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Summary The central purpose of this paper is to develop and test a case for compulsory pressurisation testing for new dwellings. The authors have argued elsewhere in favour of such a policy. The paper reviews the available information on airtightness in the UK housing stock, the impact of airtightness on ventilation and fabric heat losses, the information that is available on the costs of making houses airtight and the logistics of pressurisation testing. The authors use this information to explore the costs and benefits that might accrue at the national level from the introduction of such a policy. While a number of areas of uncertainty are apparent, the analysis shows a modest but apparently robust economic case for the introduction of pressurisation testing of new housing.

Review of possible implications of an airtightness standard for new dwellings in the UK

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List of symbols

n_{50}	Air leakage rate (ac h^{-1}) measured by pressurisation to a test pressure of 50 Pa
$<n>$	Heating season mean ventilation rate (ac h^{-1})
$P_0(n_{50})$	Probability distribution function of air leakage rates before the introduction of pressurisation testing
$P(n_{50})$	Probability distribution function of air leakage rates following the introduction of pressurisation testing.

1 Introduction

Airtightness is of crucial importance to the thermal performance of buildings(1), and contributes to a number of other areas of performance including resistance to driving rain and sound transmission. Lack of airtightness affects thermal performance in the following ways:

- through the need to heat infiltrating air to the internal temperature of the dwelling
- by increasing conduction losses of elements through which and within which air movement takes place(2)
- by increasing temperature stratification and air movement within the dwelling, both of which will tend to be offset by occupants through increased thermostat setpoints.

Airtightness cannot be considered in isolation from ventilation. Ventilation is essential for a healthy indoor environment and Part F of the Building Regulations for England and Wales contains a requirement for adequate ventilation(3). However, ventilation is also a source of heat loss. The prerequisite for minimising the energy and environmental impact of ventilation is control of the air flow through the dwelling. Air flow must be sufficient to maintain concentrations of indoor air contaminants, including moisture, at an acceptable level, but, to the extent that air flow exceeds this level, space heating will be increased with no significant benefit to the occupants of the dwelling.

Ventilation in most new UK dwellings can be described as natural with intermittent mechanical assistance. This strategy is simple and cheap. It relies for adequate ventilation on a combination of relatively high levels of envelope air leakage, additional trickle vents required by the Building Regulations(3), and occupants' window-opening behaviour.

It is difficult to determine the minimum level of air leakage that is necessary for dwellings operating under this strategy. The relationship between air leakage under pressurisation and ventilation rate under normal conditions of occupation is complex, but for large numbers of dwellings where physical data are limited, a 1/20 rule is often used(4). This rule of thumb has been incorporated into the Standard Assessment Procedure (the energy calculation procedure specified in the Building Regulations for England and Wales)(5). On this basis, an air leakage rate of 10 ac h^{-1} at 50 Pa would provide a heating season mean ventilation rate in the region of 0.5 ac h^{-1}. (Air leakage is normally measured with trickle vents and flues sealed.) If it were provided on a continuous basis, this would probably be acceptable. Such dwellings would, however, still experience overventilation under windy and cold conditions, and without intervention by occupants they would tend to be underventilated in calm, mild weather. The installation and operation of trickle vents provides additional air flow, as well as ensuring that leakage is distributed around the dwelling rather than being concentrated in particular parts of the building envelope. Trickle vents, when open, add something like 5 ac h^{-1} at 50 Pa to envelope air leakage in a typical dwelling. (This is based on a total vent area of 0.044 m^2 in a dwelling of 200 m^3 volume.) Installation and operation of extraction fans further increases leakage and ventilation rates in use and, if appropriately controlled, will tend to reduce underventilation. (Such fans tend to have a high ventilation efficiency as they are located close to sources of water vapour and indoor air pollution. Their impact on air quality is therefore likely to be disproportionate to the total volume of air moved.) It is thus likely that dwellings with air leakage rates as low as 55 ac h^{-1} at 50 Pa can be adequately ventilated by the strategy of mechanically assisted natural ventilation, coupled with occupant intervention. The complete avoidance of a need for occupant intervention in ventilation would require very high envelope air leakage rates, probably in excess of 20 ac h^{-1} at 50 Pa. Such dwellings would be unacceptably overventilated in windy and cold weather.

One of the most recent comprehensive published surveys of airtightness in the UK housing stock was presented by Perera and Parkins(6) (see Figure 1). This shows a very wide range of air leakage rates and the presence of large numbers of

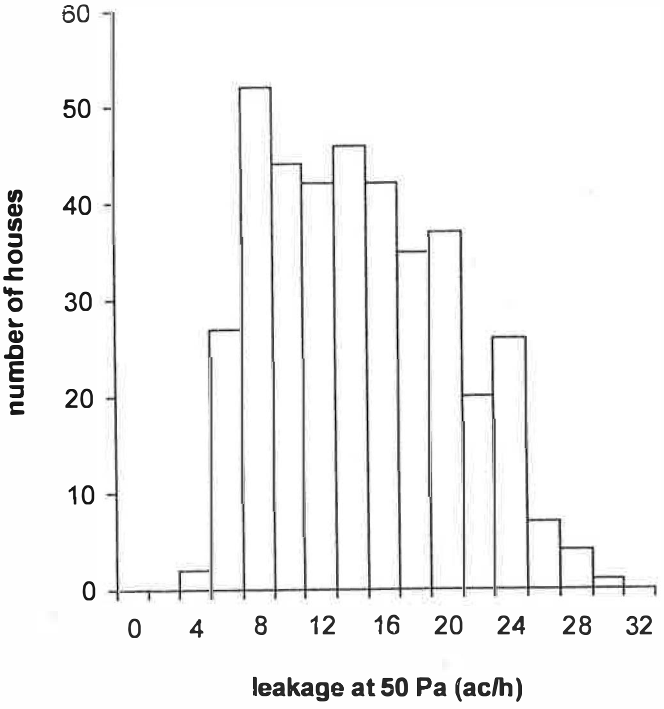

Figure 1 Distribution of air leakage rates in UK dwellings. After Perera and Parkins(6)

dwellings with air leakage rates substantially in excess of the levels required for the prevailing strategy of mechanically assisted natural ventilation. Cohort data presented by these authors suggest that dwellings built between 1980 and about 1991 are, on average, as leaky as dwellings built at the turn of the century. While it is clear that airtightness data for dwellings that have seen several cycles of decoration and repair are not likely to be a reliable guide to airtightness as-built, this suggests that little improvement has taken place in the airtightness of new dwellings over the last century.

Air leakage data for dwellings built since 1995 are limited. While there is some evidence to suggest that these dwellings may be more airtight than the domestic stock as a whole(7),* sample size and structure preclude certainty. On this basis, we have taken Figure 1 to be representative of air leakage rates in current new dwellings. The possibility that this may overestimate leakage rates will be addressed as part of the sensitivity analysis presented in section 6.

2 Possible regulatory approaches to airtightness

The 1995 edition of the Building Regulations for England and Wales(5) already adopts a prescriptive approach to airtightness in dwellings, in the form of practical guidance on reducing air leakage (draught sealing around windows and doors, etc.). Although this would be of some benefit if it were widely understood and applied, in our experience there is little evidence of either. There is no provision in the Regulations for such work to be checked by building control officers and there are currently no means by which designers and builders can be given feedback on the actual results of airtightness measures that are applied. Thus, airtightness is effectively unregulated in new UK dwellings.

Currently, the only practical way of measuring air leakage is by fan pressurisation. This technique can form the basis for regulation of airtightness based on post-construction testing. Such an approach was first introduced widely in Sweden in 1980(8). We consider that the alternative prescriptive approach, if pursued rigorously, would be likely to be viewed by the construction industry as unnecessarily restrictive, and would be likely to act as a brake on the development and introduction of new construction techniques. Airtightness is so dependent on construction quality that, in our view, a prescriptive approach alone is unlikely to be effective in reducing air leakage in new housing.

3 Airtightness and demand for space heating

The purpose of this section is to explore the case for introducing a compulsory airtightness standard on energy conservation and environmental grounds. While we do not intend to pursue it further here, the probability of there being a substantial number of dwellings with air leakage rates above 20 ac h^{-1} at 50 Pa suggests that there is also a consumer protection argument for such a standard.

For the purposes of this paper, the version of BREDEM incorporated into the Standard Assessment Procedure(5) has been used to estimate the impact of dwelling airtightness on annual space heating demand and carbon dioxide emissions. The relationship between airtightness and space heating demand is complicated by window-opening behaviour and interactions between ventilation heat loss and heating season length. These effects are modelled in this version of BREDEM, with window-opening behaviour taken into account through the use of a simple heuristic relationship between annual average ventilation $<n>$ rate and air leakage measured at 50 Pa (n_{50}):

for $n_{50} \leq 20$,

$$<n> = [1 + (n_{50}/20)^2]/2 \qquad (1)$$

and for $n_{50} > 20$,

$$<n> = n_{50}/20 \qquad (2)$$

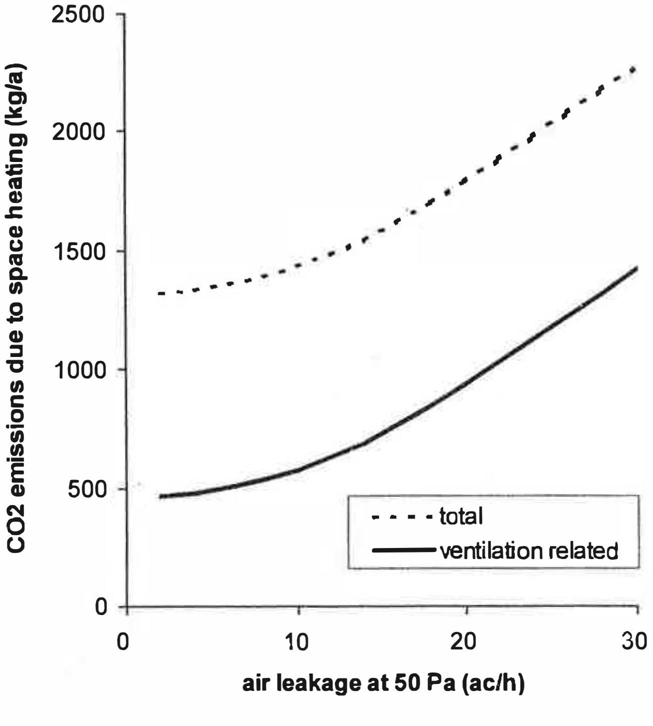

Figure 2 Carbon dioxide emissions from space heating versus air leakage at 50 Pa

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* Also Oreszczyn, T Personal communication (1998)

It is hard to justify more complexity given the paucity of measured data on ventilation rates and window-opening behaviour.

The resulting relationship between space heating requirements and air leakage at 50 Pa is shown, for a typical 85 m^2 gas-heated semi-detached dwelling, in Figure 2. The data for ventilation loss actually represent the increase in total heat loss compared with a hypothetical dwelling with no ventilation. This formulation is necessary since an increase in ventilation rate results both in a direct contribution to heat loss and in an indirect contribution arising from the increase in fabric heat loss due to a longer heating season. The details of the dwelling modelled are presented in Table 1.

The assumptions that underpin the relationship shown in Figure 2 are subject to considerable uncertainties. Nevertheless, the relationship shown is qualitatively plausible for naturally ventilated dwellings. The graph shows a transition from a low-leakage region, in which mean heating season ventilation rates approach an asymptote of 0.5 ac h^{-1} and are determined largely by window-opening behaviour, to a high-leakage region in which mean heating season ventilation rates are simply proportional to the 50 Pa air leakage rate.

The above estimates of savings from airtightness can be combined with the data presented in Figure 1 to give an estimate of savings that would result from the imposition of any particular air leakage limit. To do this it is necessary to predict the strategy that the construction industry would adopt in response to such a regulatory change.

We take the view that the house construction industry would respond to the introduction of compulsory pressurisation testing by adopting construction practices that would shift the whole distribution of air leakage rates to lower levels. In theory, this shift would continue until the industry judged that marginal costs associated with additional airtightness just balanced the costs associated with test failure and consequent remedial work. In this strategy, the initial test failure rate that is found by the construction industry to be acceptable, together with the maximum allowable air leakage, determines the shift in the distribution of air leakage. The modelling assumes that those dwellings that fail an initial pressurisation test have their air leakage reduced to the maximum level allowed under the regulations. We consider it likely that the low costs of achieving airtightness during normal construction, and the inconvenience and much higher costs associated with remedial works, would, following an initial period of adjustment, result in a low overall failure rate.

Table 1 Energy related details of standard dwelling

Gross floor area	85 m^2
Plan aspect ratio	1.2 (ratio of plan depth to width)
Number of storeys	2
Height	5 m
Glazing ratio	0.15 (ratio of window to gross floor area)
Wall *U* value	0.45 W m^{-2}K^{-1}
Roof *U* value	0.25 W m^{-2}K^{-1}
Floor *U* value	0.45 W m^{-2} K^{-1}
Window/door *U* value	3.0 W m^{-2} K^{-1}
Solar heat gain fraction	0.56
Solarity	0.5 (ratio of south to total window area)
Total solar gain	214 W (heating season mean)
Number of occupants	2.7
Internal free heat gain	514 W (heating season mean)

It is impossible to know in advance what the distribution of air leakage would be following the introduction of compulsory pressure testing. In order to make progress, it has been assumed that the existing distribution of leakage rates, shown in Figure 1, would be scaled according to the following model:

$$P(n_{50}) = aP_0(an_{50}) \tag{3}$$

where $P_0(n_{50})$ is the distribution of air leakage rates in current new dwellings, $P(n_{50})$ is distribution of air leakage rates following the introduction of pressurisation testing, and a is a variable scaling parameter.

This transformation reduces both the mean air leakage rate and the standard deviation of leakage rates in the same proportion. Other transformations are tenable, but the data are not available to allow a reasoned choice between them.

Figure 3 shows the resulting distribution of air leakage rates, with a failure rate set arbitrarily at 10%, and an air leakage limit of 10 ac h^{-1} at 50 Pa. In our view, the house building industry would almost certainly adopt some variant of this strategy. The main uncertainties at this stage are in the current distribution of air leakage rates for new dwellings (P_0) and the rate of initial test failures that would emerge.

Having established and described this strategy for coping with compulsory pressurisation testing, it is now possible to estimate the mean ventilation-related space heating energy that would result, as a function of maximum leakage rate. Results for initial failure rates of 5%, 10% and 20% are shown in Figure 4.

This graph is at the heart of the argument for the introduction of compulsory pressurisation testing. It shows that making new dwellings more airtight can in principle reduce average ventilation-related energy use by almost 40%. Most (approximately 80%) of the available savings are captured by an air leakage

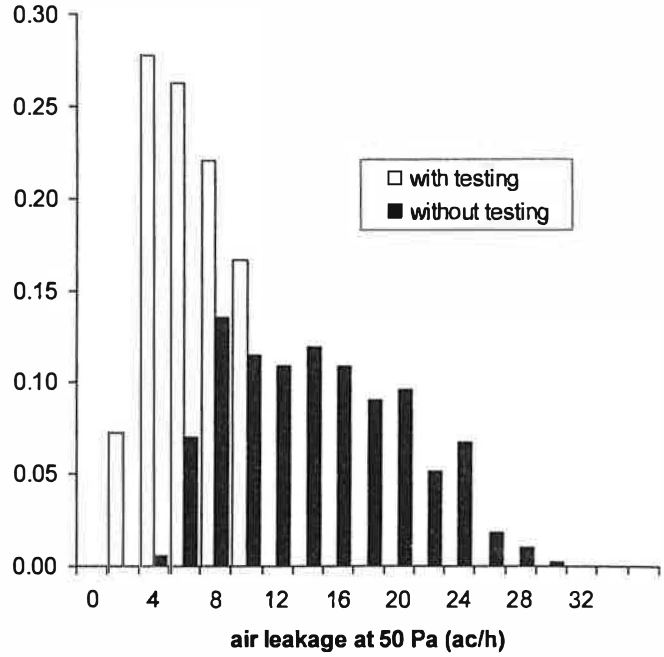

Figure 3 Distribution of air leakage rates with testing, compared with assumed distribution in current new dwellings. Distribution with testing assumes a maximum air leakage 10 ac h^{-1} at 50 Pa, with 10% failure rate on initial test

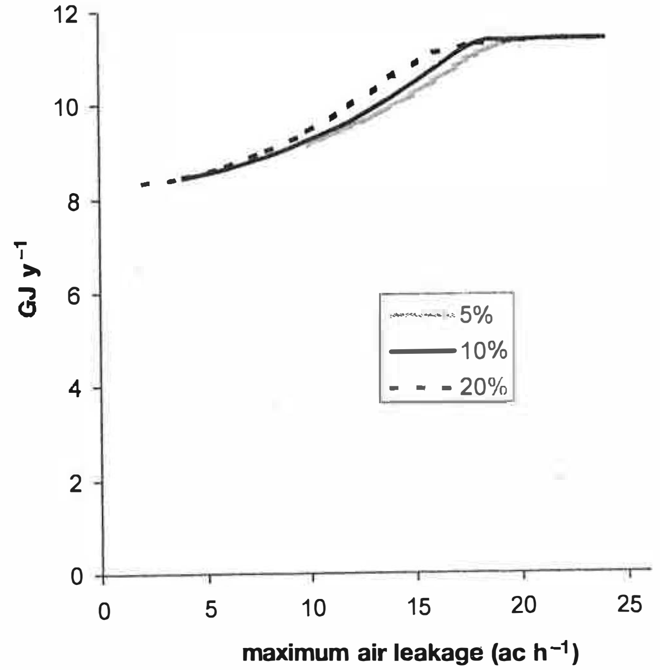

Figure 4 Delivered energy for ventilation-related space heat, as a function of maximum air leakage rate and initial pressurisation test failure rate

target set at 10 ac h^{-1} at 50 Pa. For this limit, ventilation-related space heating requirements are reduced by approximately 32% (4.2 GJ(delivered) y^{-1}) for the standard dwelling. Corresponding carbon dioxide savings can be conservatively estimated as 230 kg y^{-1}, on the assumption of efficient gas-fired heating. Energy savings that result from pressurisation testing are relatively weakly dependent on the magnitude of the initial failure rate: reducing the initial failure rate from 20% to 5% changes the reduction in average ventilation related energy use from 4.0 to 4.3 GJ y^{-1}.

Of considerable importance in terms of the fairness of a proposed mandatory airtightness standard is that these savings are inevitably concentrated in the most leaky dwellings. The air leakage of the worst-performing dwellings is currently possibly as high as 30 ac h^{-1} at 50 Pa. The above strategy, with a maximum leakage rate of 10 ac h^{-1} and an assumed 10% initial failure rate, would shift the distribution of air leakage rates to bring the leakiest dwellings down to about 13 ac h^{-1} before testing, and to the air leakage limit of 10 ac h^{-1} after a test had been undertaken and remedial measures had been applied. The resulting reductions in energy use and carbon dioxide emissions for these dwellings are shown in Table 2.

On these assumptions, compulsory pressurisation testing would lead to energy savings in the leakiest dwellings amounting to about 15 GJ y^{-1}, with a monetary value in the region of £65 y^{-1} at current (nondiscounted) gas prices. Carbon dioxide emissions would be reduced by around 800 kg y^{-1} for these houses.

It is important to remind the reader that the magnitudes of all these estimates are determined by the nature of the ventilation model used. The most important aspect of this model is the assumption that heating season mean ventilation rate does not fall below 0.5 ac h^{-1}, regardless of airtightness. Underventilation is implicitly assumed to be eliminated by user behaviour. In this respect, the calculations presented in this paper will tend to underestimate the energy savings that would result from the introduction of compulsory pressurisation testing, at the cost of taking a possibly optimistic view of air quality in the most airtight of dwellings.

Table 2 Consequences of the introduction of pressurisation testing for ventilation-related energy use and carbon dioxide emissions in very leaky, gas-heated dwellings

	No testing	Testing mandatory	
	Distribution of air leakage as in Figure 1	Before test and remedial measures	After test and remedial measures
n_{50}	30	13.1	10.0
Delivered energy use (GJ y^{-1})	25.1	11.8	10.3
Carbon dioxide emissions (kg y^{-1})	1397	654	571

4 Airtightness standards and the incidence of very airtight dwellings

Acceptable air quality requires a minimum level of ventilation. In very airtight dwellings that are reliant entirely on background infiltration (i.e. in which occupants do not open windows or trickle vents), ventilation rates may be inadequate. While, as has been observed above, the combination of user intervention and mechanical assistance makes it difficult to define a precise level at which a dwelling becomes too airtight, there is likely to be a consensus that an air leakage rate of 3 ac h^{-1} at 50 Pa will result in underventilation. With the trickle vents required by the Building Regulations open, the effective leakage rate in these houses would rise from 3 to roughly 8 ac h^{-1} at 50 Pa. With no window opening, heating season mean ventilation rates in such a dwelling could be as high as 0.4 ac h^{-1}, but would fall to as little as 0.15 ac h^{-1} with trickle vents closed. Figure 5 shows the incidence of such dwellings as a function of maximum air leakage, with an assumed initial failure rate of 10%.

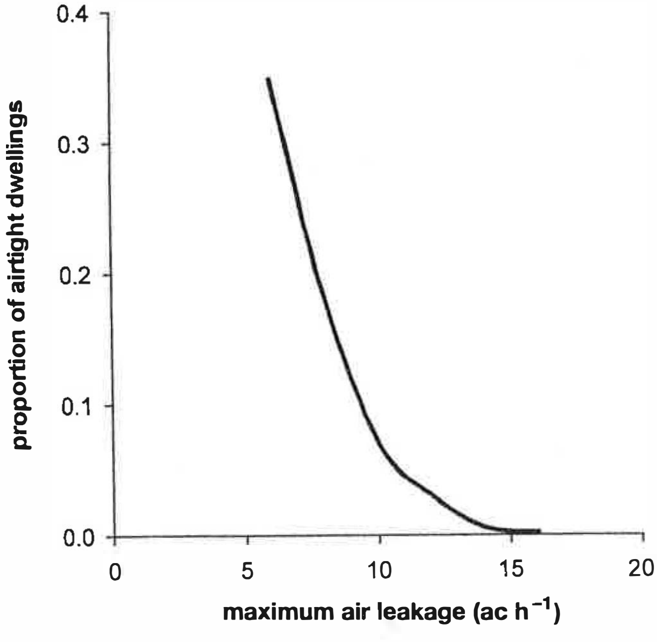

Figure 5 Projected incidence of dwellings with air leakage less than 3 ac h^{-1} at 50 Pa, as a function of maximum allowable air leakage rate

Figure 5 shows the incidence of very airtight dwellings rising steeply as maximum air leakage falls below 10 ac h^{-1} at 50 Pa. (To describe such dwellings as 'very airtight' is correct in the UK context. In Canada and much of Europe the term would properly be reserved for dwellings with air leakage rates between 3 and 10 times lower.) For a maximum air leakage rate of 10 ac h^{-1}, roughly 7% of dwellings would fall into this category, while, for a maximum of 6 ac h^{-1}, roughly 35% would do so. We suggest that if the house building industry began to build a substantial number of very airtight dwellings, alternatives to the currently dominant strategy of mechanically assisted natural ventilation would need to be implemented. We tentatively suggest that until more experience with such approaches has been gained by the UK industry and population, and pending revision of Part F of the Building Regulations, airtightness standards should be set at a level that would restrict the number of dwellings falling into this category to around 10% of new construction. On the basis of the modelling presented above, this would require that the limit on air leakage be set initially no lower than 10 ac h^{-1} at 50 Pa.

However, it is important to recognise that pressurisation testing can identify builders who regularly construct very airtight dwellings, and enable them to modify their practices, either to achieve greater air leakage, or to adopt ventilation strategies better suited to the level of leakage that they attain. By making the industry and dwelling occupants more aware of airtightness, and by providing such specific feedback, mandatory pressurisation testing may, perhaps paradoxically, tend to ameliorate rather than exacerbate the problem of underventilation in very airtight dwellings.

5 Economic analysis of proposals for compulsory pressurisation testing

The purpose of this section is to begin to quantify the economic costs and benefits that would be likely to arise from the introduction of a compulsory airtightness standard. The main categories of cost are the costs of improving airtightness in all dwellings, the costs of pressurisation testing and the costs of remedial work necessary in those dwellings that fail a test. The main external micro-economic benefits would be the value of energy savings that arise from a more airtight stock of new dwellings.

We have undertaken this exercise using the conventional framework of discounted cashflow analysis. Default assumptions for discount rate and rate of future fuel price change are taken from the Compliance Cost Assessment prepared for the 1994 revision to the Building Regulations.* These are shown in Table 3.

Although we have observed elsewhere that these assumptions are individually questionable(1), they will form the basis for the analysis presented here. To calculate the value of energy savings, it has been conservatively assumed that all dwellings are heated with gas-fired condensing boilers, with a gas price of 3.6 £ GJ^{-1} (1.3 p kWh^{-1}). This includes value-added tax at 8% and takes account of discounts to domestic consumers that were offered by suppliers during 1998.

Table 3 Default economic assumptions for economic analysis

Test discount rate	6%
Rate of fuel price change	+2%
Physical life	60 y
Equivalent payback time	23 y

The introduction of an air leakage limit of 10 ac h^{-1} at 50 Pa for new housing would result in a reduction of the mean leakage rate from around 14 ac h^{-1} to perhaps 6 ac h^{-1} at 50 Pa. The costs of this are not known, and in our view would be hard to measure empirically. With the possible exception of dwellings built using plasterboard-on-dabs, this level of air leakage does not require anything beyond good workmanship and sensible design, based on an understanding of the factors that contribute to airtightness. Since this is the minimum that any house purchaser should expect, it is possible to assert that in an ideal world the marginal cost of this level of airtightness would be close to zero.

The costs of a compulsory airtightness standard will depend critically on the protocol for its enforcement. We do not consider that it is necessary, desirable or practical to undertake pressurisation tests in all new dwellings. The details of how dwellings would be selected need to be addressed carefully.

We suggest that tests should be undertaken in perhaps 10% of new dwellings. Where a dwelling fails an initial test, we propose that remedial work should be undertaken by the builder, and that a re-test should be undertaken to demonstrate compliance. It is possible that an initial failure would be indicative of construction practices that would be likely to lead to a high proportion of dwellings exceeding the air leakage limit. To guard against this, it is proposed that, following a test failure, additional dwellings constructed by the same builder should be selected and tested, until compliance is demonstrated in, say, three consecutive dwellings.

The commercial cost of undertaking a pressurisation test in a single low-rise dwelling is currently of the order of £400. We would expect this figure to fall if pressurisation were undertaken widely, through economics of scale, the effects of competition, and the rationalisation of the testing process. On the other hand, costs associated with quality assurance under a regime of compulsory airtightness standards would tend to raise the price. A default figure of £400 per dwelling has therefore been adopted for this exercise.

The cost of remedial work in dwellings that exceed a leakage target is not well known, but we can suggest an approximate upper limit based on our own work on refurbishment of a group of 12 existing houses at Derwentside(9). These houses had been constructed in the 1970s using dry-lined loadbearing masonry. By 1997 they were in a poor state of repair, and measured air leakage rates were in the region of 26 ac h^{-1} at 50 Pa. A programme of remedial airtightness work was carried out by Leeds Metropolitan University in conjunction with a partial refurbishment undertaken by Derwentside District Council. This resulted in a reduction of air leakage in all dwellings into the range 10–13 ac h^{-1} at 50 Pa. The dwellings contained features such as a soil stack in a duct built into the inner leaf of the wall that could not be sealed. Furthermore, the way in which the refurbishment was carried out made it impossible to seal significant sections of the external wall, in particular behind kitchen units. Had these problems not been encountered, we are reasonably confident that an air leakage rate of 10 ac h^{-1} could have been achieved in all 12 dwellings. We consider that it is unlikely that features such as these would survive the introduction of compulsory pressurisation, and would not expect such problems to occur frequently, even in dwellings that exceeded a mandatory limit of 10 ac h^{-1} at 50 Pa.

The costs of undertaking the work amounted to 3 man-days per house, plus approximately £200 worth of materials

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* King E Personal communication (1997)

(mainly polyurethane foam). The total cost to a builder of undertaking this work would be in the region of £560 per dwelling (assuming a gross labour rate of £15 per hour). We believe that this figure will exceed the true costs of remedial work in most cases. It has nevertheless been assumed to represent the average cost of remedial work in all dwellings that fail an initial pressurisation test. The resulting costs and benefits from the introduction of compulsory pressurisation testing are summarised in Table 4.

The sensitivity of the net present value of the measure to the main sources of uncertainty is presented in Table 5. The largest change in the predicted economic benefit of the standard results from assuming the mean air leakage of current new construction to be 10 ac h^{-1} rather than 14.6 ac h^{-1} at 50 Pa. Under this assumption, the estimate of the economic value of the measure falls by a factor of four to £70 per dwelling.

The net present value of a compulsory airtightness standard based on the assumptions presented above is positive in all the cases examined and, we would argue, is large enough, despite the exclusion of costs of airtightness work undertaken before testing and the substantial uncertainties, to justify the introduction of such a measure.

6 Logistics of compulsory pressurisation testing in the UK

A review of the case for compulsory pressurisation testing would be incomplete without a brief discussion of the logistics that would be involved. The questions that will be addressed here are, how many blower doors would be needed to undertake the task of pressure testing new homes, and what level of economic turnover would be generated by the activity.

Table 4 Micro-economic costs and benefits of compulsory airtightness standard. Note that this table does not include the costs of airtightness work undertaken before testing in each dwelling

Cost per test	£400/dwelling tested
Proportion of dwellings tested	0.1
Initial test failure rate	0.1
Cost of remedial work	£560/dwelling failing test
Present value of energy savings	£347/mean dwelling
Cost of initial tests	£40/mean dwelling
Cost of remedial work	£6/mean dwelling
Cost of re-tests	£16/mean dwelling
NPV of compulsory airtightness standard	£286/mean dwelling

Table 5 Sensitivity of net present value of compulsory pressurisation testing to changes in main parameters. Positive NPV denotes that benefits exceed costs

Mean cost/dwelling (£)	NPV of airtightness standard	Change with respect to base case
Base case (see Tables 1, 3 and 4)	286	0
50% increase in cost per test	258	−28
100% increase in cost of remedial work	280	−6
100% increase in initial failure rate	264	−22
Halve proportion of dwellings tested	316	+30
Current mean leakage rate in new dwellings 10 ac h^{-1} at 50 Pa	70	−216

The factors that determine the answer to the first of these questions are:

- the distribution of wind speeds
- the maximum wind speed at which pressurisation testing can be reliably undertaken
- the number of new houses constructed each year
- the proportion of houses tested.

Pressurisation testing becomes unreliable when pressure differences generated by the wind reach a substantial fraction of the test pressure difference (normally 50 Pa). Pressurisation tests are unreliable if undertaken with wind speeds above 3 m s^{-1}(10). An analysis based on hourly wind data for Kew 1967 was undertaken to determine the approximate number of tests that could be undertaken in each month and over a year. The Kew 67 datafile contains wind speed data measured at 10 m height at Kew, a site in the western suburbs of London. The data were firstly corrected to a height of 7 m (corresponding to the ridge height of a typical two-storey dwelling), using a velocity height exponent of 0.17. It was assumed that tests would only be undertaken during normal working hours between Monday and Friday, and that a maximum of two tests could be conducted in a single working day, one in the morning and one in the afternoon. With these assumptions, a total of 202 tests could be undertaken in a year by a single team with one blower door. Figure 6 shows the month-by month variation in this activity.

It is clear from Figure 6 that pressurisation testing is strongly affected by mean wind speed, with an almost six-fold variation in opportunities to test between the windiest and least windy months. Kew has a comparatively low wind speed, which would lead to a considerable overestimate of the number of tests per blower door that would be possible in a year in the UK as a whole. This fact was taken into account by scaling the raw hourly wind speeds in the Kew 67 weather data file. This transformation preserves the shape of the annual probability exceedance curve, and the autocorrelation properties of the raw Kew 67 data, but makes it possible to simulate locations with arbitrary annual mean wind speeds. There is no reason to believe that Kew 67 is unusual in respect of these

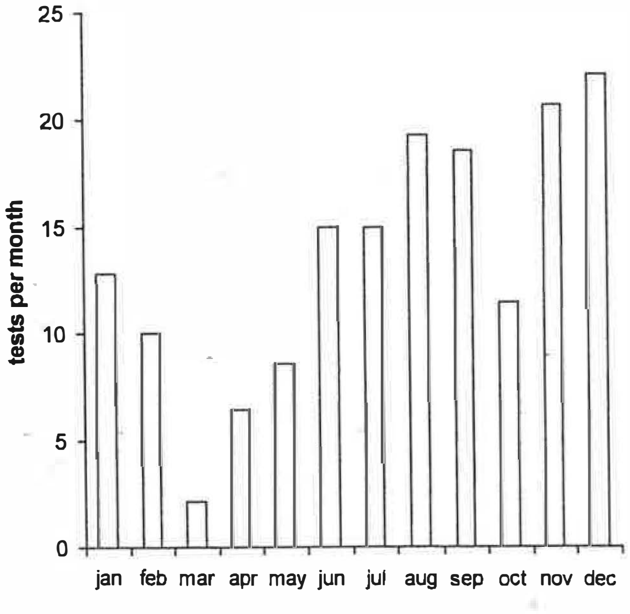

Figure 6 Distribution of testing activity for a single team through a typical year. Based on hourly weather data for Kew 1967

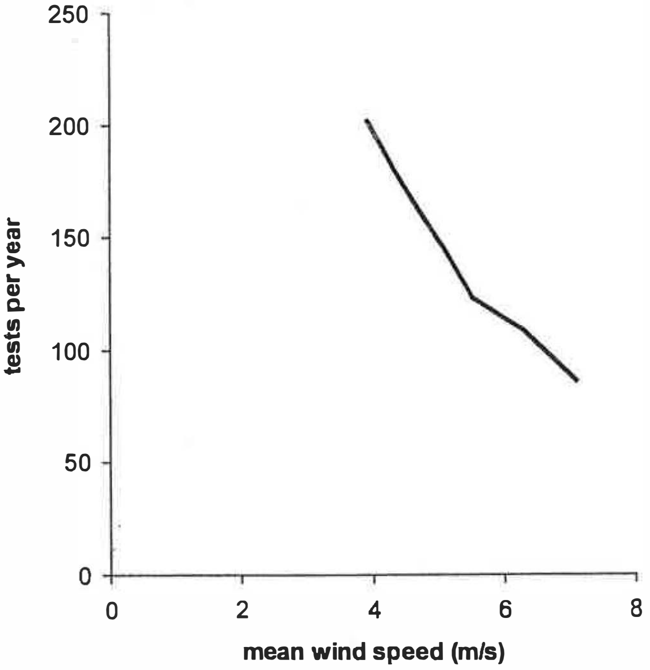

Figure 7 Number of tests per blower door, per year, versus site annual mean wind speed

properties compared with other UK weather years, and this approach was deemed to be adequate to the task. The resulting variation in the number of tests that can be undertaken over a year is shown in Figure 7. This figure covers the whole range of wind speeds found in the UK.

For a mean wind speed of 4.5 m s^{-1}, which is more representative of the UK than the 3.9 m s^{-1} recorded at Kew in 1967, weather would allow approximately 160 tests per blower door to be undertaken in a typical year. The testing protocol described in section 5 would result in approximately 14 pressurisation tests per 100 new dwellings. (It would be misleading to express this as a percentage since dwellings that fail an initial test would be tested twice under the protocol outlined in section 5.) Assuming a construction rate of 200 000 new dwellings per year, just over 170 blower doors would be required to support compulsory airtightness standards in the UK. Assuming a price of £400 per test, the average turnover per door would be in the region of £65 000.

7 Discussion and conclusions

We have attempted to explore the implications of introducing an airtightness standard based on compulsory pressurisation testing for new UK housing. The main conclusions from this exercise can be summarised as follows:

- Based on the model of ventilation used in BREDEM, and on published information on airtightness in the UK housing stock, ventilation-related energy use in new dwellings can be reduced by up to 40% by reducing uncontrolled air leakage.
- We have modelled the impact of the introduction of an airtightness standard by scaling the current distribution of air leakage rates in the UK stock. Assuming that the mean leakage rate of current new dwellings is similar to that in the existing stock, at just over 14 ac h^{-1} at 50 Pa(6), most of the available savings would be captured if the maximum leakage rate were set at 10 ac h^{-1} at 50 Pa. At this level, carbon dioxide emissions for a typical dwelling would be reduced by some 230 kg y^{-1}. Assuming that such a standard were introduced shortly after the year 2000, and the construction of 200 000 new dwellings per year, total savings would amount to approximately 460 000 te of carbon dioxide per annum by 2010. These estimates of energy savings exclude the reduction in fabric *U* values that would be likely to result from improved airtightness, and the complex impact of improved thermal comfort.
- There are a number of sources of uncertainty in the above estimates. The most important is the distribution of airtightness in housing constructed now. The possibility that new housing is more airtight than the stock as a whole has been included in the sensitivity study presented in section 5. If the mean air leakage in current new housing were already as low as 10 ac h^{-1} at 50 Pa, the energy and carbon dioxide savings from the proposed standard would be reduced by a factor of approximately three.
- For the purpose of calculating the economic costs of implementing an airtightness standard, it has been assumed that the industry would be prepared to accept a 10% failure rate. The overall shift in air leakage rates and the resulting energy savings that would be achieved by such a standard are, however, relatively insensitive to this failure rate.
- It is very likely that an airtightness standard would result in a significant increase in the number of very airtight dwellings. Based on the response model described above, a maximum leakage rate of 10 ac h^{-1} at 50 Pa would result in approximately 7% of new dwellings achieving a leakage rate under 3 ac h^{-1} at 50 Pa. We leave open the question of how the regulatory system should respond to this. One set of options would be to use the results of pressurisation testing to identify builders who regularly build very airtight dwellings so that measures could be taken either to increase leakage rates or to fit appropriate means of ventilation. An alternative would be to require the installation of passive stack ventilation or continuous mechanical extract ventilation in all new dwellings.
- The micro-economic benefit of improved airtightness over a 60-year period, excluding additional construction costs, appears to be of the order of almost £300 per house, under default assumptions. The benefit remains positive under a range of assumptions, including the assumption that mean air leakage in current new dwellings is 10 ac h^{-1} at 50 Pa. We do not have data on the additional construction cost of meeting an airtightness standard of 10 ac h^{-1} at 50 Pa, but we consider that for most builders this would be significantly less than £300 per dwelling.
- Apart from the additional construction cost, the proportion of dwellings to be tested is the most important source of uncertainty in the estimate of economic cost of the proposed standard.
- An airtightness standard based on pressurisation testing would need a significant expansion of the number of blower doors operational in the UK. Accuracy requires that tests be undertaken at low wind speeds. This single condition reduces the number of tests that can be conducted in a year by a factor of three. Taking this into account, and assuming that initial tests would be required in a sample of 10% of new housing, it appears that approximately 170 blower doors would be needed to support an airtightness standard.

The energy and economic benefits of mandatory pressurisation testing are modest, but appear to be positive under all of the assumptions tested. Nevertheless, the importance of such a standard goes beyond the immediate benefits discussed in the body of the paper. First, the systematic measurement of air leakage in new housing will provide a firmer basis for public policy in this area. Second, we expect that the widespread use of tools for measuring air leakage would initiate a dynamic, industry-wide process of learning that would in turn result in a steady fall in air leakage in new dwellings. This process is likely to be reinforced by market demand, once the general public begins to experience the benefits of living in draught-free dwellings. The achievement of a steady fall in air leakage from new dwellings would require further regulatory response, particularly with respect to the installation of open-flued fuel-burning appliances. It would also make it possible to consider the widespread introduction of ventilation strategies that can reduce ventilation-related energy use even further, when coupled with very low levels of air leakage. These include mechanical extract ventilation (which, when associated with occupancy or air quality sensors and with air leakage rates in the range 2–3 ac h^{-1}, can reduce ventilation-related energy use by 30–40% below what is achieved by a dwelling with an air leakage of 10 ac h^{-1}), and whole-house mechanical ventilation with heat recovery (which in dwellings with air leakage of less than 1 ac h^{-1} at 50 Pa can achieve a further halving of ventilation-related energy use(11)).

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