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CHAPTER 22

VENTILATION AND INFILTRATION

Ventilation Requirements; Types of Ventilation; Driving Mechanisms for Natural Ventilation and Infiltration; Natural Ventilation; Infiltration and Air Leakage; Air Leakage Sources; Empirical Models; Infiltration Measurement

OUTDOOR air that flows through a building either intentionally as ventilation air or unintentionally as infiltration (and exfiltration) is important for two reasons. Dilution with outdoor air is a primary means of control of indoor air contaminants, and the energy associated with heating or cooling this outdoor air is a significant, if not a major, load on the heating and air-conditioning system. Thus a knowledge of the magnitude of this air flow is needed for *maximum* load conditions to properly size equipment, for *average* conditions to properly estimate average or seasonal energy consumption, and for *minimum* conditions to assure proper control of indoor contaminants. In larger buildings, knowledge of ventilation and infiltration flow patterns is also important for assessing ventilation effectiveness, and smoke circulation patterns in the event of fire. This latter need is covered in Chapter 41 of the 1980 SYSTEMS VOLUME.

Ventilation occurs by two means, natural and forced. Natural ventilation in turn can be classified as infiltration or controlled natural ventilation. Infiltration is that flow of air through cracks, interstices, and unintentional openings due to the pressure of wind and the buoyancy effect caused by differences between the indoor and outdoor temperatures. Controlled natural ventilation is that which is due to openable windows and doors. Control is manual. This is an important means of ventilation in residences in mild weather when infiltration is at a minimum.

Forced ventilation is mandatory in larger buildings where a minimum amount of outdoor air must be supplied to meet the needs of occupants. ASHRAE Ventilation Standard 62-73[1,2] (or the latest issue) specifies the ventilation required. Past practice has specified a minimum and a recommended amount of outdoor air for various activities and conditions. The technology of air contaminant measurement now permits alternate methods based on assuring that indoor air quality meets specified conditions. This permits a variation in the amount of outdoor air based on the actual requirements of occupants in the space. The ASHRAE Ventilation Standard[2] defines these conditions.

This chapter focuses on envelope or shell-dominated buildings; i. e., residences or small commercial buildings in which the energy load is determined by the construction and performance of the building envelope. The physical principles discussed herein also apply to large buildings. With large buildings, however, ventilation energy load and indoor air quality conditions depend more on ventilation system design than on the performance of the building envelope. These system design requirements are dictated by the processes served by the ventilation system and are treated in Chapters 21 and 22 of the 1980 SYSTEMS VOLUME.

The preparation of this chapter is assigned to TC 4.3, Ventilation Requirements and Infiltration.

VENTILATION REQUIREMENTS

The amount of ventilation needed has been debated for over a century, and the different rationales developed have led to radically different ventilation standards.[3] Considerations such as the amount of air required to expel exhaled air, moisture removal from indoor air, and control of carbon dioxide (CO_2) were each primary criteria used at different times during the nineteenth century.

Current ventilation rates in commercial and residential buildings are based on a number of research projects carried out in the 1920's and 1930's, including that of Yaglou.[4,5] This research investigated the ventilation rates required to keep body-generated odors below an acceptable level in rooms with comfortable levels of temperature and humidity. It was found that the required ventilation rates varied considerably, depending on the cleanliness of the subjects and how many were present in the chamber. (See Chapter 12.) Researchers also found that CO_2 concentration was not a good indicator of the ventilation rate above 5 L/s (10 cfm) per person; the CO_2 concentration was almost always lower than expected for a given ventilation rate. However, below 5 L/s (10 cfm) per person the discrepancies were not so great, and in fact the current rationale for the 2.5 L/s (5 cfm) per person minimum outside air requirement is based on CO_2 concentration.

The amount of CO_2 produced by an individual depends on the diet and the activity level.[6] A representative value of CO_2 production by an individual is 0.0055 L/s (0.011 cfm). When a steady state is reached in a ventilated space in which no removal mechanisms for CO_2 exist other than ventilation, the concentration of CO_2 is given by:

$$C_i = C_o + F/Q \tag{1}$$

where

C_i = concentration of CO_2 inside the space.
C_o = concentration of CO_2 outside the space.
F = generation rate of CO_2.
Q = ventilation rate (outside air only).

Current ASHRAE standards assume that 0.25% CO_2 is an acceptable limit. Since the outside concentration of CO_2 is 0.03%, the minimum ventilation rate is:

$$0.25 = 0.03 + (0.0055 \times 100)/Q$$
$$Q = 2.5 \text{ L/s } (5 \text{ cfm}) \tag{2}$$

Minimum Outdoor Air Supply Rates

ASHRAE Ventilation Standard 62-73 (or the most current revision)[1,2] defines minimum outdoor air supply rates for various conditions. These rates have been arrived at through a consensus of experts working in the field. As shown in Eq 2, a minimum rate of 2.5 L/s (5 cfm) per person for sedentary activity and normal diets will hold the CO_2 level in a space 0.25% under steady state conditions. While normal healthy

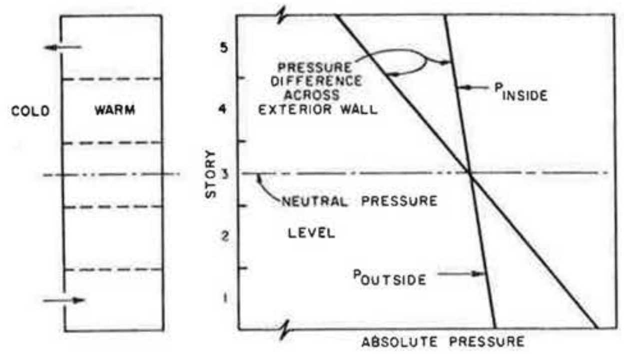


Fig. 2A Stack Effect in a Building with No Internal Partition

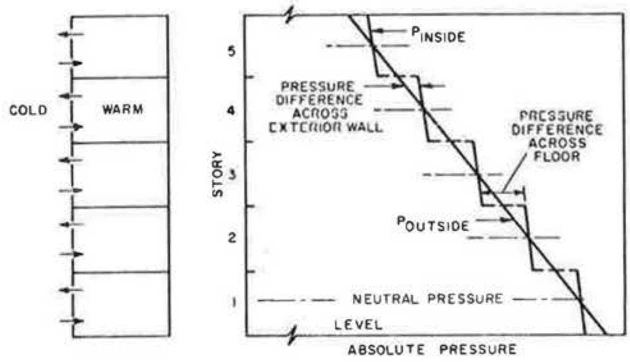


Fig. 2B Stack Effect in a Building with Airtight Separation of Each Story

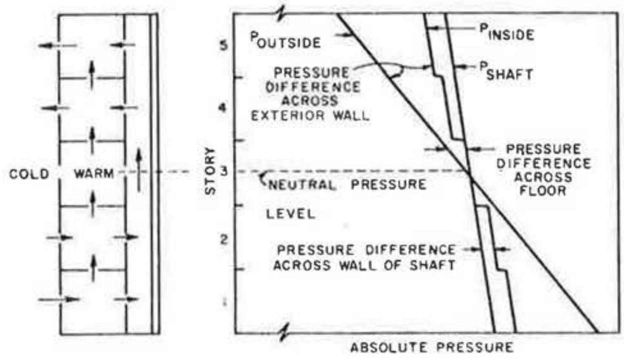


Fig. 2C Stack Effect for an Idealized Building

distributed vertically, the NPL will be at the midheight of the enclosure. Locating the NPL for simple enclosures with openings of known air flow characteristics is straightforward. For example, with two openings A_1 (lower) and A_2 (upper) separated by vertical height, H, the NPL, h, measured from the lower openings is given by:

$$h = \frac{H}{1 + [(A_1/A_2)^2 (T_i/T_o)]} \tag{5}$$

In Eq 5, $T_i > T_o$. If $T_i < T_o$, the ratio T_i/T_o is inverted.

The effects of internal partitions, stairwells, elevator shafts, utility ducts, chimneys, vents, and mechanical supply and exhaust systems complicate analysis in larger buildings. Chimneys are openings at or above roof height and they raise the NPL, most significantly in small buildings. Exhaust systems increase the height of the NPL and outdoor air supply systems lower it, when $T_i > T_o$.

Available data on the NPL in various kinds of buildings are limited. The NPL in tall buildings has varied from 0.3 to 0.7 of total building height.[12, 13, 14] For houses, the NPL is usually above midheight, and a chimney will raise the NPL as outdoor temperature drops.

A pressure difference across an actual building wall, divided by the pressure difference as determined from Eq 4, is termed the *thermal draft coefficient,* and depends on tightness of the floor separation relative to that of the exterior walls. For a building without internal partitions, the whole pressure difference due to stack effect is across the exterior walls (Fig. 2A). For a building with airtight separations at each floor, there can be no air flow between stories, so each story acts independently, its own stack effect unaffected by that of another (Fig. 2B). The sum of pressure differences across the exterior walls at top and bottom of any story equals the stack effect for that story. This is equivalent to the pressure difference acting across each floor, and is represented by the horizontal line at each floor level. The total stack effect for the total building height is the same as for Fig. 2A.

Real multistory buildings are neither open inside (Fig. 2A), nor airtight between stories (Fig. 2B). There are vertical air passages, stairwells, elevators, and other service shafts penetrating and permitting air to flow across the floors. Fig. 2C represents a heated building with uniform openings in the exterior wall, through each floor, and into the vertical shaft at each story. Between floors, the slope of the line representing the inside pressure is the same as in Fig. 2A, but there is a discontinuity at each floor as in Fig. 2B, representing the pressure difference across it. Total stack effect for the building remains the same, but some of the total pressure difference is needed to maintain flow through openings in the floors and vertical shafts, so pressure difference across the exterior wall at any level is less than with no internal flow resistance. As internal resistance increases, the pressure differences across floors and vertical shaft enclosures increase and the pressure differences across the exterior walls decrease. As height and number of stories increase, the total resistance of the flow path through floor openings increases faster than through vertical shafts, so the shafts mainly govern total resistance to flow in high buildings.

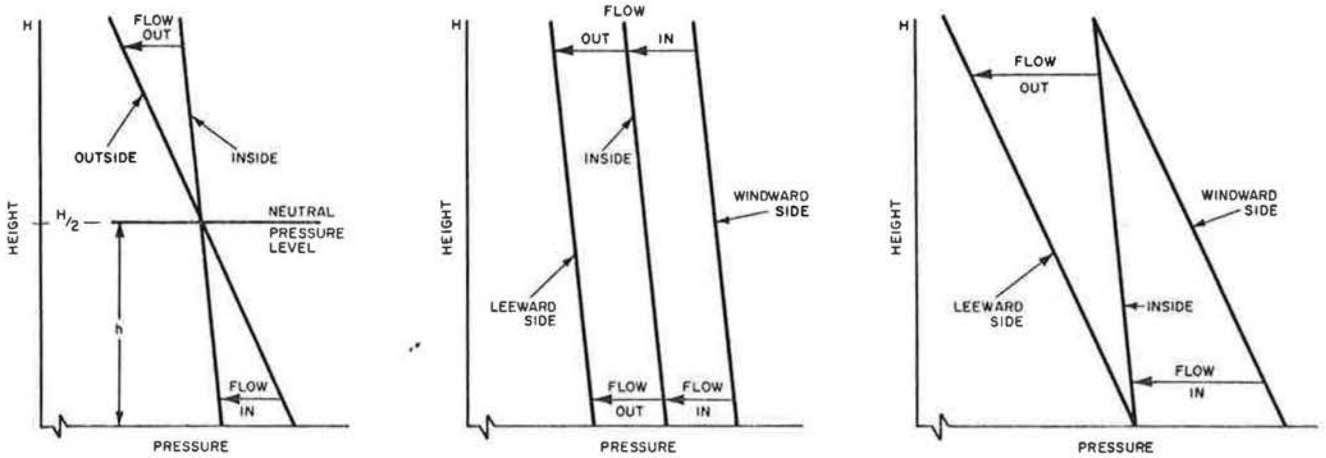
The effects of leakage between floors are especially important in the event of fire in a tall building. This is discussed in Chapter 41, 1980 SYSTEMS VOLUME.

Measurements of pressure differences on three tall office buildings[14] indicated that the thermal draft coefficient varied from 0.63 to 0.82.

Combining Pressure Terms

Pressures on the exterior faces of buildings caused by the wind and by temperature differences, and shifts in interior pressures caused by mechanical systems each cause the flow through the shell to change. *Pressures* from the various mechanisms *simply add.* However, since the flows are not proportional to the pressure differences, the *flows* due to each source *do not add.* Thus, successful models for calculating infiltration first calculate pressure distributions.

Action of pressure forces is considered qualitatively in Fig. 3 for a building with uniform openings above and below midheight and without significant internal resistance to flow. The slopes of lines are functions of densities of indoor and outdoor air. In Fig. 3, with inside warmer than outside and pressure difference due only to thermal forces, the NPL is at midheight, with inflow through lower openings and outflow through higher openings. A chimney or mechanical exhaust shifts inside pressure line to the left, raising the NPL; an excess of outdoor supply air over exhaust would lower it. Fig.



(a) STACK ACTION ONLY WITH NEUTRAL PRESSURE LEVEL AT MID-HEIGHT

(b) WIND ACTION ONLY WITH PRESSURES OF EQUAL MAGNITUDE ON WINDWARD AND LEEWARD SIDES

(c) WIND AND STACK ACTION COMBINED

Fig. 3 Distribution of Inside and Outside Pressures Over the Height of a Building

3B shows pressure differences due to wind alone, with the effect on windward and leeward sides equal but opposite.

Fig. 3C represents the condition where wind force of Fig. 3B has just balanced thermal force with no pressure difference at the top windward or bottom leeward side. Total flow is only slightly more or less than with wind action alone. Pressure differences from wind and thermal forces acting singly can be added to approximate the combined effect.

In tall buildings, exfiltration from windward rooms in upper stories occurs at low outdoor temperatures even with relatively high winds.[14] Pressures due to thermal forces in winter dominate at entrances to tall buildings.[12] Thus, thermal forces must be weighed in estimating air flow into tall buildings. In low buildings, the terrain and adjacent structures have a major effect on wind velocity and therefore on relative importance of wind and thermal forces. In two houses,[15] thermal forces were at least as important as wind forces corresponding to weather station winds of 6.7 m/s (15 mph), when indoor-outdoor temperature differences were 39°C (70 deg F) or greater in one instance, and 11°C (20 deg F) or greater in the other.

If excess outdoor air is supplied uniformly to each story, the change in the exterior wall pressure difference pattern due to thermal forces is uniform. With a nonuniform supply of outdoor air (for example, to one story only), the extent of pressurization will vary from story to story and will depend on internal resistances. Pressurizing all levels uniformly has little effect on the pressure differences across floors and vertical shaft enclosures, but pressurizing individual stories increases the pressure drop across these internal separations.

The flow through the building shell is dominated by kinetic energy loss mechanisms, where the flow is proportional to the square root of the pressure difference. Therefore, the total flow caused by adding the pressures from the various sources at any leakage site is the square root of the sum of the squares of the flows caused by each source. The simplest model to compute the total flow from the two sources, then, is to combine the flows using this "square" rule.

$$Q_{ws} = (Q_w^2 + Q_s^2)^{0.5} \quad (6)$$

where

Q_{ws} = infiltration from both wind and stack effects, L/s (cfm).
Q_w = infiltration from the wind, L/s (cfm).
Q_s = infiltration from the stack effect, L/s (cfm).

A computer model[16] which calculates infiltration in high-rise buildings has been used to compute an expression for the total infiltration:

$$Q_{ws}/Q_{lrg} = 1 + 0.24\,(Q_{sml}/Q_{lrg})^{3.3} \quad (7)$$

where Q_{ws} is the infiltration assigned to the combined actions of the wind and stack effects and Q_{lrg} and Q_{sml} are the individual infiltration values due to the larger and smaller pressure effects, respectively. Note that the simple quadrature expression, Eq 6, gives a slightly larger estimate of total infiltration than does Eq 7. Both results are plotted in Fig. 4.

Whenever mechanical ventilation equipment is in operation, it will cause internal pressure to shift so that total air entering due to infiltration will equal the total amount of air leaving the house. This is illustrated qualitatively in Fig. 5 for the case of an exhaust fan and a pressure distribution caused by the stack effect.

If an exhaust fan is turned on in a one-story house at a time of no wind in cold weather, the total air flow out of the house is the sum of the natural exfiltration and exhaust fan flow. This must be equal to the amount of air entering the house due to infiltration. Thus, the surface pressures are redistributed, the NPL rises, and the new pressure distribution is as shown in Fig. 5.

When the NPL rises, the exfiltration that occurred before the fan was turned on decreases. Thus the flow out the

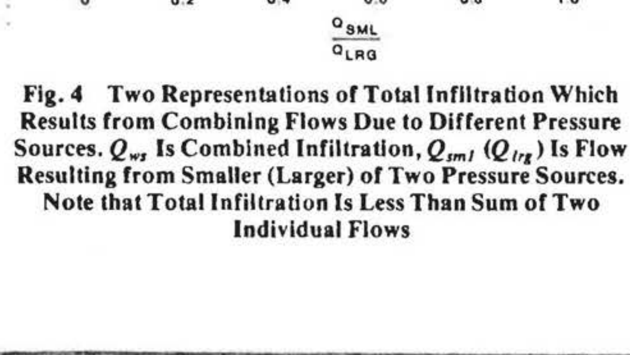


Fig. 4 Two Representations of Total Infiltration Which Results from Combining Flows Due to Different Pressure Sources. Q_{ws} Is Combined Infiltration, Q_{sml} (Q_{lrg}) Is Flow Resulting from Smaller (Larger) of Two Pressure Sources. Note that Total Infiltration Is Less Than Sum of Two Individual Flows

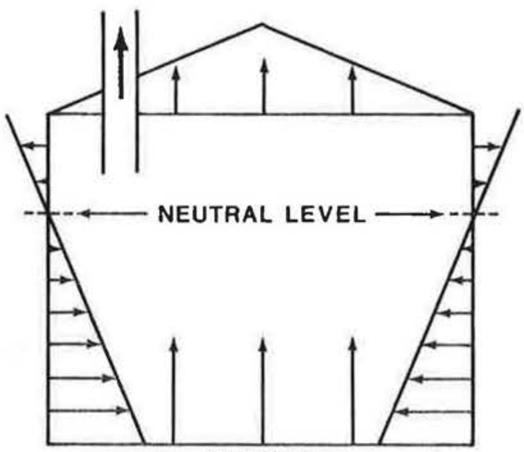


Fig. 5 Surface Pressure Distribution on House in Winter When Both Stack Effect Is Present and Interior Exhaust Fan Is Operating, but There Is No Wind

mechanical exhaust comes partly from increased infiltration and partly from decreased exfiltration. If the leaks in the structure are of uniform size and uniformly distributed, only half of the exhaust system flow would contribute to increased infiltration. Measurements of infiltration induced by residential combustion systems which draw combustion air from the conditioned space show that on the average 70% of the exhaust flow is made up by increased infiltration.[17]

NATURAL VENTILATION

Natural or passive ventilation occurs because of wind and thermal forces which produce a flow of outdoor air through the various openings in a building. Infiltration is the flow through the unintentional openings. Flow of outdoor air through openable windows, doors, and other controllable openings can be effectively used for both temperature and contaminate control. Temperature control by natural ventilation conserves energy and is particularly effective in mild climates. The arrangement, location, and control of ventilating openings can be designed to combine the driving forces of wind and temperature.

Natural Ventilation Openings

Types of openings include: (1) windows, doors, monitor openings, and skylights; (2) roof ventilators; (3) stacks connecting to registers; and (4) specially designed inlet or outlet openings.

Windows. Windows transmit light and provide ventilating area when open. They may open by sliding vertically or horizontally; by tilting on horizontal pivots at or near the center; or by swinging on pivots at the top, bottom, or side. Air flow per unit area of opening is identical. Type of pivoting is an important consideration for weather protection.

Roof Ventilators. A roof ventilator provides a weatherproof air outlet. Its capacity depends on its location on the roof; the resistance it and the ductwork offer to air flow; its ability to use kinetic wind energy to induce flow by centrifugal or ejector action; and the height of the draft.

A roof ventilator should be positioned so that it receives the full, unrestricted wind. Turbulence created by surrounding obstructions including higher adjacent buildings will impair a ventilator's ejector action. The ventilator inlet should be conical or bell mounted to give a high flow coefficient. The opening area at the inlet should be increased if screens, grilles, or other structural members cause flow resistance.

Building air inlets at lower levels should be larger than the combined throat areas of all roof ventilators.

Natural draft, or gravity, roof ventilators may be stationary, pivoting or oscillating, and rotating. Selection criteria are: ruggedness; corrosion-resistance; storm-proofing features; dampers and operating mechanisms; possibility of noise; original cost; and maintenance. Natural ventilators can supplement power-driven supply fans; the motors need only be energized when the natural exhaust capacity is too low. Gravity ventilators may have manual dampers or dampers controlled by thermostat or wind velocity.

Stacks or vertical flues should be located where wind can act on them from any direction. Without wind, the chimney effect alone removes air from the room with the inlets.

Required Flow

The ventilation flow needed to remove a given amount of heat from a building can be calculated from Eq 8 if the quantity of heat to be removed and the average indoor-outdoor temperature difference are known.[18]

$$Q = \frac{H}{60\, C_p\, \varrho\, (t_i - t_o)} = \frac{H}{C\,(t_i - t_o)} \tag{8}$$

where

Q = air removed, L/s (cfm).
H = heat removed, W (Btu/h).
C_p = specific heat of air at constant pressure, 1025 J/kg · K (0.245 Btu/lb · F).
ϱ = density of standard air, 1.2 kg/m^3 (0.075 lb/ft^3).
$t_i - t_o$ = average indoor-outdoor temperature difference, °C (deg F).
C = 1.23 (1.1).

Flow Due to Wind

Factors affecting ventilation wind forces include average velocity, prevailing direction, seasonal and daily variation in velocity and direction, and local obstructions such as nearby buildings, hills, trees, and shrubbery.

Wind velocities are usually lower in summer than in winter; frequency from various directions differs in summer and winter. There are relatively few places where velocity falls below half the average for more than a few hours a month. Thus, natural ventilating systems are often designed for wind velocities of half the average seasonal velocity.

Eq 9 shows the quantity of air forced through ventilation inlet openings by wind, or determines the proper size of openings to produce given air flow rates:

$$Q = C_v A v \tag{9}$$

where

Q = air flow, L/s (cfm).
A = free area of inlet openings, m^2 (ft^2).
v = wind velocity, m/s (mph).
C_v = effectiveness of openings (C_v should be taken as 0.50 to 0.60 for perpendicular winds, and 0.25 to 0.35 for diagonal winds).

Inlets should face directly into the prevailing wind direction. If they are not advantageously placed, flow will be less than that from the equation; if unusually well-placed, flow will be slightly more. Desirable outlet locations are: (1) on the leeward side of the building directly opposite the inlet; (2) on the roof, in the low pressure area caused by the jump of the wind; (3) on the sides adjacent to the windward face where low pressure areas occur; (4) in a monitor on the leeward side; (5) in roof ventilators; or (6) by stacks.

Flow Due to Thermal Forces

If there is no significant building internal resistance, and assuming indoor and outdoor temperatures are close to 26.7°C (80 F), the flow due to stack effect is:

$$Q = C A \sqrt{h(t_i - t_o)/t_i} \quad (10)$$

where

Q = air flow, L/s (cfm).
A = free area of inlets or outlets (assumed equal), m^2 (ft^2).
h = height from inlets to outlets, m (ft).
t_i = average temperature of indoor air in height h, °C (F).
t_o = temperature of outdoor air, °C (F).
C = constant of proportionality, 116 (9.4), including a value of 65% for effectiveness of openings. This should be reduced to 50% if conditions are not favorable [C = 89 (7.2)].

Eq 10 applies when $t_i > t_o$. If $t_i < t_o$, replace t_i in denominator with t_o.

Greatest flow per unit area of openings is obtained when inlets and outlets are equal; Eqs 9 and 10 are based on their equality. Increasing the outlet area over inlet area, or vice versa, will increase air flow but not in proportion to the added area. When openings are unequal, use the smaller area in the equations, and add the increase, as determined from Fig. 6.

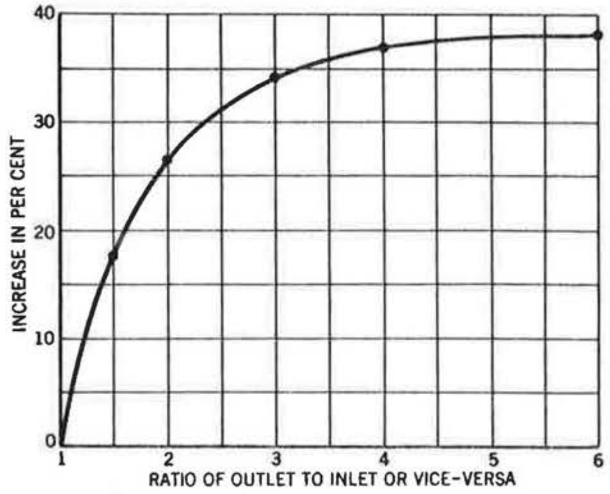


Fig. 6 Increase in Flow Caused by Excess of One Opening Over Another

Natural Ventilation Rules

Several general rules should be observed in designing for natural ventilation:

1. Systems using natural ventilation should be designed for effective ventilation regardless of wind direction. There must be adequate ventilation when the wind does not come from the prevailing direction.
2. Inlet openings should not be obstructed by buildings, trees, signboards, or indoor partitions.
3. Greatest flow per unit area of total opening is obtained by using inlet and outlet openings of nearly equal areas.
4. The neutral pressure level tends to move to the level of any single opening, with a resulting reduction in pressure across the opening. Two openings on opposite sides of a space will tend to increase the ventilation flow. If the openings are at the same level and near the ceiling, much of the flow may bypass the occupied level and be ineffective in diluting contaminants at the occupied level.
5. There must be vertical distance between openings for temperature difference to produce natural ventilation; the greater the vertical distance, the greater the ventilation.
6. Openings in the vicinity of the NPL are least effective for ventilation.
7. Openings with areas much larger than calculated are sometimes desirable when anticipating increased occupancy or very hot weather. The openings should be accessible to and operable by occupants.
8. When both forces act together, even without interference, resulting air flow is not equal to the two flows estimated separately. Flow through any opening is proportional to the square root of the sum of the pressure differences acting on that opening.

INFILTRATION

Infiltration is the uncontrolled flow of air through openings in the building envelope driven by pressure differences across the shell. The terms infiltration and air leakage are sometimes used synonymously but are different, though related, quantities. Infiltration is balanced by an equal amount of exfiltration since, except for transient conditions, there is no net storage of air in a building. Air leakage is the sum of all parallel air flows through cracks and other openings into or out of a building without regard to flow direction.

The air leakage rate describes the relative tightness of a building. The rate can be measured under standardized conditions by connecting a suitable fan and flow measurement section to the building. The building is either pressurized or depressurized and flow is measured as a function of pressure difference between inside and outside. Typical leakage rates are 8 to 15 air changes per hour at 50 Pa (0.2 in. H_2O) pressure difference. The Swedish building standard is three air changes per hour at 50 Pa.[19]

Infiltration is caused by the pressure forces discussed in the section Driving Mechanisms. Procedures for relating leakage to infiltration are included in the discussion of each calculation method.

Air Leakage Sites

A knowledge of where and how big the air leaks are is very useful in controlling infiltration. Leakage openings can also cause moisture problems (see Chapter 21). Leakage sites in American houses that have been measured during weatherization projects are (percentages show the range and average values for the relative amount of leakage):[20]

1. *Walls* (18-50%; 35%). Both interior and exterior walls contribute to the leakage of the structure. Leakage between the sill plate and the foundation, cracks remaining below the bottom of the gypsum wall board, electrical outlets, plumbing penetrations, and leaks into the attic at the top plates of walls all occur. Since interior walls are not filled with insulation, open paths connecting these walls and the attic permit the walls to behave like heat exchanger fins within the conditioned living space of the house.
2. *Ceiling Details* (3-30%; 18%). Leakage across the top ceiling of the heated space is particularly insidious because it reduces the effectiveness of the insulation on the floor of the attic as well as contributing to infiltration heat loss. Ceiling leakage may reduce the effectiveness of ceiling insulation. Recessed lighting, plumbing, and electrical penetrations leading to the attic make the ceiling a particularly important area to seal.
3. *Heating System* (3-28%; 15%). Such items as (a) location of the furnace or ductwork in conditioned or unconditioned space, (b) use of electric or fuel-burning furnace, and (c) presence or absence of outdoor combustion and makeup air all affect total leakage. Duct leakage in an unconditioned space (crawl space or attic) is often the air which has just been heated (cooled) by the furnace (air conditioner).
4. *Windows and Doors* (6-22%; 15%). The generic window type rather than manufacturer is the most important determinant in the leakage of a window (Table 4). Windows which seal by compressing the weatherstrip (casements, awnings) show significantly lower leakage than windows with sliding seals.
5. *Fireplaces* (0-30%; 12%). Fireplaces are inefficient because excess combustion air is drawn from the room and escapes up the chimney. When the fireplace is not in use, poorly fitting dampers

allow air to escape. Glass doors are useful for reducing excess air while a fire is burning but rarely seal the fireplace structure more tightly than a closed damper. Chimney caps or fireplace plugs with "tell tales" warn that they are in place and are most effective in reducing leakage through a cold fireplace.

6. *Vents in Conditioned Spaces* (2-12%; 5%). Vents in conditioned spaces frequently have no dampers or dampers which do not close properly.

7. *Diffusion through Walls* (<1%). Infiltration is dominated by flow through holes and other openings in the structure. By comparison, diffusion is not an important flow mechanism. Measurements of the permeability of building materials at 5 Pa or 0.02 in. H_2O (a relatively large pressure for infiltration) produced an air exchange rate of less than 0.01 air changes per hour by wall diffusion in a typical house. The flow through holes in the structure dominates.

Other Construction Details

A continuous plastic film vapor barrier on the warm side of the insulation is one of the most effective means of reducing air leakage through walls and around window and door frames. Builders frequently install the plastic film on the inside of the studding in frame houses; during construction the film also covers the window frames. Gypsum wall board is placed over the plastic vapor barrier. Trim at the window frames completes the seal at the frame. The plastic covering the windows is removed after the trim is in place. Installed in this way, the plastic film produces a continuous film that seals both the wall and the crack around the window frame. It also protects the window during construction.

Plastic vapor barriers installed in the ceiling should have a tight seal with the outside walls and should be continuous over the partition walls. A seal is needed at the top of partition walls to prevent leakage into the attic; a plate on top of the studs generally gives a poor seal. Chapter 21 provides additional information on vapor barriers (retarders).

It is generally desirable to make a building as tight as possible and to provide mechanical ventilation with heat recovery, thus minimizing energy consumption and the amount of ventilation needed. The Nordic countries have pioneered this approach. Continuous vapor barriers are installed with carefully sealed joints at intersections of external walls and floors, all walls and attic floors, joints around window and door frames, and service penetrations. Exhaust fans and air intake slots above windows provide constant ventilation independent of weather.

Calculating Air Leakage (Infiltration)

Most of the models used for estimating infiltration are actually air leakage models. Assumptions must be made as to which parts of the building are subject to infiltration and which are subject to exfiltration in order to convert leakage calculations to infiltration estimates. Several techniques have been used for doing this.

Air Change Method. The air change method for estimating infiltration is based on past experience. It applies to average residential construction under average weather conditions. Table 2 presents the number of air changes per hour to be expected in rooms with varying exposures. These are air leakage rates.

The infiltration rates for average buildings under average conditions can be assumed to be one-half the values given in Table 2.[15, 21-26] The procedure for using Table 2 is to multiply the volume of each room by the appropriate air change rate. The sum of all of the leakage rates is then divided by the total building volume to get the building leakage rate in air changes per hour. This total may then be divided by two to get the estimated infiltration rate.

The air exchange method has a size effect. A large room with a small window will have a lower air exchange rate than a small room with a large window. The data in Table 2 apply to average residential conditions. Large rooms, high ceilings, excessive glass, etc., will cause departures from these estimates.

Table 2 Air Changes per Hour Occurring Under Average Conditions in Residences, Exclusive of Air Provided for Ventilation

Kind of room	Single Glass, No Weatherstrip	Storm Sash or Weatherstripped
No windows or exterior doors	0.5	0.3
Windows or exterior doors on one side	1	0.7
Windows or exterior doors on two sides	1.5	1
Windows or exterior doors on three sides	2	1.3
Entrance halls	2	1.3

Calculations by the air change method have been compared with tracer gas measurements for two California houses and two Minnesota houses.[26] The comparison indicated the air change method can give estimates within 20% of measurements for average construction under average conditions. Differences of 50 to 100% occur for extra tight houses, for houses where furnace ducts are outside the conditioned space, or for unusual wind conditions. Thus the air change method should be considered a gross estimate at best.

Crack Method. The crack method calculates the flow produced by the pressure difference acting on each leakage path or building component. The flow is given by:

$$Q = C\,(\Delta P)^n \qquad (11)$$

where

Q = volume flow rate of air, L/s (cfm).
C = flow coefficient, volumetric flow rate per unit length of crack, or unit area, at a unit pressure difference.
ΔP = pressure difference.
n = flow exponent, between 0.5 and 1, usually near 0.65 for leakage openings.

Pressure difference caused by thermal forces is found from Eq 4, corrected for the character of interior separations. Pressure difference due to wind is the difference between the outside pressure and inside. Inside pressure depends on the ratio of inlet and outlet area which can change with wind direction. Pressure difference across the windward wall is:

$$P_w - P_i = \frac{P_w - P_L}{1 + (A_w/A_L)^{1/n}} \qquad (12)$$

where

P = wind pressure.
A = leakage area.
n = flow exponent.

Subscripts

w = windward.
i = inside.
L = leeward.

For example, for a square building with leakage openings uniformly distributed, the pressure difference across the windward wall for a quartering wind (at 45 degrees to the wall) ($A_w/A_L = 1$) is 50% of the difference between the windward and leeward pressures. For the same building with wind normal to one face of the building ($A_w/A_L = 1/3$) with $n = 0.65$, it is 85% of the difference between the windward and leeward pressures.

Table 3 Infiltration Through Double-Hung Wood Windows
[L/s · m (cfh/ft) of crack]

Type of Window	Pressure Difference, Pa (in. H_2O) 25 (0.10)	50 (0.20)	75 (0.30)
A. Wood Double-Hung Window (Locked)			
1. Nonweatherstripped, loose fit[a,b] or weatherstripped, loose fit	2.0 (77)	3.1 (122)	3.9 (150)
2. Nonweatherstripped, average fit	0.7 (27)	1.1 (43)	1.5 (57)
3. Weatherstripped, average fit	0.36 (14)	0.59 (23)	0.77 (30)
B. Frame-Wall Leakage[c] (Leakage is that passing between the frame of a wood double-hung window and the wall)			
1. Around frame in masonry wall, not caulked	0.43 (17)	0.67 (26)	0.88 (34)
2. Around frame in masonry wall, caulked	0.08 (3)	0.13 (5)	0.15 (6)
3. Around frame in wood frame wall	0.34 (13)	0.54 (21)	0.75 (29)

[a]A 2.4-mm (0.094-in.) crack and clearance represent a poorly fitted window, much poorer than average.

[b]The fit of the average double-hung wood window was determined as 1.6-mm (0.0625-in.) crack and 1.2-mm (0.047-in.) clearance by measurements on approximately 600 windows under heating season conditions.

[c]The values given for frame leakage are per metre (foot) of sash perimeter, as determined for double-hung wood windows. Some of the frame leakage in masonry walls originates in the brick wall itself, and cannot be prevented by caulking. For the additional reason that caulking is not done perfectly and deteriorates with time, it is considered advisable to choose the masonry frame leakage values for caulked frames as the average determined by the caulked and noncaulked tests.

The building with a quartering wind would experience infiltration leakage into the building on two sides and out of the building on two sides. Thus, only one-half the total crack length, if uniformly distributed, would allow infiltration. Exfiltration would occur through the other half of the cracks. In the case of wind normal to one wall, infiltration would occur through one-quarter of the cracks. Thus, both the effective wind pressure and the effective crack length are influenced by the wind direction and distribution of cracks.

Accuracy of the crack method for design load calculations is restricted by the limited data on air leakage characteristics of components and by the difficulty of estimating pressure differences under appropriate design conditions of temperature and wind. Specific air leakage data are available for a variety of components used in buildings, but differences develop between components as tested and as installed or constructed. The major limitation, however, is in estimating the appropriate pressure differences.

Eq 3 gives the wind pressure. The variation of wind velocity with height should be considered for tall buildings. Eqs 4 and 5 give the pressure difference due to thermal gradients or stack effect. Thermal induced pressure gradients are small for one- or two-story buildings, but may be the dominant air leakage force in tall buildings.

A mathematical model can simulate air flow in a building. To construct one requires knowledge of air leakage characteristics of exterior walls and interior separations, such as walls of vertical shafts and floor construction. Wind and temperature can be simulated by specifying outside pressures at each level caused by the two forces. The effect of air handling systems is simulated by specifying supply or exhaust rates in floor spaces or vertical shafts. Inside pressures are determined to obtain a mass flow balance for each floor and vertical shaft which results in a set of simultaneous nonlinear equations requiring iterative computer calculations of pressure differences and flow rates. With such a model, infiltration rates and air flow patterns can be determined for various conditions of wind and outside temperature and operation of the air handling systems.[27]

Infiltration by thermal forces comprises the major portion of infiltration for a multistory building in cold weather. For a building with a constant cross-sectional area and uniform distribution of openings with height, total air infiltration is:[28]

$$Q = CS\left[\mathrm{CF}\,\gamma P\,\frac{(T_i - T_o)}{T_i T_o}\right]^n \frac{(BH)^{n+1}}{n+1} \qquad (13)$$

where

Q = total infiltration rate, L/s (cfm).
C = flow coefficient, L/s · m² · (Pa)^n [cfm/ft² · (in. H_2O)^n].
S = perimeter of the building, m (ft).
γ = ratio of actual to theoretical pressure difference (thermal draft coefficient).
P = atmospheric pressure kPa (psi).
T_o = absolute temperature outside, K (R).
T_i = absolute temperature inside, K (R).
H = building height, m (ft).
n = flow exponent.
B = ratio of height of neutral pressure level to building height.
CF = 0.0342 (0.52).

Infiltration should be calculated separately for exterior walls of the ground floor, since its leakage tends to be higher than the other floors. Suggested values of C and n for exterior walls are in the section, Air Leakage Through Walls.

AIR LEAKAGE SOURCES

Air leakage through windows may be expressed as flow rate per unit length of sash crack or flow rate per unit area. The assumption that all cracks in a window are the same is not precise; but sufficient information is available from manufacturers to estimate air leakage. It is necessary to calculate the ratio of crack length on the windward side to that on the leeward side in order to convert leakage estimates to an infiltration estimate. (See also Chapter 25.)

Table 3 gives air leakage rates typical for older types of windows[29, 30] and may be used to estimate air leakage in existing buildings.

A variety of windows are used in residences and commercial buildings. Table 4 indicates common specifications used, and information on air leakage. Air leakage standards of these specifications are determined under specific pressure differences, size limitations, and specimen preparations. Actual air leakage from laboratory tests is available from some manufacturers. Air leakage for other pressure differences can also be estimated by Eq 11.

Just how a window is closed, or fits when closed, and its workmanship in general, have considerable influence on air leakage. The specifications listed in Table 4 attempt to establish minimum workmanship criteria, and certification programs are in operation to maintain quality.

Variation in air leakage for a single type of window may be quite large, depending on design, fit, and materials. Warping can cause windows of apparently similar fit to have considerable leakage differences.

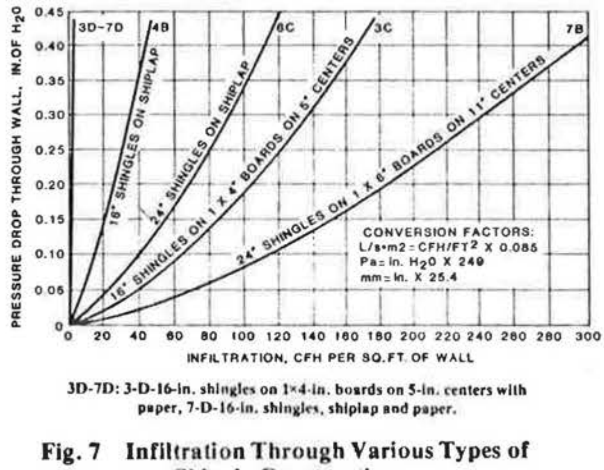
Recent measurements[31] of leakage in wood frame windows after installation have shown average leakage values for casement, sliding, and hung windows of 0.36, 1.07, and 1.19 L/s · m of crack, respectively (14, 42, and 46 cfm/ft, respectively). These field measured data include both frame and sash leakage. The specifications (ANSI A200.1) in Table 4 are for sash leakage only.

Storm windows added to prime windows reduce infiltration and provide an air space to reduce heat transmission and help prevent frosting. The leakage rate for a well-fitted, wood

Table 4 Window and Door Specifications

Specification/Material	Air Leakage[a] [At 75 Pa (0.3 in. H_2O) Unless Noted]
ANSI A134.1 (Windows, Aluminum)	
A-A2 (Awning), C-B1, C-A2, C-A3 (Casement) DH-A2, DH-A3, DH-A4 (Hung) HS-A3 (Sliding) P-B1, P-A2 (Projected) VP-A3 (Pivoted)	0.77 L/s · m crack (0.50 cfm/ft crack)
A-B1 (Awning) DH-B1 (Hung) HS-B1, HS-B2, HS-A2 (Sliding) JA-B1, (Jai-Awning) VS-B1 (Vertical, Sliding)	1.16 L/s · m crack (0.75 cfm/ft crack)
J-B1 (Jalousie)	7.62 L/s · m^2 (1.50 cfm/ft^2)
P-A2.50 (Projected) TH-A2 (Inswing) VP-A2 (Pivoted)	0.58 L/s · m crack (0.375 cfm/ft crack)
P-A3 (Projected)[b] TH-A3 (Inswing) VP-A3 (Pivoted)	1.16 L/s · m crack[b] (0.75 cfm/ft crack)
ANSI A134.2 (Sliding Glass Door, Aluminum)	
SGD-B1	5.08 L/s · m^2 (1.0 cfm/ft^2)
SGD-B2, SGD-A2 SGD-A3[b]	2.54 L/s · m^2 (0.50 cfm/ft^2)
ANSI A200.1	
All Types Wood Windows, Class A & B	0.77 L/s · m (0.50 cfm/ft)
ANSI A200.2	
All Types Sliding Glass Doors, Wood	2.54 L/s · m^2 (0.50 cfm/ft^2)
Fed. MHC & SS[c] 280.403	
All Types Windows and Sliding Glass Doors	2.54 L/s · m^2 (0.50 cfm/ft^2)
Fed. MHC & SS[c] 280.405	
All Types Vertical Entrance	5.08 L/s · m^2 (1.0 cfm/ft^2)

[a] At 75 Pa (0.30 in. H_2O) pressure or 11.2 m/s (25 mph) wind velocity.
[b] At 300 Pa (1.20 in. H_2O) pressure or 22.3 m/s (50 mph) wind velocity.
[c] Federal Mobile Home Construction and Safety Standard.



3D-7D: 3-D-16-in. shingles on 1×4-in. boards on 5-in. centers with paper, 7-D-16-in. shingles, shiplap and paper.

Fig. 7 Infiltration Through Various Types of Shingle Construction

hang-on window, 1.6-mm (0.0625-in.) crack and 0.8-mm (0.03125-in.) clearance, equals that of a loose-fit, double-hung wood sash window, not weatherstripped. Leakage rate of openable aluminum storm windows depends on fit and if weatherstripped or not, but may be estimated from Table 4. Leakage rate of the storm unit of a double window is usually about the same as that of the prime unit, but leakage through the combination depends on their individual leakage characteristics. Leakage of the combination in terms of the leakage of the prime window alone, assuming the flow exponent n, is equal for the prime and storm window, as:

$$Q_c = Q_p \left[\frac{1}{(C_p/C_s)^{1/n} + 1} \right]^n \qquad (14)$$

where

Q_c = flow rate for combined prime and storm window.
Q_p = flow rate for prime window.
C_p = proportionality constant for prime window.
C_s = proportionality constant for storm window.

For $n = 0.65$, leakage through a combination whose storm unit has the same leakage characteristic as the prime is about 35% less than that through the prime alone. By applying tight storm window units to poorly fitted windows, leakage may be reduced 50%, roughly equivalent to weatherstrips.

Air Leakage Through Walls

Infiltration data through brick and frame walls[32-35] are in Table 3. Plastering reduces leakage about 96%; a heavy coat of cold water paint, 50%; and three coats of oil paint carefully applied, 28%. Table 3 shows that infiltration through properly plastered walls can be neglected.

The value of building paper applied between sheathing and shingles is shown by curve 3D-7D, Fig. 7, for outside construction without lath and plaster. Standards of the National Association of Architectural Metal Manufacturers call for maximum leakage of 0.3 L/s · m^2 (0.06 cfm/ft^2) at a pressure difference of 75 Pa (0.3 in. H_2O) through curtain wall specimens, exclusive of leakage through operable windows. The corresponding flow coefficient, C, assuming a flow

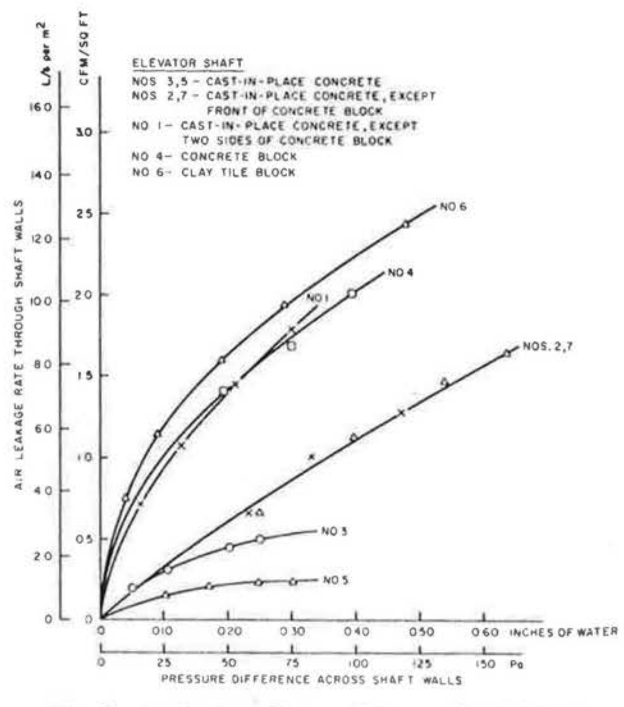


Fig. 8 Air Leakage Rates of Elevator Shaft Walls

Table 5 Air Leakage Through Walls
[$L/s \cdot m^2$ (cfh/ft^2)]

Type of Wall	Pressure Difference, Pa (in. H_2O)			
	12 (0.05)	25 (0.10)	50 (0.20)	75 (0.30)
Brick Wall: 8.5 in.				
Plain	0.42 (5)	0.76 (9)	1.35 (16)	2.03 (24)
Plastered Two coats on brick	0.004 (0.05)	0.007 (0.08)	0.012 (0.14)	0.017 (0.20)
Brick Wall: 13 in.				
Plain	0.42 (5)	0.68 (8)	1.18 (14)	1.69 (20)
Plastered Two coats on brick	0.001 (0.01)	0.004 (0.04)	0.004 (0.05)	0.008 (0.09)
Plastered, Furring, Lath Two coats gypsum Plaster	0.003 (0.03)	0.020 (0.24)	0.039 (0.46)	0.056 (0.66)
Frame Wall:				
Bevel siding painted or cedar singles, sheathing, building paper, wood lath, and three coats gypsum plaster	0.008 (0.09)	0.013 (0.15)	0.019 (0.22)	0.025 (0.29)

exponent of 0.65, is 0.018 $L/s \cdot m^2 \cdot Pa$ (0.13 $cfm/ft^2 \cdot in.$ H_2O). Based on measured leakage of eight multistory office buildings with sealed windows and spandrel panels of precast concrete or steel,[28] flow coefficients for tight, average, and loose walls (depending mainly on joint design and workmanship) can be assumed as 0.03, 0.09, and 0.18 (0.22, 0.66, and 1.30), respectively. These values can be used in Eq 11 or 13 for calculating curtain wall infiltration rates.

Measured leakage of a nine-story building[13] with masonry walls and operable aluminum sash windows was 9.84 $L/s \cdot m^2$ (1.90 cfm/ft^2) of outside wall area. For an assumed leakage of 2.32 $L/s \cdot m$ (1.50 cfm/ft) of sash crack at 75 Pa (0.3 in. H_2O) pressure difference, the windows and doors contributed about one-fourth of the total, with the remainder through the wall.

Recent studies[36] on houses with a pressurization fan indicated that typical total leakage area was almost equivalent to an orifice of 0.14 m^2 (1.5 ft^2), or about 0.33 $m^2/1000\ m^3$ (1 $ft^2/10\,000\ ft^3$) of house volume. Leakage flow through storm windows and doors was about 20% with the remainder through walls and ceilings. A pressure difference of 75 Pa (0.3 in. H_2O) produced leakage rates of: 1.4 to 4.8 $L/s \cdot m^2$ (16 to 57 cfh/ft^2) through the ceiling; 3.4 to 5.9 $L/s \cdot m^2$ (40 to 70 cfh/ft^2) through frame walls with brick veneer or metal siding; 0.8 to 1.0 $L/s \cdot m^2$ (9 to 12 cfh/ft^2) through stucco finish walls.

Table 5 shows that a frame wall would have a leakage rate of 0.025 $L/s \cdot m^2$ (0.29 cfh/ft^2) at 75 Pa (0.3 in. H_2O) pressure difference. Thus, in-place wall leakage is substantially greater than laboratory measurements.

Air Leakage Through Walls of Elevator and Stair Shafts

Elevator and stair shafts, floor construction, interior partitions, and service shafts are major separations in a building. Because they provide internal resistance to air flow, their air leakage characteristics are needed to determine infiltration through outside walls and the air flow pattern within a building. In cold weather, most upward air flow is inside vertical shafts, the least resistance path from floor to floor and the main avenue for transfer of odors and air contaminants.

In case of fire, measures to prevent smoke contamination of elevator and stair shafts used for evacuation and firefighting are essential (see Chapter 41, 1980 SYSTEMS VOLUME).

Pressurization is one means of maintaining a shaft habitable during a fire. Pressure inside the shaft is increased above adjacent floor spaces by forcing outdoor air into the shaft by a fan. Air flow direction is from shaft to floor spaces, and smoke from a fire is impeded from entering the shaft. Air supplied to the shaft also dilutes smoke, which may have migrated into the shaft prior to pressurization or when several shaft doors are opened during evacuation and firefighting.

For design of stair shaft pressurization systems, information on both airtightness of shaft walls and the pressure loss characteristic is required. Flow resistance of the channel formed by the staircase and walls has a significant effect on vertical distribution of pressurization.

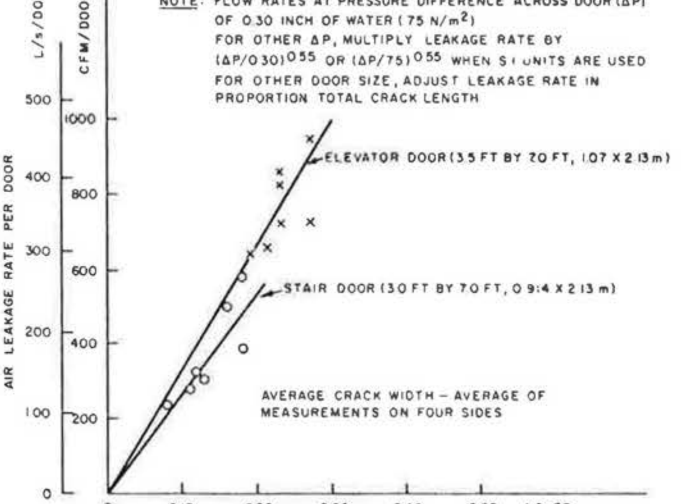


Fig. 9 Air Leakage Rate of Door vs. Average Crack Width

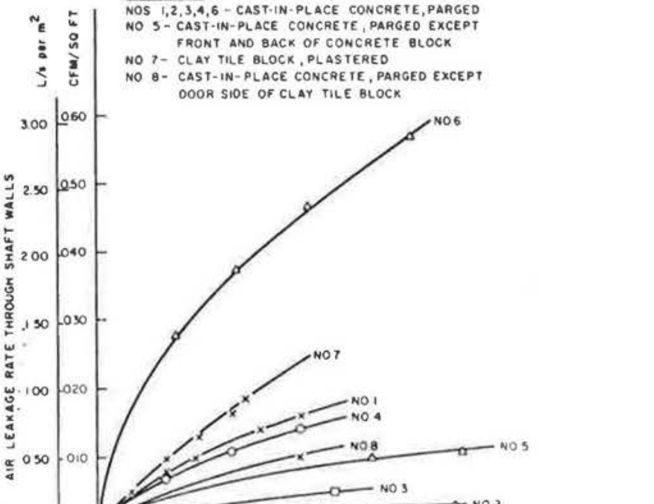


Fig. 10 Air Leakage Rates of Stair Shaft Walls

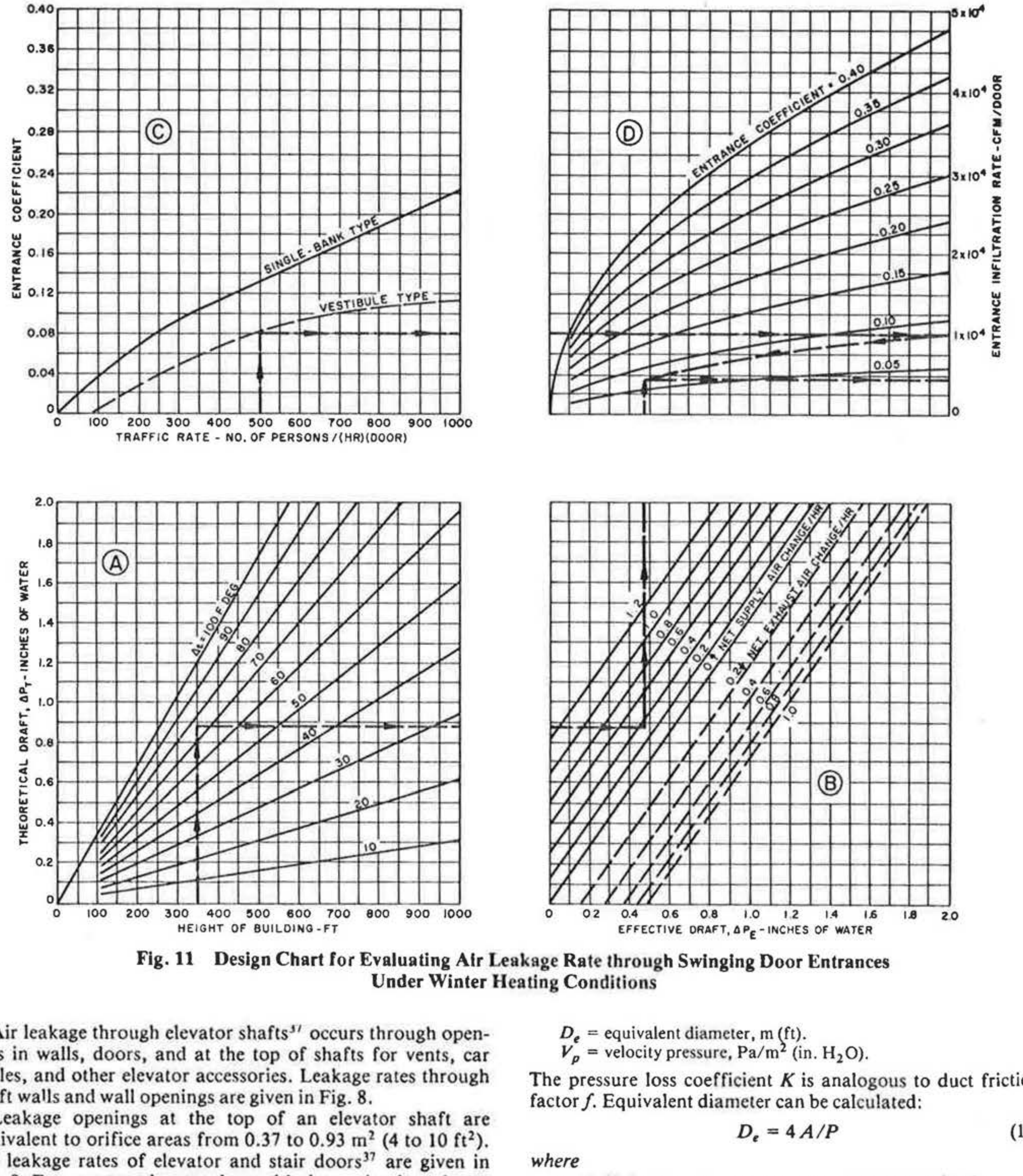


Fig. 11 Design Chart for Evaluating Air Leakage Rate through Swinging Door Entrances Under Winter Heating Conditions

Air leakage through elevator shafts[37] occurs through openings in walls, doors, and at the top of shafts for vents, car cables, and other elevator accessories. Leakage rates through shaft walls and wall openings are given in Fig. 8.

Leakage openings at the top of an elevator shaft are equivalent to orifice areas from 0.37 to 0.93 m^2 (4 to 10 ft^2). Air leakage rates of elevator and stair doors[37] are given in Fig. 9. For an open elevator door with the car in place, it can be assumed leakage is equivalent to a 0.56-m^2 (6-ft^2) orifice.

Air leakage rates through the stair shaft walls are in Fig. 10, and are similar to those of cast-in-place elevator shafts. Variation in the air leakage rates shown in Fig. 10 is probably due to workmanship in sealing openings.

Pressure losses inside a stair shaft can be calculated by considering it a rectangular air duct:

$$\Delta P_L = (KLV_p)/(D_e) \tag{15}$$

where

ΔP_L = total pressure loss per floor, Pa/m^2 (in. H_2O).
K = pressure loss coefficient.
L = height of shaft per floor, m (ft).
D_e = equivalent diameter, m (ft).
V_p = velocity pressure, Pa/m^2 (in. H_2O).

The pressure loss coefficient K is analogous to duct friction factor f. Equivalent diameter can be calculated:

$$D_e = 4A/P \tag{16}$$

where

A = inside horizontal cross-sectional area of shaft, m^2 (ft^2).
P = outer perimeter of the inside horizontal cross section of shaft, m (ft).

The velocity pressure of the flow of air at standard condition can be expressed:

$$V_p = (Q/CA)^2 \tag{17}$$

where

Q = flow rate, L/s (cfm).
C = 1.29 (4005).

Field tests gave K as 35. This value, compared with air duct friction factor, f, of 0.01 to 0.05, indicates flow resistance in stair shafts is several orders greater than that of air ducts.

In contrast to ordinary stair shafts, scissor stairs have two separate staircases in one shaft. Thus, half the cross-sectional area should be used to determine velocity pressure. The value of K is approximately 15.

Air Leakage through Exterior Doors

Door infiltration depends on the type of door, room, and building. For residences and small buildings where doors are used infrequently, infiltration can be estimated on the basis of air leakage through cracks between door and frame. Door fit varies greatly and is affected by warping. For a well-fitted door, leakage approximates a poorly fitted double-hung window; for a poorly fitted door, the figure may be doubled. If the door is weatherstripped, the values may be halved. A frequently-opened single door, as in a small retail store, may have a value three or more times that of a well-fitted door as an allowance for opening and closing losses. Doors of commercial buildings with heavy traffic have high leakage rates. An ASHRAE research program provides comprehensive data on air leakage characteristics of swinging door entrances[12] and revolving doors.[38] Complementary data on pressure differences across entrances of tall buildings are included.[12]

Swinging Door Entrances

A simplified design chart[39] (Fig. 11) can be used to estimate infiltration through swinging door entrances if building height, inside-outside temperature difference, net outdoor air supply or exhaust air change, type of entrance, and traffic rate are known.

Entrance coefficients for summer cooling are essentially the same as for winter heating.[9] Pressure differential data across the entrance, due to combined temperature difference and fan operation in summer cooling, are not available. A complete inversion of pressure difference for winter heating may be assumed for summer cooling: the negative pressure differential (inside pressure greater than outside pressure due to heavier inside air) can be determined by Fig. 11B. Note that, in winter heating, exhaust fans raise the pressure differential at the entrance; while, in summer cooling, they decrease negative pressure differential and exfiltration. The curve for net supply in winter heating in Fig. 11B becomes the curve for net exhaust in summer cooling. Entrance exfiltration can then be evaluated by Figs. 11C and 11D.

Leakage through door cracks (significant only in periods of very low traffic) can be found from Fig. 12, once the entrance pressure differential is determined from Fig. 11.

Infiltration through revolving doors is influenced by movement of the door, leakage past door seals, temperature and wind pressure difference between indoors and outdoors, traffic pattern, and traffic rate.[38] Inside and outside air turbulence and condition of the door seals also have effect.

Leakage through door seals is due to pressure differential across the building entrance and size of openings at the seal. Revolving the door causes almost equal exchange of indoor and outdoor air, which depends on door speed, temperature differential, and somewhat on wind and indoor air velocities.

A design chart [39] based on an ASHRAE research report[38] evaluates infiltration through manually-operated and power-operated revolving doors (Fig. 13). Fig. 13C is for a worn seal which still provides good contact with adjacent surfaces. When further wear reduces contact, leakage increases.

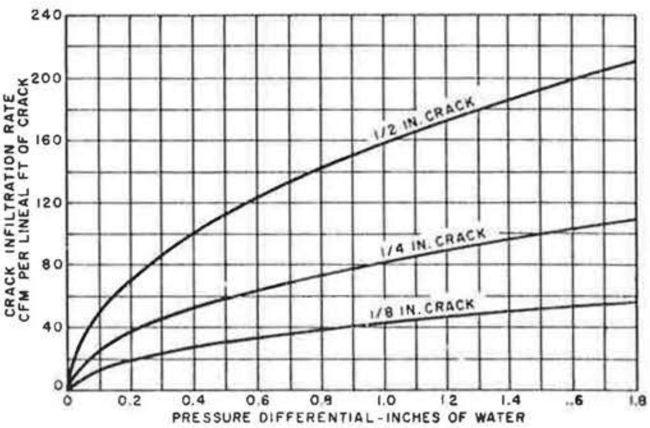


Fig. 12 Leakage Rate through Swinging Door Cracks

EMPIRICAL MODELS

Empirical models of infiltration have been generated based on long-term field measurements. The technique uses measured hourly infiltration rates and weather data to develop different regression models relating the two sets of variables.

The simplest of the many regression models has the form

$$I = K_1 + K_2\,\Delta t + K_3\,v \qquad (18)$$

where

I = air change rate per hour.
Δt = indoor-outdoor temperature difference, °C (deg F).
v = wind speed, m/s (mph).
K_1, K_2, K_3 = empirical constants derived from measurements at the site.

Constants vary significantly from site to site. Care must be exercised in using this general regression expression as a predictive model of an arbitrary house. Typical values of the constants suitable for different classes of houses are given in Table 6.[40]

Air Leakage/Infiltration Correlations

The previous calculation procedures described are simple but of uncertain precision. Better precision is possible if the house condition is explicitly measured and if the weather at the site rather than the weather for the region is used in the calculation. The most straightforward method for measuring the leakage rate of a house uses fan pressurization. An infiltration model which combines the results of air leakage measurements using fan pressurization and weather effects at the house are described below. In this model the infiltration, Q, is the larger of two values, Q_{stack} and Q_{wind}, in which;[41]

$$Q_{stack} = f_s^* A_l \sqrt{\Delta T} \qquad (19)$$

$$Q_{wind} = f_w^* A_l\, v \qquad (20)$$

where

Q_{stack} = stack dominated infiltration, L/h (ft³/h).
Q_{wind} = wind dominated infiltration, L/h (ft³/h).
f_s^*, f_w^* = dimensionless building parameters.
A_l = leakage area of house, m² (ft²).
ΔT = indoor-outdoor temperature difference, °C (F).
v = measured wind speed, m/s (mph).

Table 6 Coefficients for Multiple Linear Regression Infiltration, Eq 1

Construction Type	K_1	K_2	K_3	Description
Tight	0.10	0.011	0.034	New building where special precautions have been taken to prevent infiltration.
Medium	0.10	0.017	0.049	Building constructed using conventional construction procedures.
Loose	0.10	0.023	0.067	Evidence of poor construction or older buildings where joints have separated.

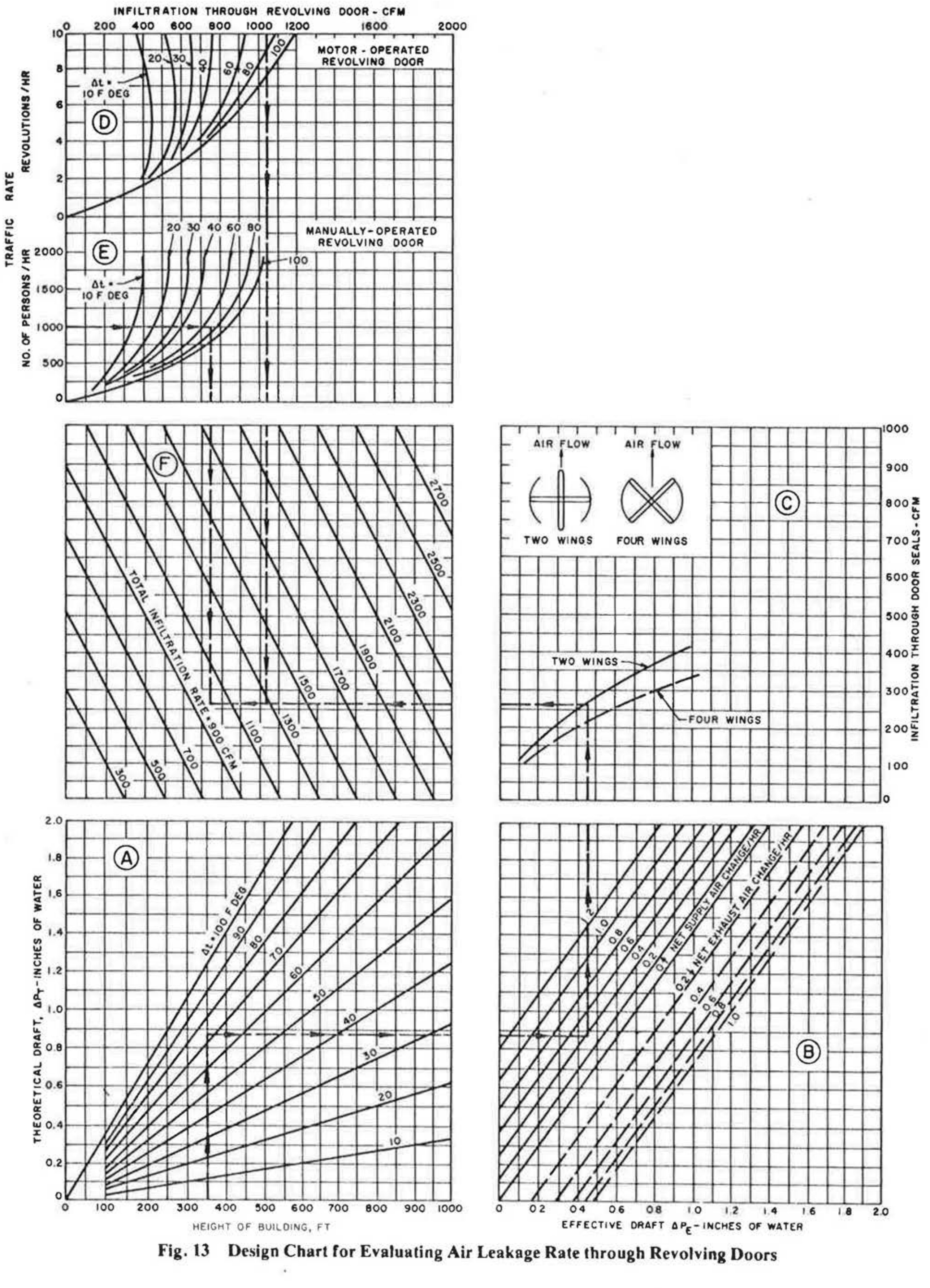


Fig. 13 Design Chart for Evaluating Air Leakage Rate through Revolving Doors

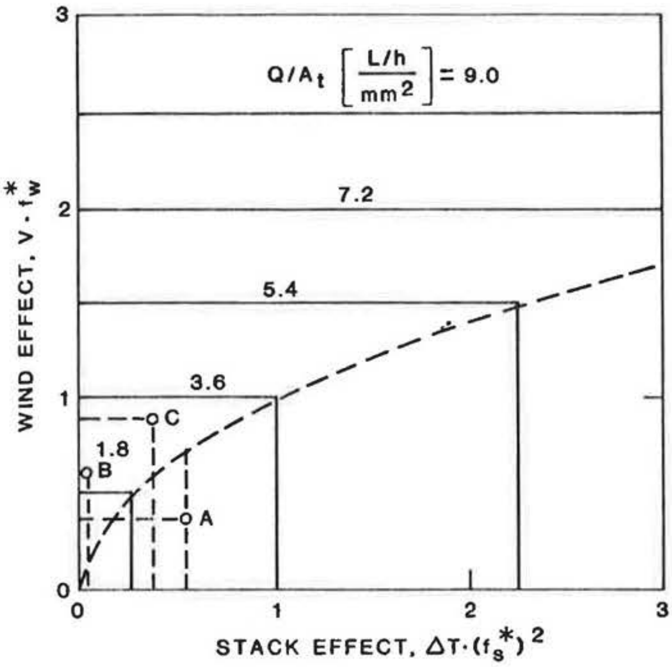


Fig. 14 Lines of Constant Infiltration as a Function of Wind Speed and Temperature Difference. Dashed Line Separates Wind-Dominated Regime from Stack-Dominated Regime. Points A, B, and C Are Results from Examples 1 and 2

Infiltration for a structure can be determined directly from Fig. 14. The wind parameter, f_w^* (Eq 22), which is unique for a particular building, is multiplied by the measured wind speed (e.g., from a meteorological station at an airport) to find a coordinate on the vertical axis. The square of the stack parameter, $(f_s^*)^2$ (Eq 23), is multiplied by ΔT to find a coordinate on the horizontal axis. The point defined by these coordinates determines the infiltration prediction. If this point is above the dashed line, the infiltration is wind dominated, if below, stack dominated.

Once the point is located on the graph, the ratio of infiltration to leakage area is determined by interpolating between the lines of constant infiltration drawn on the body of the graph. In the wind dominated portion of the figure (above the dashed line) this is simply a linear interpolation between lines separated by 1.8 L/h · mm². In the stack dominated regime, the interpolation is more difficult because of the quadratic spacing of the lines. The simplest procedure is to move vertically from the point to the dashed line (the locus of points where the infiltration from the stack effect and the wind effect are equal). The linear interpolation in the wind regime then can be used. The number read from the graph is multiplied by the leakage area of the house to determine the infiltration, L/h.

In this model, the leakage area of the building, measured a single time at the site, is the scale factor that allows the infiltration to be predicted for many different weather conditions. Low pressure flow measurements show[42] that a suitable model for flow in the pressure range characterized by infiltration is:

$$Q \propto (\Delta P)^{0.5}$$

where

Q = total flow through the building shell.
ΔP = inside-outside pressure difference.

Field measurements at pressures above 10 Pa show that the exponent of the pressure term is often larger than one-half.[43]

Table 7 Terrain Parameters for Standard Terrain Classes

Class	α	γ	Description
I	1.30	0.10	Ocean or other body of water with at least 5 km (3.1 miles) of unrestricted expanse.
II	1.00	0.15	Flat terrain with some isolated obstacles (e.g., buildings or trees well separated from each other).
III	0.85	0.20	Rural areas with low buildings, trees, etc.
IV	0.67	0.25	Urban, industrial, or forest areas.
V	0.47	0.35	Center of large city (e.g., Manhattan).

Therefore, the effective leakage area is computed by plotting Q vs. ΔP on log-log graph paper, extracting the flow at $\Delta P = 4$ Pa from the graph and using this in the defining equation (Eq 17) for the effective leakage area.

$$A_t = \frac{Q}{\sqrt{(2\,\Delta P/\varrho)}} \qquad (21)$$

where

A_t = effective leakage area, m² (ft²).
Q = flow at measured P, L/s (cfm).
ΔP = measured indoor-outdoor pressure difference, Pa (in. H_2O).
ϱ = air density, kg/m³ (1.2 at sea level and 294 K) [lb/ft³ (0.075 at sea level and 530 R)].

If insufficient data exist to determine the flow at 4 Pa (0.016 in. H_2O), Eq 21 may be used directly for the lowest pressure-flow measurement available. The building parameters f_w^* and f_s^* are defined in Eqs 22 and 23.

$$f_w^* = \frac{3 - R}{9}\left[\frac{\alpha\,(H/10)\,\gamma}{\alpha'(H'/10)\,\gamma'}\right] \qquad (22)$$

where

R = ratio of the leakage area in the horizontal surfaces of the building to the total leakage area of the building.
H = height of the floor of the attic of the building, m (ft).
H' = height of the wind speed measurement, m (ft).
$\alpha, \gamma, \alpha', \gamma'$ = constants which define the change of wind speed with height in the expression:[44]

$$v = v_o\,\alpha\,(h/h_o)^\gamma$$

where v is the wind speed at height h, v_o is the wind speed at height h_o, and α and γ are constants defined for terrain classes listed in Table 7.

In Eq 18, the primed quantities refer to the terrain class at the wind measurement location, the unprimed quantities to the terrain class of the house.

It is important to emphasize that f_s^* and f_w^* are building parameters which need to be calculated only once for a structure. All infiltration results are then related directly to measurements of windspeed and temperature difference. The stack parameter f_s^* is given by:

$$f_s^* = \left(\frac{2 + R}{9}\right)\left(2g\,\frac{H}{T}\right)^{0.5} \qquad (23)$$

where

g = acceleration of gravity, 9.8 m/s² (32.2 ft/s²).
H = height of the floor of the attic, m (ft).
T = absolute temperature of the interior of the building, K (R).

The constant R is given by,

$$R = (A_c + A_f)/A_t \qquad (24)$$

where

A_c = leakage area of the ceiling of the living space, m² (ft²).
A_f = leakage area of the floor, m² (ft²).

A = total leakage area of the structure, m^2 (ft^2).

The leakage areas of the floor and ceiling, A_f and A_c, which are required to compute R, can be determined by (1) direct measurement, (2) identifying leaks in the ceiling and floors, or (3) assuming uniform leakage and scaling by the surface area (most often used). Examples 1 and 2 compare calculations by the simple air change method with air leakage extrapolation and infiltration measurements. The comparison is made for a two-bedroom, single-story frame house in Ottawa, Ontario, shown in Fig. 15.

Example 1: Compute the infiltration for the Ontario house shown in Fig. 15 using the Air Change method. None of the windows in this house is weatherstripped.

Solution: The volume of each room is computed using the dimensions from Fig. 15. The product of the volume of the room and the number of air changes assigned using Table 2 gives an infiltration value. The sum of the infiltration values for all the rooms gives the total infiltration, m^3/h, for the house. Dividing this value by the house volume gives the infiltration rate, air changes per hour.

Room	Volume, m^3	Air Changes per Hour	Infiltration, m^3/h
Living Room	57	1	57
Kitchen	22	1.5	33
Dining Room	21	1	21
Bathroom	13	1	13
Bedroom 1	25	1	25
Bedroom 2	35	1	35
Basement	160	1.5	240

Total infiltration: 420 m^3/h.
Volume of house: 337 m^3.
Predicted leakage rate: 420/337 = 1.3 air changes per hour.
Predicted infiltration rate: 1.3/2 = 0.65 air changes per hour.

It must be emphasized that this prediction is an average value, independent of any weather condition.

Example 2: Air Leakage Extrapolation Model Infiltration rates are to be calculated for:

(A) $t = 29.4°C$, $v = 1.4$ m/s
(B) $t = -1.1°C$, $v = 2.7$ m/s
(C) $t = 18.6°C$, $v = 4.0$ m/s

The leakage flow measured at 7.5 Pa was 547 L/s and flow vs. pressure was found to be $Q = C(\Delta P)^{0.65}$.

Solution: Using this relationship with the flow value at 75 Pa leads to a flow at 4 Pa of:

$$(Q)_4 = (Q)_{75}\,(4/75)^{0.65} \times 10^3 = 81 \text{ L/s}$$

Therefore, the effective leakage area is

$$A_t = \frac{81 \times 10^3}{(2 \times 4/1.2)^{0.5}} = 32\,000 \text{ mm}^2$$

Note: 10^3 converts m^3/s to L/s and to mm^2, respectively.

The measurements of wall and ceiling leakage gave ceiling leakage of 65% of the total leakage of the structure. Since the basement was a conditioned space, leakage into the basement was considered part of the wall leakage. Therefore, A_f is zero. The value of R is

$$R = (A_c + A_f)/A_t = 0.65$$

The wind speeds given are for conditions when measurements were made at the site on a 7.6 m weather tower. The height of the ceiling (floor of the attic) above grade was 3.1 m, and the houses were judged to be located in terrain class III. Therefore $\alpha = \alpha' = 0.85$; $\gamma = \gamma' = 0.20$. The expression for f_w^* is now:

$$f_w^* = \frac{2 - 0.65}{9}\,\frac{[0.85\,(0.31)^{0.20}]}{[0.85\,(0.76)^{0.20}]} = 0.22$$

The stack parameter is easier to compute:

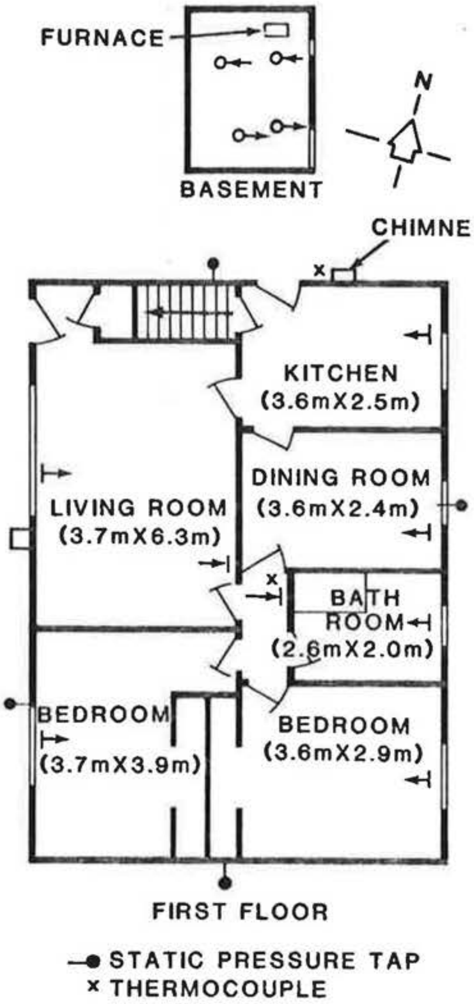


Fig. 15 Plan View of House No. 1 from Tamura (1979).[45] The House, Located in a Residential Area of Ottawa, Ontario, Has a Volume of 337 m^3

$$f_s^* = \frac{2 + 0.65}{9}\sqrt{2\,(9.8)\,3.1/293} = 0.13$$

The coordinates for Fig. 14 for the three cases listed are:

$\lvert\Delta T\rvert$ (°C)	v (m/s)	$(f_w^*)\,v$	$(f_s^*)^2 \cdot \lvert\Delta T\rvert$
29.4	1.4	0.31	0.53
1.1	2.7	0.59	0.02
18.6	4.0	0.88	0.33

These values of $[(f_w^*) \cdot v]$ vs. $[(f_s^*)^2 \cdot \lvert\Delta T\rvert]$ are plotted as points A, B, and C in Fig. 14. Point A in the temperature dominated region is projected up to the dashed curve to find a value of $Q/A_t = 2.5$. This is multiplied by the measured leakage area of 32 000 mm^2 to give a predicted infiltration flow rate of 80 000 L/h. When divided by the house volume of 337 m^3 the predicted infiltration rate becomes 80 000 × 10^{-3}/337 = 0.24 air changes per hour.

Points B and C are in the wind dominated region. Their values of Q/A_t are 2.1 and 3.1 rspectively. The infiltration flow rates are 68 000 and 100 000 L/h, giving infiltration rates of 0.20 and 0.30 air changes per hour, respectively. These predictions are compared below with the measured infiltration rates:

Case	Predicted Q (L/h)	Predicted I*	Measured I*
A	80 000	0.24	0.22
B	68 000	0.20	0.16
C	100 000	0.30	0.23

*Air changes per hour.

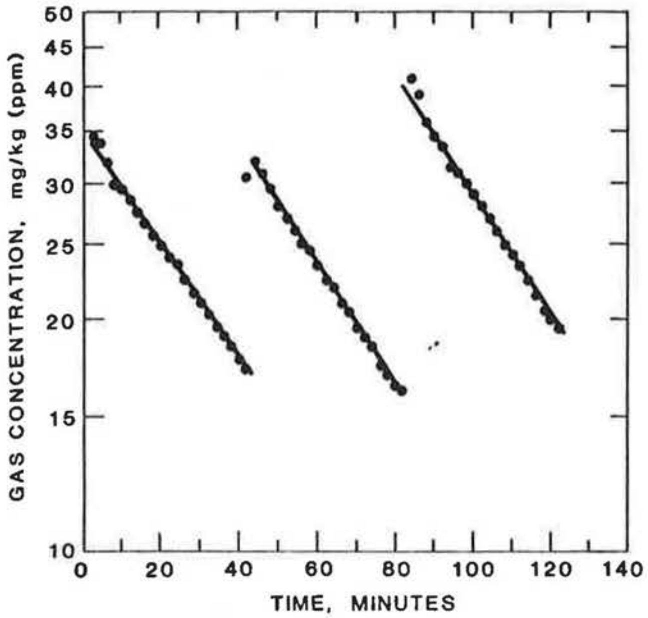


Fig. 16 Tracer Gas Concentration vs. Time. Points Represent Three Consecutive Decays Separated by Rapid Injections of Tracer Gas. Slopes of Straight Lines Give Air Infiltration Rates: in This Case 1.02, 1.06, and 1.07 Air Changes per Hour, Respectively

These predictions are seen to agree with measurements much better then the simple air change method (0.65 air changes per hour). The Air Leakage Extrapolation method does, however, require on-site measurements. Thus it is less attractive for routine use.

Network models. A final class of computation procedures, called network models, produces the best available estimates of infiltration.[46] These models use the basic computation philosophy of the crack method, i.e., a detailed inventory of the flow characteristics of each of the openings in the building shell, and the pressure differences across these openings are combined to compute the air flow through the structure.

INFILTRATION MEASUREMENT

Tracer gas measurements are the practical means of direct measurement of infiltration. An inert or inactive gas easily detected in dilute quantities is uniformly mixed in the atmosphere in the building. If the tracer does not react and is not absorbed or adsorbed on building materials and furnishing, its flow rate through the building will provide an accurate analog of the air flow rate, i.e., infiltration rate. ASTM Standard E 741-80 describes a standard tracer dilution method for infiltration measurement.

The tracer gas selected should be nontoxic and nonreactive, and should behave like air as it flows through the structure. Gases used have included coal gas, carbon dioxide, hydrogen, argon, krypton, nitrous oxide, helium, methane, ethane, and sulfur hexafluoride. Ethane has a molecular weight nearly equal to air, while methane is somewhat lighter and diffuses rapidly. They are safe when used in concentrations 50 to 100 times less than the lower flammability limit. Sulfur hexafluoride, although much heavier than air, is popular because it can be readily measured in concentrations in the parts per billion range. It does not settle out after it is dispersed in very dilute concentrations.[47] The other gases are usually used in concentrations from 10 to 1000 parts per million.

Tracer gas measurements are based on the continuity equation. The rate of change of tracer gas in the test space, $V\,(dc/dt)$, is the difference between the gas injected into the space, F, and the tracer gas leaving the space due to exfiltration, Qc:

$$V(dc/dt) = F - Qc \tag{25}$$

where

c = tracer concentration.
V = space volume containing tracer gas, m^3 (ft^3).
F = tracer injection rate, L/s (cfm).
Q = exfiltration (or infiltration), L/s (cfm).

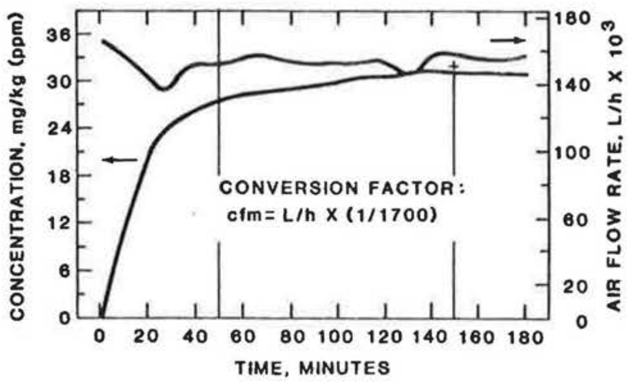


Fig. 17 Infiltration Measurement by Constant Tracer Flow Method

Either a tracer decay method or a constant flow method may be used.

Tracer Decay Method

The Tracer Decay method is the most common and requires the simplest apparatus. Tracer gas is initially injected into the test space long enough to give a safe but easily measured concentration. After injection stops, F is identically zero and the solution of the continuity equation is:

$$c(t) = c_o e^{-(Q/V)t} \tag{26}$$

where c_o is the concentration at $t = 0$.

The ratio of the infiltration, Q, to the volume sampled by the tracer gas, V, has units of number of volumes/time (i.e., air changes per hour) and is called the infiltration rate, I. Thus

$$c(t) = c_o e^{-It} \tag{27}$$

A plot of concentration vs. time on a semi-log graph gives a straight line if the tracer concentration is uniform in volume and the infiltration is constant. Several periodic injections give a group of straight lines. The slope of each straight section is the air infiltration rate for that time interval. This is shown in Fig. 16.

Constant Flow Technique

The Constant Flow technique gives a means of continuous infiltration measurement. As in the decay technique, the test space is initially charged with a tracer gas. The injection rate is then set to a constant value which produces an easily measured concentration; the flow rate and concentration are then monitored. Solving the continuity equation (Eq 25) in this case for the infiltration gives:

$$Q = \frac{F}{c} - \frac{V}{c}\left(\frac{dc}{dt}\right) \tag{28}$$

Note that whenever the concentration is approximately constant over time, dc/dt vanishes and the infiltration, Q, is given by:

$$Q = F/c \tag{29}$$

This technique requires slightly more equipment than the decay technique, but can be used more easily for long-term

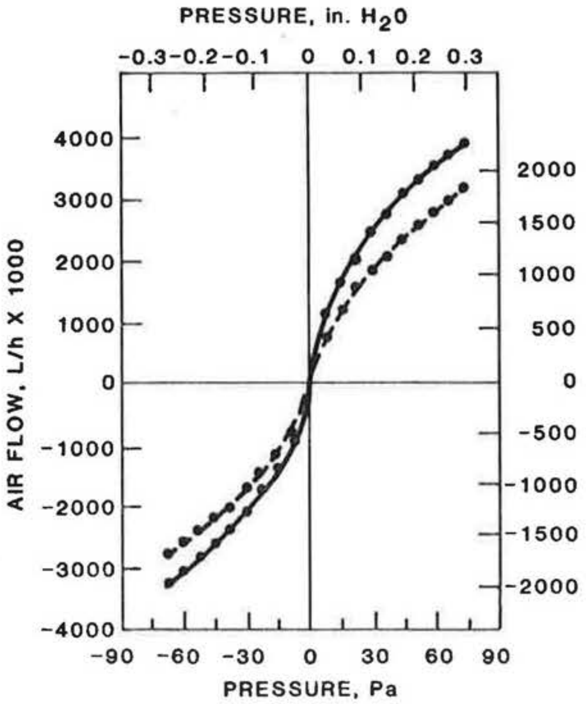


Fig. 18 Pressure vs. Flow Leakage from Pressurization Measurements. Solid Line Shows Leakage of House with Ductwork Open. Dashed Line Was Obtained When All Entrancesto Ductwork from Living Space Were Sealed with Plastic Sheets[10]

measurements. Fig. 17 shows measurement results from a continuous-flow system.[48]

The infiltration calculated using Eq 28 is shown on the right vertical axis. Tracer gas was injected at a rate of 13.6 L/h (0.008 cfm) for the first 30 minutes of the measurement; the flow was then reduced to a constant value of 5 L/h (0.003 cfm). The solid vertical lines at 50 and 150 minutes represent the contribution of the first term in Eq 28 to the value of Q; the dashed vertical lines are the contributions of the *correction* term which includes the rate of change of concentration.

Other tracer gas systems have been introduced using microprocessors for control, data logging, and calculation.[49]

Mixing Problems

Mixing problems present a major source of error. The tracer gas must be uniformly mixed throughout the test space so that the concentration of tracer gas measured accurately represents the concentration in the space. For precision infiltration measurements consult Ref 50.

To assure adequate mixing:

1. Inject tracer gas at several points simultaneously using multiple or perforated injection lines.
2. Use auxiliary fans to initially mix the tracer gas throughout the test space. Frequently the blower in a forced air heating or cooling system is used to distribute and sample the tracer. Several researchers,[17, 51] however, have reported additional infiltration whenever the blower is in operation. This was due to duct leakage (particularly when ducts pass through unconditioned spaces) and to a change in the effective volume sampled by the tracer gas (see item 4, below).
3. Analyze samples of air from several locations of the test space to ensure that the concentration of tracer gas is uniform throughout. Doors to closets, cupboards, etc. should be kept open to assure good mixing. If the concentrations cannot be made uniform, multichamber analysis must be used to adequately treat the data.
4. Change the measurement technique, if necessary, to minimize the mixing problem.

If the tracer is added at a constant measured flow rate for a measured time interval, the effective volume of the space can be calculated from the initial concentration at the end of the charging period.[17]

$$V_s = \frac{F}{c_o} \times \frac{1}{I} (1 - e^{-It}) \tag{30}$$

where

V_s = space volume, m^3 (ft^3).
F = tracer gas flow rate, L/h (cfm).
c_o = tracer concentration at end of charging period and start of decay period.
I = infiltration, air changes per unit time, h (min).
t = time of charging period, h (min).

The volume measured in this way can be compared to geometric measurements. Differences indicate incomplete mixing or duct leakage. If the furnace blower is being used to distribute and sample the tracer, loss of tracer due to duct leakage will cause the initial concentration c_o to be lower and the house volume will appear to be too large. Incomplete mixing also tends to cause the semi-log plot of tracer decay, Fig. 13, to depart from a straight line.

Item 4 refers to a situation that occurs if the physical volume of the test space is not the volume sampled by the tracer gas. The latter volume, called the effective volume, can be larger or smaller than the physical volume of the space. A decay measurement, yielding an infiltration rate, I, is converted to an infiltration flow rate Q when I is multiplied by the effective volume. If the effective volume and physical volume are not equal, a significant error can exist in the calculated value of Q because the effective volume is unknown and must be approximated by the physical volume. The constant flow technique, which uses Eq 28 to calculate Q, minimizes this problem. Whenever the system is near equilibrium (i.e., the concentration is nearly constant) the volume term enters the computation of the infiltration flow rate only as a small correction term. Consequently uncertainties in the effective volume cause only minor uncertainties in the value of the infiltration flow rate.

Fan Pressurization

The fan pressurization method characterizes the building leakage rate independent of weather conditions. Equipment required for a quantitative measurement includes a blower, a flow meter, a pressure gage, and possibly a smoke source or an infrared scanning device to locate leaks.[52] The blower is temporarily sealed to the building envelope and its flow adjusted to produce a pressure drop of the order of 10 Pa (0.04 in. H_2O) across the building shell. This is repeated at intervals of approximately 10 Pa (0.04 in. H_2O) until the pressure-flow characteristic for the range from 0 to 50 Pa (0 to 0.2 in. H_2O) is measured. The flow direction is reversed to depressurize the building and the process is repeated. Typical data obtained from these measurements are shown in Fig. 18.

The data from these measurements can be used for a comparison between structures by dividing the average flow (pressurization and depressurization) at 50 Pa (0.20 in. H_2O) by the volume of the structure to give the number of air changes per hour at 50 Pa (0.20 in. H_2O), as a defined measure for comparing building tightness.

A more useful number calculated from fan pressurization measurements is the effective leakage area. It can be used for comparison and as a basis for modeling infiltration. If the flow is assumed proportional to the square root (or to the 0.65 power) of the pressure difference over the shell (kinetic energy loss mechanisms are dominant) then a measurement of flow through the building shell can be used to calculate the effective orifice area which would show the same pressure-flow characteristic.

Fan pressurization-depressurization measures a property of a structure that varies little with time and is independent of weather. It is a useful measurement for comparing the tightness of buildings. There is, however, no direct means for converting leakage rate to infiltration rate. If the leaks are of relatively the same size and uniformly distributed over the structure, the infiltration rate will be about one-half the leakage rate for a pressure difference equal to the infiltration pressure difference. Further discussion is presented in the discussion of infiltration models.

Leakage Sites

Leakage sites can easily be located during pressurization-depressurization tests. Potential leakage sites can be tested qualitatively with smoke sources; when a building is depressurized in cold weather, leakage sites can be felt with the hand or face. Infrared thermography is also effective when a building is pressurized if there is sufficient indoor-outdoor temperature difference.

Acoustic sensors and the use of a simple window fan or whole house ventilation fan together with a smoke source have both been employed to locate leaks in a building envelope.[53] The techniques are not quantitative but are easily performed and inexpensive. The obvious places to look for leakage sites are described in the Air Leakage section of this chapter.

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