# AIR INFILTRATION RATES IN SOME AUSTRALIAN HOUSES

K.L. Biggs, I.D. Bennie and D. Michell*
CSIRO Division of Building Research, Melbourne, Australia

## Abstract

Air infiltration rates measured by a tracer gas method in seven unoccupied houses in suburban Melbourne are reported. The rates for each house correlate with wind speed measured by the Bureau of Meteorology, and a single linear relation between infiltration rate and wind speed provides a good approximation to all the data. The results are similar to those obtained for houses in the United Kingdom. The data are considered in terms of the conflicting requirements for satisfactory indoor air quality and minimum energy consumption, and it is concluded that no general recommendation to 'tighten' houses should be made.

Keywords - Air infiltration; ventilation; tracer gas; wind speed; energy conservation; indoor air quality.

## INTRODUCTION

Infiltration into a house may be defined as uncontrollable ventilation, i.e. as the ingress of air from outdoors when controllable ventilation openings are closed. The associated egress of air from the house is called exfiltration, but it is usual, since the flows are equal, to refer only to infiltration when discussing these phenomena.

To reduce energy consumption for heating and cooling of houses, the ventilation rate should be minimised. On the other hand, since air exchanges dilute the contaminants generated indoors and reduce the build-up of moisture, which can lead to condensation and mould growth, air quality would be improved by increasing the ventilation rate. A balance has to be struck between these conflicting courses of action. In the Nordic countries (Norway, Sweden, Finland, Denmark, and Iceland), a minimum ventilation rate of 0.5 air changes per hour (ac/h) is recommended (Nordic Committee on Building Regulations 1980); in fact it is mandatory in Sweden (Swedish National Board of Physical Planning and Building 1975). Minimum rates of the order of 0.8 ac/h have been recommended in Germany (Gertis and Erhorn 1985). An analysis concerned with the avoidance of condensation and mould growth in dwellings in the United Kingdom concluded that between 0.5 and 1.0 ac/h was needed (Loudon 1971).

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* Retired from CSIRO Division of Building Research

Data on infiltration rates of Australian houses are very sparse. The only Australian investigations of infiltration published hitherto were those of Howard (1966) and Coldicutt (AHRC 1978). Howard's study only dealt with single rooms, reflecting the conditions at the time, when heating only one room was the norm. Coldicutt measured whole-house infiltration rates in a set of houses, most of which incorporated areas of fixed ventilation larger than normal as a means of reducing the risk of condensation.

The present paper describes investigations of whole-house infiltration rates in houses typical of those built in the populous south-eastern region of Australia. The purpose of the study was to obtain infiltration rate data, related to wind speed, for use in energy and indoor air quality studies in general, and in particular for consideration of the advisibility and cost effectiveness of 'house tightening' measures for reducing infiltration rates in houses.

## BACKGROUND

### The Causes of Air Infiltration

For an exchange of air between indoors and outdoors to occur, there must be gaps and cracks in the building envelope, and pressure differences must exist across these apertures. (The process of diffusion may be ignored in this context since the mass transfer rates are very low in comparison with rates due to pressure differences (Bilsborrow 1972).) In the absence of mechanical ventilation, the only pressure differences that occur are those caused by the action of the wind and those arising from differences in temperature between indoors and outdoors.

When a wind blows at a structure, patterns of air pressure are developed over the various surfaces of the building envelope. These pressures may be related to the dynamic pressure of the wind by coefficients which depend on the shape of the building and its orientation with respect to the wind (see, for example SAA 1981). The dynamic pressure of the wind, P, is given by the expression $P = 0.5\rho V^2$, where $\rho$ is the density of the air and V is the speed of the wind. Thus $\Delta P_W$, the wind-induced pressure difference across the envelope at a given point, is proportional to $V^2$, i.e. $\Delta P_W = AV^2$, where A is a constant.

When there is a temperature difference between indoors and outdoors, pressure differences are developed across the building envelope. This phenomenon is often called the 'stack effect'. The magnitude of the pressure difference due to the stack effect, $\Delta P_S$, at a given location is influenced by the size and distribution of openings in the building envelope, because these determine the location of the neutral pressure plane, i.e. the region where $\Delta P_S = 0$. In general $\Delta P_S$ is approximately proportional to the product of the average temperature difference between indoors and outdoors, $\Delta T$, and the vertical distance, H, of the region of interest from the neutral plane (ASHRAE 1985), i.e. to a first approximation $\Delta P_S = BH(\Delta T)$, where B is a constant.

Since they are produced by different processes, the one external, the other internal, the wind and temperature-induced pressure differences are independent of each other, and the net pressure difference, $\Delta P$, across a given crack is the sum of the two pressure differences acting at that point, i.e. $\Delta P = \Delta P_W + \Delta P_S$.

The rate of flow of air, F, through a crack may be expressed empirically as being proportional to the pressure difference across the crack, $\Delta P$, raised to the power n, where n takes values between 0.5 (fully turbulent flow) and 1.0 (pure laminar flow), i.e. $F = K(\Delta P)^n$, where K is a constant taking into account, among other things, the area of the crack (Handa 1979).

The infiltration rate of a house, for a given set of climatic conditions, depends on the size and location of all the openings in the building envelope. Although it is virtually impossible to measure all of these directly, a measure of the overall air permeability of the envelope may be obtained by measuring the air flow into the building necessary to maintain a standard pressure difference (commonly 50 Pa) between indoors and outdoors (Kronvall 1980). The permeability of the envelope may then be obtained, in units of $m^3/m^2h$, by dividing the volume of air entering and leaving per hour by the surface area of the envelope (external walls, ceiling, and floor if suspended). In the course of determining permeability, a value is obtained for the effective flow exponent, n.

Given sufficient data, the pattern of pressure differences over the surfaces of the building envelope arising from wind and temperature difference effects could be applied to the distribution of the cracks, and given a knowledge of the appropriate values of the exponent n and the areas of the cracks, the rate of flow induced could be predicted. Since such a procedure is not normally feasible, in practice, air infiltration rates have to be measured and empirically related to wind speed and temperature difference.

Since, for a given region, i, of the building envelope, $F_i = K_i(\Delta P_i)^{n_i}$, and $\Delta P_i = A_i V^2 + BH_i(\Delta T)$,

it follows that $F_i = K_i[A_i V^2 + BH_i(\Delta T)]^{n_i}$. For the whole house

$$F_H = \sum_i K_i[A_i V^2 + BH_i(\Delta T)]^{n_i}, \qquad (1)$$

where the summation is carried out over all regions.

The air change rate, $\gamma$, would be obtained by dividing $F_H$ by the volume of the house.

The values of the constants for each part of the envelope will normally not be known, so in practice $\gamma$ cannot be calculated from Equation (1). Nevertheless, the theoretical derivation suggests a model to which empirical data could be fitted, viz.

$$\gamma = [\phi V^2 + \lambda(\Delta T)]^n + \alpha, \qquad (2)$$

where n, $\phi$, $\lambda$, and $\alpha$ are constants specific to a given house. The constant $\alpha$ is included for generality, i.e. to allow for the possibility of an empirical non-zero value of $\gamma$ when V and $\Delta T$ are both zero.

## Correlation of Infiltration Rate with Wind Speed

Air infiltration due to the wind blowing at the house is the result of the interaction between the house and the airstream that would otherwise blow across the site. Ideally, the wind speed against which to plot the values of the infiltration rate would be the speed of that airstream.

A good approximation might be expected from wind instruments mounted at eaves height, in the vicinity of the house, but far enough away to be out of range of the influence of the house on the wind. However, differences in the amounts of shielding afforded by vegetation, neighbouring houses, and other obstructions, for each wind direction, will often cause wind data obtained in this way to differ from the wind speed and direction it is desired to measure.

Another approach, followed by other workers in this field, is to recognise that a local wind is the product of prevailing large-scale meteorological conditions and that infiltration rates can therefore be related to the wind data recorded for the region at some central location by (in Australia) the Bureau of Meteorology. These data diverge from those applicable at a local site because of differences of topography and of height and shielding conditions between the official measuring site and the local one, and the distance between them. The differences introduced in this way will tend to reduce the correlation between the regional wind data and the wind-driven infiltration rates. Bureau of Meteorology data are often used because they are readily available, records cover many years, and the data relate to the whole region.

## EXPERIMENTAL

Air infiltration rate measurements were carried out in seven unoccupied houses made available to the authors. These were all single storey, suburban Melbourne houses that varied widely in age and materials of construction, and included examples of the more significant types of houses to be found in the building stock in south-eastern Australia at the time of measurement (1981-1984). All houses were well constructed, had floor coverings, and were painted throughout. No windows were weatherstripped but in two houses external doors were weatherstripped (Table 1). For consistency, the numbering of the houses follows that adopted in a study (Biggs et al. 1986) of the air permeability of a set of 32 houses. The set included the seven houses made available for extended periods for infiltration rate measurements.

During the measurement period, all windows and external doors were shut and all internal doors except the toilet door were open. The latter door was closed on the assumption that this would be the normal practice of the householder. Heaters were not operated. These conditions mean that the infiltration rates measured were close to the minimum values to be expected of the houses since, in normal use, many houses would have some windows open to some extent. Furthermore, in winter, heaters would be operated, which would tend to increase the infiltration rates both from increased stack effect and from the passage of air through the flue where flued combustion heaters are used.

Infiltration rates were determined by a tracer gas technique developed by Michell and Biggs (1983). This method was a combination of the 'constant gas emission' and the 'constant gas concentration' techniques described by Kronvall (1980). Figure 1 is a block diagram of the apparatus. The concentration of nitrous oxide tracer gas at six locations within a house is measured by an infra-red gas analyser in a regular sequence, a complete cycle taking four minutes. At each location tracer gas is released, once per cycle, in a quantity proportional to the difference between the measured value of gas concentration just measured and some reference value. This results, for a particular value of air infiltration rate, in

Table 1. Brief details of the houses studied

| House no. | 1 | 2 | 3 | 4 | 13 | 14 | 18 |
|---|---|---|---|---|---|---|---|
| Floor area* ($m^2$) | 136 | 116 | 83 | 113 | 110 | 157 | 105 |
| Floor type: Suspended timber | x | x | x | x | | | |
| Concrete on ground | | | | | x | x | x |
| External walls: Timber | | | x | | | | |
| Brick veneer | | | | x | x | | x |
| Cavity masonry | x | x | | | | x | |
| Internal walls: Plasterboard | | | x | x | x | | x |
| Brick/Masonry | x | x | | | | x | |
| Roof: Pitched, tiled | x | x | | x | | | |
| Low pitch metal | | | | | | x | |
| High pitch metal | | | x | | | | x |
| Fixed vents: Yes | x | x | x | x | x | x | |
| No | | | | | | | x |
| External door stripping: Yes | x | | | | | | x |
| No | | x | x | x | x | x | |
| Shelter by surroundings: Less than average | | | x | | x | | x |
| Average | x | x | | | | | |
| More than average | | | | x | | x | |
| Time monitored (days) | 13 | 15 | 22 | 15 | 21 | 23 | 70 |
| Number of data points | 38 | 41 | 41 | 28 | 64 | 58 | 191 |

*Measured between the internal surfaces of external walls.

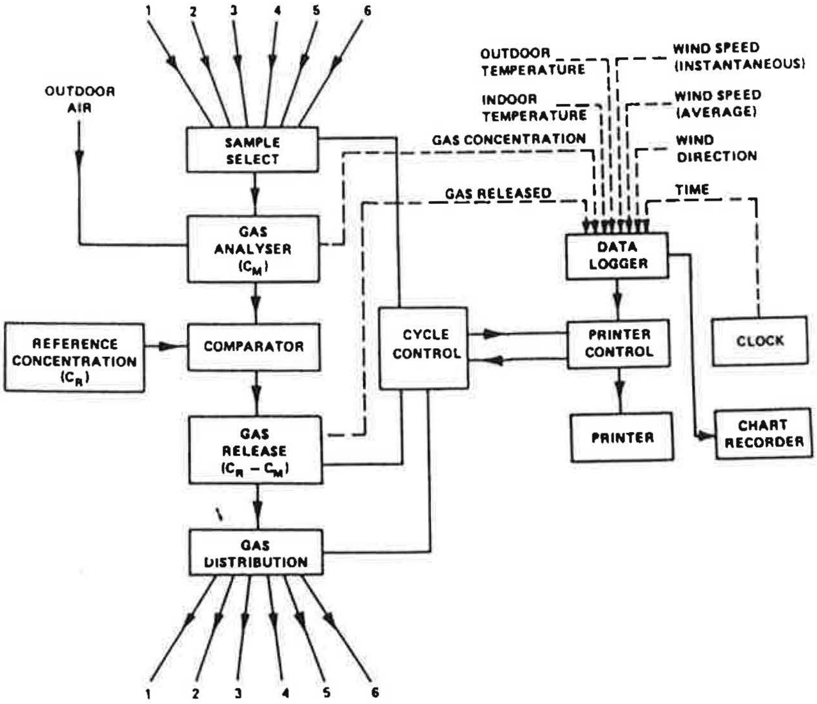

Figure 1. Block diagram of apparatus for continuous monitoring of air infiltration rate.

an almost constant value of gas concentration. Should the rate of air infiltration change, the concentration of gas is affected, so the quantity of gas released automatically changes too, and the interaction of the two influences (infiltration and gas release) establishes a new value of gas concentration.

For steady conditions, the amount of gas released in an hour (Q,$m^3$/h) in order to maintain an average gas concentration (C, ppm) in a house of volume V ($m^3$) when the infiltration rate is $\gamma$ (ac/h), is $\gamma VC \times 10^{-6}$, thus $\gamma = Q \times 10^6/CV$.

Relevant environmental data were recorded along with the gas concentration. Indoor and outdoor air temperatures were monitored continuously. Data on wind speed and direction, measured at a height of 3 m above the ground with instruments mounted on a pole located within the site boundaries of the given house, were recorded in the form of 10-minute averages of wind speed and instantaneous wind directions sampled at 4-minute intervals. Corresponding data, relating to a height of 28 m above the ground at a site to the north-east of the Melbourne central business district and pertaining to the 10 minutes preceding each hour, were obtained from the Bureau of Meteorology for the period of measurement. The number of different wind directions considered was limited to the eight principal compass bearings. Individual wind directions were assigned to the appropriate 45° sector.

When there is a change in the infiltration rate, several cycles of measurement and gas release are needed to establish the new equilibrium value of gas concentration. In order to obtain reliable results it has been the practice to average the values of the variables over 15 cycles, i.e. one hour, for periods when weather conditions are stable or changing only slowly. Any short-term instability in the weather reduces the number of occasions during which stable conditions are maintained for an hour, but on the other hand extended periods of stability in the weather reduce the range of values that may be deduced from the basic data. In practice, to obtain a useful range of data, it has been found necessary to monitor a given house for several weeks.

## RESULTS

Overseas reports (for example, Malik 1978, Etheridge et al. 1981) indicate that, for houses in the Northern hemisphere, the stack effect can make a significant contribution to air infiltration. However, conditions in those countries (houses often of two storeys and indoor/outdoor temperature differences up to 35°C) are much more conducive to stack-induced infiltration than conditions encountered during the measurements reported here (single-storey houses, indoor/outdoor temperature differences rarely greater than 10°C). When the data were fitted to the general expression given by Equation (2), $\gamma = \alpha + [\phi V^2 + \lambda(\Delta T)]^n$, it was found that $\alpha$ was always significantly different from zero, and in all except one instance (house 14) the fitted value of $\lambda$ was not significantly different from zero at the 5 per cent significance level. Accordingly, no further attention was given to the stack effect, and the expression for $\gamma$ becomes $\gamma = \alpha + \beta V^{2n}$, where $\beta = \phi^n$.

Fitting the data to this expression, allowing different values for $\alpha$ and $\beta$ for each house but a common value of n, yielded an estimate of the exponent of 0.65 (standard error 0.053), which was in excellent agreement with the mean value, 0.65, obtained empirically from permeability measurements made on the same houses by Biggs et al. (1986).

A linear fit of the data, holding the exponent $n = 0.5$, was found to be almost as good as when $n$ was 0.65. (The residual standard deviation in the regression analysis was 0.133 in the former case, and 0.132 in the latter, on 446 and 445 degrees of freedom respectively.) Since the linear form $\gamma = \alpha + \beta V$ has practical advantages, it has been adopted for analysis and reporting of the data.

For each house, the measured one-hour average values of infiltration rate were plotted against the corresponding average wind speeds for the given hours. This was done for wind speeds measured both locally on site and at the Bureau of Meteorology. The average local wind speed for a given one-hour period over which infiltration rate was averaged was obtained from the mean of the 10-minute local wind averages included in that hour. For data from the Bureau of Meteorology, interpolation between the relevant 10-minute averages taken prior to each clock hour was carried out to determine the speeds at the start and finish of the hour period, and the results averaged. An example of these plots is given in Figure 2 where the data for house 13 are plotted against the Bureau of Meteorology wind speeds for the various wind directions, without distinction as to the indoor/outdoor temperature difference. The data were fitted using a multiple regression model incorporating an intercept with the infiltration rate axis, $\alpha$, which was common to all wind directions since direction cannot be a factor when the wind speed is zero. In statistical terms, plotting against the local wind speed was found to give a slightly better fit of the data than plotting against the Bureau of Meteorology wind data (residual standard deviations 0.12 and 0.13 respectively), but for the reasons stated in the section 'Correlation of Infiltration Rate with Wind Speed', it was decided to utilise the latter data.

It will be seen that $\alpha$ is positive. This result is almost always obtained (Peterson 1979), and has never been fully explained. Diffusion is insufficient to account for it (Bilsborrow 1972) and, as indicated above, stack effect is of minor importance in the results reported here. There is some evidence to suggest that air turbulence plays a part (Chandra et al. 1983). Whatever the explanation, it is clear that the seven Australian houses studied exhibited significant 'background' infiltration rates, i.e. finite rates at very low indicated wind speeds. The average rate, for zero wind speed at the Bureau of Meteorology, was found to be 0.33 ac/h.

Part of the spread of the data points in Figure 2 is due to directional sensitivity, i.e. to differing effects when the wind blows from different directions at a given speed. For houses 2, 3, and 4 there were insufficient data to demonstrate statistically significant directional effects, but significant directional sensitivity was shown by houses 1, 13, 14, and 18. For example, for house 18 the infiltration rate was found to change least rapidly with increasing wind speed when the wind was from the west (Table 2). This behaviour may be explained by the fact that the house presented to the wind from this direction an almost blank brick facade, the only break being a well-weatherstripped door.

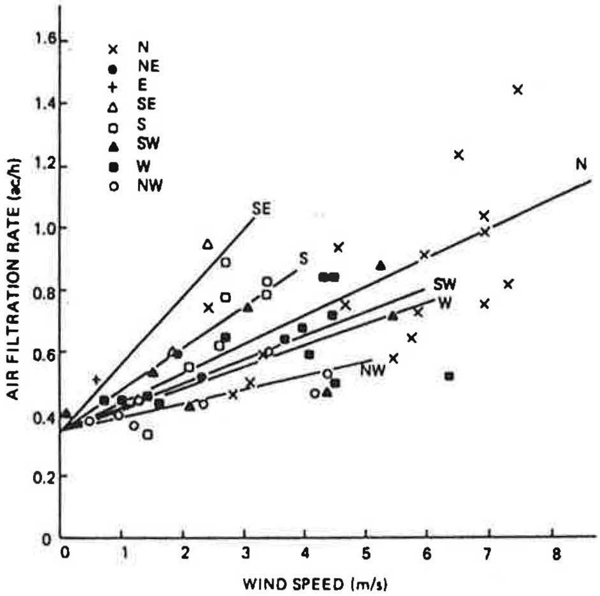

Figure 2. Air infiltration rates for house 13 for various wind speeds and directions reported by the Bureau of Meterorology, Melbourne (both infiltration rates and wind speeds arc 1-hour average values).

Table 2. Values of $\beta$, in air changes per hour per metre per second in the expression $\gamma = \alpha + \beta V$, for given wind directions, for house 18 ($\alpha$ = 0.347 air changes per hour, standard error 0.018)

| | Wind direction | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | N | NE | E | SE | S | SW | W | NW |
| $\beta$ | 0.080 | 0.144 | 0.095 | 0.076 | 0.066 | 0.053 | 0.041 | 0.057 |
| Standard error of $\beta$ | 0.006 | 0.017 | 0.076 | 0.102 | 0.006 | 0.007 | 0.006 | 0.009 |

Linear regression of infiltration rate against wind speed, irrespective of direction, was carried out for the seven houses and the resulting lines of best fit are shown in Figure 3. There are significant differences between houses, both in slope ($\beta$) and intercept ($\alpha$) of the regression lines. The infiltration rate behaviour of houses 1 and 14 suggested that there might be physical differences between these houses and the others which render them, respectively, exceptionally 'tight' or exceptionally 'leaky'. In fact, house 1 was a very well maintained house with all skirting and architrave cracks sealed, and wooden sash windows which sealed tightly when closed. House 14, on the other hand, incorporated a ceiling comprising plasterboard panels fitted between wooden beams, full-width slots at the head of every external door and window, and unweatherstripped wooden awning windows. Measurements (Biggs et al. 1986) of the permeability of the houses confirmed that house 1 was the least permeable, and house 14 was the most permeable of the seven houses. Houses 1 and 14 are not considered further here.

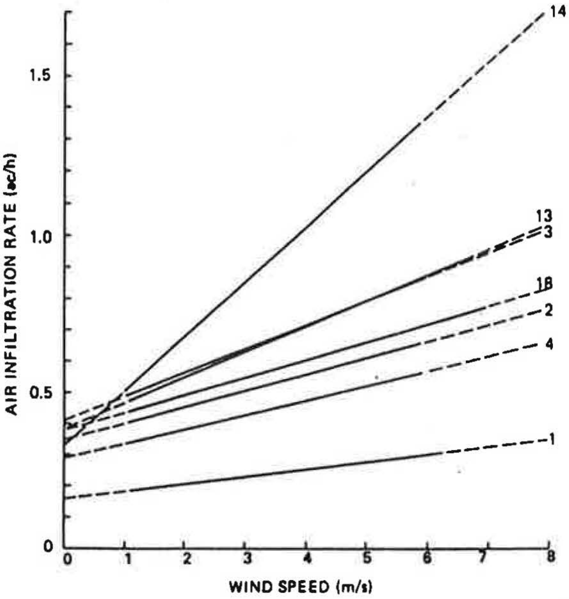

Figure 3. Linear regression, for each house, of infiltration rate on wind speed reported by the Bureau of Meteorology, Melbourne. Numbering of the regression lines identifies the houses concerned.

The separate relationships between air infiltration rate and wind speed for the 'average group' (houses 2, 3, 4, 13, and 18) are represented in Figure 4 by a single relationship, $\gamma = 0.37 + 0.062V$, obtained by averaging the separate values of $\alpha$ and $\beta$. Also shown are the 95% confidence limits of the trend value. Strictly speaking, this result applies only in Melbourne, and modified expressions would be needed for other cities to account for the different heights and exposure conditions at which the Bureau of Meteorology measures the wind data in the various cities (Bureau of Statistics 1981). However, the effect of these factors is expected to be small.

The houses studied are reasonably typical of Melbourne and as they are similar to housing in other parts of south-eastern Australia the results could be useful in that wider geographic context.

## DISCUSSION

It is interesting to compare these results with those published for houses in other countries. Data are scarce but studies in Sweden (Gustén and Johansson 1978) showed that for 50 houses built between 1960 and 1980, the infiltration rates were between 0.2 and 0.4 ac/h. The severe winter climate in Sweden and the lack of natural energy sources has led to the use of building techniques and sealing practices that keep leakage air exchanges to a low level. In the United Kingdom, where the climate is closer to that in the temperate regions of Australia, a study of 25 houses yielded an average infiltration rate of 0.7 ac/h (Warren and Webb 1980). This is marginally higher than the average air change rate (approximately

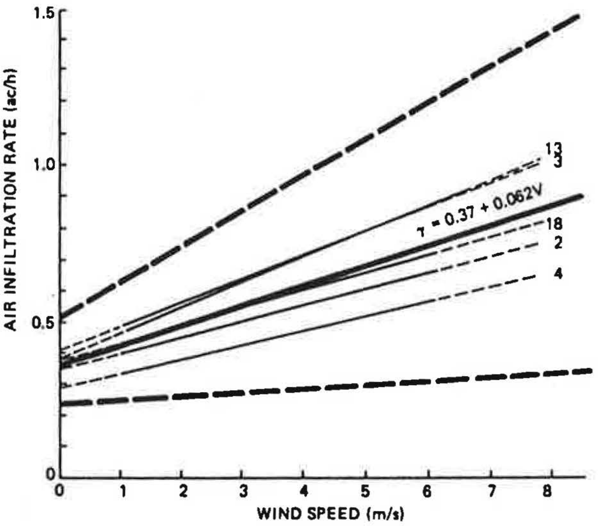

Figure 4. The linear relationship $\gamma = 0.37 + 0.062V$ (thick, solid line) representative of the linear relationships (thin, solid lines) found for the 'average group' of houses (houses 2, 3, 4, 13, and 18). The thick, broken lines are the 95 per cent confidence limits for the representative relationship.

0.6 ac/h) of the houses reported here for a wind speed of 3.4 m/s (the average wind speed for Melbourne). The increased stack effect induced in the two-storey British houses would contribute to this difference.

The data of Figures 3 and 4 invite consideration of how well the conflicting aims of achieving satisfactory indoor air quality and reducing energy consumption are met by these typical houses, and whether changes should be recommended in current building practices and sealing methods.

Taking the expression for the average group of houses, $\gamma = 0.37 + 0.062V$, and using for V the annual average wind speeds for four capital cities, namely Canberra 1.6, Sydney and Hobart 3.2, and Melbourne 3.4 m/s, the average air infiltration rates for this group of houses are found to be 0.44, 0.55, and 0.57 ac/h respectively. Australia does not have a mandatory minimum air change rate for houses, but in terms of the Swedish Building Code (Swedish National Board of Physical Planning and Building 1975), which requires a minimum of 0.5 ac/h in houses to disperse internal pollutants and to reduce moisture levels, these rates are marginally acceptable. However, as average wind speeds were used, it follows that for approximately half the time the air infiltration rates would be below the values stated, and for the 'tighter' houses in the group, the rates would be lower still. In practice, though, air change rates in occupied houses will usually be considerably higher than the rates when the houses are unoccupied.

In a study of 23 dwellings in Denmark (Ksvisgaard 1985) it was found that on average the air change rates in occupied dwellings were 3-4 times higher than the rates when the dwellings were unoccupied, although the data exhibited considerable variability. Reasons for this increase include the use of exhaust fans, periodic 'airing', movement of people in and out of the house, passage of air up flues, and the practice of leaving some windows permanently ajar. In regard to the last factor, measurements in house 18 showed that at a wind speed of 3.4 m/s the air change rate doubled when one top-hung window in each of the three bedrooms was opened by only 30 mm.

Nevertheless, there will be instances in which living patterns are such that air change rates would be little different from the rates for the unoccupied houses. Furthermore, some houses (for example, house 1) may be so impermeable that they would still be underventilated despite the increases brought about by being occupied. For these reasons it is inappropriate, on indoor air quality grounds, to make a general recommendation to reduce house permeabilities in order to achieve energy savings.

In particular instances, such as those in which a house is exceptionally permeable, or an 'average' house is subject to exceptionally windy conditions, it would be reasonable to tighten the house to reduce air infiltration rates in order to save energy. However, the question then arises as to whether such measures would be cost effective.

This question has been addressed, for average houses, by preliminary calculations (Biggs et al. 1986) and by a more detailed analysis in a subsequent paper (Biggs and Bennie 1987). The latter analysis took into account annual energy savings, energy costs, costs of house-tightening measures, inflation and discount rates, and also included consideration of the expected life of the tightening measures, and average lengths of residency. As a result it was concluded that with the temperate climate of the most populous parts of south-eastern Australia (mean winter temperatures; Sydney 12.6, Melbourne 10.1, Canberra 6.2, Hobart 8.4°C) and 1986 levels of 'house-tightening' and energy costs, retrofit tightening of the 'average' house would only rarely be economically worthwhile.

With houses subject to higher than average infiltration rates, the potential for energy savings is greater, but house tightening may still not be economically attractive. Individual cases would need to be considered on their merits.

It may be remarked that cost-benefit is not always the primary consideration when implementing house-tightening measures. Weatherstripping is often installed to reduce draughts. In such situations the occupant is seeking improved comfort rather than energy savings.

## CONCLUSIONS

Infiltration rate measurements on seven unoccupied Melbourne houses, of which five were typical of the building stock of south-eastern Australia, indicate that in this respect these houses are similar to houses in the United Kingdom, but are more prone to wind-induced air exchanges than Swedish houses.

A representative expression for the infiltration rate, $\gamma$ ac/h, for these five houses with windows and external doors closed, in terms of the wind speed, V m/s reported for Melbourne by the Bureau of Meteorology, is $\gamma = 0.37 + 0.062\ V$. At the mean value of V, 3.4 m/s, $\gamma$ has the value 0.58 ac/h and the 95 per cent confidence interval is approximately 0.27 to 0.88 ac/h. Given the similarities in construction of houses in Melbourne to those in south-eastern Australia generally, the equation for $\gamma$ could well prove a useful indicator for that region as a whole.

In the light of this relationship, consideration of the need to achieve satisfactory indoor air quality leads to the conclusion that no general recommendation to 'tighten' average houses should be made.

For houses with higher than average infiltration rates, where tigthening would be in order, the question remains whether doing so would be worthwhile. It has been shown elsewhere that retrofit tightening of the 'average' house would rarely be economically worthwhile, but with these higher-than-average houses, individual circumstances would have to be considered in each case.

## ACKNOWLEDGMENTS

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