²Site B was built in two phases: Phase 1 consisted of only detached and semi-detached dwellings, Phase 2 contained all dwelling types. Site D was built in three phases: Phase 1 was comprised of apartments, detached and semi-detached dwellings, Phase 2 only detached and semi-detached dwellings, Phase 3 included apartments, detached, and end and mid-terraced dwellings.

Figure 9 Number of NHBC registered dwelling completions, by month, for 2004 and 2005 (Source: NHBC, 2006).

	January		June		December	
	000's	% of annual total	000's	% of annual total	000's	% of annual total
2004	7.1	5.0	15.5	11.0	15.0	10.6
2005	7.1	4.9	16.1	11.2	15.8	10.9

Table 5 Number, and proportion of annual total, of NHBC registered dwelling completions for selected months in England and Wales (Adapted from: NHBC, 2006).

- 63 Given the data on numbers of hours for which testing is possible and the seasonal trends in dwelling completions, it is conceivable that the average number of tests to be carried out each working day, in England and Wales, could exceed 200 or fall below 80 depending purely on the month of the year. This vast range can be further compounded by considering additional regional variations, atmospheric conditions and levels of exposure.
- 64 The number of tests that could be undertaken in a day by a single team is not only dependent upon the weather conditions, location of the development compared with tester and proximity of sites (if more than one site is to be tested in one day), but also upon dwelling availability. Our experience suggests that currently it is unusual on low-rise developments to have more than two or three dwellings available on each development at any one time. Staggered build programmes are favoured by many developers as they allow a smaller number of subcontractors of a single trade to move from plot to plot, rather than a larger number all hired at once, giving greater flexibility. The introduction of compulsory pressure testing may encourage developers to revise build programmes once testing costs and availability begin to gain more consideration. This is not such an issue for larger apartment blocks where whole blocks, or a number of apartments in a particular section, are completed for handover at the same time, allowing a number of dwellings to be tested in a single visit.
- 65 Estimates that eight to 10 pressure tests can be undertaken in a day by a single test team have been suggested.⁶³ Our experience indicates that this figure is unrealistic, and that a maximum of three or four tests per day is more likely. This figure is based upon a brief time and motion study (Appendix F) on how long it takes to undertake a test, and the fact that there are rarely more than two or three dwellings at a suitable stage of completion for testing at any one time on any one site before being handed over to the purchaser. It also does not take into account the number of times when a testing team turns up on site to perform a pre-arranged pressure test and the test cannot be conducted for other unforeseen reasons such as water leaks, damage caused through theft and vandalism, and dwellings not being ready on time. However, it is anticipated that commercial imperatives are likely to reduce this problem in the medium to long term.
- 66 Assuming that a single testing team can perform pressure tests on an average of three or four dwellings per working day, the above figures would require a minimum of 20 to 25 testing teams available in January to cover the testing requirements in England and Wales under ADL1A 2006. In June and December the minimum number of teams required would rise to between 50 and 65. If, given all the factors, the average testing rate falls to two dwellings per day per team, the number of teams required to meet the testing demand would increase to over 40 in January and more than 100 in June and December.

Costs involved in undertaking pressure tests

- 67 The commercial charge for undertaking a pressurisation test on a single dwelling on a single site is currently of the order of £500 excluding VAT plus travel/subsistence costs, although quotations far in excess of this are not uncommon. The introduction of compulsory airtightness testing for dwellings may result in increased competition and economies of scale which will reduce this figure in the medium and long term. However, the dominating factor in estimating the cost per test is how many tests can be performed in a single visit and, as noted above it is currently uncommon for more than two or three dwellings to be ready for testing on any given day. Experience suggests that instances where greater numbers of dwellings are available for testing normally only occur with

⁶³ BSRIA seminar 11-Oct-2005

multi-dwelling buildings such as apartment blocks. The costs associated with undertaking any additional tests once on site are marginal, and are of the order of £100 per dwelling excluding VAT.

- 68 The number of tests possible in a single visit can vary considerably depending on whether the dwellings have been fully prepared prior to the tests. With a fully prepared dwelling the time taken to perform an individual pressure test (dwelling inspection, equipment assembly and disassembly, recording of atmospheric data, taking test readings) can be as little as 30 minutes, however, this is rarely the case. Most dwellings will require additional preparation prior to the test being performed if accurate results are to be achieved. If the tester has to perform temporary sealing, additional costs are incurred in terms of both labour and consumables. The processes of signing in and out of site, undergoing a site induction, obtaining access to the dwellings, unloading and loading equipment from the vehicle and waiting for operatives to vacate the dwelling can all add significant amounts of time, and therefore cost, to the test procedure (see Appendix F). Travelling time between sites may also become a key cost factor, particularly in more rural areas with smaller sites and a greater geographical distribution.
- 69 In consideration of current commercial charges for performing domestic pressure tests, rates are weighted towards staffing costs. With direct costs for travel and subsistence overshadowing those for consumables. Capital costs and overheads will vary greatly depending upon the size of the testing organisation, and the infrastructure that the organisation presently has in place. ATTMA members and other UKAS accredited testing stations will benefit from in house facilities to calibrate test equipment and train staff.
- 70 Appendix E lists the necessary equipment for a blower door kit and suggests a current approximate net cost of around £3,200. This figure does not include delivery, calibration or training, and assumes that the purchaser will already own certain essential items including a computer suitable for running the necessary software. The cost of such a blower door kit should not prove prohibitive for most house builders should they want to perform pre-completion testing themselves to ensure that their dwellings will achieve the desired level of airtightness in a subsequent authorised test. However, it remains to be seen whether developers adopt this approach as the testing regime matures.

Remedial costs

- 71 The costs associated with failing to gain the pressure test result required to achieve the TER may not initially be fully appreciated by the developers until they have experienced it. As well as incurring costs associated with improving the airtightness performance of the failed dwelling to the re-test target level, the developer will also have to pay to re-test the dwelling and test another additional dwelling of the same type on the development. In addition, it is also likely that leakage detection will also be performed on the failed dwelling so that any remedial action can be better focused. This detection work will also increase the costs associated with failing the initial pressure test.
- 72 Little is known about the costs associated with undertaking remedial work in dwellings that have exceeded an air permeability target. However, experience suggests that the costs could vary significantly and will be dependent upon the scale of the reductions in air permeability that will be required, the location of the main air leakage points and the amount and nature of the remedial work that is required to be undertaken. For instance, it may be possible to reduce the air permeability of the dwelling by undertaking some simple secondary sealing measures such as sealing service penetrations through walls, whilst in other instances much more intrusive work may need to be undertaken such as replacing plasterboard dry-lining, removing carpets, replacing floors and redecoration.
- 73 An indication of the costs associated with undertaking remedial airtightness work on dwellings has been obtained from work on a small number of existing dwellings (12 in total) that were refurbished at Derwentside, County Durham (see Johnston and Lowe, 2006). The dwellings were built in the early 1970s using dry-lined load-bearing cavity masonry construction and, prior to the refurbishment, the dwellings were in a poor state of repair with an air permeability of between 24 and 26 m³/(h.m²) @ 50Pa. A programme of general and targeted airtightness work was carried out by Leeds Metropolitan University in conjunction with a partial refurbishment undertaken by Derwentside District Council. Following these works, the air permeability of the dwellings was reduced by almost 55%, to a mean of just over 11 m³/(h.m²) @ 50Pa. The costs of undertaking the remedial airtightness work were in the region of four man days per dwelling, plus approximately £200 in total material costs (majority of which was expanding polyurethane foam). Assuming a

labour cost of approximately £250 per day, the total costs at current rates would be in the region of £1,200 per dwelling. Of course the lack of published data on this issue means that any figures quoted at this stage are highly speculative.

Cost of making dwellings airtight

74 Little is also known about the additional costs associated with achieving the airtightness standards in ADL1A. Costs are likely to be dependent upon the method of construction used, the approach taken to make the dwellings airtight and the target air permeability rate. However, the results obtained from Phase 3 of the project provide some evidence. In the case of eight dwellings from Phase 3 significant reductions in air permeability were achieved (reductions averaging 47% and up to 60% were observed based upon the Phase 1 mean) by introducing design-led changes that focus attention on the primary air barrier, its identification and its continuity (see Table 6). The direct costs of achieving this ranged from a relatively modest one man day per dwelling plus minimal material costs, suggesting figures around £300 to £400 (dwellings B16 and B17), to an estimated amount possibly in excess of £1,000 (dwellings A79 and A80). Although the changes adopted and the scale of the reductions achieved varied between the developers, all of the dwellings achieved an air permeability of less than $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$.

Dwelling	Action taken	Construction type	Phase 1 equivalent ($\text{m}^3/(\text{h.m}^2) @ 50\text{Pa}$)	Phase 3 test result ($\text{m}^3/(\text{h.m}^2) @ 50\text{Pa}$)
A79	Additional sealing (with mortar, tape, mastic and expanding polyurethane foam) of blockwork, loft boundary and service penetrations prior to dry-lining.	Dry-lined load bearing cavity masonry	14.3	6.5
A80	Additional sealing (with mortar, tape, mastic and expanding polyurethane foam) of blockwork, loft boundary and service penetrations prior to dry-lining.	Dry-lined load bearing cavity masonry	11.8	5.6
B16	All internal blockwork and junctions inspected at pre-plaster stage and additional pointing work undertaken to remedy any defects.	Dry-lined load bearing cavity masonry	10.5	5.6
B17	Application of a 3-6mm full parging layer to the blockwork prior to dry-lining.	Dry-lined load bearing cavity masonry	10.5	5.7
D76	Additional sealing (with tape, mastic and expanding polyurethane foam) and a minor design change at the intermediate floor level.	Light steel frame	13.5	8.9
C17	Application of a full parging layer to the blockwork prior to dry-lining.	Dry-lined load bearing cavity masonry	11.7	6.1
C19	Amended semi-exposed wall detail and application of a full parging layer to the blockwork prior to dry-lining.	Dry-lined load bearing cavity masonry	15.2	7.3
C193	Amended semi-exposed wall detail and additional detailed inspection of blockwork, openings and service penetrations prior to dry-lining.	Dry-lined load bearing cavity masonry	15.0	9.6

Table 6 Reductions in air permeability that were achieved by introducing design-led changes.

75 Data obtained from the Stamford Brook project (Lowe and Bell, 2002) suggests that very high levels of airtightness, by UK Standards, can also be achieved for moderate costs. Besides additional staff training in airtightness awareness, the two main material measures adopted within the dwellings was the application of a thin plaster-based parging coat to the internal blockwork face of all of the external and party walls and high performance windows and doors with improved U values, sealing and trickle vents (see Figure 10). The costs associated with incorporating the parging layer into the dwellings have been estimated at ranging from £277 to £693 depending on the size of the dwelling. Although the specification of high performance windows and doors contributed to improved airtightness the additional cost (£1,535 to £1,673, Roberts, Anderson, Lowe, Bell and Wingfield, 2005) is not primarily related to airtightness, since much of the cost lies in achieving a U-value of 1.3 W/m²K and the specification of timber instead of PVCu. In principle there is no reason why well sealed windows should add any additional cost since, with the possible exception of the trickle vents, most standard frame units are as airtight as those used at Stamford Brook. The cost of higher performance trickle vents is almost certainly marginal. The resulting mean air permeability of the dwellings tested to date on this site is 4.9 m³/(h.m²) @ 50Pa, with the test sample consisting of 31 dwellings in total including 28 houses and three apartments.

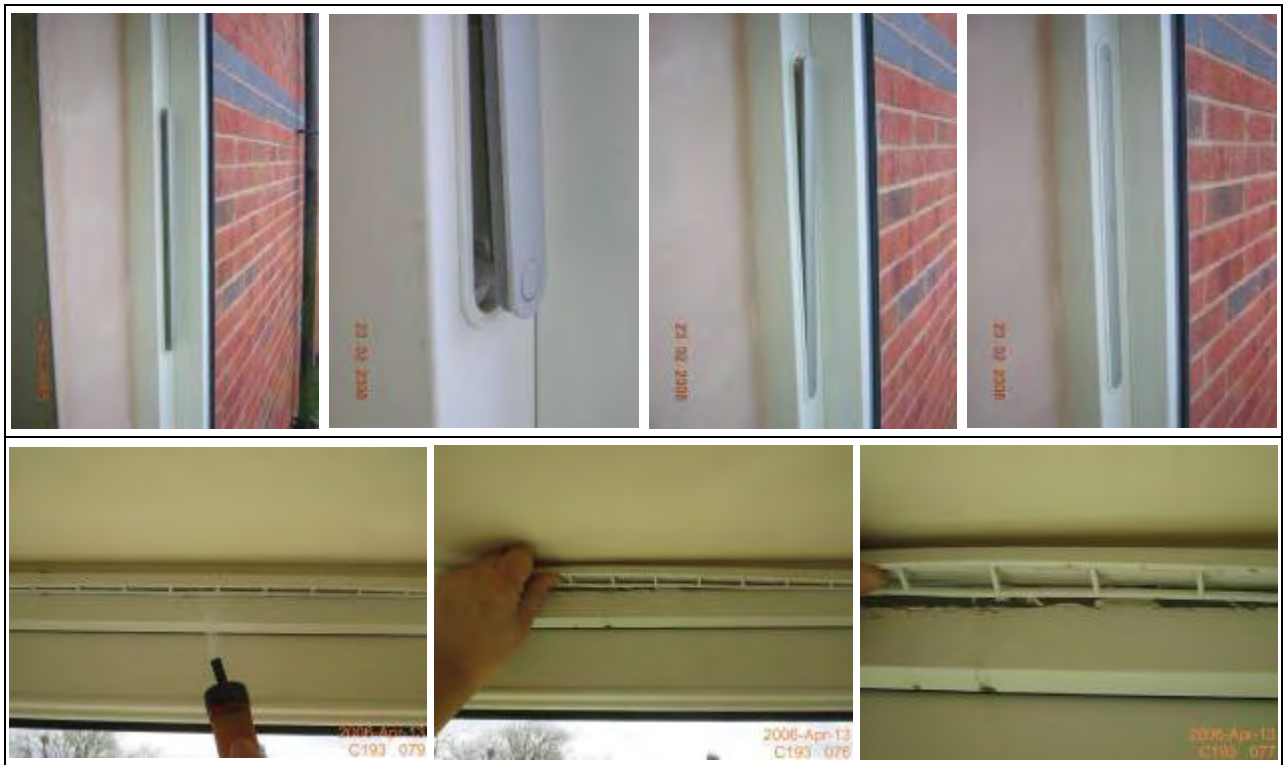


Figure 10 High performance trickle vents with compressible seals fitted at Stamford Brook (top) compared with a typical, significantly less airtight example observed during this project (below).

Proposals for Pressure Testing

76 It is clear from the previous discussions that there are a number of limitations associated with the pressure testing regime that is currently incorporated within ADL1A 2006. In order to address a number of these limitations, we have proposed three possible approaches to improving the testing regime contained within ADL1A 2006: These approaches are intended to represent three distinct methodological approaches to incorporating a pressure testing regime into ADL1A 2006. The approaches proposed are as follows:

- Direct quality control.
- Indirect quality control.

- Compulsory pressure testing of all new dwellings.

Direct quality control

- 77 This option would follow the approach established in ADL1A 2006 but with considerable revision. These revisions would concentrate on improving the nature of the sampling regime and the guidance given on pressurisation testing. The amendments would be as follows:
- a) The current definition of dwelling type that is contained within ADL1A 2006 would be revised so that it is capable of capturing the considerable differences in geometric form and complexity of construction that can exist within dwellings of the same generic form. This would not be a straightforward process since it would require some complex definitions of house type and could be prone to misinterpretation.
 - b) Clear guidance incorporated within ADL1A 2006 stating how dwellings will be selected for testing. Dwellings would be selected independently at the pre-handover inspection stage to prevent developers undertaking 'additional measures' on only those dwellings that are to be tested. Dwellings would also be selected from various different stages of the construction programme. This is intended to ensure that all of the dwellings on a particular development are constructed to a comparable standard of airtightness.
 - c) A clear definition within the Approved Document of who can undertake pressure tests and issue certificates. This would prevent any issues regarding variances in interpretation and prevent the same developer being treated differently in different regions of the country. In addition, there should be a requirement within the Approved Document that pressure tests are to be undertaken in an independent manner by a suitably qualified third party. This would prevent developers testing their own dwellings or employing a testing organisation that has a vested interest in the outcome of the test results.
 - d) As a minimum, the sampling frequency would be altered such that a representative sample of dwellings was tested on every site. This sample would reflect the size of the development, the variety of dwelling types on the development and the method of compliance. The sampling frequency would be increased if non-accredited construction details are adopted as the method of regulatory compliance.
 - e) Clearer guidance incorporated within ATTMA Technical Standard 1 (2006) on how dwellings should be prepared for testing. For instance, this guidance should state that all external windows and doors are closed, all trickle ventilators are closed, all water traps in sinks, baths, shower trays and WCs are filled with water or temporarily sealed, extract fans are switched off and the extract grilles are temporarily sealed. This is likely to result in separate guidance being developed for domestic and non-domestic buildings. The Technical Standard would also incorporate a statement making it clear that the responsibility for the preparation of the building must be agreed between the contractor/client and the testing organisation prior to any testing work being undertaken.
 - f) The testing procedure contained within ATTMA Technical Standard 1 is revised, requiring two sets of measurements to be undertaken, one for pressurisation and one for depressurisation. This will prevent developers submitting only the most favourable of the sets of results.

Indirect quality control

- 78 This option would concentrate efforts on ensuring that a robust and rigorous airtightness quality control system is put in place which is operated alongside but not part of the direct building control process. This would operate as an alternative to compulsory BCB pressure testing requirements. The quality control system would be run and administered by a not-for-profit organisation and developers would be required to pay a plot registration fee for every dwelling built using the system. This would be akin to the system that is currently being run by Robust Details Ltd for compliance with Part E of the Building Regulations. The system would require developers to specify the location of the primary air barrier, identify any potential discontinuities in that air barrier, and provide information on what measures need to be adopted on site to ensure continuity of the air barrier during construction. The details used would be part of a Robust Detail system that ensured good detailing practice.
- 79 For this approach to be successful it is important that developers put in place a third party quality control system for their design process for new dwellings and for any subsequent design changes. Visual inspections of work in progress and field tests of completed dwellings would then be undertaken using a rigorous quality control sample approach. This would ensure that design

standards are being followed, that details have been built as designed and that the dwellings meet the airtightness requirements.

- 80 It is suggested that, within this framework, there would be scope for larger developers to consider the appointment of a senior quality manager at either regional or national level. The remit of such a role would be to develop robust quality systems to monitor and control the performance of new dwellings not just in terms of airtightness, but also other important measurable performance indicators such as continuity of insulation and acoustics. It is envisaged that the developers would want to develop their own testing expertise and to monitor a set of key performance indicators using a statistically based process control system (SPC). The quality system would ideally link with the product development, design and group purchasing functions.
- 81 Adopting such an approach may result in fewer pressurisation tests being undertaken than would currently be the case under Part L1A 2006. Under steady state conditions sampling under the Part E Robust Details model is expected to deliver around about 1,000 visual inspections and 2,000 acoustic tests per year. In the first 18 months of operation of the Part E scheme some 1,500 inspections and 1,000 tests have been carried out with testing success rates over 95%.⁶⁴ Although any sampling and inspection regime for airtightness may require a different sample size the number of inspections and tests are likely to be of the same order of magnitude. This would represent a significant reduction in the testing requirement but with robust quality control sampling, it could result in a much more robust overall system and one which is much more efficient in the application of testing resources. Such a system would enable the systematic building of a robust database that could be used to improve the system overall and provide evidence that could be applied to future reviews of performance standards.

Compulsory testing of all new dwellings

- 82 This is the most radical, and expensive of the three approaches proposed and is the only approach that will ensure that the air permeability is within reasonable limits in all new dwellings. This proposal would involve pressure testing all new dwellings after the pre-completion handover inspection by the warranty provider. However, such an approach will require a significant increase in the number of pressure testing teams to meet the required demand.

Conclusions

- 83 This paper reviews the pressure testing regime incorporated within Part L1A 2006 of the Building Regulations, analyses the logistics associated with compulsory pressure testing and discusses the effect that the testing regime is likely to have on new dwellings.
- 84 The review highlighted a number of issues associated with the pressure testing regime incorporated within Part L1A 2006. These issues relate to the following:

Dwelling type — The testing regime incorporated within ADL1A 2006 involves categorising dwellings by their generic form. Such a categorisation is unlikely to capture a number of important house type issues that influence airtightness. For instance, dwellings of the same generic form can display considerable differences in geometry and complexity of construction. The results obtained from Phase 1 of the project and Stamford Brook suggest that differences in geometry and complexity of construction can result in variations in air permeability of up to 4 m³/(h.m²) @ 50Pa, with higher levels of air permeability being consistently observed in those dwellings containing the most complex detailing. The results also suggest that the issues associated with geometry and the complexity of the construction may have a much greater influence on the eventual airtightness of a dwelling than those issues associated with generic form alone.

Dwelling selection — There is little guidance given within ADL1A 2006 relating to dwelling selection. For instance, no advice is given relating to dwelling notification. Depending upon when developers are notified of the dwellings to be tested, there may be scope for additional measures to be undertaken on the selected dwellings to ensure that they meet the required airtightness target. In addition, ADL1A 2006 suggests that a significant proportion of the

⁶⁴ It is inevitable that testing rates will take time to build up since there is a significant time lag between plot registration and completion. The RSD Ltd business model indicates that steady state conditions will be reached in around two years. The data for the first 18 months (Robust Details Ltd, 2006) would indicate that good progress is being made towards their inspection and testing targets.

dwellings should be tested early on in the construction programme to enable any lessons learnt to be fed back into the construction and design process. However, this approach is based upon the premise that once a developer has demonstrated that the selected dwellings meet a particular air permeability target, the remaining dwellings will also be constructed to the same standard of airtightness. Anecdotal evidence obtained from Phase 3 of the project suggests that this is unlikely to be the case as there was a noticeable difference in the quality of workmanship in relation to airtightness in those dwellings that were participating in the project and those that were not. Consequently, the airtightness performance of those dwellings that are selected to be tested is unlikely to be representative of the performance of other dwellings of the same type on the same development.

Registered testers — Local authorities are authorised to accept a certificate from a person who is registered by BINDT in respect of pressure testing for the airtightness of dwellings. However, there is no clear guidance given about who else can undertake the tests and issue certificates. It will therefore be up to individual BCBs to decide who is technically competent to undertake the tests and issue certificates. This may lead to issues relating to equity and fairness if BCBs adopt different practices and developers are treated differently in different parts of the country.

Independence of the pressure testing — Currently, there is no specific requirement for pressure tests to be carried out by an independent testing organisation. Consequently, a series of issues may arise if developers are allowed to test and issue certificates for their own dwellings.

Sampling frequency — Sampling frequencies outlined in ADL1A 2006 are likely to result in a small non-random number of dwellings tested on each development. The sample sizes involved are also unlikely to be statistically significant; therefore, the results obtained may not be indicative of the airtightness performance of other dwellings on the development. The results obtained from this project suggest that the proportion of dwellings requiring testing is likely to vary considerably between developments, in this case between 1% and 14%, and will depend upon the number of dwelling types on the development and the method of compliance. In addition, where apartments are being constructed, a significantly greater proportion of apartments are likely to require testing than other dwelling types. This is despite the fact that apartments tend to be intrinsically more airtight than other dwelling forms of equivalent area.

Preparation for testing — Experience obtained from Phase 1 and Phase 3 of this project suggests that developers appear to be unaware of how to prepare a dwelling for a pressure test and, in some instances, tests have had to be abandoned as the dwelling was not in a finished state. The incidence of unprepared and unfinished dwellings being presented for testing is likely to reduce in the medium to long term as developers become accustomed to pressurisation testing and realise that they will have to pay for the service irrespective of whether the dwelling is tested or not.

Air permeability target — The design air permeability target for many dwelling designs is likely to be considerably lower than the maximum level of $10 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ specified within ADL1A 2006, particularly where fuels with a higher carbon intensity than gas are to be used. Modelling work suggest that an average air permeability of around 7, 5 and $3 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ would need to be achieved by a developer to meet a design air permeability target of 10, 7 and $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$, respectively, assuming a 10% initial failure rate. Although an average air permeability of $5 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ has been measured in new UK dwellings (measured at Stamford Brook), achieving an average air permeability of around $3 \text{ m}^3/(\text{h.m}^2) @ 50\text{Pa}$ will be technically demanding. Such levels of air permeability are likely to require a fundamental rethink of airtightness design in new dwellings if they are to be consistently achieved in mass UK housing. Results from Stamford Brook also suggest that even when a demanding design air permeability target has been set, the air permeability of the dwellings constructed on site may increase over time due to a deterioration in site workmanship and quality.

Testing procedure — The way in which the dwelling is tested can influence the eventual levels of air permeability achieved and bias the results. The approved procedure for pressure testing a dwelling, ATTMA Technical Standard 1 (ATTMA, 2006), states that valid test results can be achieved by: pressurising the dwelling; depressurising the dwelling; or pressurising and depressurising the dwelling and averaging the results. The results obtained from Phase 1 and Phase 3 of the project indicate that the results obtained by depressurising the dwelling only are, in most cases, lower than the corresponding pressurisation test results. This suggests that more favourable test results could be achieved by adopting this method of testing. In addition, the difference between the pressurisation and the depressurisation results can be as much as 14%. This is consistent with the figures quoted by CIBSE (2000) and Stephen (1998).

- 85 The number of new dwellings requiring testing each year will be dependent upon the strategy adopted for regulatory compliance by the developer, the size of the development and the variation in dwelling types across the developments. Based on construction statistics for 2004 and 2005, it is estimated that the number of dwellings that will require testing will fall in the range 25,000 to 42,000 dwellings per year. The figure is likely to lie towards the higher end of this range due to re-tests and the trend towards constructing more multi-dwelling buildings.
- 86 Wind speed can have a significant effect on the accuracy of pressure tests. ATTMA's Technical Standard 1 (ATTMA, 2006) standard test procedure allows tests to be carried out only when wind speeds are below 6 ms^{-1} . An approved extended test procedure is also available for wind speeds greater than 6 ms^{-1} . Hence wind conditions can have a major effect on the number of hours when a reliable pressure test result is achievable. Assuming a working day from 8am to 6pm, an analysis of the CIBSE/Met Office weather data for a semi-empirical Test Reference Year (corrected to a height of 2 m above ground level) suggests that the average maximum number of hours available for testing in a year over the 11 sites incorporated within the Test Reference Year would be reduced by just over 7%. This analysis assumes a Terrain Category III, which simulates a suburban location. The number of hours available for testing are likely to reduce further as tests are undertaken in more exposed locations, the temperature differences experienced in winter increase the incidence of less reliable test data and time is spent travelling between sites in order to undertake tests in different locations on the same day.
- 87 Taking into account seasonal trends in dwelling completions and the number of hours available for testing, the average number of tests that are required to be undertaken in a single day could exceed 200 or fall below 80, depending upon the month of the year. Assuming that an average of three to four tests could be undertaken by a single testing team in a day, a minimum of 20–25 testing teams would be required in January to cover the testing requirements, rising to a minimum of 50–65 testing teams in December. These figures would double if it was only possible for the testing team to undertake two tests per day.
- 88 The commercial charge for undertaking a single pressure test is of the order of £500 excluding VAT plus travel and subsistence. Additional tests performed on the same visit are of the order of £100 per test excluding VAT.
- 89 Limited data are available on the costs associated with undertaking remedial work in dwellings that have failed a pressure test. Experience obtained at Derwentside suggests a cost in the region of £1,200 per dwelling. However, there are no reliable data available that would enable a firm estimate to be provided.
- 90 Three separate approaches have been identified to address a number of the limitations previously identified with the pressure testing regime that is currently contained within ADL1A 2006. These are as follows:

Direct quality control — This approach involves making a number of amendments to the current edition of ADL1A 2006. These amendments concentrate on providing clearer and more detailed guidance on a range of factors such as dwelling type, dwelling selection, registered testers and dwelling preparation. In addition, it is also suggested that the current sampling frequency should be increased such that a representative sample of dwellings are tested on each development.

Indirect quality control — This approach involves putting in place an airtightness quality control system as an alternative to compulsory pressure testing. A random sample of visual inspections and pressure tests of completed dwellings would then take place to ensure that the dwellings are built as designed and meet the airtightness requirements of the Approved Document. Care would need to be taken with such an approach to ensure that the sample sizes chosen are representative of the dwellings being constructed using this approach and a greater proportion of dwellings are tested than would otherwise be the case under the current edition of Part L1A 2006.

Compulsory testing — This is the most radical of all three approaches and would involve the compulsory pressure testing of all new dwellings. This is the only approach that would ensure that the air permeability of all new dwellings is within reasonable limits.

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Appendix A

Approved Document L1A Criterion 4 — Number of Pressure Tests to be Performed

Number of dwelling pressurisation tests required under ADL1A.

Site and Dwelling Type		No. of Dwellings	Non-accredited details		Accredited details	
			No. to test (ADL1A)	% to test (ADL1A)	No. to test (ADL1A)	% to test (ADL1A)
Site A						
Mid-terrace		24	2	8.3	1	4.2
End-terrace		21	2	9.5	1	4.8
Semi-detached		14	2	14.3	1	7.1
Detached		8	2	25.0	1	12.5
Apartments 2 Blocks	Top floor	4	2	50.0	2	50.0
	Mid floor	4	2	50.0	2	50.0
	Ground floor	4	2	50.0	2	50.0
Combination dwelling type		1	1	100.0	1	100.0
Total		80	15	18.8	11	13.8
Site B						
Mid-terrace		8	2	25.0	1	12.5
End-terrace		14	2	14.3	1	7.1
Semi-detached		22	2	9.1	1	4.5
Detached		28	2	7.1	1	3.6
Apartments 2 Blocks	Top floor	4	2	50.0	2	50.0
	Mid floor	4	2	50.0	2	50.0
	Ground floor	4	2	50.0	2	50.0
Combination dwelling type		2	1	50.0	1	50.0
Total		86	15	17.4	11	12.8
Site C						
Mid-terrace		75	4	5.3	1	1.3
End-terrace		74	4	5.4	1	1.4
Semi-detached		48	3	6.3	1	2.1
Detached		81	5	6.2	1	1.2
Total		278	16	5.8	4	1.4
Site D						
Mid-terrace		4	2	50.0	1	25.0
End-terrace		6	2	33.3	1	16.7
Semi-detached		34	2	5.9	1	2.9
Detached		46	3	6.5	1	2.2
Apartments 4 Blocks	Top floor	18	6	33.3	4	22.2
	Mid floor	16	4	25.0	4	25.0
	Ground floor	18	6	33.3	4	22.2
Combination dwelling type		1	1	100.0	1	100.0
Total		143	26	18.2	17	11.9
Site E						
Apartments 4 Blocks	Top floor	32	8	25.0	4	12.5
	Mid floor	64	8	12.5	4	6.3
	Ground floor	32	8	25.0	4	12.5
Total		128	24	18.8	12	9.4
Overall		715	96	13.4	55	7.7

Appendix B

Phase 1 and Phase 3 Pressurisation Test Results

Phase 1 Pressurisation Test Results

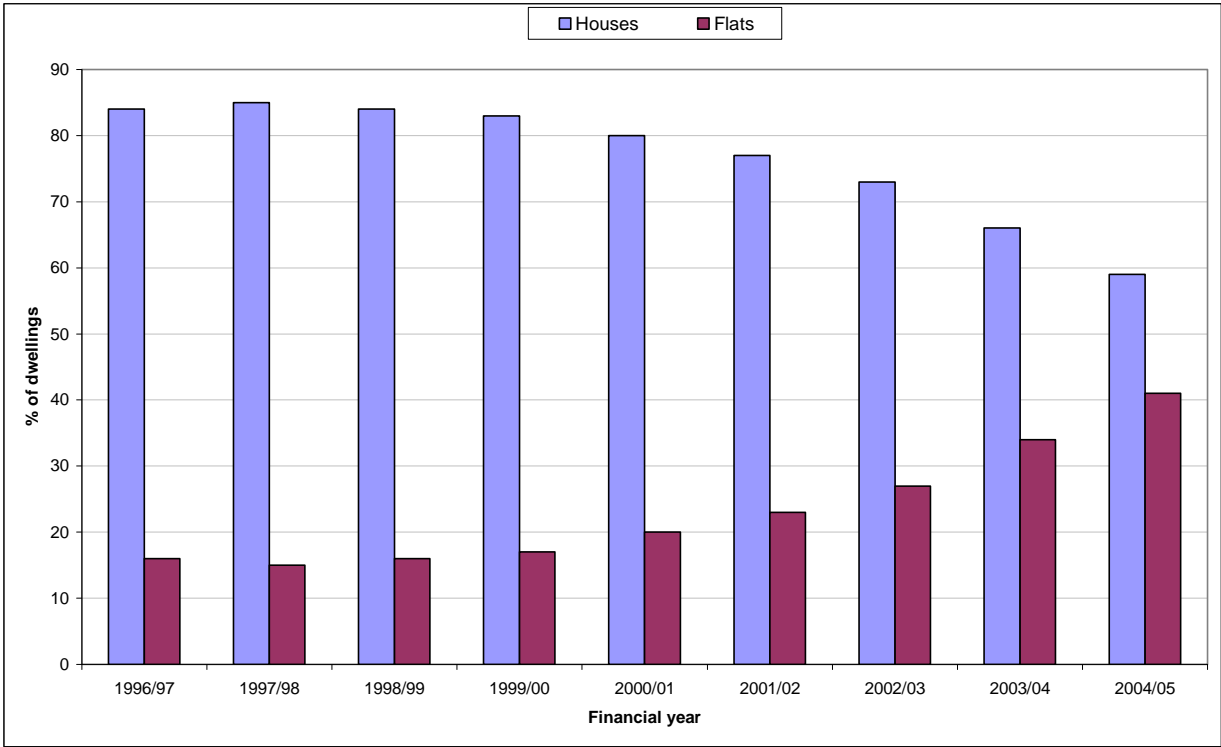
Developer	Dwelling	Pressurisation test (m ³ /(h.m ²) @ 50Pa)	Depressurisation test (m ³ /(h.m ²) @ 50Pa)	Mean permeability (m ³ /(h.m ²) @ 50Pa)
A	9	13.95	13.86	13.91
	11	15.46	14.66	15.06
	12	12.12	12.49	12.31
	13	14.51	14.16	14.33
	14	15.33	15.71	15.52
B	79	8.96	9.02	8.99
	80 (pre-completion)	15.70	15.32	15.51
	80 (completed)	11.76	11.20	11.48
	81	10.11	9.66	9.89
	82	12.04	11.53	11.79
C	236	16.81	16.26	16.53
	237	14.08	13.98	14.03
	238	11.17	11.02	11.09
	239	12.46	11.90	12.18
	240	12.11	11.40	11.76
D	39	12.82	12.61	12.72
	42	15.55	16.37	15.96
	43	12.10	11.44	11.77
	44	14.58	14.94	14.76
	59	12.50	11.76	12.13
E	CG01	5.13	4.90	5.01
	CG02	4.37	4.32	4.35
	C201	4.79	4.43	4.61
	C202	3.94	3.96	3.95
	C301	7.46	7.38	7.42
	C302	5.53	4.97	5.25

Phase 3 Pressurisation Test Results

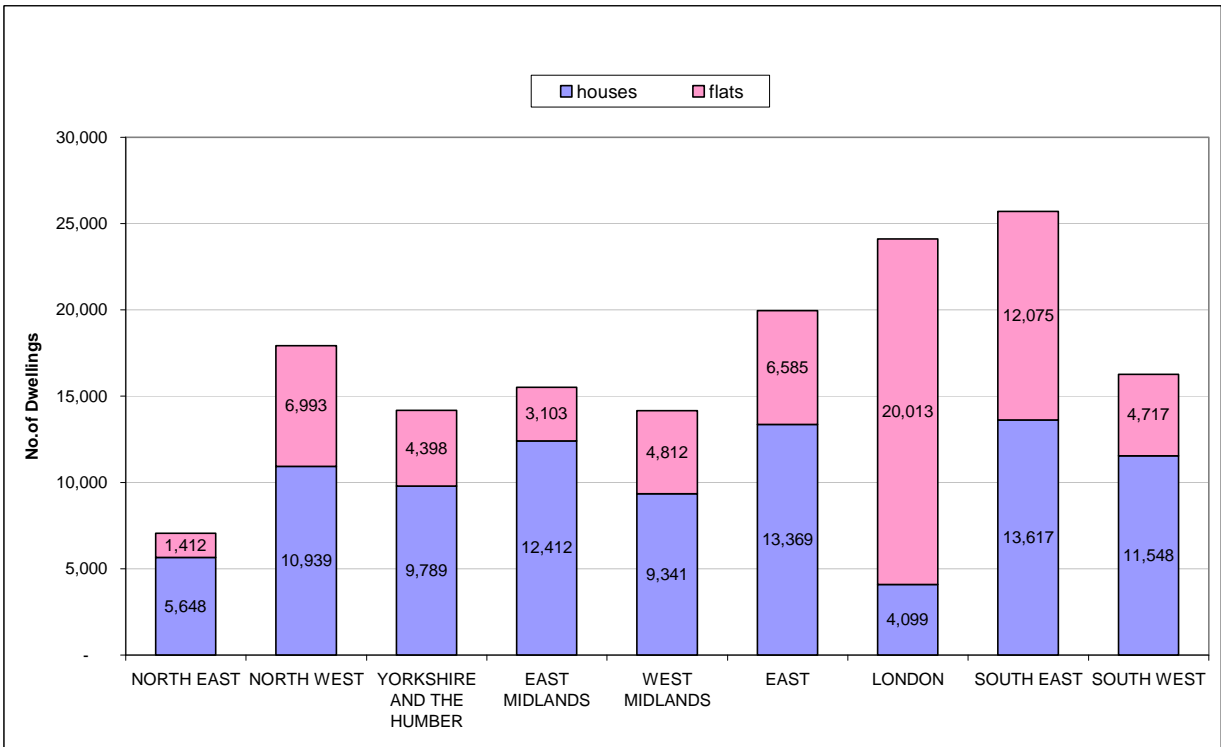
Developer	Dwelling	Pressurisation test (m ³ /(h.m ²) @ 50Pa)	Depressurisation test (m ³ /(h.m ²) @ 50Pa)	Mean permeability (m ³ /(h.m ²) @ 50Pa)
A	64	10.68	10.19	10.44
	65	8.44	7.67	8.06
	66	8.01	7.96	7.98
	79	6.45	6.59	6.52
	80	5.54	5.65	5.59
B	14	9.33	8.15	8.74
	16	5.50	5.69	5.60
	17	5.61	5.76	5.69
	21	7.31	7.27	7.29
	22	7.44	7.31	7.37
C	193	9.82	9.45	9.64
	194	15.90	14.02	14.96
	17 (1 st fix)	16.57	16.37	16.47
	17 (2 nd fix)	7.64	7.37	7.51
	17 (completed)	6.17	5.95	6.06
	18	9.13	9.69	9.41
	19 (1 st fix)	15.71	15.76	15.74
	19 (2 nd fix)	11.39	11.58	11.48
	19 (completed)	7.32	7.29	7.30
	20	10.77	10.12	10.45
	21	10.40	9.80	10.00
D	73	13.39	13.22	13.31
	74	12.62	12.80	12.71
	75	10.97	10.22	10.60
	76 (pre-completion)	10.48	9.70	10.09
	76 (completed)	9.23	8.56	8.89
	96	11.52	10.77	11.14
E	AG01	6.56	6.57	6.56
	AG02	4.98	4.74	4.86
	A201	7.11	6.89	7.00
	A202	5.47	5.36	5.41
	A301	6.24	6.05	6.15
	A302	4.92	4.96	4.95

Appendix C

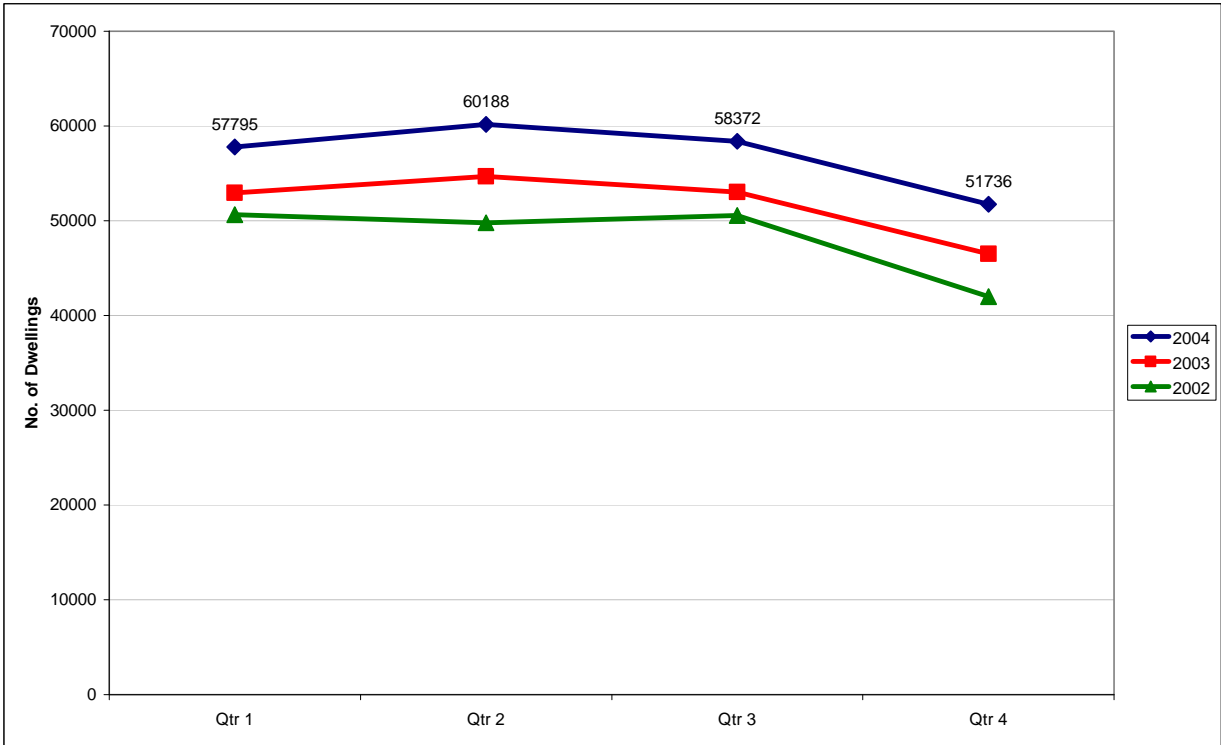
Housebuilding Data from ODPM Live Tables



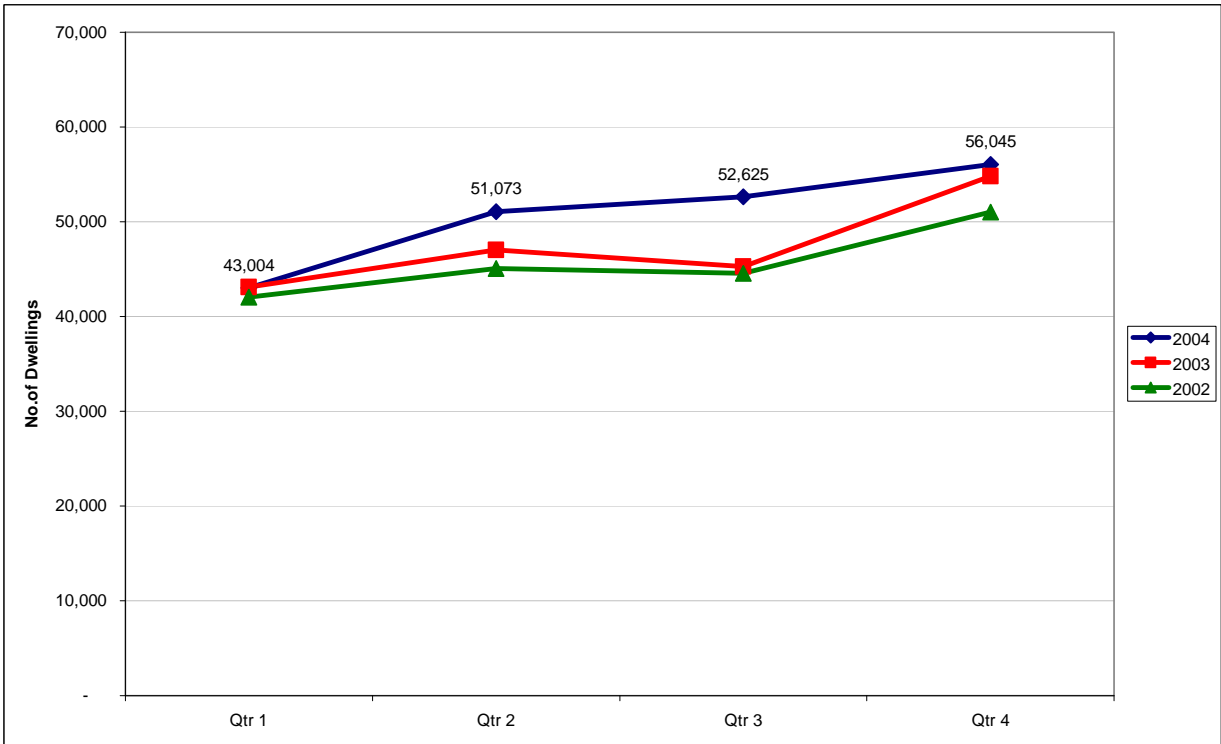
Source: ODPM Live Table 251 – Comparison of annual UK dwelling completions by type.



Source: ODPM Live Table 232 – 2004/5 dwelling completions by type and region.



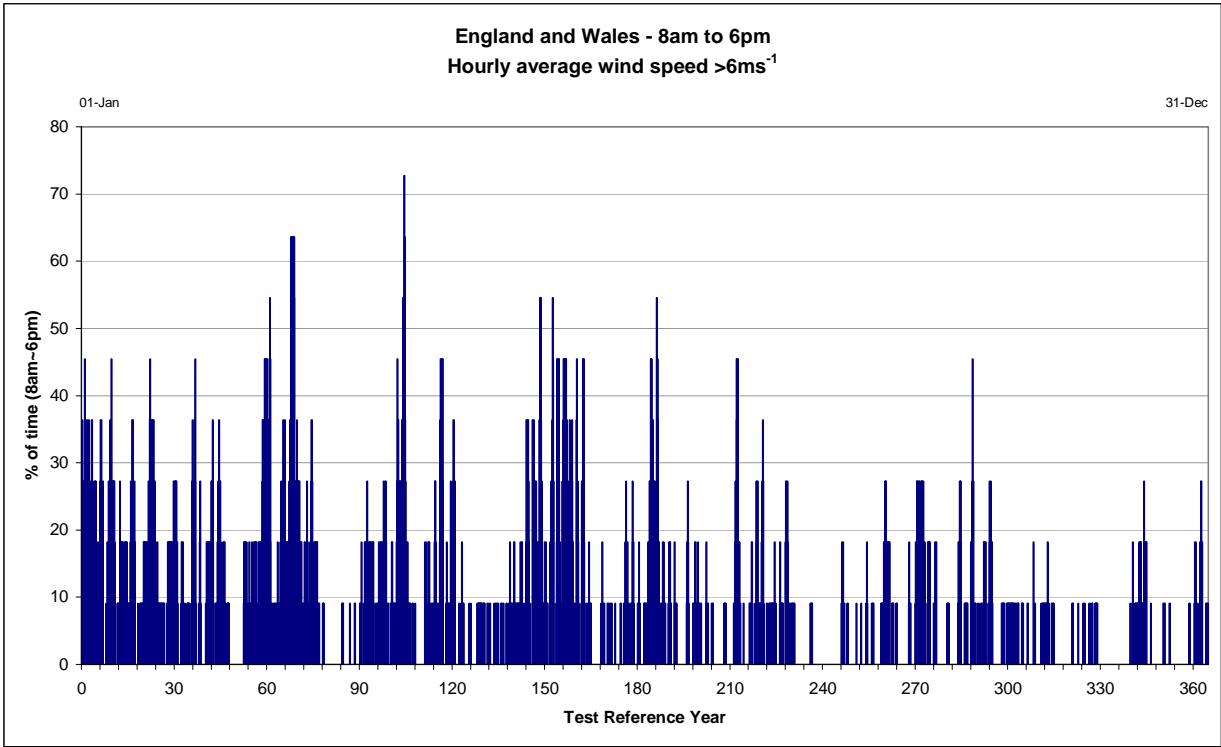
Source: ODPM Live Table 211 – UK dwelling starts per quarter.



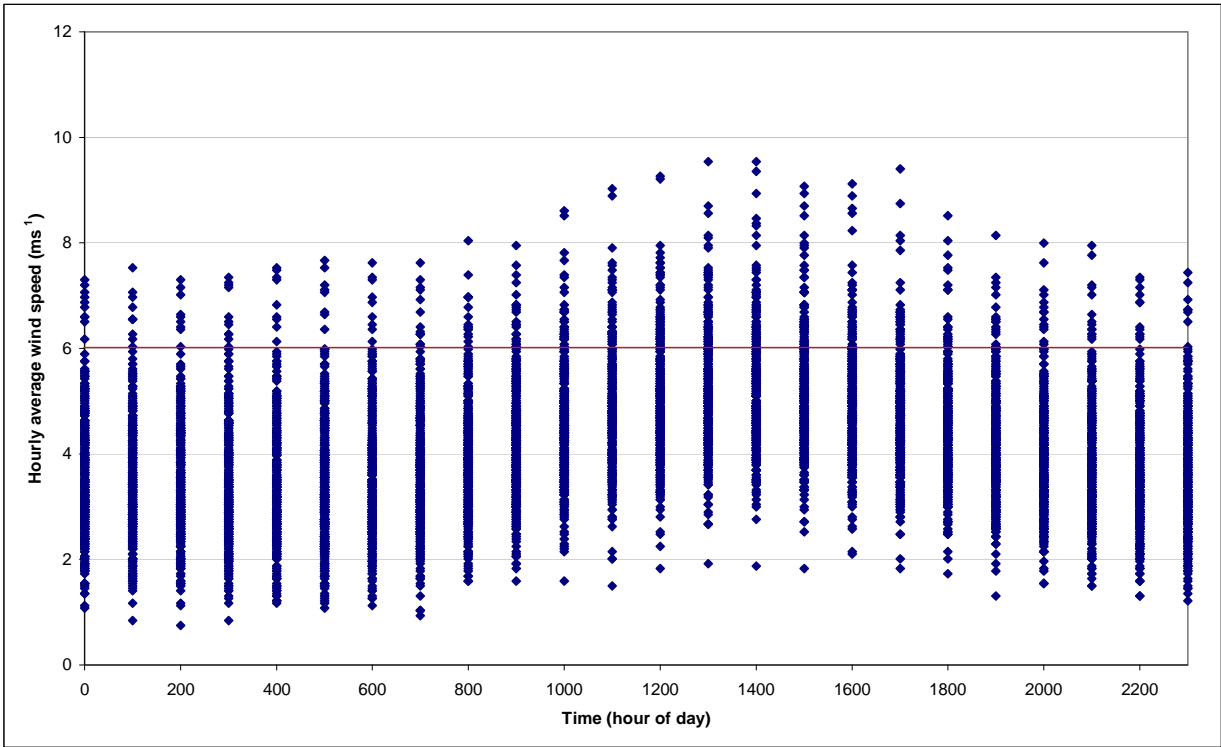
Source: ODPM Live Table 211 – UK dwelling completions per quarter.

Appendix D

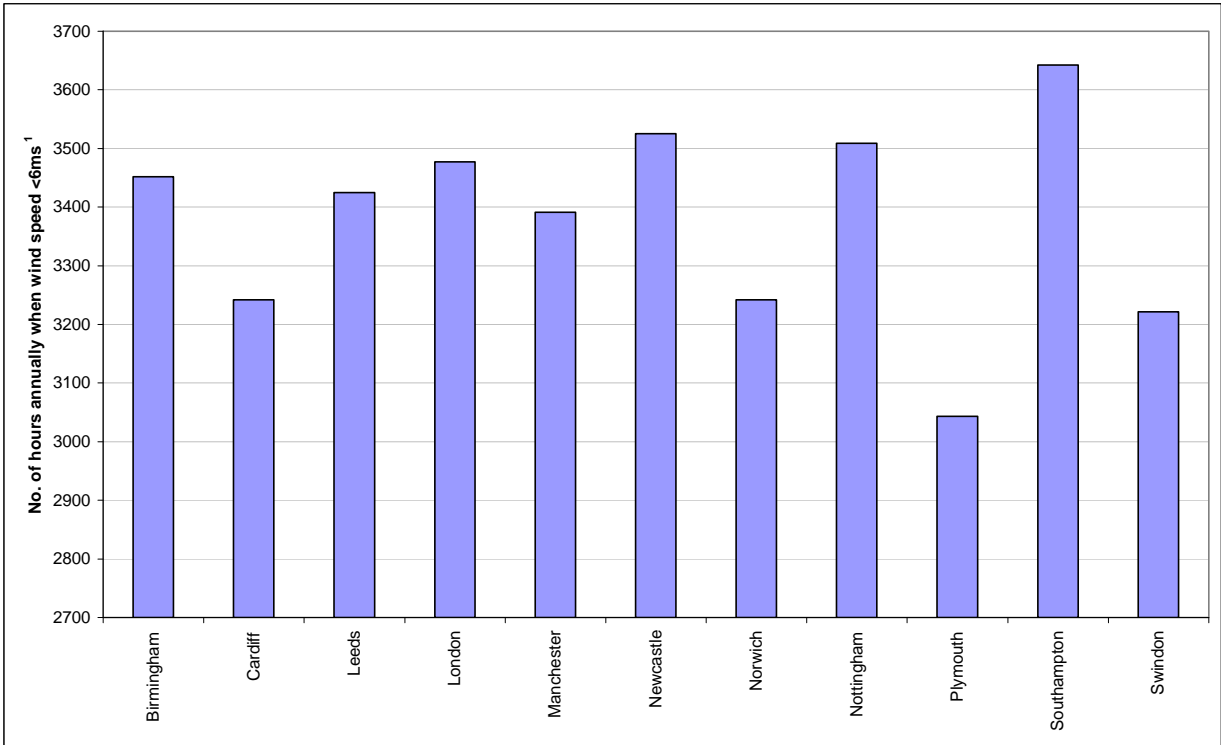
CIBSE/Met Office Hourly Weather Data



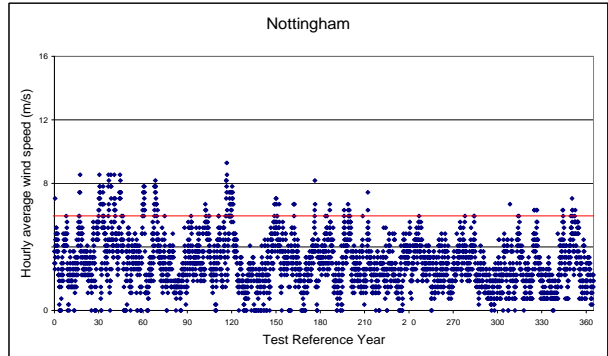
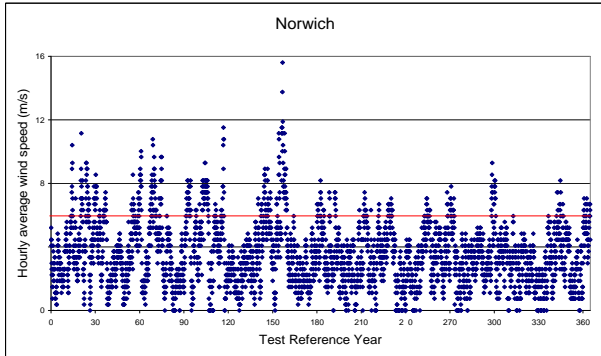
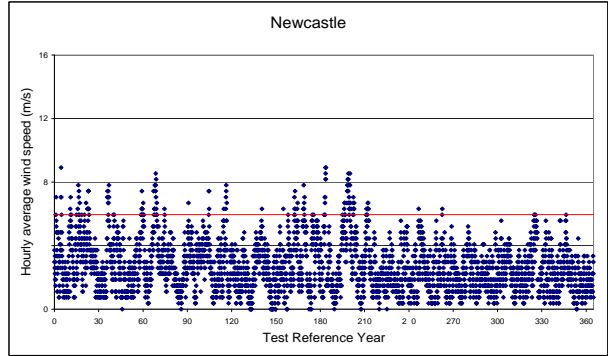
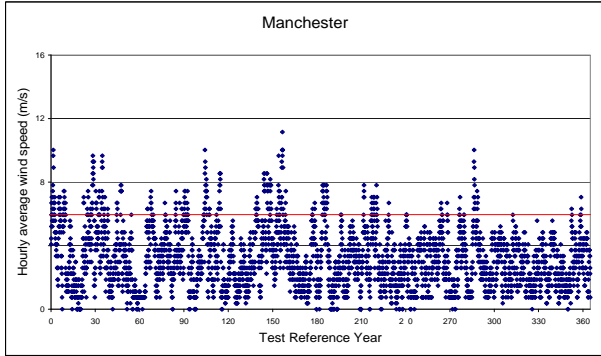
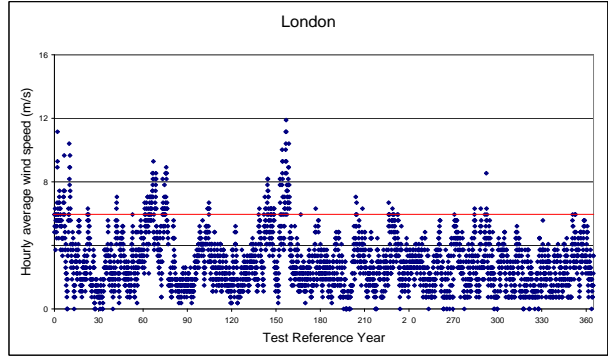
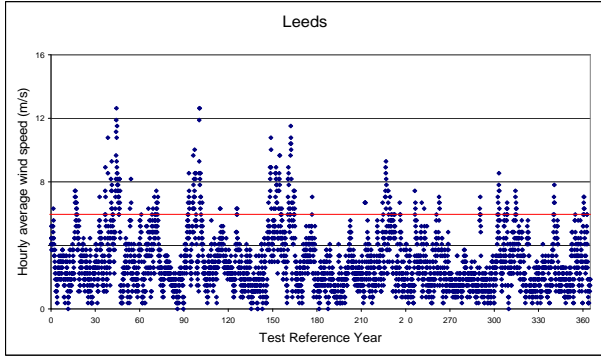
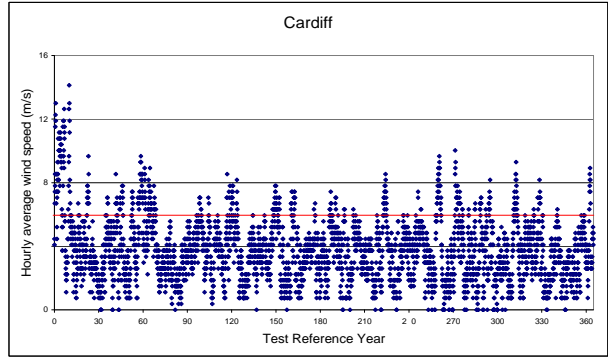
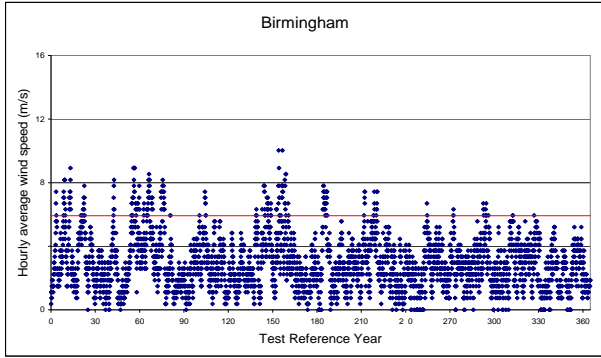
Source: CIBSE/Met Office Hourly Weather Data – 11 vertical lines for each day, one for each weather station, all normalised to 2 m above ground and Terrain Category III.

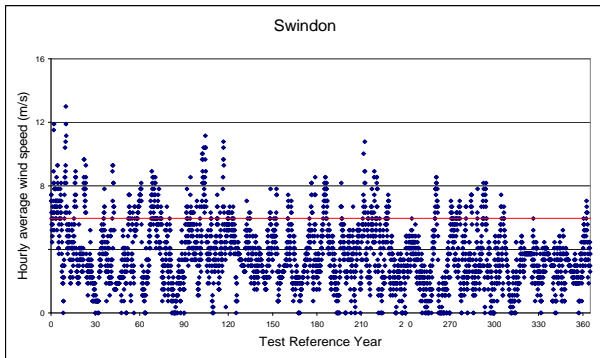
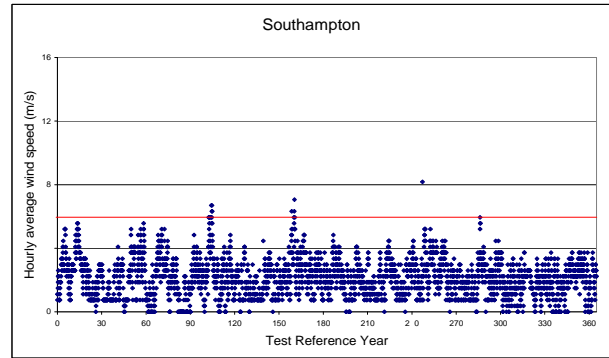
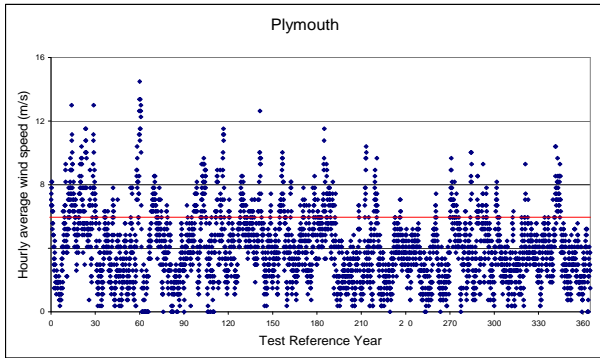


Source: CIBSE/Met Office Hourly Weather Data – England and Wales, hourly average wind speed.



Source: CIBSE/Met Office Hourly Weather Data – Annual number of hours between 8am and 6pm when wind speed $<6\text{ms}^{-1}$, all normalised to 2 m above ground and Terrain Category III.





Source: CIBSE/Met Office Hourly Weather Data — Hourly average wind speed between 8am and 6pm, normalised to 2 m above ground and Terrain Category III.

Appendix E

Pressure Test Equipment

Domestic pressure test equipment



Item	Approximate cost (plus VAT & carriage) £
Blower door system (including frame, controller and gauge)	2,500
Additional low-flow ring	50
Fan case	100
Airtightness test and analysis software	150
Atmospheric data meters (anemometer, thermometer, RH meter, barometric pressure gauge)	200
Sealing film/tape	30
Smoke puffer/pencil	40
Access equipment (ladder/steps)	100
Extension cable + RCB	30
Total	£3,200
Plus: (additional equipment) Laptop computer, camera, transformer, PPE kit.	

Appendix F

Time and Motion Study

Task		Time Taken (man.minutes)		
		Min.	Max.	Av.
1	On arrival at site			
	Sign In	4	8	6
	Site Induction	0	40	4
	Gain access to dwelling(s)	1	2	2
	Wait for cleaners/decorators/etc. to vacate premises	0	14	2
	Total	5	50	14
2	Pre-test requirements			
	Initial inspection of dwelling readiness for testing	6	19	9
	Unload car	4	6	5
	External temperature/RH/wind-speed measurements	2	8	5
	Assemble test equipment	10	16	14
	Extraordinary items: a, b	0	22	2
	Total	22	37	35
3	Pre-test inspection			
	Check/Close all external, wedge open internal doors	1	5	4
	Check/Close windows and trickle vents	1	4	3
	Check/Fill drainage traps	1	4	3
	Check extracts (inc. vents & cooker hood) and seal if required	3	10	7
	Check combustion appliances shut down	1	1	1
	Total	8	24	18
4	Perform test			
	Initial internal temperature and RH measurements	1	4	2
	Calculate baseline figure	1	3	2
	Depressurisation test (extended if windy)	9	29	17
	Pressurisation test (extended if windy)	8	23	15
	Final internal temperature and RH measurements	1	1	1
	Extraordinary item: c	0	12	1
	Total	22	67	38
5	Additional tasks and measurements			
	Perform minor alterations and re-test (if necessary)	0	21	2
	Perform minor alterations and take spot readings (if necessary)	0	15	2
	Leakage detection (if required)	29	35	32
	Total	29	56	36
6	Post-test			
	Remove all temporary sealing	3	7	5
	Dismantle test equipment	6	16	11
	Final check of dwelling	1	1	1
	Load car	6	12	7
	Total	16	30	24
7	On departure from site			
	Return keys	0	4	2
	Inform site management of results and findings	16	34	25
	Sign out	1	1	1
	Total	17	39	28
8	Total Permeability-Test Time	119	302	191
Comments:				
	Max. time taken totals are measurements for an actual test, not a sum of timings for all tasks in that section. Calculation of envelope was performed prior to arrival on site in all cases.			
Extraordinary items:				
a	Clean around threshold to get good seal around blower door			
b	Acquire electricity & water supply			
c	Tape up loft hatch as it was blowing open under pressurisation			

Timings are based on nine pressure tests performed by teams of Leeds Met research staff between January and March 2006, covering a range of house types and locations, with either two or three team members performing each test.