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Air Infiltration: A Review of Some Existing Measurement Techniques and Data

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ABSTRACT: This paper reviews the state of the art in the measurement of ventilation and air infiltration. It considers tracer gas techniques and discusses some of the tracer gases used as well as some of the potential sources of error. It also discusses fan pressurization-evacuation procedures for measuring building tightness and compares fan and tracer measurements. It discusses the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) crack method. It also considers a number of factors influencing infiltration rates and finally reviews a few of the empirical equations that have been developed to correlate infiltration rate with wind velocity and inside-outside temperature difference.

KEY WORDS: air leakage measurement, infiltration review, ventilation analysis, air infiltration, measurements

Air infiltration is a component of the heating and cooling loads of buildings, which is more difficult to predict and model than other components, such as losses due to thermal conductivity through elements of the building envelope, for example. For this reason, in the most careful analyses of the energy requirements of buildings, air infiltration is measured experimentally. Tracer gas methods are used for this purpose. This paper briefly reviews some tracer gas techniques and lists a few of the gases that have been used for the purpose. It discusses some of the potential sources of error. It also considers some of the empirical equations for correlating infiltration rate with weather parameters. In addition to tracer techniques, fan pressurization-evacuation procedures have been developed to estimate comparative

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tightness of buildings and also to identify the places where leakage occurs. This paper presents comparisons of fan and tracer measurements in the same building.

A new technique for studying the response of buildings to inside-outside pressure differences is the infrasonic method, in which a compressional wave of alternating positive and negative pressures is generated in the test building. This approach is comparatively new and is described in the literature [*1*].[2]

Before going into the measurement of infiltration, it should be pointed out that there are reviews on the subject such as the one by Hitchin and Wilson [*2*]. A published review by Ross at the Department of Energy and Grimsrud at the Lawrence Berkeley Laboratory has also been of assistance in preparing this overview [*3*]. Chapter 9 of the Ohio State Electric Power Research Institute (EPRI) final report also contains review material [*4*], and finally the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) *Handbook of Fundamentals* [*5*] devotes a chapter to infiltration and ventilation.

Tracer Gases

A number of gases have been used to measure air infiltration. Some characteristics of an ideal tracer gas have been listed by Bargetzi et al [*6*] and by Honma [*7*]. Drawing on their suggestions the following list is developed:

1. The gas can be determined accurately in the lowest possible concentration.
2. The analytical method for the gas has negligible cross-sensitivity for other constituents in air.
3. The tracer is inexpensive and readily available.
4. It is not adsorbed by walls and furnishings.
5. It has high chemical stability and does not decompose or react with building surfaces or constituents of air.
6. It has no adverse health effects in the concentrations used.
7. It is neither flammable nor explosive.
8. It has a density comparable to air.
9. It is not normally present as a background constituent in air, and there is no source in the building under test.

To this list it might be added that the analytical method is readily available, inexpensive, and lends itself to automation. No gas meets all of these criteria, but any gas that has been used successfully as a tracer gas meets most of them.

Helium and hydrogen were among the first gases used as tracers [*8–12*].

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

Helium can be determined in concentrations of the order 0.5 percent using thermal conductivity measurements. Hydrogen, although less foolproof than helium, can be measured in somewhat lower concentrations. Katharometers for the purpose have been described [*8,9,12*]. Usually absolute concentrations are not determined. Instead, the thermal conductivity of air containing the tracer is determined relative to the starting thermal conductivity. Helium has great stability and is not toxic. The molecular weight of helium is 4 compared with an average molecular weight of air of about 29. The molecular weight of hydrogen is 2. These low molecular weights are what make the thermal conductivity easy to perform, although refined thermal conductivity techniques have been applied to other gases such as argon [*13*].

If air and tracer movements in infiltration are essentially convective, so that molecular diffusion plays a very minor role, molecular weight is unimportant. Howard [*14*] reported higher apparent infiltration rates with hydrogen as a tracer than with nitrous oxide (N_2O) when measuring buildings with walls of bare gypsum. In buildings with comparatively nonporous walls, such as concrete or painted gypsum, hydrogen and N_2O gave essentially the same result. Hunt and Burch [*15*] simultaneously measured infiltration in a townhouse with inside surfaces of gypsum board by means of sulfur hexafluoride (SF_6) and helium. These gases have a molecular weight ratio of 36 to 1. They found no evidence that helium disappeared faster than SF_6.

Nitrous oxide has been used extensively for tracer measurements [*6,12,16*]. It is usually measured by infrared absorption spectroscopy. Lidwell [*16*] has reported concentration measurements of the order of 100 ppm by this means. Nitrous oxide has a significant solubility ~~in water,~~ but this apparently has presented no problems in its use as a tracer.

Methane [*17*] and ethane [*18*] have also been used as tracer gases. They may be determined with a total hydrocarbon analyzer, but greater selectivity can be achieved with a gas chromatograph equipped with a flame ionization detector. Janssen et al [*17*] have reported measurement of methane concentrations of the order of 40 to 400 ppm, while Elkins and Wensman [*18*] reported measurement of ethane concentrations in the range of 20 to 200 ppm. Both gases fulfill most of the requirements for a good tracer except that they are capable of forming explosive mixtures with air. The concentrations in which they are used in infiltration measurements are far below their explosive limits. Nevertheless, their use requires closer supervision than more inert gases. This also applies to the use of hydrogen as a tracer gas.

Carbon dioxide (CO_2) has been also used as a tracer [*7,19*]. Nondispersive infrared analyzers are available that can analyze this gas in concentrations as low as a few parts per million. This gas is easy to monitor, but it has some drawbacks. For example, there are background concentrations of CO_2 of the order of 400 to 600 ppm in building air, and occupants generate significant quantities of this gas.

Sulfur hexafluoride has come into increasing use as a tracer gas [*4,15,20*-

25]. It can be conveniently measured in concentrations of a few parts per billion with electron capture detector. Where it is advantageous to do so, still lower concentrations may be measured. This means that in a typical house an amount of gas equal to about half the volume of a ping pong ball is sufficient to make a measurement. Oxygen in air is also an electron capturing gas, so that for maximum sensitivity it is common practice to separate SF_6 from oxygen chromatographically as part of the analytical procedure. Sulfur hexafluoride is nonflammable and comparatively nontoxic. According to manufacturer's literature, when mice are exposed to mixtures of 80 percent SF_6 and 20 percent oxygen for 24 h, none of the mice may show signs of distress if the batch of gas is to be certified as chemically pure. The gas has also been tried experimentally in breathing gases for divers in concentrations as high as 70 percent, since it is quite inert and has a very low solubility in water. Also according to the manufacturer's literature on stability, the gas can withstand temperatures up to 500°C (932°F) in quartz before decomposing; however, decomposition may occur at lower temperatures in the presence of some metals. The high sensitivity with which the gas may be measured is not without certain problems. For example, leakages from regulators and other sources that might go unnoticed with other gases can introduce significant contamination when SF_6 is used as a tracer. On the other hand, the high sensitivity makes it eminently feasible to perform tracer measurements in large buildings [23]. Finally, SF_6 lends itself well to procedures that require metering of gas into a building over a long period of time.

Use of other gases such as chlorothene [26], carbon monoxide (CO), and fluorinated hydrocarbons [24] has been reported. Hitchin and Wilson have listed still other gases and vapors that have been tried as tracers. These include compounds such as water vapor, ammonia, argon 41, acetone, and chloroform. Many of these compounds fail to exhibit a number of the requirements listed previously for a good tracer gas.

Principle of the Tracer Method

The tracer measurement of air exchange rates may be performed by mixing tracer gas throughout the ventilated space and monitoring the decrease in concentration as a function of time. The rate of change in the amount of tracer in a ventilated space may be expressed by the relationship

$$V \frac{dc}{dt} = c_o \dot{v} + G - c\dot{v}, \tag{1}$$

where

V = volume of the ventilated space;
c = concentration of tracer in the ventilated space at time t;

c_o = concentration of tracer in the outside air;
$\dot{v}$ = rate at which air leaves the ventilated space in volume per unit time, and also rate at which air enters the ventilated space normalized to inside temperature; and
G = net rate of generation of tracer in the ventilated space.

If the concentration of tracer in the incoming air is negligible (that is, $c_o = 0$), and no tracer is generated or absorbed within the space, Eq 1 reduces to

$$\frac{dc}{dt} = -\frac{\dot{v}}{V}c \tag{2}$$

which may be solved to give

$$\ln \frac{c}{c_{\text{init}}} = -\frac{\dot{v}}{V}t = -It \tag{3}$$

where

c_{init} = initial concentration of tracer, and
$I = \dot{v}/V$ = air changes per unit time.

If $\ln c/c_{\text{init}}$ is plotted against elapsed time in hours, the slope of the line equals $-I$, the infiltration rate normalized to inside temperature and expressed in air changes per hour.

An alternate method of data analysis is to consider relative concentration on a point-by-point basis. Equation 3 may be expressed in the form

$$I = -\frac{1}{t_m}\ln\frac{c_n}{c_{n-1}} \tag{4}$$

where

t_m = time interval between measurement of c_{n-1} and c_n,
c_{n-1} = concentration of tracer at the beginning of time interval, and
c_n = concentration of tracer at the end of the time interval.

This method of analysis has the advantage of simplicity and is easier to program than the graphical approach. It has the drawback of being very sensitive to errors in concentration measurement when the sampling interval is short. The error in infiltration rate, e_i, may be calculated from the equation

$$e_i = \frac{1}{t_m}\left\{\ln\frac{c_n}{c_{n-1}}(1+a) - \ln\frac{c_n}{c_{n-1}}\right\} \tag{5}$$

where a = fractional error in c_n/c_{n-1}. Equation 5 is plotted in Fig. 1. From

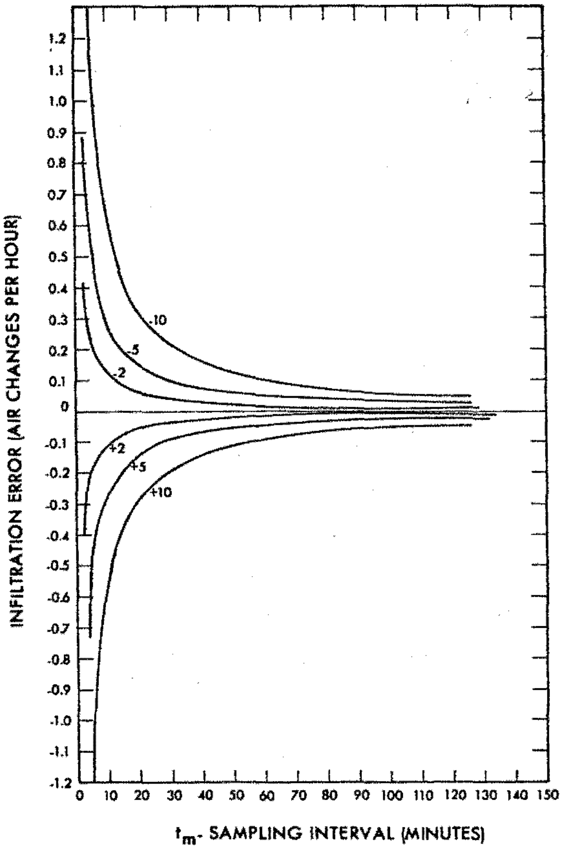

FIG. 1—*Graphical representation of* $e_i = 1/t_m \{ln\ c_n/c_{n-1}(1 + a) - ln\ c_n/c_{n-1}\}$ *as a function of the sampling interval where* a, *the fractional error* $ln\ c_n/c_{n-1}$ *equals 0.02, 0.05 and 0.1, or 2,5 and 10 expressed in percent.*

this figure, for example, it may be seen that with a 5-min sampling interval an error of 5 percent in c_n/c_{n-1} results in an error of 0.5 to 0.6 air changes per hour in infiltration rate. With a 1-h sampling interval the corresponding error in infiltration rate is about 0.05 air changes per hour. The use of short sampling intervals is sometimes suggested for measuring short term fluctuations in infiltration rate. However, according to the foregoing analysis, point-by-point calculations taken over short sampling intervals reflect magnification of sampling errors.

An alternate method of measuring air change rate is to feed a tracer at a constant rate and monitor its concentration as a function of time. Honma [*7*] has used this method and described a form of generator for producing CO_2 from dry ice at a steady rate. Foord and Lidwell [*24*] and Baird [*28*] have also used constant feed rate. For the case of constant feed rate and negligible outside concentration Eq 1 reduces to

$$V \frac{dc}{dt} = G - c\dot{v} \tag{6}$$

Integrating

$$V \int_{c}^{c_{\text{init}}} \frac{dc}{G - c\dot{v}} = \int_{t}^{0} dt \tag{7}$$

or

$$V \ln \frac{G - c\dot{v}}{G - c_{\text{init}}\,\dot{v}} = -\,\dot{v}t \tag{8}$$

If $c_{\text{init}} = 0$, in exponential form Eq 8 becomes

$$1 - \frac{c\dot{v}}{G} = e^{-(\dot{v}/V)t} \tag{9}$$

or

$$c = \frac{G}{\dot{v}}\left(1 - e^{-(\dot{v}/V)t}\right) \tag{10}$$

$G/\dot{v}$ is the final steady state concentration while $1 - e^{-(\dot{v}/V)t}$ expresses the rate at which it is approached. In Fig. 2, $1 - e^{-(\dot{v}/V)t}$ is plotted as a function of time for different air exchange rates. From the graph it may be seen that at six air changes per hour the ultimate steady-state concentration is approached closely within an hour, while at 0.12 air changes per hour nearly 20 h elapse before the concentration reaches 90 percent of its steady-state level. The constant feed method has the advantage of simplicity in long-term monitoring. It has the disadvantage that at the typical air exchange rates encountered with natural leakages several hours may be required before the final steady state is approximated. Mixing of tracer in air may also present greater problems in the constant-feed method than in the rate-of-decay method. Also it is necessary to measure absolute concentrations rather than relative concentrations. The constant-feed method finds its greatest usefulness in situations where there is a high rate of internal mixing. Where there is not homogeneous mixing it is useful in determining air movements between different parts of a building. The "transfer index" of Lidwell [*2,16*] undertakes to quantify this process.

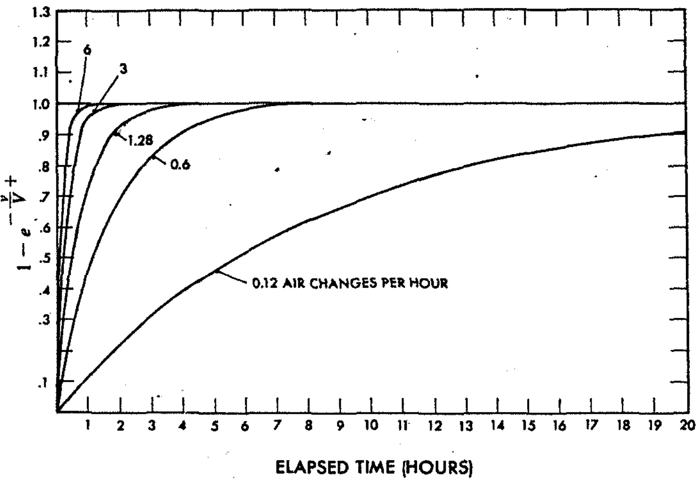

FIG. 2—*The exponential function* $1 - e^{-(\dot{v}t/V)}$ *plotted as a function of time for air exchange rates of 0.12, 0.6, 1.28, 3, and 6 air changes per hour.*

Mixing

The foregoing analysis of the tracer technique for measuring air exchange rates assumes perfect mixing both initially and throughout the measurement process. This condition is not achieved in practice, but is usually approached closely enough to give good approximations of air exchange rates. When mixing is not good there is a sampling problem plus inherent errors even if sampling is perfect. For descriptive purposes this may be illustrated by some examples comparing perfect mixing with some models of imperfect mixing or nonmixing as is done in Fig. 3. Figure 3*a* represents the case of perfect mixing. A sample drawn anywhere in the enclosed volume has the same concentration at a given time, and Eq 3 accurately gives air exchange rate as a function of tracer decay rate.

Figure 3*b* illustrates a hypothetical case where after the initial mixing the lower half of the volume remains stagnant, while all of the air movement occurs in the upper half. If air sampling represents only the upper half, and if air is passed through it at two air changes per hour, the air exchange rate averaged over the whole volume will be one air change per hour. The air exchange rate for the entire chamber may be represented by a modified form of Eq 3,

$$\ln \frac{c}{c_{\text{init}}} = -k \frac{\dot{v}}{V} t \qquad (11)$$

where k is a constant, in the example chosen, $k = 0.5$. Use of such constants is limited to cases where it is possible to evaluate k independently. It also

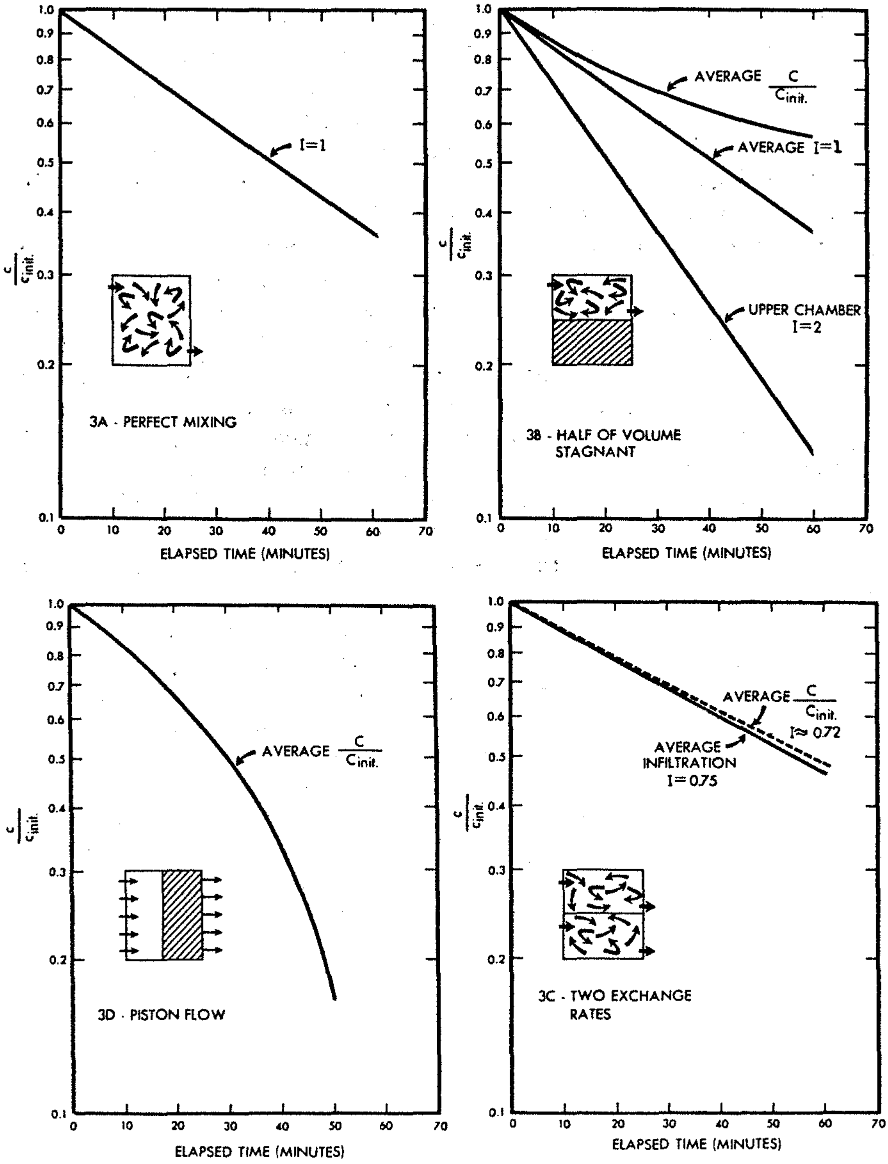

FIG. 3—*Comparison of concentration versus time relationships for four simple models ranging from perfect mixing to complete nonmixing.*

assumes that concentration decays logarithmically. Actually poor mixing generally destroys the simple logarithmic decay rate. If in Fig. 3*b* sampling were averaged throughout the entire volume, ln c/c_{init} as a function of time, would have a curvature as shown in the upper curve of the figure.

Stratification is illustrated in Fig. 3*b* would not be likely to occur in a room, yet it provides a simple model of a situation where there are dead spots. A more common case would be rooms that are ventilating at different rates. Figure 3*c* represents a case where one room ventilates at 1 air change per hour while another equivalent room exchanges at 0.5 air change per hour. The average exchange rate for the two rooms is 0.75 air changes per hour. However, if the rooms are sampled representatively, and the samples blended and analyzed over the first hour, ln c/c_{init} versus time would have a slight curvatuve as shown by the dotted line in the figure, and an estimated air exchange rate about 3 to 4 percent less than the true value would be obtained. If sampling is repeated during the second and subsequent hourly periods, the discrepancy between the true and calculated infiltration rate would become greater. Hitchin and Wilson [2] have called attention to this behavior. This is important, because when averaging several rooms with a single analytical instrument, it may be convenient to sample and blend from all of the rooms simultaneously. Average infiltration rates obtained this way tend to be a little less than the true average if there are differences in the air exchange rates of the different rooms.

Another model, which might be considered, is shown in Fig. 3*d*. This is piston or plug flow. The entering air displaces air already present without mixing. Analysis averaged over the entire volume would lead to a plot of ln c/c_{init} versus time, having a downward curvature as shown in the figure.

Another form of imperfect mixing that is not included in any of the foregoing models is the effect of closets, cabinets, and other enclosed volumes imperfectly lined to the main ventilated space. If these volumes are small, or if their effect can be nullified by opening to the main space, or if air passes through them to the outside without returning to the main space, their influence on the tracer dilution rate is not measureable. If such volumes are significant in comparison with the main ventilated volume, concurrent analysis of tracer dilution in these subsidiary volumes and in the main space will show how much they contribute to the average tracer dilution rate for the total structure.

Fan Pressurization-Evacuation

Tracer procedures provide a measure of air leakage rates under more or less natural conditions. Where building tightness is of primary concern, apart from weather conditions, fan pressurization or evacuation techniques have been used [*29-31*]. A fan is sealed into a window or doorway and allowed to move air into or out of the building at a measured rate. Inside-outside pressure difference is measured as a function of flow rate. A scaled down version of this approach is also used for measuring air leakages of windows, doors, and wall sections.[3] One of the particular applications of the method is to identify leakage paths. By selectively covering different parts of houses with plastic sheet, Tamura *[28]* was able to determine the fraction of the total air leaking through different components of the building envelope such as roof, windows, and doors. Some of Tamura's results are summarized in Table 1.

Teitsma and Peavy *[32]* have similarly used fan pressurization to identify leakage paths in a mobile home. Some of their results are summarized in Table 2.

Fan pressurization or evacuation data may be usually expressed in the form of an equation

$$Q = K\Delta p^n \tag{12}$$

where

Q = flow rate in volume per unit time,
K = flow coefficient,
p = pressure difference between the inside and outside of the test structure, and
n = flow exponent having a value between 0.5 and 1.

Equation 12 has the form of a straight line in a log-log plot where n is the slope. Dividing both sides of the equation by V, the volume of the ventilated space, converts flow rate into air changes per unit time. Such a plot is shown

TABLE 1—*Total leakage rates through house enclosures and through selected components of the building envelope* [30].[a,b]

House	Total Leakage	Ceiling[c]	Outside Walls[c]	Windows and Doors[c]
1	1160	750 (65)	170 (15)	240 (20)
2	1100	630 (67)	230 (21)	240 (22)
3	2410	390 (16)	1560 (65)	460 (19)
4	2620	900 (34)	1100 (42)	620 (24)
5	2170	100 (8)	1680 (77)	330 (15)
6	2240	250 (11)	1490 (66)	500 (23)

Conversion factor—1 $ft^3/min = 0.000479\ m^3/s$.

[a] Leakage values exclude those of fireplace, smoke pipe, and exhaust vents.

[b] Windows and doors provided with storm units.

[c] Figures in parentheses indicate percentage of total leakage rate.

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[3] See British Standard 4315, 1968; French Standard NFP 20-302; German Standard DIN 18055, and ASTM Standard on Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors (E 283-73).

TABLE 2—*Mobile home forced air leakage characteristics* [32].

Sequence of Sealing	Potential Leak Location Sealed or Unsealed	Residual Air Leakage, ft^3/min	Reduction In Air Flow Due to Sealing of Leak, ft^3/min (%)	Sequence of Seal Removal	Increase in Air Flow Due To Removal of Seal, ft^3/min
1	Original condition	1020	...	13	1039
2	Bathroom ventilation fan	869	151 (14)	11	156
3	Between ceiling and chimney	789	80 (8)	9	88
4	Lower hinge side of rear entrance door	783	6 (< 1)	2	
5	Two plumbing holes through floor	744	39 (4)	8	38
6	Duct system (register opening and blower return opening)	744	...	10	6
7	Wall heater	716	28 (3)	7	36
8	All exterior outlets and switches	699	17 (< 2)	5	19
9	Windows sealed to inside surface of wall paneling	511	188 (18)	1	240
10	Front base of furnace	497	14 (1)	12	...
11	Paneling side joints	420	77 (8)	4	76
12	Joint between wall and ceiling	282	138 (14)	3	90
13	Furnace room door	275	7 (< 1)	6	...

Conversion Factor—1 $ft^3/min = 0.000479\ m^3/s$.

Note: All leakage rates were taken with inside to outside pressure difference of 0.2 in water gage.

in Fig. 4. These data were obtained by pressurizing or depressurizing individual dwelling units in apartment houses [*34*]. There are probably small differences between pressurization and evacuation data due to elements in the structure that can act somewhat as flap valves. However, at this stage no attempt is made to evaluate this refinement. Data by Teitsma and Peavy [*32*] are also included. Air exchange rates by SF_6 tracer measurements are also shown in the same graph. These are plotted at the value of Δp that would be required to produce the same exchange rates by fan pressurization or evacuation. Plotting tracer data in this way tacitly assumes that the log-log extrapolation of fan data is valid. From the plot it may be seen that very low pressures of the order of 0.007 to 0.0025 mm (0.0003 to 0.001 in.) water gage would have been required to produce air exchange rates comparable with the tracer values.

Two important differences between natural air leakage and fan-induced air leakage should be mentioned. Firstly, fan-induced air exchange rates are usually much larger than normal air leakage rates, secondly, fan-induced pressures whether positive or negative are applied equilaterally to all walls and surfaces, while forces due to wind or stack effect are asymmetrical. Wind

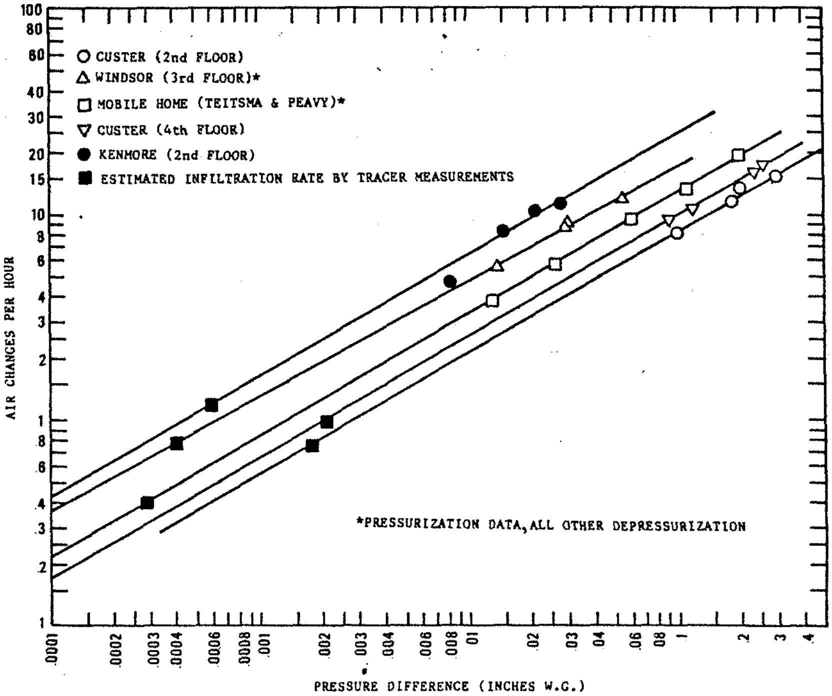

FIG. 4—*Air exchange rate as a function of applied pressure difference for a number of apartment dwelling units and a mobile home* [34].

pressures develop primarily across external walls, while thermal heads have a vertical thrust.

It would be useful, if possible, to predict natural air leakage rates from fan pressurization or evacuation data, because fan measurements are easier to perform, except possibly in very large buildings. In fact, there have been limited experiments that undertake to do this [*33*]. However, the results shown in Fig. 4 suggest that there is no simple formula for converting fan data to natural leakage rates that can be applied across the board to all kinds of buildings. This may not rule out the possibility of some connection between the two methods that might be applied to houses of closely similar structure, but this has yet to be determined.

ASHRAE Crack Method

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) *Handbook of Fundamentals* [*5*] presents a method of estimating infiltration based on measuring the lengths of cracks such as those around windows and doors. A table of air leakage rates per foot of crack is then given for double hung windows at pressure differences of 2.54, 5.08, 7.62, 10.16, and 12.7 mm (0.1, 0.2, 0.3, 0.4 and 0.5 in. of water). To apply the method, however, it is necessary to know the actual pressure difference between the inside and outside, and at present time there is no simple procedure for estimating this other than direct measurement. This limits the predictive value of the method. However, by overestimating this pressure difference, it is possible to obtain results that range from plausible to too high. Hunt et al [*34*] demonstrated that by assuming a pressure difference of 2.54 mm (0.1 in.) of water an air exchange rate more than three times the measured rate was obtained in an apartment dwelling, even though fan pressurization showed that windows and doors did not account for most of the leaks. Bahnfleth et al [*11*] reported reasonable agreement between infiltration rates by the crack method and those obtained by helium tracer measurements. These were calculated for wind impact velocities of 16 and 30.5 km/h (10 and 15 mph). Doeffinger [*25*], on the other hand, calculated air change rates by the crack method where average pressure differences of 0.68 mm (0.027 in.) of water were measured. The infiltration values were reported to be about 10 percent of the tracer-measured values.

Another factor that may be important is that wind pressures are usually treated as steady-state quantities, while experimental measurements indicate considerable fluctuations in wind pressure can occur. Hill and Kusuda [*19*] measured air leakages in a sealed room with a window crack of known dimensions. At the same time they monitored pressure differences across the crack. They found that flow appeared to be a pulsed phenomenon and that air change rates measured by tracer decay were less than those predicted from average pressure differences across the crack, particularly at wind velocities greater than 8 km/h (5 mph). With fluctuating pressures they suggested the possibility of simultaneous inward and outward flow through different parts of the same crack.

Effect of Weather on Infiltration

Air infiltration is not only a function of building tightness but is also influenced by wind velocity and inside-outside temperature difference. A number of empirical equations for correlating infiltration with these weather parameters have been developed. For example, Dick and Thomas [*35*] made a study of two groups of houses, one in a comparatively exposed location so that wind had a dominant effect on infiltration. The other group was more protected, so that they were able to show that under some conditions the effect of wind predominated, and under others the effect of inside-outside temperature difference controlled the infiltration rate. They indicated the relative effect of wind pressure to stack pressure to be $v^2/\Delta T$, where v is wind speed in miles per hour and is inside-outside temperature difference in F, and also developed an experimental graph similar in form to the one shown in Fig. 5 where I/v and $I/\Delta T^{1/2}$ are plotted against log $v^2/\Delta T$. It may be seen that when log $v^2/\Delta T > 0.3$, $I/\Delta T^{1/2}$ increases as $v^2/\Delta T$ increases, because temperature difference no longer controls the process and wind velocity takes over. When log $v^2/\Delta T < 0.3$, I/v increases as $v^2/\Delta T$ decreases, and the stack effect predominates. Thus, in this particular paper they suggest that infiltration rate may be expressed by the relationship

$$I = E\,\Delta T^{1/2} \text{ for the closed house} \tag{13}$$

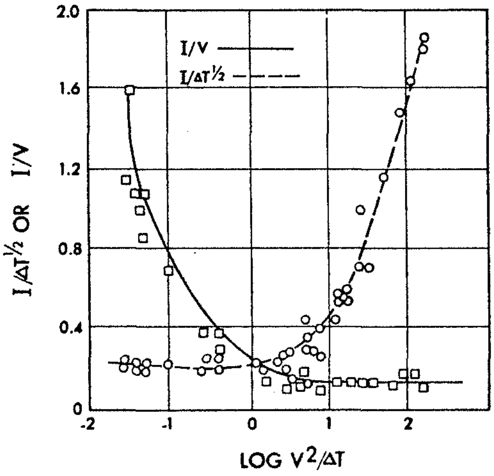

FIG. 5—*Dick and Thomas'* [35] *representation of infiltration rate as a function of wind velocity and inside-outside temperature difference.*

and

$$I = (E + Fn)\Delta T^{1/2} \text{ or the house with } n \text{ windows open} \tag{13a}$$

when log $v^2/\Delta T$ is less than 0.3, and

$$I = Bv \text{ for the closed house} \tag{14}$$

and

$$I = (B + D_m)\,v \text{ for the house with } n \text{ windows open} \tag{14a}$$

when log $v^2/\Delta T$ is greater than 0.3. where

I = infiltration rate, and
ΔT = inside-outside temperature difference B, D, E and F are constants.

Bahnfleth et al [*11*] made measurements in two houses, and their results indicated that at constant wind speed infiltration rate there was essentially a linear function of inside-outside temperature difference, while at constant temperature difference it was proportional to wind speed. Coblentz and Achenbach [*36*] have put this in the form of the equation

$$I = A + BW + CT \tag{15}$$

where

W = wind velocity,
T = inside-outside temperature difference, and
A, B, C = constants.

The ASHRAE *Handbook of Fundamentals* [*5*] expresses the flow due to the stack effect in the form

$$Q = 9.4A\sqrt{h\,(t_i - t_o)} \tag{16}$$

where

Q = air flow in cubic metre per second (cubic foot per minute),
A = free area of inlets and outlets (assumed equal), and
t_i, t_o = inside and outside temperatures, respectively.

At first glance this is quite different from the foregoing linear relationships. However, the form of the function is such that it approximates a straight line over a considerable range and drops off rapidly to zero at $\Delta T = 0$ [*15*]. With normal scatter of data it is difficult to prove whether Eq 16 or a straight line better expresses the temperature term in the correlation.

Correlations of the form

$$I = A + BT^{1/2} + CW \tag{17}$$

have also been used [*37*]. Equations 15 and 17 present the effects of wind and the stack effect as additive. The work of Dick and Thomas [*35*] indicated that they are not additive. Sinden [*38*] has developed a theoretical analysis which suggests that they are sub-additive.

Sepsy et al [*4*] reported the results of measurements on several houses, logging nearly 2000 h of data. After trying a number of correlation formulas, considering such factors as wind velocity, wind direction, ΔT, crack lengths, and other parameters, they proposed the formula

$$I = \beta_0 C_T \sqrt{4 \cdot \Delta p_T + 2 \cdot \Delta p_w} \tag{18}$$

where

β_0 = a statistical regression coefficient,
C_T = total crack length over four exposures,
Δp_T = theoretical pressure difference across enclosures due to chimney effect, and
Δp_w = theoretical pressure difference across enclosures due to wind effect.

This equation was a compromise between optimum predictive value and simplicity. By including the crack length, C_T, in the relationship they found that the same relationship could be applied with reasonable accuracy to all of the houses studied. Since cracks around windows and doors do not usually account for most of the leakage paths, this suggests that in the houses included in the study these cracks may have accounted for a fairly consistent fraction of the total leakage.

Wind direction was not considered important enough to warrant special consideration. Malik [*39*] on the other hand, found wind direction to have significant effect. He presented the idea that surroundings such as trees and other buildings may have an effect if a building is protected in some directions and exposed in others. Also, most of his measurements were made with townhouses which, being row structures, are not equally exposed on all sides. He also separately analyzed data for wind speeds above and below 9.6 km/h (6 mph) and concluded that wind effects predominated at high wind velocities while ΔT exerted a predominant effect at lower wind velocities.

The ASHRAE *Handbook of Fundamentals* [*5*] references a number of papers on wind effects. Ahrens and Williams [*40*] have also briefly reviewed the effect of wind on energy consumption in buildings. Mattingly and Peters [*41*] have described wind tunnel studies showing that simulated trees upwind from a model house could greatly alter the pressure profile over the house in a way that would be expected to reduce infiltration. Malik's preliminary observations with real trees and full scale houses revealed that trees could produce some reduction in infiltration rates at high wind speeds over what would have been expected without trees. Here wind direction also played a part. At low wind speeds there appeared to be some enhancement of infiltration rate in the presence of trees that was not explicitly predicted in the model studies.

In addition to wind and stack effect, other variables can influence infiltration rate. Luck and Nelson [*26*] presented data showing inside relative humidity exerted a significant effect on infiltration in frame houses. Increase in relative humidity, it was postulated, produced swelling of wood and any hygroscopic elements of the wall structure and thereby reduced infiltration.

Correlation of infiltration rate with weather parameters requires collection of a large number of data points under different weather conditions. Harrje et al [*22*] have described an automated system for doing this using SF_6 as a tracer. More recently Harrje and Grot [*42*] have added an electronic data acquisition and cassette recording processor and magnetic tape capabilities to the system, so that it can collect data in a form suitable for computer processing. In addition, different types of apparatus have been developed that do not have this full capability but are essentially routiners that collect air samples from a number of sites in an automatically timed sequence and analyze for tracer content [*6,25,43*].

Computational Prediction of Air Exchange Rates

This paper deals primarily with the experimental measurement of air leakage in buildings and also considers a number of empirical correlations between infiltration rate and weather conditions. In addition, computational methods have been developed for predicting air exchange rates from temperature and wind data, a complete discussion of which is beyond the scope of the present paper. However, a few treatments of the subject should be mentioned. For example Tamura and Shaw [*44,45*] have developed analytical procedures for estimating the infiltration rates of tall buildings from wind data and inside-outside temperature measurements. These have been developed in part from fan pressurization data that have been used to correlate leakage rates with inside-outside pressure differences. Wind tunnel studies of models have been also made. They also cite some computational approaches of others [*46,47*] plus the work of Sander and Tamura [*48*]. To these might also be added work by Svetlov [*49*] and Gabrielson and Porra [*50*].

In addition to the studies by Tamaru and Shaw, which have been directed primarily to high-rise buildings, Honma [*7*] and Sinden [*51*] have developed analytical models of air exchange between rooms in a building and with the outside that have been alluded to earlier in this paper.

Opportunities for Further Work

Important progress has been made in the measurement of infiltration rates and building tightness. However, there are areas where there is room for improved methodology as well as greater use of existing methodology. For example, the problem of measuring infiltration in buildings with central mechanical ventilation systems seems to be solved, and may even be performed on an automated basis. On the other hand, multiroom structures, particularly large buildings, without central air distribution systems are more difficult to characterize experimentally. Further study is needed. Another problem which taxes current tracer procedures is the measurement of air exchange rates when windows are open and air mixing may not keep pace with air exchange.

Perhaps greater use may be made of fan procedures for estimating the flow resistance of the building envelope, somewhat along the lines described by Tamura and Shaw [*44*]. Further comparisons of fan and tracer measurements are necessary to better define the role of fan data in predicting air leakage under more normal conditions.

In most calculation procedures, wind is treated as a steady-state phenomenon. Experimental measurements show that inside-outside pressure differences due to wind have a strong fluctuating component [*19*]. The full significance of this behavior in modeling the effect of wind on infiltration has not been established. Perhaps infrasonic measurements will shed some light on this problem, since this procedure experimentally imposes a fluctuating pressure on the building and measures the response. The technique, referred to earlier, was described at the 1978 ASTM Symposium on Air Change Rate and Infiltration Measurement and also in an earlier report by Card et al [*1*].

An important goal of infiltration measurement is to provide experimental backup for the development of improved computer simulation of air exchange. At the present time, simulation of air exchange is one of the least satisfactory parts of the modeling of energy use by buildings. Complete testing of existing models may require experimental measurements over a considerable range of weather conditions. This is difficult, because weather is not always cooperative. Perhaps a completely accurate computer simulation based on software alone is not possible, but it would be an important step forward if reliable extrapolations could be developed for use with limited experimental data.

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