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BUILDING SITE MEASUREMENTS FOR PREDICTING AIR INFILTRATION RATES

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BUILDING RESEARCH ASSOCIATION OF NEW ZEALAND

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Building Site Measurements for Predicting Air Infiltration Rates

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ABSTRACT: This paper examines the sensitivity of the predicted air infiltration rate to measured building airtightness data and the wind exposure index determined from site inspection. Results of airtightness tests in New Zealand houses are presented to indicate the range of leakage resistance for components (windows, doors, and chimneys, etc.), for solid materials (such as wall and ceiling lining materials), and for cracks separating major components such as the floor and walls. The distribution of leakage opening is discussed in relation to the driving forces of wind- and stack-induced airflows and also in relation to New Zealand styles of house building.

The building site exposure class must be determined in order that standard wind engineering formula can be used to calculate site wind speeds from meteorological weather data recorded some distance away. In the New Zealand situation, with high wind speeds and modest indoor-outdoor temperature differences, predicted natural air infiltration rates are particularly sensitive to site exposure details. Examples of measured and predicted air change rates are given for a number of houses together with comment on the sensitivity to experimental error.

KEY WORDS: air infiltration, airtightness, air leakage in buildings

Air infiltration studies in New Zealand only recently have begun to address two prevalent problems in houses. These problems are:

1. Control of indoor moisture.
2. Winter space heat loss.

The first ranks as the most common reason for unsatisfactory house performance and is likely to be more prominent in comparatively airtight houses where windows are kept closed during colder winter periods. At the opposite

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end of the scale are particularly loose houses on wind-exposed sites. One way of identifying houses that could benefit from improved airtightness and those where some form of ventilation assistance is necessary is to estimate the mean air infiltration rate from building airtightness and weather information. This paper is concerned with the provision of airtightness information for New Zealand houses. It places some emphasis on the accuracy of measurements and the resolution necessary for estimates of mean air infiltration rate.

Airtightness Measurements

Test Method

The simplest method of measuring the leakage characteristics of a building employs a fan to hold a steady pressure difference between inside and outside while the leakage rate is measured. Results at a number of pressures then are combined in the form of a leakage function characteristic of the building. The total airflow resistance of the building envelope will be a parallel combination of leakage resistances through many paths, each having a characteristic leakage function that in broad terms will lie between the extremes of orifice or turbulent flow and laminar flow. These flow regimes are represented approximately by the following general equation

$$Q = C(\Delta P)^E$$

$$Q = \frac{1}{R}(\Delta P)^E \qquad (1)$$

where

Q = volume flow, m^3/s,
ΔP = pressure difference, Pa,
R = resistance to flow, Ns/m^3,
C = flow coefficient, and
E = exponent between 0.5 and 1.0.

The leakage function can be quite complicated in detail, especially in the region where flow and pressure depend strongly on the Reynolds number. Nevertheless, it has become normal practice to use a simple leakage function of the just-cited form to describe the total building leakage.

Equipment

A brief summary is given here of the equipment used for blower door airtightness tests by the Building Research Association of New Zealand. Figure 1 shows the fan and airflow measuring equipment set up in a house. A 380-mm

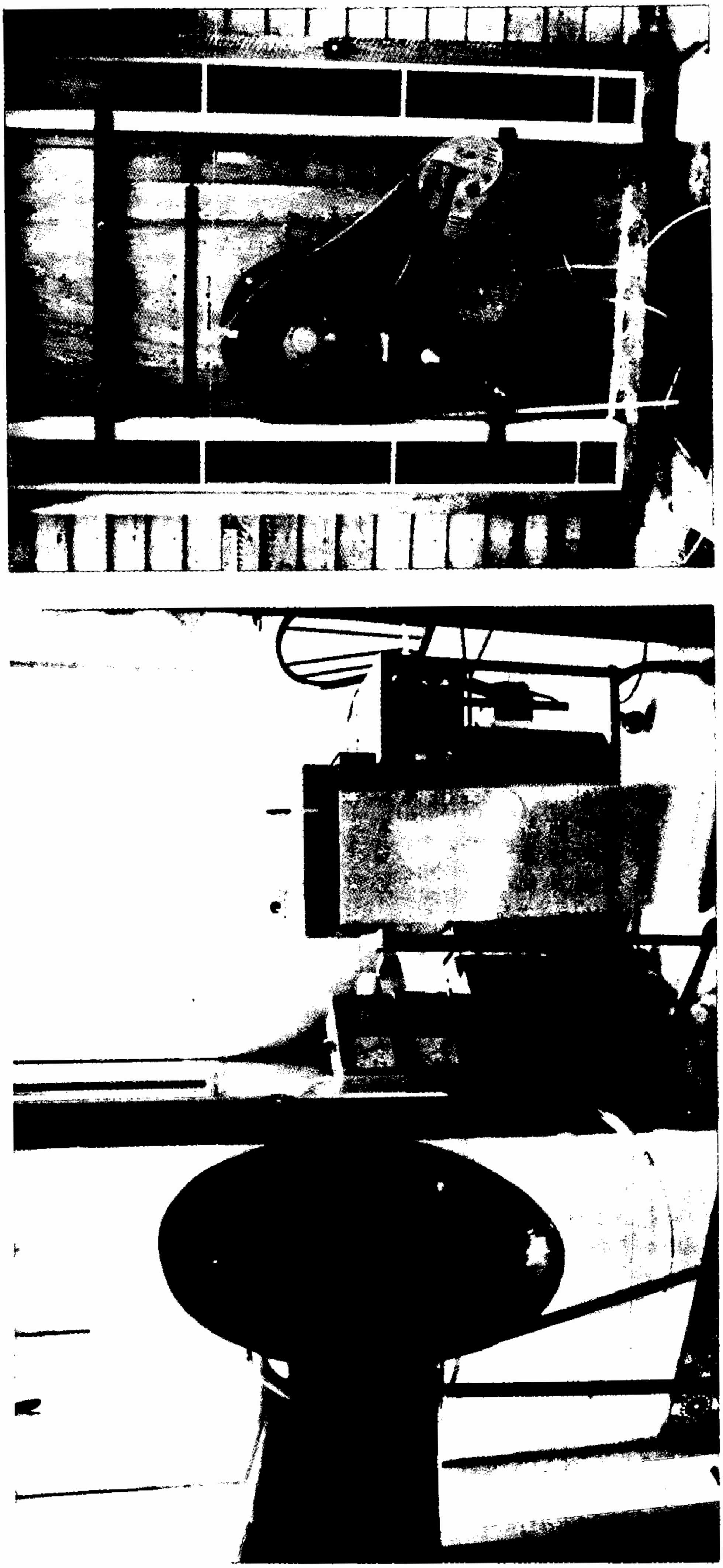

FIG. 1—*Fan and airflow measuring equipment used for airtightness test.*

airfoil fan is mounted in an adjustable door panel and fixed in place in an external door opening. It is driven by a lightweight 1600-W, three-phase motor. Synchronous speed control is achieved with a controller, which synthesizes adjustable frequency, three-phase power from a standard 230-V, single-phase outlet. Airflow measurements are made from the static pressure in the throat of a long radius flow nozzle calibrated in the laboratory using ASTM Test for Average Velocity in a Duct (Pitot Tube Method) (D 3154-72). Pressures were measured using a digital manometer calibrated in 0 to 200 and 0 to 2000-Pa ranges. Each test was based on 6 to 9 indoor-outdoor pressure differences in the range 10 to 150 Pa, the lower limit being appreciably above wind pressure measured across the windward wall using an externally mounted pressure tap.

Reproducibility

An assessment has been made of the reproducibility of the blower door method, including the widely used practice of masking leakage openings around doors and windows with tape. Table 1 shows the results of a sequence of airtightness tests carried out on the same house on three separate occasions spaced about a week apart. In this case, the results are expressed as leakage areas at 50 Pa, defined as the area of sharp edge orifice required to pass the same volume flow at 50 Pa.

$$A = \frac{Q}{Cd\left(\frac{2\Delta P}{\rho}\right)^{1/2}} \tag{2}$$

TABLE 1—*Test of reproducibility.*

	Leakage Area at 50 Pa, m^2			
Action	Test A	Test B	Test C	Error
1. House with doors and windows closed	0.152	0.151	0.153	0.007
2. Same as No. 1 with cracks around openable windows and doors taped	0.096	0.096	0.097	0.005
3. Same as No. 2 with shower vent and free standing fire place flue blocked	0.086	0.084	0.086	0.004
4. Leakage area of cracks around openable windows and doors	0.056	0.055	0.056	0.003
5. Leakage area of shower vent and fire place flue	0.010	0.012	0.011	0.003

where

A = leakage area, 50 Pa/m^2,
Q = volume flow, m^3/s,
Cd = discharge coefficient = 0.6,
ρ = density of air, kg/m^3, and
P = pressure difference, Pa.

The errors listed in Table 1 are approximate 95% confidence intervals determined from the residuals of the fit between the model and experimental data points.

It can be seen that the results of three separate measurements agree within the limits of the random error, indicating that the blower door procedure can at least be satisfactorily reproduced. There are systematic errors associated with pressure and airflow measurements that add a further 2% uncertainty to approximately 5% for the random part.

Further examination of the residuals of fitting measurements to the power law equation (Eq 1) has shown that part of the error previously assigned as random is in fact serially correlated to the indoor-outdoor pressure difference.

Figure 2 indicates the size of the serially correlated error and also shows that the power law equation is accurate enough for interpolation within the range of measurement.

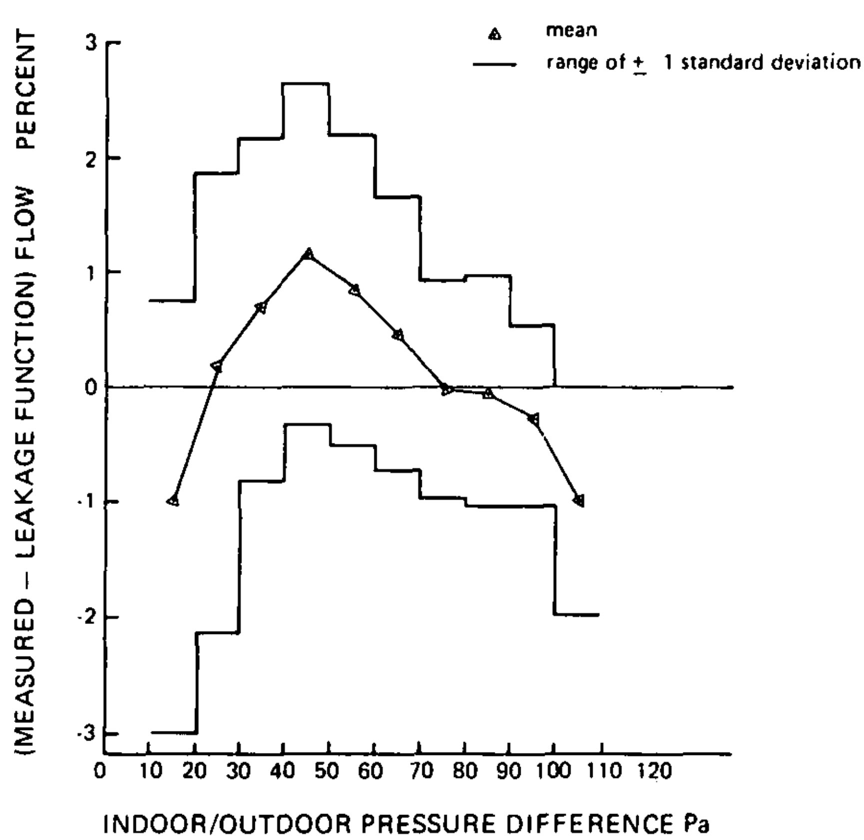

FIG. 2—*Correlation of residuals with pressure. Mean and standard deviation for 50 airtightness tests.*

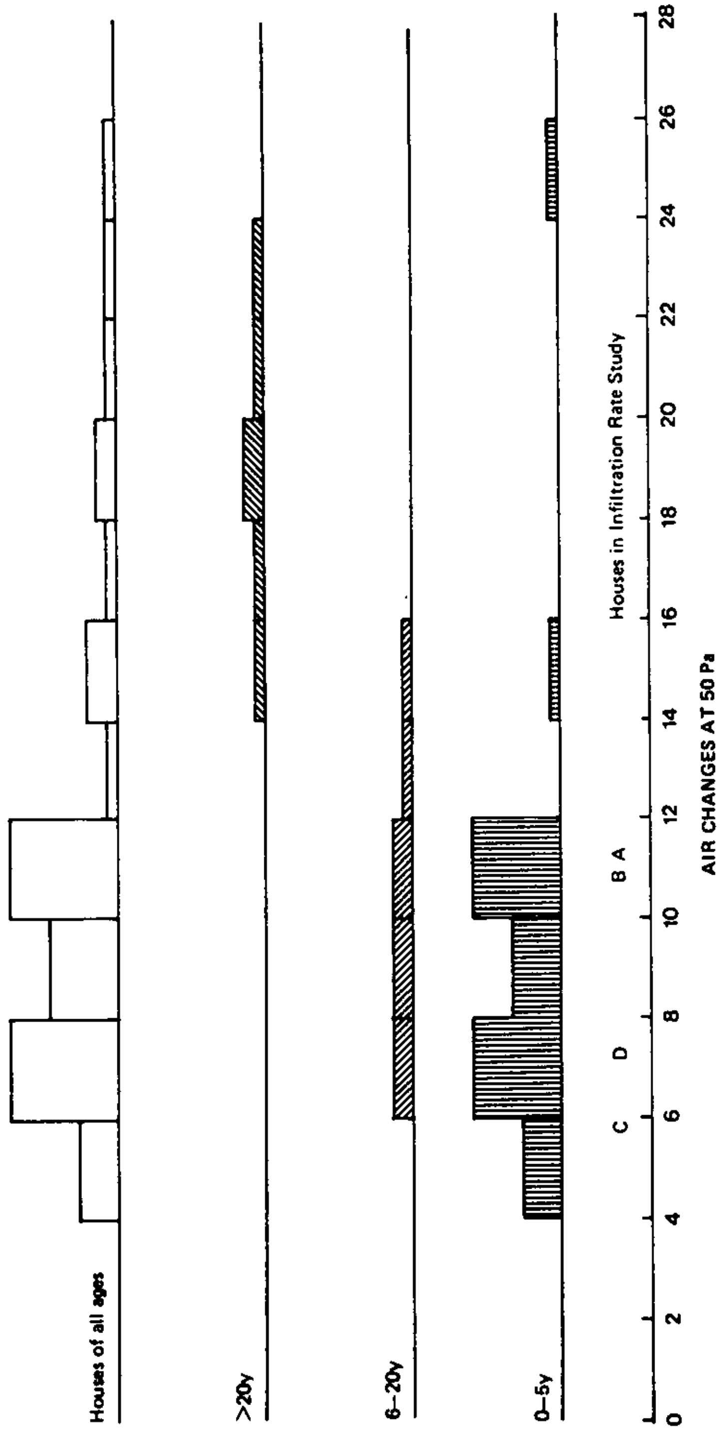

FIG. 3—*Histogram of air change rates at 50 Pa for 40 New Zealand houses.*

House Airtightness Results

A Survey of 40 Houses

A survey of house airtightness was completed in 1982 by Bassett [*1*]. It used the blower door method to measure the air leakage characteristics of 40 houses of different age and construction type in Wellington.

A histogram of house airtightness expressed in air changes/hour (ACH) is given in Fig. 3. The houses are divided into three age groups, chosen to approximately separate insulated houses into a group less than 5 years old, and those with strip flooring into a group greater than 21 years old. Most results lie in the range of 4 to 26 ACH, with 75% between 4 and 12 ACH. Subdividing by age group shows the 0 to 5 and 6 to 20-year groups to be indistinguishable, but also shows that the 21-plus-year age group, represented by six houses, was less airtight at 16 to 24 ACH.

Airtightness and Design Complexity

Two houses in the 0 to 5-year age group were quite leaky, and it was noted that they both had an unusually complicated shape. This raises the possibility that some design details influence airtightness in a way that can be identified and used at the stage buildings are designed.

In Fig. 4, we attempt to show how the leakage rate at 50-Pa per m^2 shell

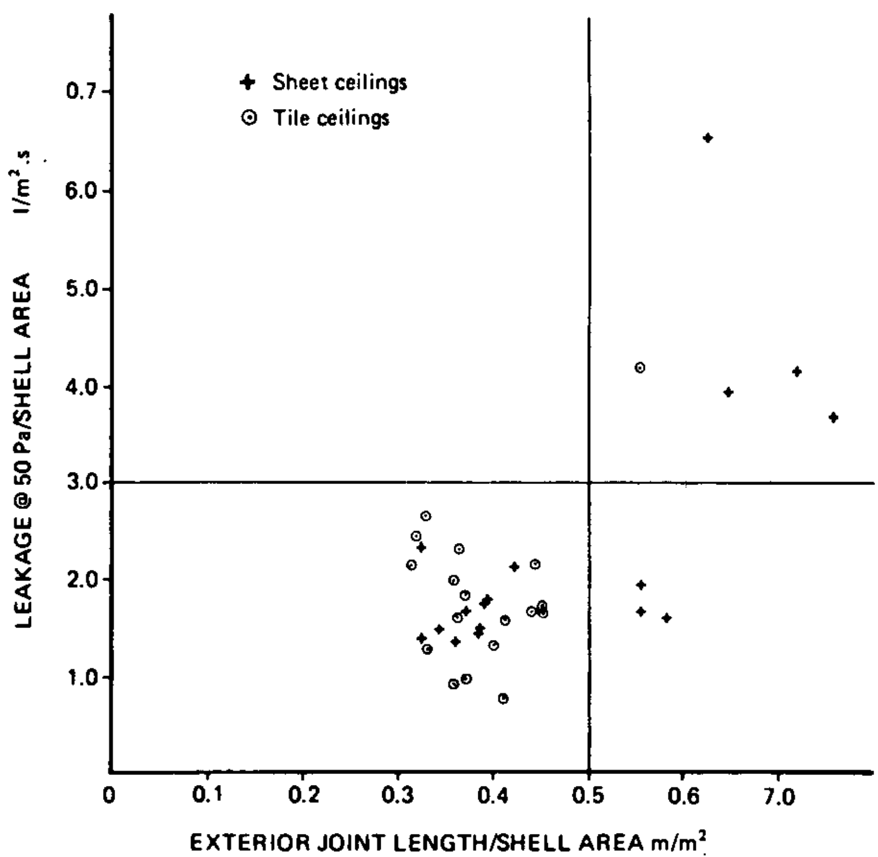

FIG. 4—*Measure of building shell complexity against leakage/shell area at 50 Pa.*

area depends on shell complexity. As a measure of the latter, we add the perimeter length of top and bottom plate, together with vertical lengths of exterior corners, and the boundaries of changes of ceiling pitch. The total is divided by shell area to give a notional measure of shell complexity. Figure 4 shows this variable plotted against the leakage rate at 50 Pa divided once again by shell area. Leakage around doors, windows, and through vents and chimneys also has been subtracted to ensure that the leakage rate is as shape specific as possible.

Figure 4 suggests a subdivision of houses into the following four groups:

1. Average tightness and average shell complexity—23 houses.
2. Below average tightness and average shell complexity—0 houses.
3. Below average tightness and above average shell complexity—5 houses.
4. Average tightness and above average shell complexity—3 houses.

It seems that while some houses of complicated shape can be less airtight than average, this is not always the case. There are eight houses of above average shell complexity; five have higher than average leakage rates, but the other three are about average. It can, however, be said that there is a high degree of association between shape and tightness, since there are no examples of average houses with high leakage rates.

Air Leakage Through Solid Materials

Diffusion of air through the solid components of a building (such as its walls, floor, and ceiling) is potentially important, because these areas are orders of magnitude larger than the size of cracks and joints. Air diffusion resistance measurements were made in the laboratory for a range of interior and exterior lining materials. A summary of the results is given in Table 2, together with a brief physical description of each material. The resolution of the data indicates the range of diffusion resistance for materials of the same description but different batch.

The airflow resistance is defined by Eq 3

$$R = \frac{A \Delta P}{Q} 10^{-6} \quad \frac{\text{MNs}}{\text{m}^3} \tag{3}$$

where

R = leakage resistance, MNs/m^3,
A = area of material, m^2,
Q = volume flow rate of air, m^3/s, and
ΔP = air pressure difference across the material, N/m^2.

As an aid to interpreting Table 2, a reference airflow resistance can be calculated to give a volume flow rate of 2×10^{-5} m^3/m^2 s at 50 Pa. This is 2.5

TABLE 2—*Bulk air flow resistance of common building materials.*

Material	Coating	Density, kg/m^3	Thickness, mm	Order of Magnitude Resistance, MNs/m^3
Flooring grade wood chipboard	none	700	20	10
	varnish	...	...	10^4
Exterior grade plywood asbestos cement board	none	900	4	10
	none	1500	6	10
Paper-coated gypsum, plasterboard	none	750	9.5	10
	alkyd paint system	...	...	$>10^7$
	acrylic paint system	...	...	10^5
	vinyl wall paper	...	...	10^3
Interior grade wood chipboard (low density)	none	600	10	1
	acrylic paint system	...	...	10^5
Wood fiberboard (low density)	prepainted	330	13	1
Wood fiberboard (high density)	none	1130	5	10
	alkyd paint system	...	...	$>10^7$
	acrylic paint system	...	...	10^4
	varnish	...	...	10^6
Glass fiber reinforced gypsum plasterboard	none	910	8	1
Melamine formaldehyde laminate for wet areas		1130	5	$>10^7$
[a]Lapped weatherboards	alkyd paint system		18	10^{-1}
[a]Rusticated weatherboards	none		18	10^{-2}
[a]Wood fiberboard ceiling	none		13	10^{-1}

[a]Includes joints.

MNs/m^3, which is about 1% of the average leakage rate/m^2 of shell area for New Zealand houses less than five years old. A quick scan of the airflow resistances for solid materials in Table 2 shows that only unpainted lining materials are likely to contribute significantly to measured leakage rates. The normal practice of interior decorating by painting greatly increases the airflow resistance to the point where air leakage can be considered insignificant. Samples painted with an alkyd paint system proved to be tighter than our equipment could measure, and a lower limit is recorded in Table 2.

Board or tile materials with joints included in the leakage measurement have lower airflow resistances. However, of the three examples in Table 2, the two outdoor sheathing materials are likely to be fixed in series with a much higher resistance interior lining. This leaves the ceiling tile system as the only lining material in wide use with significant joint system leakage. In a house with average leakage characteristics and a low density wood fiber tile ceiling, leakage through joints in the ceiling could contribute 10% of air leakage under airtightness test. Further reference can be made to Fig. 4, where houses are separated into those with tile ceilings and those with sheet ceilings. In the average tightness-average complexity classification, no significant difference can be attributed to ceiling type. A 10% difference, if present, would be significant at the 80% level.

Component Leakage Information

There are two reasons for surveying the leakage characteristics of joint systems and components of the building envelope. Firstly, it is necessary to know how the leakage opening is distributed in a building in order to calculate the stack- and wind-induced airflows. Secondly, there is the prospect, already demonstrated by Reinhold and Sonderegger [2], that acceptable airtightness estimates might be calculated from plan drawings and tables of leakage resistances so that an estimate of the infiltration rate would be available at the design stage.

Leakage Through Openable Window and Door Joinery

Homeowners are frequently exposed to advertising for draft-stopping materials for windows and doors. This may give them the impression that the bulk of air leakage originates from these sources, but a recent survey of 20 houses by Bassett [1] in New Zealand showed that these sources are unlikely to exceed 25% of the total leakage area.

Window and door leakage measurements were completed using the technique of masking joints and remeasuring the total house leakage rate. Windows and doors of all types were masked together and statistical methods used to resolve differences attributed to joinery type. The most important difference is that between aluminum and wood-framed joinery with the following leakage rate and 95% confidence interval applying at 50-Pa pressure difference.

Window and Door Joinery Type	Leakage/m at 50 Pa, L/s · m
Aluminum extrusion	0.5 ± 0.5
Wood molding	4 ± 1

Figure 5 summarizes window leakage measurements and shows the sample of older New Zealand wooden windows to be similar to those measured by Tamura [3] in Canada and comparable with average data given in the IHVE guide [4] and the "ASHRAE Handbook of Fundamentals" [5]. Also of note is

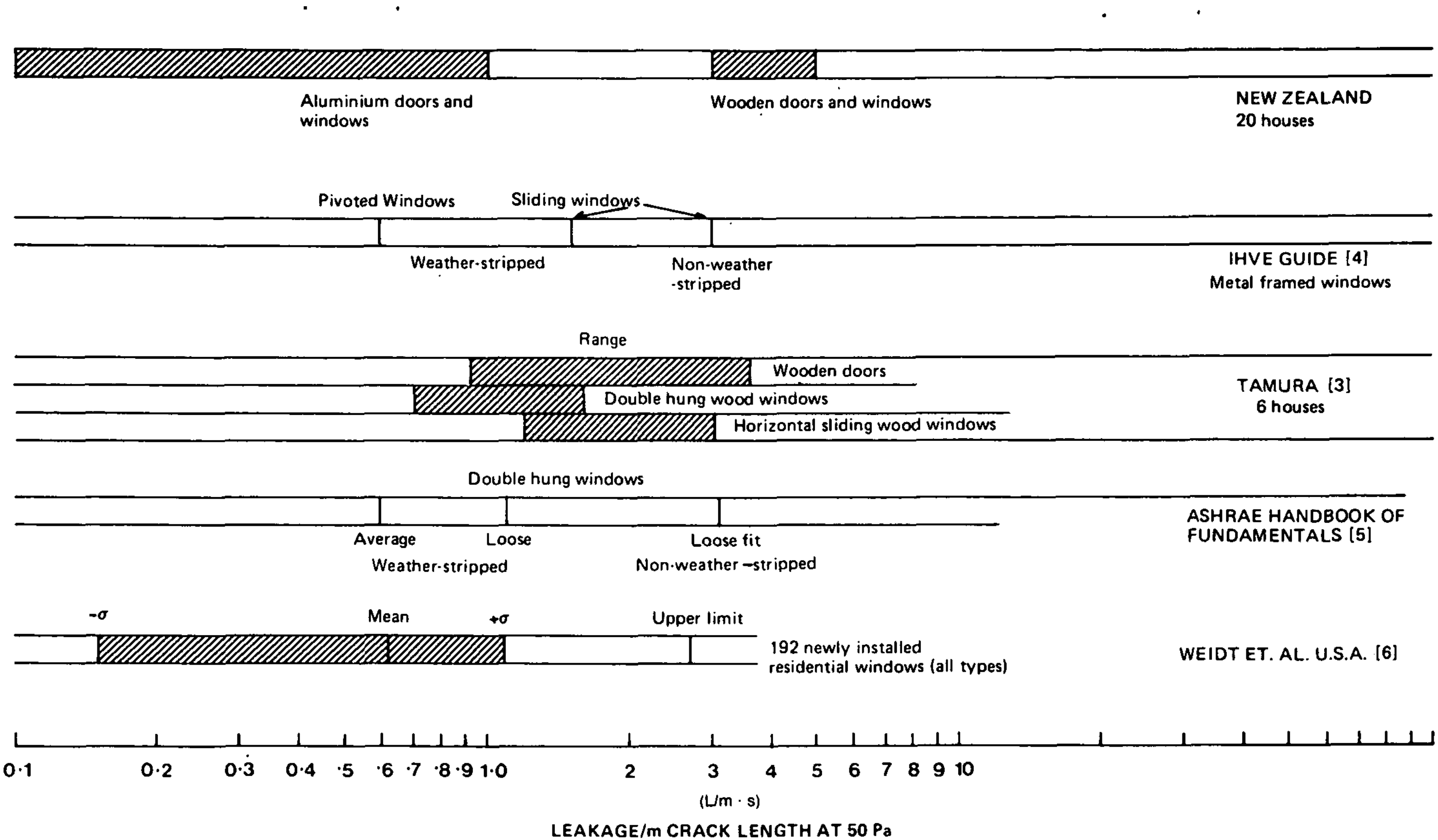

FIG. 5—*Results of window/door leakage tests.*

the similarity between leakage rates for aluminum joinery in this country and the measurements of Weidt et al [*6*] for newly installed residential windows in the United States.

Standards for Window Air Leakage

There are standards for window airtightness giving leakage rates at a range of pressures. Often the applied pressure is much higher than the reference 50 Pa used in airtightness studies because of the need to test for frame distortion at peak wind speeds. For comparative purposes, Fig. 6 gives flow rates at 50 Pa converted using the following equation

$$Q_{50} = Q(n)\left(\frac{n}{50}\right)^{0.65}$$

where

n = standard pressure, Pa.

Where leakage rates are given on an area basis, the following approximate conversion is used

$$1(\mathrm{L/m^2 \cdot s}) \text{ equivalent to } {}^{1}\!/_{4}(\mathrm{L/m \cdot s})$$

The New Zealand Standard, Specifications for Performance of Windows (NZS 4211) [7], defines three grades of leakage. When converted to a leakage rate at 50 Pa, they are as follows:

1. Grade A—0.3 L/s · m.
2. Grade B—1.0 L/s · m.
3. Grade C—2.0 L/s · m.

Leakage rates at 50 Pa are shown in Fig. 6 from a number of standards for comparison.

Leakage Through Construction Joints

A limited amount of leakage information has been measured for construction joints in new timber frame houses. These data are summarized in Table 3, and, while not sufficiently complete to be used to predict leakage characteristics of new houses, the data can be used as a guide to the distribution of leakage openings.

Leakage At Services Entry and Other Openings

While a house is under airtightness test, it is a relatively simple matter to look for major leaks by detecting drafts. On a number of occasions, leakage

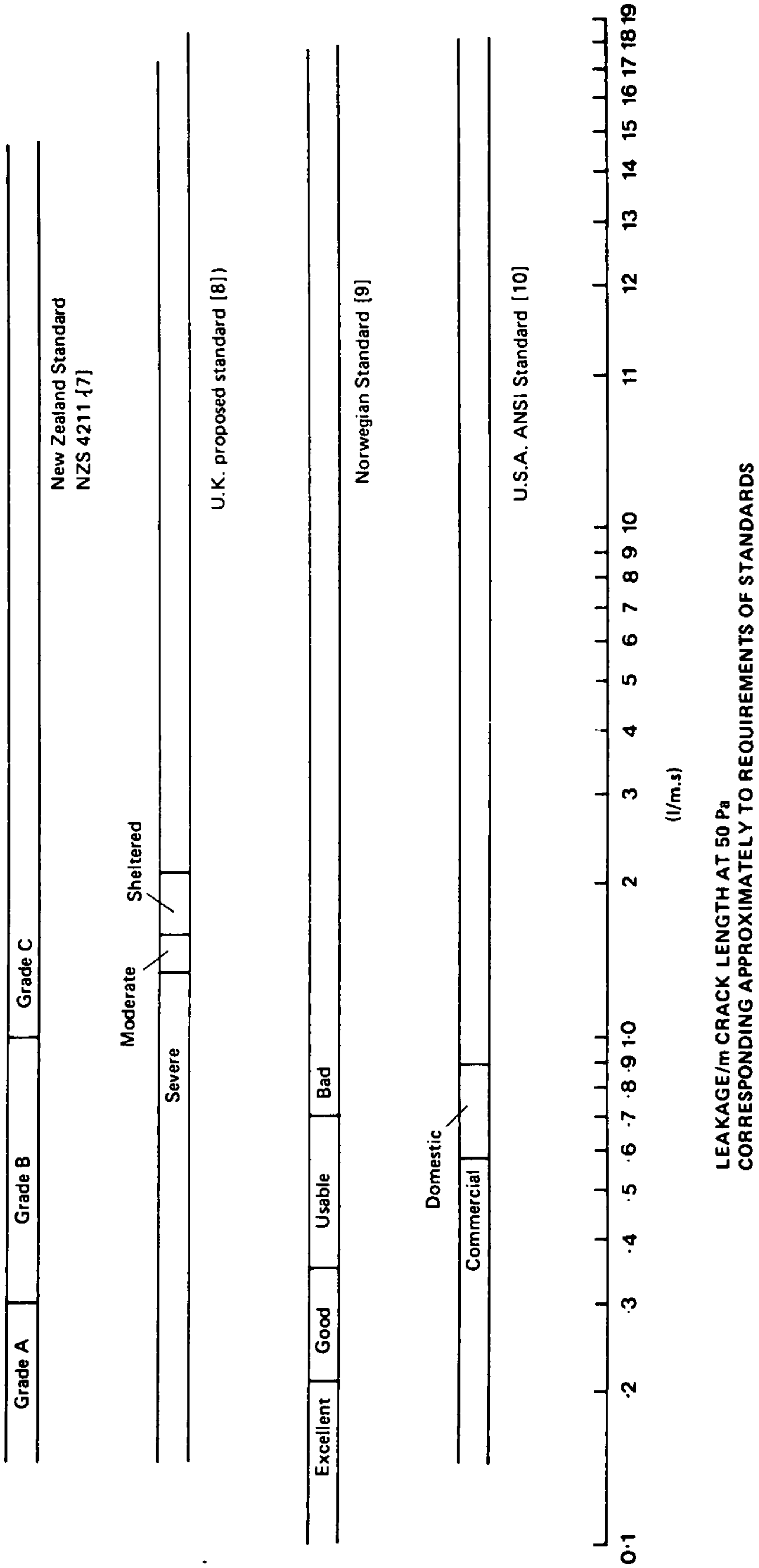

FIG. 6—*Standards for window air leakage.*

TABLE 3—*Measured construction joint leakage rates at 50 Pa pressure in two new houses.*

Joint	Max	Min	Mean	Units
Bottom plate: wood chipboard prelaid floor, gypsum plaster board wall	0.1	0.03	0.08	L/s · m
Top plate: gypsum plaster board wall, low density wood fiberboard ceiling	0.4	0.3	0.3	L/s · m
Window architraves: gypsum plaster wall board overlapped by wood architrave	0.8	0.7	0.7	L/s · m

openings discovered this way were blocked and a new tightness test performed to measure the improvement. It is helpful to compare the size of some of these leaks with chimneys and other common vents and with the house envelope leakage. Table 4 shows the relative sizes of leakage openings around electrical and plumbing service entry together with chimneys and some of the most extreme examples of workmanship defect. Because there is great variety in the types and sizes of leakage openings, these openings should be considered as examples rather than statistically secure mean values and ranges.

Of immediate note is the relatively small leakage area of chimneys and workmanship defects compared with the total envelope leakage area. It was found to be quite difficult to make major improvements to houses in this test sample within the practical constraints of taping over accessible cracks. For example, blocking the cracks around openable windows and doors to simulate a weather-stripping operation reduced the overall leakage by between 17 and 23%. This indicates that a large variety of leakage openings contribute to the total and that the location and size of many of these openings are not yet known for New Zealand houses.

TABLE 4—*Specified leakage openings.*

Leakage in L/s at 50 Pa Applied Pressure				
Location and Description	Max	Min	Mean	Units
Average 100-m^2 house in survey sample less than 5 years old	...	...	620	L/s
Wood frame external door, ten cases	80	24	43	L/s
Aluminum ranch slider doors	2.6	...	...	L/s · m
Louver windows, leakage per louver (50 louvers)	4.5	...	...	L/s · louver
Plumbing to bath with bath enclosed, three cases	71	11	38	L/s
Most severe workmanship defect	43	...	...	L/s
Manhole cover-access to roof space, one case	10	...	...	L/s
Brick chimney and open fire place, one case	120	...	...	L/s

Airtightness Requirements for Infiltration Rate Prediction

Infiltration Prediction Models

There are a number of simplified procedures for calculating air infiltration rates. Three categories of input data are generally necessary, and these categories can be listed as follows:

1. Airtightness data to characterize the building.
2. Weather office records of wind and temperature.
3. Site exposure details to transform wind records from the weather office into wind speeds at the building site.

The simplified infiltration model developed at Lawrence Berkeley Laboratories (LBL) by Sherman and Grimsrud [*11*] is used here to calculate infiltration rates in four houses. The results are then compared with measured infiltration rates, and an assessment is made of the accuracy in airtightness information worth striving for.

The LBL Model

The basic form of the air infiltration model is

$$Q = L\sqrt{f_s^2 \Delta T + f_w^2 V^2}$$

where

Q = infiltration, m^3/s,
L = effective leakage area, m^2,
ΔT = indoor-outdoor temperature difference, K,
f_s = stack parameter, $m/s/K^{1/2}$,
V = wind speed, m/s, and
f_w = wind parameter.

The stack and wind parameters take the following form

$$f_s = \frac{(1 + R/2)}{3}\left(1 - \frac{X^2}{(2 - R)^2}\right)^{3/2}\sqrt{\frac{gH}{T}}$$

$$f_w = C'(1 - R)^{1/3}\left(\frac{\alpha(H/10)^{\gamma}}{\alpha'(H'/10)^{\gamma'}}\right)$$

where R and X are leakage area distribution parameters

$$R = \frac{L_c + L_f}{L} \quad \text{and} \quad X = \left|\frac{L_c - L_f}{L}\right|$$

where

C' = shielding class coefficient,
α,γ = the coefficients describing terrain class near the building,
α',γ' = coefficients describing terrain class near the weather tower,
H,H' = heights of the building and the weather tower, respectively,
L_c = ceiling leakage area, m^2, and
L_f = floor leakage area, m^2.

Airtightness Measurements for Four Houses

Air infiltration rate, wind speed, and temperature measurements are available for four of the houses in the airtightness survey. Three of the houses (A, B, and C) are similar in type, size, and sheathing materials. They are detached, single-story houses with about 100 m^2 of floor area, suspended particleboard floors, and similar interior lining materials. House D is semidetached with a concrete block party wall. It is split level, has a basement underneath, and has a skillion roof lined with particleboard.

Airtightness data for the four houses is marked on Fig. 3. House C is rather tighter than A, B, and D, which in terms of leakage rate at 50 Pa/shell surface area are quite similar.

Blower door airtightness data and information from Tables 3 and 4 were used to calculate values for R and X. These values appear in Table 5, together with values calculated on the basis of leakage distributed uniformly over the shell.

Finally, the infiltration rates are calculated for a range of wind speeds and compared with measured infiltration rates in Fig. 7. With low indoor-outdoor temperature differences and wind speeds above 2 m/s, the leakage rate is a linear function of wind speed and can be expressed in terms of air changes/kilometre wind run.

TABLE 5—*Building airtightness information for four houses.*

	Calculated Leakage Distribution		Uniform Leakage Distribution	
Building	R	X	R	X
A	0.52	0.17	0.62	0
B	0.48	0.12	0.61	0
C	0.44	0.00	0.64	0
D	0.64	0.04	0.63	0

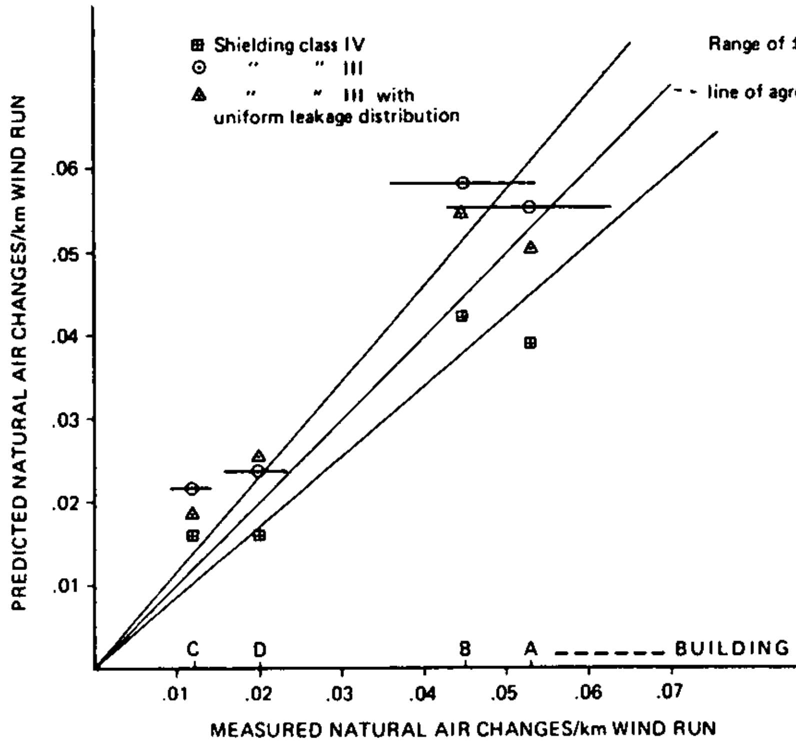

FIG. 7—*Correlation of infiltration rate predictions using LBL model with experiment.*

Infiltration Rate Measurements for Four Houses

Air infiltration rate, wind speed, and temperature measurements are available for houses A, B, C, and D. The measurements were made by Clarkson [*12*] using the tracer gas decay method and SF_6 as a tracer material. On-site, wind-speed measurements were made above roof height and were similar in strength to wind speeds measured at a meteorological station less than 10 km away. The work was completed in the summer when indoor-outdoor temperature differences were less than 3°C. Air infiltration rates, at three wind speeds between 2 and 10 m/s, were found within experimental error to form a linear relationship with wind speed. A series of 16 measurements had been made in two similarly sited houses and found to be largely independent of wind direction, which at house level generally bore no relation to wind directions measured in the free air stream.

In Fig. 7, three calculated infiltration rates/kilometre wind run are plotted against the measured value. For Shielding Class III, two similar results are calculated, one using detailed air leakage data and the other assuming the leakage is distributed uniformly over wall, floor, and roof areas. Also shown in Fig. 7 is the effect of changing the exposure class from Class III to IV, indicating that for wind-dominated infiltration it is more important to know the wind exposure class than to have accurate knowledge of the leakage distribution. The authors of the LBL model recommend that major leakage openings be assigned to wall, roof, or floor locations and the balance of house leakage be assigned according to component area.

In winter, when indoor-outdoor temperature differences are higher than those measured in this study, the stack-induced leakage becomes more important. For the four buildings in this study located in Wellington, it still remains more important to have the site exposure class correctly assigned than it is to take proper account of the distribution of leakage openings.

Conclusions

The material gathered in this paper summarizes the house airtightness information now available in New Zealand and also shows more clearly the detail of airtightness information needed for predicting season air infiltration rates. The conclusions are:

1. House airtightness expressed either as leakage area or leakage rate at 50 Pa can be determined from blower door results with a total error of less than 10%.
2. Taping over leakage openings as a way of subtracting the leakage component from the whole house leakage has been shown to be reproducible.
3. Leakage through solid interior lining materials should contribute less than a few percent to whole house leakage and much less when painted. The bulk of air leakage, therefore, must flow through cracks and construction joints.
4. A simple model of airtightness in terms of building complexity shows that high leakage can be associated with complicated shell detail, yet on its own the model is insufficiently accurate for predicting airtightness.
5. Infiltration rates calculated using the LBL model for four different houses agree with the experiment to the limit of our ability to assign wind exposure factors.
6. The uncertain inputs into the calculated season infiltration rate can be ranked in order of importance as follows:
   (*a*) Site exposure index.
   (*b*) Whole house airtightness.
   (*c*) The distribution of leakage openings.

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