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CALCULATING INFILTRATION: IMPLICATIONS FOR A CONSTRUCTION QUALITY STANDARD

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CALCULATING INFILTRATION: IMPLICATIONS FOR A CONSTRUCTION QUALITY STANDARD

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Calculating Infiltration: Implications for a Construction Quality Standard*

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ABSTRACT

Extensive work in infiltration measurement and modeling has led to a simple method to calculate the leakage area of a house regardless of design or weather conditions. The leakage area, in turn, is used in the LBL infiltration model to calculate infiltration for any weather condition. This method, which uses fan pressurization to measure the leakage area, has been used in a survey of over 300 houses located throughout North America. This paper presents the results of that survey and suggests that the present capability in infiltration modeling offers an excellent framework for an air leakage standard for residential building. Examples of the interpretation of such a standard are described based on the ventilation rates adopted in ASHRAE Standard 62-1981. The results of the interpretations illustrate differences in structural requirements that will occur when such a standard is applied to several ventilation system designs.

Keywords: air infiltration, building standards, ventilation, air leakage, infiltration measurements, infiltration modeling.

INTRODUCTION

Several issues must be considered in setting standards for acceptable building performance. Some are societal and institutional while others are purely technical. This paper focuses on technical issues associated with the development of a standard for air tightness in residential buildings.

Two major technical issues must be addressed in constructing such a standard. The first is the question of measurement and control. If an acceptable level of air tightness is specified, how is this translated to a ventilation rate? How can the air tightness value be measured? How can a designer or builder modify a building design or construction practice to achieve this value?

The second issue is the ventilation specification. Before a ventilation rate can be translated into an air tightness value, the amount of ventilation air required to assure acceptable indoor air quality must be known.

This paper focuses on the former issue. We show that a technique that is currently available to calculate infiltration rates of buildings contains the information required to support a standard. Examples of the calculation procedure are presented for many types of houses found in different areas of the country.

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The research described in this paper was done using SI units; only these units are incorporated in this paper. Table 1 gives conversion factors to convert important quantities in this paper to the inch-pound system of units.

CALCULATING INFILTRATION

Infiltration, the random flow of air through openings in the building shell caused by weather-induced pressures, can be measured using standard tracer gas techniques.[1] The interpretation of the tracer gas measurement is limited to the weather conditions that are present during the measurement. Extrapolation of an individual measurement to predict the infiltration for an entire heating season is not a well-defined procedure.

For this reason an alternative procedure has been developed to find the average infiltration rate of a structure for an arbitrary period of time. The procedure is based upon the observation that infiltration, a flow problem, can be broken into two parts. Pressures caused by local weather conditions cause airflow through openings in the building envelope. Calculating this flow then requires information about (1) the pressures and (2) the openings in the envelope.

Consider the latter problem first. A technique known as fan pressurization can be used to measure the total leakage of the building envelope. This procedure recently was incorporated into ASTM Standard E779.[2] A fan mounted on an adjustable wooden plate is sealed into a doorway of a house to be tested. The fan speed, which can be adjusted using a DC motor and controller, is varied to produce a pressure drop, ΔP, across the building envelope. The flow through the fan required to produce this pressure difference is measured and the process repeated for fixed pressure increments to produce a curve relating the pressure drop across the envelope to the flow required to produce it. The fan direction is reversed and a corresponding curve of depressurization versus flow is obtained in the same manner. Typical data obtained using this measurement procedure are shown in Fig. 1.

The data contained in Fig. 1 can be interpreted in several ways. Since the pressures that typically drive infiltration most frequently occur in the range of -5 to 5 Pa we use the average flow at 4 Pa Q_4, to compute a quantity we call the *effective leakage area*. This is defined by Eq 1.

$$L_o = \frac{Q_4}{\sqrt{2\Delta P/\rho}} \tag{1}$$

where

L_o is the effective leakage area [m^2]
Q_4 is the flow at 4 Pa [m^3/s]
ΔP is the pressure causing this flow [4 Pa]
ρ is the density of air [1.2 kg/m^3]

The effective leakage area can be interpreted physically as an approximation of the total area of physical openings in the building shell that allows airflow (infiltration) to occur.

A simplified technique to obtain the effective leakage area that is applicable for field use is shown in Fig. 2. Empirically, we find that in almost all cases in which leakage curves are measured, the data are accurately represented by an equation of the form

$$Q = K(\Delta P)^n \tag{2}$$

where

Q is the flow through the fan [m^3/h]
K and n are empirical constants
ΔP is the pressure difference across the building shell

Data represented by Eq 2 will fall on a straight line when plotted on graph paper using logarithmic scales on both axes. Extrapolation to find the flow at 4 Pa simply requires extending the line to intersect the 4-Pa pressure line. From this point read directly across the graph to the right-hand axis to find the leakage area in cm^2. (Leakage areas in this paper are reported consistently in cm^2. The rationale for this choice is revealed by consulting Table 5. This table gives, in addition to the leakage areas of over 300 houses, a normalized leakage area called the "specific leakage area". We find that dividing the leakage area (expressed in cm^2) by the floor area of the house (in m^2) gives a number between about 1 and 10 (with units of cm^2/m^2) that is a "figure-of-merit" for the leakage of a residence.)

The other half of the infiltration problem, determining the surface pressures that drive airflow through the openings measured by fan pressurization, is somewhat more complicated. The details of the derivation of the expressions used below have been presented elsewhere.[3] This problem also has two parts, (1) calculating the pressures caused by indoor-outdoor temperature differences leading to the "stack effect" and (2) the pressures caused by the wind striking the building, the "wind effect."

Infiltration for the two regimes is expressed as

$$Q_{stack} = L_o f_s (\Delta T)^{1/2} \tag{3}$$

and

$$Q_{wind} = L_o f_w v \tag{4}$$

where

Q_{stack} and Q_{wind} are stack- and wind-dominated infiltration, respectively $[m^3/s]$
L_o is the effective leakage area of the house $[m^2]$
ΔT is the indoor-outdoor temperature difference [K]
v is the measured wind speed [m/s]
f_s is the stack parameter $[m/s \cdot K^{1/2}]$
f_w is the wind parameter

These equations display the inherent simplicity of the model. The model predicts that the infiltration separates into the simple product of terms (L_o, f_w, and f_s) that depend on the structure of the house and its surrounding terrain but are independent of the weather and of the terms (ΔT, v) that depend only on the weather.

The terms f_s and f_w are complex expressions, but their interpretations are straightforward. Two additional expressions are introduced. The fraction of the total leakage found on horizontal planes, i.e., the sum of the floor and ceiling leakage areas divided by the total is called R.

$$R = \frac{L_c + L_f}{L_o} \tag{5}$$

The fractional difference between the ceiling leakage area L_c and floor leakage area L_f is called X:

$$X = \frac{L_c - L_f}{L_o} \tag{6}$$

The stack parameter is expressed in terms of R, X, the acceleration of gravity, g, the absolute indoor temperature, T, and the height of the ceiling above grade, H_h, as

$$f_s = \frac{1}{3}\left(1 + \frac{R}{2}\right)\left[1 - \frac{X^2}{(2 - R)^2}\right]^{3/2}\left[\frac{gH_h}{T}\right]^{1/2} \tag{7}$$

The wind pressures on the surface of the house depend upon the terrain class and the shielding class of the structure. The terrain class is affected by the large-scale obstructions in the several-square-km region of the house while the shielding class is determined by the number of trees, fences, and other buildings located in the immediate vicinity of the house.

The wind speed at a measurement site in the region is first corrected to a speed at a standard height using the terrain class at the measurement site, then is adjusted back to the wind speed at the height of the house using the terrain class of the house. Combining all the terms we have

$$f_w = C'(1 - R)^{1/3}\left[\frac{\alpha_h (H_h/10)^{\gamma_h}}{\alpha_m (H_m/10)^{\gamma_m}}\right] \tag{8}$$

where

C' is the shielding coefficient for the house site
R is the fractional horizontal leakage area
α_h and γ_h are terrain constants for the house
H_h is the height of the house from grade to the top of the living space [m]
α_m and γ_m are terrain constants for the wind measurement site
H_m is the height of the wind measurement site [m]

The values of α and γ for standard terrain classes are presented in Tab. 2. Most airport wind-speed measurements are made in terrain class II while most houses are located in terrain classes III and IV. The generalized shielding coefficients are presented in Tab. 3.

The total infiltration is obtained by combining the surface pressures point-by-point over the building envelope and calculating the flows that result. We have adopted a model that assumes the flows are proportional to the square root of the pressure difference.[4] Therefore, we combine the two flows in the same manner:

$$Q = \sqrt{Q^2_{stack} + Q^2_{wind}} \tag{9}$$

or

$$Q = L_o\sqrt{f_s^2 \Delta T + f_w^2 v_m^2} \tag{10}$$

where

Q is the infiltration [m^3/s]
L_o is the effective leakage area [m^2]
f_s is the stack parameter [$m/s \cdot K^{1/2}$]
ΔT is the indoor-outdoor temperature difference [K]
f_w is the wind parameter
v_m is the measured wind speed [m/s]

Equation 10 shows the explicit proportionality between the effective leakage area and the infiltration.

The model has been validated in several studies in the United States and Japan.[5-7] These field validations allow us to place confidence limits on the ability of the model to predict average infiltration results. Using short term (one hour) averages for ΔT and v_m in Eq 10, the relative standard deviation of the infiltration is approximately 35%. This value decreases as the averaging time increases. When one-week weather averages are used, the relative standard deviation is approximately 20%.

EXAMPLE CALCULATIONS

Example Calculation: An Individual House

The use of the predictive model of section III is illustrated by computing the infiltration for the heating season (November through March) for a house located in Albany, New York.

1. Find the effective leakage area. Using Fig. 2 we find that the flow at 4 Pa is 620 m^3/h. This gives an effective leakage area of

$$L_o = \frac{620}{(3600)(2.58)} = 6.7 \text{ X } 10^{-2} m^2 \qquad (11)$$

or 670 cm^2.

2. Find the stack parameter. Before computing the stack parameter given in Eq 7 we must know the fractional horizontal leakage R (Eq 5), the ceiling-floor leakage difference X (Eq 6), the height of the ceiling above grade, H_h, and the absolute indoor temperature T.

It is difficult to measure either R or X with any precision. Fully 50 to 75% of the leakage area in a house is distributed throughout the structure as background leakage and cannot be localized by any simple measurement.[8] We therefore recommend that as the leakage characteristics of the house are measured, major leakage sites be identified and their locations (ceiling, walls, or floor) and sizes noted. After the measurements are completed the sum of the leakage areas noted should be subtracted from the total area measured with the aid of the fan. We now assume that the remainder, the background leakage area, is uniformly distributed around the surface of the house, i.e., that the background leakage areas are proportional to the surface areas of their respective components.

To continue our example we assume that 100 cm^2 was identified in the ceiling and 60 cm^2 in the walls. The house is a one-story house having 111 m^2 (1200 ft^2) (9.1 m by 12.2 m) of floor and ceiling area. The surface area of the outside walls is 104 m^2 (1120 ft^2). Since there are 670 cm^2 of total leakage, 670 - 160 = 510 cm^2 is background leakage. The total surface area is 326 m^2 so the background leakage is divided into (510)(111)/326 = 174 cm^2 in the floor and ceiling and 162 cm^2 in the walls. The total effective leakage areas of the walls, floor, and ceiling are therefore 220, 170, and 270 cm^2, respectively (rounding off to the nearest 10 cm). The values of R and X are therefore 0.66 and 0.15, respectively. The height of the ceiling of the living space above grade is assumed to be 3.0 m (10 ft). The average indoor temperature is 20°C = 293 K. Gathering these data together

$$f_s = (0.333)(1.33)\left[1 - 0.01\right]^{3/2}\left[\frac{(9.8)(3.0)}{293}\right]^{1/2} = 0.14 \frac{m}{s \cdot K^{1/2}}$$

3. Find the wind parameter. Descriptions of the local shielding around the house and the value of the shielding class that results are given in Tab. 3. In this case there are several large trees in the yard surrounding the house but no other close buildings. Shielding Class III is chosen where C' is given the value of 0.25.

The wind speed is measured at an airport several miles from the house. Airport wind measurement sites are typically terrain class II; the measurement height of the wind speed is 10 m. From Tab. 2 $\alpha_m = 1.00$ and $\gamma_m = 0.15$. The house is located in terrain class III with $\alpha_h = 0.85$ and $\gamma_h = 0.20$. The height of the house, again, is 3.0 m. We have

$$f_w = (0.25)(1 - 0.66)^{1/3}\left[\frac{(0.85)(0.30)^{0.20}}{(1.00)(1.00)^{0.15}}\right]$$

or

$$f_w = 0.12.$$

4. Compute the infiltration. Our basic expression for infiltration is now

$$Q = (0.067)\left[(0.14)^2\,\Delta T + (0.12)^2 v_m^2\right]^{1/2} \qquad (12)$$

where

Q is infiltration [m^3/s]
ΔT is indoor-outdoor temperature difference [K]
v_m is measured wind speed [m/s]

To compute the average infiltration for an interval, we must know the average temperature difference and wind speed for that interval. In Albany, for example, the average values of ΔT and v_m for the November-March heating season are 42.5 °F (23.6 °C) and 11.6 mph (5.2 m/s). The average infiltration for this house is thus

$$Q = (0.067)\left[(0.14)^2(23.6) + (0.12)^2(5.2)^2\right]^{1/2}$$

$$Q = 0.062\ m^3/s = 223\ m^3/h$$

The house has a volume of 9.1 by 12.2 by 2.4 = 266 m^3 (9600 ft^2). Therefore we predict that this house in Albany has an average infiltration for the heating season of 223/266 = 0.84 air changes per hour (ach).

Several comments should be made about the calculation. The calculation assumes that the leakage area of the house is constant through this time period. This is not the case, in fact, since occupants open windows and doors, which adds to the infiltration of the structure. There have been no direct measurements of the influence of occupants on the infiltration of a structure. We estimate, based upon our observations of living habits, that the occupants add 0.10 to 0.20 ach to the infiltration we have predicted.

Our second comment concerns the role of the leakage area in the calculation. It assumes the role of a scale constant and could as well be omitted from the calculation. We would then compute an infiltration per unit leakage area for our house in that environment. An example of this is presented in the next section.

Example Calculation: The Reference House

The same calculation is now repeated for a standard house. However, in this case we specify neither the leakage area nor the location. The house will then be assumed to be moved to each of the 59 U.S. locations that have Test Reference Year weather tapes available. The infiltration of this test house will be computed in each of these cities.

The house is assumed to have an interior temperature of 20°C, a height of 2.5 m, leakage distributions R = 0.5 and X = 0, and to belong to terrain class III and shielding class III. With these assumptions:

$$f_s = 0.120 m/s \cdot K^{1/2}$$

$$f_w = 0.128$$

The ratio of infiltration to effective leakage area is then

$$\frac{Q}{L_o} = [(0.120)^2\Delta T + (0.128)v_m^2]^{1/2}$$

This expression, with average weather data for Albany, New York, for the November-March heating season, gives an infiltration per-unit-leakage area of 0.31 $m^3/h \cdot cm^2$. This is the combination of a stack term (0.21 $m^3/h \cdot cm^2$) and a wind term (0.23 $m^3/h \cdot cm^2$). By multiplying the 0.31 $m^3/h \cdot cm^2$ by the specific heat of air per-unit-volume and by the degree-hours using the base temperature of 65 ^oF (18.3 ^oC) for Albany, we obtain a seasonal heating load per-unit-leakage area of 30.7 MJ/cm^2.

Table 4 shows these figures for Albany, New York and for an additional 58 cities across the United States. Weather tapes for Test Reference Years (TRY tapes) were used to gather the necessary temperature and wind speed data. Based on the same data, infiltration contour maps of the U.S. were constructed. Fig. 3 shows the curves of constant infiltration per-unit-leakage area in $m^3/h \cdot cm^2$. Figure 4 shows similar contours for heating load. As in Tab. 4, all figures are normalized per-unit-leakage area.

It is interesting to note that the variation in infiltration per-unit-leakage area across the United States is relatively small for this reference case. It is typically a factor of two for stack-driven infiltration and a factor of three for wind-driven infiltration. As expected, stack-driven infiltration is highest in New England and the North Central States, where the weather is coldest, and lowest near the Gulf of Mexico and in California. Wind-driven infiltration is highest in Montana and lowest in Southern California and Arizona. The combined infiltration per-unit-leakage area is shown in Fig. 3. The highest values are encountered in Montana, closely followed by those around the Great Lakes. The high infiltration values reach down through the midwest and taper off toward east and west. A similar trend, but more pronounced, is found in Fig. 4, which shows the seasonal infiltration heating load per-unit-leakage area. Here, typical values are 40 MJ/cm^2 for the northern United States, 15 MJ/cm^2 for the east coast, and 8 MJ/cm^2 for the west coast, the Gulf of Mexico, and Florida.

Example Calculation: Survey of Published Data

A third example of the use of the calculation procedure is to examine data in the published literature and determine average infiltration values for the November-March heating season.

Published measurements of infiltration rates in houses go back to the 1957 paper of Bahnfleth, Moseley, and Harris that reported the results of 37 tests in two Illinois residences.[9] Since the publication of that paper we have identified measurements sets in 312 other houses in Canada and the United States that are suitable for inclusion in this summary. Although other measurement sets exist, at this time the authors have insufficient information about the measurement details to include the results here.

The average infiltration values that are included are those calculated for five winter heating months, November through March. In this season the results are least likely to be affected by occupant behavior such as opening windows. The values were obtained in three ways. The first and most reliable, although possible only in a small number of cases, was to use the values supplied by the authors of the reports directly. These are labeled A in the calculation procedure column of the data table below. For our purposes, the research had to include either sufficient data for computing the average or had to include an empirical fit of the results that related weather conditions and infiltration rates. In the latter case if the weather data used in the empirical fit were weather data that are regularly published, it is possible to use the weather values for the winter heating season to compute the average infiltration. We estimate that in this case, the uncertainty in the average infiltration is about 10%.

In the majority of cases treated in this summary, fan pressurization data are available that allow the effective leakage area of the houses to be calculated. These cases are labeled B in the calculation procedure column of the table. Then, using our model that relates leakage areas and local weather to average infiltration values, the average winter infiltration values are computed. We estimate that the values computed using this procedure have an uncertainty of about 20%.

The third procedure, labeled C below, the least reliable but included to add additional cases to this small sample set, uses results of short-term infiltration measurements combined with the local weather conditions to back-solve for the effective leakage area. This value is then combined with the house characteristics and local weather data to produce an estimate of the average infiltration. We estimate the uncertainty in the averages obtained in this manner to be 30 to 40%.

The individual columns in Tab. 5 are:

1. The reference and its publication date.

2. The state or province in which the house is found.

3. The house code is the code used in the reference.

4. The construction date of the house (if known).

5. The house type: one-story (1), two-story (2), split-level (SL).

6. Floor area of the conditioned space (m^2, 1 m^2 = 10.8 ft^2).

7. The volume of the conditioned space (m^3, 1 m^3 = 35.3 ft^3).

8. The effective leakage area of the house (cm^2).

9. The ratio of the effective leakage area to the floor area of the house, called the "specific leakage area" (cm^2/m^2).

10. The infiltration averaged over the five-month period from November through March (ach).

11. Calculation procedure A implies long-term infiltration values were available to compute the average infiltration during the heating season. Procedure B uses fan pressurization measurements to determine the leakage area of the house. Procedure C begins with a short-term measurement of infiltration. The leakage area, which yields an equivalent infiltration is found and then serves as the basis for extending the result to the entire heating season.

The average seasonal infiltration values of 312 houses are presented in Tab. 5. The mean of the seasonal infiltration values is 0.63 ach. A better measure of this skewed distribution is the median, 0.50 ach. Fully 50% of the houses in this sample have infiltration values below a value that is frequently used as an acceptable ventilation rate for houses.

A histogram of the infiltration results is presented in Fig. 5. Also shown are results of measurements of 266 houses reported by Grot and Clark.[28] While the Grot and Clark results are not seasonal averages but rather individual measurements, the general shapes of the distributions are similar. The broader distribution of the Grot and Clark results is partly the result of inclusion of all individual measurements (averaging all measurements for a single house to give a single number would cause the distribution to be sharper) and partly a difference in the housing stock sampled.

A CONSTRUCTION QUALITY STANDARD FOR AIR TIGHTNESS

The first part of this paper summarized calculation procedures using the LBL infiltration model. Examples were provided showing the infiltration behavior of a reference house in different U.S. locations, using the model to extend information available in the literature. This second section uses the model as the basis for a construction quality standard for air tightness in new residential construction in the United States.

Construction Quality

Construction quality is becoming an increasingly important concept in the building industry. As materials, time, energy, and investment capital become more scarce, steps must be taken to use each more effectively. The particular focus of this paper is increasing the efficiency of energy use in buildings through improved construction quality.

Infiltration accounts for up to 40% of the energy use in small, envelope-dominated buildings such as residences. Reducing this energy use is the goal of a construction quality standard for air tightness in these buildings. In addition to reducing energy use, increasing air tightness also (1) increases thermal comfort, (2) improves the control of moisture migration that results from convective flow of water vapor through openings in the building shell, and (3) reduces noise transmission from the exterior into occupied portions of the building.

The most important benefit of improved air tightness is the control it affords the building designer and operator in supplying the desired amount of ventilation to occupied spaces in the building. With improved air tightness, ventilation can be uniform throughout the building, not randomly dependent on the locations of major leakage sites in the building shell. Furthermore, it can be uniform in time as well, independent of the vagaries of the weather.

A Standard for Air Tightness

We propose that a construction quality standard for air tightness in buildings be developed to provide guidance for designers and builders who wish to improve the performance of their buildings. A standard is but one mechanism to improve construction quality. However, if it also is a voluntary, consensus standard it can be used in several different ways to achieve the desired increase in construction quality.

This is an appropriate time to consider introduction of a standard. Infiltration and air leakage in buildings have been studied extensively for several years. It is now possible to describe a simplified test procedure to measure air leakage; this, in turn, can be related to the average infiltration of the structure. It is essential that such an interpretation of a compliance test be possible.

Ventilation Rate Targets

An air tightness standard must be interpretable in terms of a ventilation rate. Studies of indoor air quality during the past five years have shown that there is no single ventilation rate that will assure adequate air quality in all houses.[29] Pollutant concentrations in buildings depend on both the strength of the pollutant sources and on the ventilation rate in the spaces. Specifying only a ventilation rate without knowledge of source strengths cannot assure air quality within a building.

However, ventilation systems are being designed and buildings containing these systems are being built. Since we will never have sufficient information about sources to assure adequate air quality in all buildings we recommend that we proceed with a provisional air tightness standard based on best current information concerning ventilation rates that yield acceptable air quality in most buildings. As additional information is obtained about pollutant concentrations, source strengths, and health effects, these ventilation rates can be modified.

For purposes of this paper, then, we adopt the ventilation rates presented in ASHRAE Standard 62-81 as target ventilation values for new residences.[30] This standard, as currently understood, will yield ventilation values that will provide adequate air quality in most houses. ASHRAE Standard 62-81 prescribes ventilation values in single-family residences of 10 cfm (18 m^3/h) per room independent of room size. In addition, 100 cfm (180 m^3/h) ventilation capacity is required in kitchens for intermittent use (as required) while 50 cfm (90 m^3/h) ventilation capacity is required in bath and toilet rooms.

These values imply that in a house having a floor area of 139 m^2 (1500 ft^2) with seven rooms, the prescribed ventilation rate is 126 m^3/h (70 cfm) without the use of the ventilation fans in the kitchen or bathrooms. If the house has a standard 2.4 m (8 ft) ceiling, this translates to an air change rate of 0.37 ach. Use of the ventilation fans for one hour per day in each of two bathrooms and the kitchen exhaust fan for 2 hr/day adds an average of 0.06 ach to the basic rate. Other occupant activities may add another 0.1 ach yielding a total value slightly larger than 0.50 ach.

Translation of Ventilation Rate Targets to an Air Tightness Standard

Adoption of a ventilation rate target implies an air tightness value for a building. The value depends on (a) the weather conditions for the region in which the building is found, (b) specific building details, and (c) the ventilation system used in the building. The examples that follow will illustrate these ideas.

1. The air tightness standard value for an eight-room reference house (ventilation by infiltration). The calculation of infiltration for a reference house having height 2.5 m located in terrain class III and shielding class III is described above. Calculation of the infiltration to leakage area ratio for this house in 59 different U.S. locations led to the results presented in Fig. 3 and Tab. 4. Thus if an eight room house having a description similar to the reference house ($X = 0$, $R = 0.5$, $H_h = 2.5$ m, terrain class III and shielding class III) is found in Salt Lake City, Tab. 4 gives a value of infiltration to leakage area of 0.25 $m^3/h \cdot cm^2$. From ASHRAE Standard 62-81, an eight-room house requires a ventilation rate of 144 m^3/h. Therefore, if infiltration is to supply this ventilation, the builders must adopt a target leakage area of 144/0.25 = 580 cm^2. This will yield an average ventilation rate of 144 m^3/h over the heating season.

2. Same house, ventilation using exhaust fan or air-to-air heat exchanger. As Tab. 5 shows, houses in the United States can be built with significantly better air tightness than a leakage area of 580 cm^2. If mechanical ventilation is employed using either an exhaust fan or an air-to-air heat exchanger, significantly lower values of leakage area are desirable. In both cases a leakage area of 200 cm^2 could be adopted as a target. When using a balanced mechanical ventilation system with an air-to-air heat exchanger, the infiltration that occurs through the 200 cm^2 leakage area simply adds to the ventilation supplied by the mechanical system. Therefore, in this climate the infiltration will be (0.25) (200) = 50 m^3/h, so the mechanical system must supply 144 - 50 = 94 m^3/h.

The unbalanced mechanical exhaust system, on the other hand, will reduce the interior pressure in the house, making the ventilation rate almost independent of the outside weather. In this case the exhaust system should have a capacity of the target ventilation rate, or 144 m^3/h. The exact choice of the leakage area in this case is not crucial. The choice determines the reduction in interior pressure that occurs when the fan is operating. If the leakage area is 200 cm^2 the interior pressure will be 2 to 3 Pa below the outside value; if the leakage area were reduced to 100 cm^2, the interior pressure would be about 10 Pa below the outside reference pressure. In the latter case, the ventilation rate of the house is almost completely isolated from outside weather conditions, but one may begin to experience unpleasant drafts due to jets of outside air entering the living space.

3. Same house, ventilation by infiltration, terrain class IV. As characteristics of the house and its setting are changed from those of the standard reference house, adjustments must be made in the values of Q/A found in Fig. 3 and Tab. 4.

Tables 6 through 9 below give correction factors that are to be applied to the individual Q_{stack} and Q_{wind} terms for other housing configurations.

In the Salt Lake example, a change in terrain class only affects the wind term in the infiltration. From Tab. 4, $Q_{wind}/L_o = 0.16$ while $Q_{stack}/L_o = 0.19$. For the house with a height of 2.5 m the wind term in terrain class IV becomes

$$(Q_{wind}/L_o)_{IV} = 0.735(Q_{wind}/L_o)_{III} = 0.13 \ m^3/h \cdot cm^2$$

and

$$Q/L_o = [(0.13)^2 + (0.20)^2]^{1/2} = 0.22 \ \frac{m^3}{h \cdot cm^2}$$

Therefore the leakage area for a ventilation rate of 144 m^3/h using infiltration is 650 cm^2, up from 580 cm^2 when the house is found in terrain class III.

4. Same house, ventilation by infiltration, height 5.0 m, terrain class III. The height of the house affects both the stack and wind terms. The stack effect operates over a larger distance creating larger pressure differences. The wind speed increases with height, so the house will experience higher wind pressures. From Tab. 9 we have

$$(Q_{wind}/L_o)_5 = 1.149(Q_{wind}/L_o)_{2.5} = 0.21 \ m^3/h \cdot cm^2$$

and

$$(Q_{stack}/L_o)_5 = 1.414(Q_{stack}/L_o)_{2.5} = 0.28 \ m^3/h \cdot cm^2$$

Therefore

$$(Q/L_o)_5 = [(0.21)^2 + (0.28)^2]^{1/2} = 0.35 \ m^3/h \cdot cm^2$$

Consequently, for ventilation by infiltration

$$L_o = 410 \ cm^2$$

DISCUSSION OF RESULTS

A procedure to calculate infiltration when the leakage area of a house is known has been described. This procedure has been used to compute the average seasonal infiltration of 312 houses located in many different areas of the United States and Canada. The results show that 50% of the houses have infiltration rates less than 0.50 ach. By comparison a sample of 266 houses measured by Grot and Clark show a median infiltration rate of approximately 0.90 ach. These two values probably represent bounds on the median infiltration value of the North American housing stock. The group of houses in Tab. 5 are biased toward new, energy-efficient structures. The houses in the Grot and Clark sample, on the other hand, are houses found in low income neighborhoods.

The calculation procedure is used to illustrate the implementation of an air tightness standard for residences. The examples show the difficulty one encounters if infiltration is to be relied upon for ventilation in new construction. Modern buildings can be built to a tightness level that reduces infiltration considerably below current guidelines for ventilation. Rather than "punching holes" in the modern, tight house, good engineering practice would use a simple mechanical ventilation system to provide the necessary ventilation. As experience with these systems increases (as it is in Canada and

Scandinavian countries) wider use is expected in the United States.

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TABLE 1

Conversion Table

Item	Units used	IP unit	To convert to IP unit multiply
Leakage area	cm^2	$in.^2$	1.55E - 01
Airflow	m^3/s	cfm	2.12E + 03
Pressure	Pa	in. H_2O	4.01E - 03
Density	kg/m^3	lb/ft^3	6.24E - 02
Wind Speed	m/s	mph	2.24E + 00
Stack parameter	$m/s \cdot K^{1/2}$	$ft/s \cdot {}^{o}F^{1/2}$	2.45E + 00
Height	m	ft	3.28E + 00
Temperature difference	K	^{o}F	1.80E + 00
Specific leakage area	cm^2/m^2	$in.^2/ft^2$	1.44E - 02
Floor area	m^2	ft^2	1.08E + 01
Volume	m^3	ft^3	3.53E + 01
Airflow per unit leakage area	$m^3/h \cdot cm^2$	$ft^3/min \cdot in.^2$	3.80E + 00
Heating load per unit leakage area	$Mjoules/cm^2$	$kBtu/in.^2$	6.12E + 00

TABLE 2

Terrain Parameters for Standard Terrain Classes

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

TABLE 3

Generalized Shielding Coefficient vs. Local Shielding

Shielding Class	C'	Description
I	0.34	No obstructions or local shielding whatsoever
II	0.30	Light local shielding with few obstructions. Perhaps a few trees or a small shed.
III	0.25	Moderate local shielding, some obstructions within two house heights. A thick hedge or a solid fence, or one neighboring house.
IV	0.19	Heavy shielding, obstructions around most of the perimeter. Buildings or trees within 30 ft in most directions. Typical suburban shielding.
V	0.11	Very heavy shielding, large obstructions surrounding perimeter within two house heights. Typical downtown shielding.

TABLE 4

Infiltration for Refernce Case in 59 TRY Cities

City	Stack-effect infiltration ($m^3/h \cdot cm^2$)	Wind-effect infiltration ($m^3/h \cdot cm^2$)	Total infiltration ($m^3/h \cdot cm^2$)	Total seasonal heating load (MJ/cm^2)
Albany, NY	0.21	0.23	0.31	30.7
Albuquerque, NM	0.17	0.15	0.23	16.7
Amarillo, TX	0.17	0.30	0.35	23.6
Atlanta, GA	0.14	0.21	0.25	13.8
Bismark, ND	0.23	0.21	0.31	42.0
Boise, ID	0.18	0.18	0.25	20.7
Boston, MA	0.19	0.30	0.36	30.4
Brownsville, TX	0.06	0.24	0.25	4.0
Buffalo, NY	0.19	0.27	0.33	31.1
Burlington, VT	0.21	0.21	0.29	30.9
Charleston, SC	0.12	0.20	0.23	10.0
Cheyenne, W	0.19	0.27	0.34	31.6
Chicago, IL	0.19	0.21	0.28	25.2
Cincinnati, OH	0.17	0.19	0.26	19.6
Cleveland, OH	0.19	0.24	0.31	29.1
Columbia, SC	0.18	0.22	0.29	25.2
Detroit, MI	0.19	0.24	0.31	23.9
Dodge City, KS	0.18	0.28	0.33	28.1
El Paso, TX	0.13	0.17	0.22	11.2
Fort Worth, TX	0.12	0.23	0.26	12.3
Fresno, CA	0.14	0.12	0.18	9.4
Great Falls, MT	0.20	0.40	0.45	57.1
Houston, TX	0.10	0.23	0.25	9.1
Indianapolis, IN	0.19	0.23	0.30	26.7
Jackson, MS	0.12	0.20	0.24	10.9
Jacksonville, FL	0.09	0.19	0.21	6.3
Kansas City, MO	0.18	0.21	0.28	23.4
Lake Charles, LA	0.11	0.19	0.22	8.4
Los Angeles, CA	0.10	0.16	0.19	5.6
Louisville, KY	0.18	0.23	0.29	20.2
Lubbock, TX	0.15	0.28	0.31	19.2
Madison, WI	0.20	0.19	0.28	29.3
Medford, OR	0.18	0.10	0.21	13.1
Memphis, TN	0.14	0.20	0.24	14.0
Miami, FL	0.03	0.19	0.19	1.2
Minneapolis, MN	0.22	0.21	0.31	38.0
Nashville, TN	0.15	0.21	0.26	15.6
New Orleans, LA	0.11	0.20	0.23	9.5
New York, NY	0.17	0.26	0.31	22.7
Norfolk, VA	0.15	0.26	0.31	16.7
Oklahoma, OK	0.16	0.30	0.34	23.3
Omaha, NE	0.19	0.21	0.29	27.9
Philadelphia, PA	0.18	0.25	0.31	25.4
Phoenix, AZ	0.11	0.09	0.14	5.9
Pittsburgh, PA	0.18	0.23	0.29	21.5
Portland, ME	0.20	0.18	0.27	27.2
Portland, OR	0.16	0.21	0.27	15.9
Raleigh, NC	0.15	0.19	0.24	15.4
Richmond, VA	0.17	0.18	0.24	18.5
Sacramento, CA	0.14	0.12	0.19	10.9
Salt Lake City, UT	0.19	0.17	0.25	23.3
San Antonio, TX	0.11	0.20	0.23	9.6
San Diego, CA	0.10	0.13	0.16	4.4
San Francisco, CA	0.13	0.18	0.22	10.0
Seattle, WA	0.17	0.21	0.27	18.0
St. Louis, MO	0.18	0.22	0.29	24.3
Tampa, FL	0.06	0.19	0.20	3.0
Tulsa, OK	0.15	0.22	0.27	17.2
Washington, D.C.	0.16	0.16	0.23	15.6

TABLE 5

Data Summary

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
10-1979	WA	H 1	1949	1S	212	447	1050	5.0	0.95	A
10-1979	WA	H 2	1950	1S	117	248	814	7.0	2.45	A
10-1979	WA	H 3	1899	1S	78	190			0.79	A
10-1979	WA	H 4	1978	SL	164	382	1370	8.4	0.84	A
10-1979	WA	H 5	1923	1S	214	465	1080	5.0	0.75	A
11-1979	OH	B	1977	1S	129	314	441	3.4	0.33	A
11-1979	OH	C	1977	1S	129	314	652	5.0	0.55	A
12-1977	MD	B	195X	1S	192	495			0.51	A
13-1963	IN	A	1940	1S	113	276			0.49	C
13-1963	IN	B	1933	1S	114	278			0.90	C
13-1963	IN	C	1963	1S	140	342			0.28	C
13-1963	IN	D	1940	2S	114	269			0.74	C
13-1963	IN	E	1923	2S	140	366			0.81	C
13-1963	IN	F	1963	1S	154	375			0.29	C
13-1963	IN	G	1963	1S	105	240			0.71	C
13-1963	IN	H	1917	2S	158	374			0.86	C
13-1963	IN	I	1963	2S	179	410			0.43	C
13-1963	IN	J	1963	1S	56	133			0.78	C
9-1957	IL	RR2		1S	94	229			0.62	C
15-1979	OH	KTSC		2S		363			0.73	C
15-1979	OH	ETSC		2S		363			0.66	C
15-1979	OH	HSLG		SL		348			0.62	C
15-1979	OH	CTSE		2S		363			0.78	C
15-1979	OH	HTSG		2S		363			1.53	C
15-1979	OH	SRSG		1S		408			0.56	C
14-1982	WA	1	1943	1S	108	247	532	4.9	0.51	B
14-1982	WA	2	1943	1S	108	247	495	4.6	0.47	B
14-1982	WA	3	1943	1S	108	247	490	4.5	0.46	B
14-1982	WA	4	1943	1S	124	283	499	4.0	0.41	B
14-1982	WA	5	1943	1S	108	247	521	4.8	0.49	B
14-1982	WA	6	1943	1S	124	283	566	4.6	0.47	B
14-1982	WA	7	1943	1S	124	283	572	4.6	0.47	B
14-1982	WA	8	1951	1S	123	281	384	3.1	0.32	B
14-1982	WA	9	1951	1S	123	281	382	3.1	0.32	B
14-1982	WA	10	1951	1S	123	281	367	3.0	0.31	B
14-1982	WA	11	1951	1S	123	281	365	3.0	0.30	B
14-1982	WA	12	1951	1S	106	242	311	2.9	0.30	B
14-1982	WA	13	1951	1S	123	281	367	3.0	0.30	B
14-1982	WA	14	1951	1S	123	281	446	3.6	0.37	B
14-1982	WA	15	1951	1S	106	242	417	3.9	0.40	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
14-1982	WA	17	1965	1S	103	235	318	3.1	0.31	B
14-1982	WA	19	1968	1S	103	235	327	3.2	0.32	B
14-1982	WA	20	1968	1S	206	235	321	1.6	0.16	B
22-1979	CA	Niel	1924	1S	96	230	1280	13.3	1.38	B
22-1979	CA	Purd	1949	1S	93	240	855	9.2	0.88	B
22-1979	CA	SCar	1940	1S	58	147	845	14.6	2.09	B
22-1979	CA	South	1929	2S	370	1000	1640	4.4	0.71	B
22-1979	CA	Haven	1965	1S	100	230	750	7.5	1.13	B
22-1979	CA	Val I	1978	1S	104	270	560	5.4	0.55	B
22-1979	CA	Val II	1978	1S	104	270	670	6.4	0.61	B
22-1979	CA	Nogal	1977	1S	107	292	960	9.0	0.74	B
22-1979	MN	Ivanhoe	1977	2S	174	490	100	0.6	0.08	B
22-1979	MN	Telemark	1978	2S	197	480	140	0.7	0.12	B
22-1979	IA	TP	1978	2S	220	480	200	0.9	0.21	B
16-1979	NJ	SO		SL	190	535	1120	5.9	0.93	B
17-1975	ONT	1	195-	1S	77	379	316	4.1	0.28	B
17-1975	ONT	2	195-	1S	77	379	300	3.9	0.27	B
17-1975	ONT	3	195-	1S	99	487	656	6.6	0.49	B
17-1975	ONT	4	195-	1S	89	436	714	8.0	0.59	B
17-1975	ONT	5	195-	2S	108	410	591	5.5	0.63	B
17-1975	ONT	6	195-	2S	128	471	610	4.8	0.57	B
18-1980	GA	KE	1967	1	203	495	2593	12.7	1.78	B
18-1980	GA	NE	1959	2	209	510	2531	12.1	1.84	B
18-1980	GA	BR	1979	2	119	291	2103	17.6	2.02	B
18-1980	GA	KL	1970	SL	130	318	1775	13.6	1.43	B
18-1980	GA	HA	1976	2	205	500	2062	10.1	1.37	B
18-1980	GA	EW	1976	1	173	422	2573	14.9	1.91	B
18-1980	GA	SD	1977	2	197	480	2342	11.9	1.47	B
18-1980	GA	ST	1972	2	190	463	2690	14.2	1.73	B
19-1979	ONT	1	1978	SL	151	556	570	3.8	0.45	B
19-1979	ONT	2	"	2	188	765	360	1.9	0.24	B
"	"	3	"	2	202	805	800	4.0	0.47	B
"	"	4	"	SL	142	528	300	2.1	0.27	B
"	"	5	"	2	134	428	390	2.9	0.45	B
"	"	6	1978	SL	122	507	560	4.6	0.48	B
19-1979	ONT	7	"	2	161	682	830	5.1	0.57	B
"	"	8	"	2	157	531	550	3.5	0.51	B
"	"	9	"	2	202	805	610	3.3	0.37	B
"	"	10	"	2	205	772	490	2.4	0.38	B
"	"	11	1978	2	192	677	610	3.2	0.43	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
19-1979	ONT	12	1978	2	158	664	400	2.6	0.30	B
"	"	13	"	2	141	505	630	4.5	0.61	B
"	"	14	"	2	147	564	600	4.1	0.51	B
"	"	15	"	2	177	611	610	3.4	0.48	B
"	"	16	"	2	137	466	570	4.3	0.60	B
19-1979	ONT	17	1978	2	185	773	700	3.8	0.43	B
"	"	18	"	SL	170	606	430	2.5	0.32	B
"	"	19	"	1	131	458	300	2.3	0.26	B
"	"	20	"	2	118	426	440	3.7	0.51	B
"	"	21	"	SL	175	589	690	3.9	0.50	B
19-1979	ONT	22	1978	2	139	574	640	4.6	0.53	B
"	"	23	"	2	151	591	480	3.2	0.40	B
"	"	24	"	2	170	659	560	3.3	0.41	B
"	"	25	"	2	190	582	500	2.6	0.42	B
"	"	26	"	2	177	603	350	2.0	0.29	B
19-1979	ONT	27	1978	1	157	380	400	2.5	0.40	B
"	"	28	"	1	107	429	430	4.0	0.36	B
"	"	29	"	SL	162	525	630	3.9	0.51	B
"	"	30	"	2	117	391	390	3.3	0.50	B
"	"	31	"	SL	117	453	520	4.5	0.51	B
19-1979	ONT	32	1978	2	153	533	500	3.3	0.47	B
"	"	33	"	2	183	658	500	2.7	0.37	B
"	"	34	"	2	137	403	340	2.4	0.42	B
"	"	35	"	2	163	576	540	3.3	0.46	B
"	"	36	"	2	149	530	500	3.3	0.46	B
19-1979	ONT	37	1978	1	99	461	300	3.0	0.23	B
"	"	38	"	2	150	486	470	3.1	0.48	B
"	"	39	"	2	135	451	360	2.7	0.41	B
"	"	40	"	1	142	522	540	3.8	0.38	B
"	"	41	"	1	125	354	250	2.0	0.26	B
19-1979	ONT	42	1978	1	91	440	390	4.3	0.32	B
"	"	43	"	SL	161	644	520	3.2	0.35	B
"	"	44	"	2	143	496	490	3.5	0.49	B
"	"	45	"	2	133	470	480	3.6	0.50	B
"	"	46	"	2	121	395	330	2.7	0.42	B
19-1979	ONT	47	1978	SL	148	549	630	4.2	0.50	B
"	"	48	"	1	131	363	270	2.1	0.27	B
"	"	49	"	1	101	476	690	6.8	0.50	B
"	"	50	"	SL	150	602	350	2.3	0.27	B
"	"	51	"	SL	175	680	710	4.0	0.45	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
19-1979	ONT	52	1978	2	182	642	260	1.4	0.22	B
"	"	53	"	2	127	487	400	3.2	0.41	B
"	"	54	"	2	195	751	910	4.7	0.57	B
"	"	55	"	1	105	579	310	3.0	0.21	B
"	"	56	"	2	191	709	370	2.0	0.27	B
19-1979	ONT	57	1978	1	120	514	680	5.6	0.46	B
"	"	58	"	SL	181	643	690	3.8	0.47	B
"	"	59	"	2	166	587	310	1.8	0.27	B
"	"	60	"	2	118	392	330	2.8	0.43	B
"	"	61	"	2	131	504	490	3.7	0.48	B
19-1979	ONT	62	1978	2	157	583	530	3.4	0.45	B
"	"	63	"	1	104	440	380	3.7	0.30	B
"	"	I	"	2	109	399	340	3.1	0.40	B
"	"	II	"	2	109	399	270	2.5	0.33	B
"	"	III	"	2	109	399	290	2.6	0.35	B
19-1979	ONT	IV	1978	2	109	399	270	2.5	0.33	B
23-1981	CO	C2		SL	128	312	460	3.6	0.61	B
"	"	C3		2	130	353	800	6.1	0.94	B
"	"	C4		1	91	221	520	5.7	0.81	B
"	"	C7		1	91	221	830	9.1	1.29	B
23-1981	CO	C8		2	111	272	940	8.4	1.44	B
"	"	C10		SL	157	383	1220	7.7	1.32	B
"	"	C11		SL	157	383	1120	7.1	1.22	B
"	"	C13		2	180	438	920	5.1	0.88	B
"	"	C19		SL	159	388	810	5.1	0.87	B
23-1981	CO	C20		1	128	312	530	4.1	0.59	B
"	"	C21		2	244	594	990	4.1	0.69	B
"	"	C22		1	133	324	960	7.2	1.01	B
"	"	C23		1	250	611	320	1.3	0.18	B
"	"	C24		SL	86	210	1160	13.5	2.31	B
23-1981	CO	C27		1	119	289	1000	8.4	1.19	B
"	"	C28		SL	111	270	980	8.8	1.52	B
"	"	C29		SL	181	441	950	5.2	0.90	B
"	"	C30		SL	190	463	920	4.8	0.83	B
"	"	R1		SL	94	228	1770	19.0	3.24	B
23-1981	CO	R2		SL	124	303	990	8.0	1.37	B
"	"	R3		SL	158	387	760	4.8	0.82	B
"	"	R4		SL	169	413	680	4.0	0.68	B
"	"	R7		1	91	221	830	9.1	1.26	B
"	"	R8		1	91	221	900	9.9	1.37	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2 /m^2)	Average infiltration (ach)	Calc. proc.
23-1981	CO	R9		SL	152	371	1180	7.8	1.33	B
"	"	R10		1	97	235	660	6.8	0.93	B
"	"	R11		1	178	435	670	3.7	0.52	B
"	"	R15		1	87	212	930	10.7	1.48	B
"	"	R19		1	146	356	540	3.7	0.51	B
23-1981	CO	R22		1	117	317	800	6.1	0.84	B
"	"	R25		2	174	303	1340	7.7	1.85	B
"	"	R28		SL	147	358	450	3.1	0.53	B
20-1982	NY	1	1977	1	210	445	500	2.4	0.37	B
"	"	2	1977	1	190	445	390	2.1	0.30	B
20-1982	NY	3	1976	1	190	425	450	2.4	0.36	B
"	"	4	1976	2	210	466	470	2.2	0.42	B
"	"	5	1977	SL	200	456	520	2.6	0.44	B
"	"	6	1977	SL	180	450	490	2.8	0.42	B
"	"	7	1976	1	180	396	600	3.4	0.58	B
20-1982	NY	8	1977	1	190	426	480	2.5	0.41	B
"	"	9	1977	2	270	623	680	2.5	0.44	B
"	"	10	1976	1	160	378	220	1.4	0.23	B
"	"	11	1977	1	190	418	520	2.8	0.43	B
"	"	12	1976	2	250	561	740	3.0	0.56	B
20-1982	NY	13	1976	SL	180	418	350	1.9	0.29	B
"	"	14	1977	2	260	571	440	1.7	0.33	B
"	"	15	1975	2	190	419	250	1.3	0.22	B
"	"	16	1978	2	260	575	650	2.5	0.43	B
"	"	17	1979	2	300	665	700	2.3	0.41	B
20-1982	NY	18	1979	1	240	552	700	2.9	0.42	B
"	"	19	1980	2	240	552	860	3.6	0.61	B
"	"	20	1979	2	210	566	640	3.0	0.45	B
"	"	21	1978	2	290	642	840	2.9	0.50	B
"	"	22	1979	2	260	592	740	2.8	0.53	B
20-1980	NY	23	1979	1	220	509	370	1.7	0.26	B
"	"	24	1980	SL	170	379	630	3.7	0.65	B
"	"	25	1980	SL	190	466	770	4.0	0.70	B
"	"	26	1980	SL	190	466	540	2.8	0.49	B
"	"	27	1978	2	260	694	1000	3.8	0.57	B
20-1982	NY	28	1979	2	200	455	610	3.0	0.55	B
"	"	29	1980	SL	190	420	670	3.5	0.61	B
"	"	30	1980	SL	200	452	530	2.6	0.45	B
"	"	31	1980	1	180	417	510	2.8	0.47	B
"	"	32	1980	1	190	411	450	2.4	0.42	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
20-1982	NY	33	1979	2	220	527	550	2.5	0.42	B
"	"	34	1978	SL	160	377	410	2.5	0.46	B
"	"	35	1980	SL	180	396	1110	6.3	1.21	B
"	"	36	1980	1	140	319	760	5.5	1.00	B
"	"	37	1974	2	180	413	980	5.4	0.92	B
20-1982	NY	38	1973	2	250	561	1010	4.0	0.71	B
"	"	39	1973	SL	280	632	730	2.6	0.47	B
"	"	40	1980	SL	170	388	590	3.4	0.61	B
"	"	41	1979	1	200	427	530	2.7	0.42	B
"	"	42	1973	SL	340	760	1030	3.0	0.51	B
20-1982	NY	43	1974	2	180	398	1600	9.0	1.71	B
"	"	44	1978	2	280	620	640	2.3	0.41	B
"	"	45	1979	2	310	705	610	2.0	0.38	B
"	"	46	1979	SL	190	466	540	2.8	0.45	B
"	"	47	1980	SL	150	343	580	3.8	0.60	B
20-1982	NY	48	1973	SL	260	597	950	3.6	0.63	B
"	"	49	1973	2	250	561	650	3.5	0.42	B
"	"	50	1973	2	250	562	1030	4.1	0.71	B
21-1980	CA	TUN	1980	2	214	679	1710	8.0	0.59	B
21-1980	NY	BAS	1978		167	495	500	3.0	0.43	B
21-1980	CA	SCH	1930	2	139	404	1190	8.5	0.82	B
21-1980	CA	GIR	1955	1	95	246	920	9.7	0.73	B
21-1980	NM	BAL	1975	2	214	577	1020	4.8	0.54	B
24-1980	CA	511	1976	1S	104	255	930	8.9	0.63	B
24-1980	CA	506	1976	1S	149	363	1410	9.5	0.64	B
24-1980	CA	491B		1S	208	508	2240	10.8	0.72	B
24-1980	CA	489	1964	1S	175	426	1320	7.5	0.50	B
24-1980	CA	468	1972	2S	202	493	1460	7.2	0.64	B
24-1980	CA	467	1976	1S	154	376	1100	7.1	0.46	B
24-1980	CA	455	1972	1S	107	261	770	7.2	0.46	B
24-1980	CA	448	1972	1S	130	316	770	5.9	0.38	B
24-1980	CA	346	1972	1S	97	237	600	6.2	0.39	B
24-1980	CA	344	1964	1S	203	496	1680	8.3	0.61	B
24-1980	CA	326	1972	1S	249	607	1970	7.9	0.53	B
24-1980	CA	325	1972	1S	98	238	1040	10.6	0.68	B
24-1980	CA	314	1972	1S	194	473	1150	5.9	0.38	B
24-1980	CA	312	1972	1S	159	387	1290	8.1	0.52	B
24-1980	CA	310	1964	1S	242	589	1500	6.2	0.46	B
24-1980	CA	241	1973	2S	321	782	1580	4.9	0.43	B
24-1980	CA	225	1976	1S	122	298	1230	10.1	0.64	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
25-1982	CA	A2	1969	1	177	431	1420	8.0	0.62	B
25-1982	CA	A3	1955	1	146	355	1500	10.3	0.78	B
25-1982	CA	A5	1965	1	152	370	1320	8.7	0.68	B
25-1982	CA	A6	1956	1	142	346	1130	7.9	0.62	B
25-1982	CA	A7	1968	1	245	597	1640	6.7	0.52	B
25-1982	CA	A9	1966	2	172	418	1150	6.7	0.68	B
25-1982	CA	A10	1960	1	136	331	2010	14.8	1.15	B
25-1982	CA	B1	1965	2	202	491	2090	10.4	1.06	B
25-1982	CA	B2	1970	1	213	518	1920	9.0	0.70	B
25-1982	CA	B4	1969	2	261	637	2710	10.4	1.06	B
25-1982	CA	B5	1970	1	204	507	1760	8.6	0.67	B
25-1982	CA	B6	1960	1	179	436	1440	8.0	0.62	B
25-1982	CA	B7	1969	2	263	642	1460	5.6	0.57	B
25-1982	CA	B8	1969	1	248	604	3160	12.8	0.99	B
25-1982	CA	B9	1965	1	196	477	2150	11.0	0.85	B
25-1982	CA	B10	1969	2	317	773	1230	3.9	0.40	B
25-1982	CA	C1	1964	1	201	496	1650	8.2	0.63	B
25-1982	CA	C2	1970	1	220	536	1090	5.0	0.38	B
25-1982	CA	C4	1965	1	179	437	1680	9.4	0.72	B
25-1982	CA	C6	1972	1	243	592	1060	4.3	0.34	B
25-1982	CA	C7	1970	1	251	614	1500	6.0	0.46	B
25-1982	CA	C8	1970	1	219	533	1910	8.7	0.67	B
25-1982	CA	C9	1968	2	259	682	2030	7.9	0.56	B
25-1982	CA	C10	1972	1	261	635	1490	5.7	0.44	B
26-1982	CA	1	1980	1	150	350	790	5.4	0.44	B
26-1982	CA	2	1980	1	150	350	860	5.9	0.48	B
26-1982	CA	3	1980	1	150	350	940	6.4	0.52	B
26-1982	CA	4	1980	1	120	290	560	4.6	0.38	B
26-1982	CA	5	1980	1	150	350	900	6.1	0.50	B
26-1982	CA	6	1980	1	120	290	770	6.4	0.52	B
26-1982	CA	7	1980	1	150	350	770	5.2	0.43	B
26-1982	CA	8	1980	1	150	350	400	2.7	0.22	B
26-1982	CA	9	1980	1	150	350	570	3.7	0.35	B
26-1982	CA	10	1980	1	250	610	1550	6.1	0.62	B
26-1982	CA	11	1980	1	230	560	1290	5.5	0.60	B
26-1982	CA	12	1980	1	200	480	1010	5.1	0.57	B
26-1982	CA	13	1980	1	210	500	1030	4.9	0.51	B
26-1982	CA	14	1980	1	160	390	820	5.0	0.41	B
26-1982	CA	15	1980	1	130	310	570	4.4	0.36	B
26-1982	CA	16	1980	1	160	380	850	5.4	0.44	B

TABLE 5 (continued)

Ref	Location	House	Const. date	Type	Floor area (m^2)	Volume (m^3)	Leakage area (cm^2)	Spec. leakage area (cm^2/m^2)	Average infiltration (ach)	Calc. proc.
26-1982	CA	17	1980	1	160	380	440	2.8	0.23	B
26-1982	CA	18	1980	1	160	380	700	4.5	0.36	B
26-1982	CA	19	1980	1	160	380	550	3.5	0.29	B
26-1982	CA	20	1980	1	160	380	500	3.2	0.26	B
26-1982	CA	21	1980	1	160	380	440	2.8	0.23	B
26-1982	CA	22	1980	1	180	420	760	4.3	0.40	B
26-1982	CA	23	1980	1	160	380	1010	6.5	0.62	B
26-1982	CA	24	1980	1	240	570	1030	4.3	0.59	B
26-1982	CA	25	1980	1	230	560	1290	5.5	0.57	B
26-1982	CA	26	1980	1	210	490	1210	5.9	0.65	B
27-1981	OR	A	1977	1	107	260	410	3.8	0.46	B
27-1981	OR	B	1977	1	107	262	340	3.2	0.39	B
27-1981	OR	C	1976	1	102	249	260	2.5	0.32	B
27-1981	OR	D	1976	1	102	249	230	2.2	0.28	B
27-1981	OR	E	1977	1	108	264	220	2.0	0.24	B
27-1981	OR	F	1977	1	102	249	130	1.3	0.17	B
27-1981	OR	H	1979	1	81	197	350	4.3	0.49	B
27-1981	OR	I	1979	1	81	197	280	3.5	0.40	B
27-1981	OR	J	1979	1	134	326	310	2.3	0.29	B
27-1981	OR	S1	1979	1	140	390	480	3.4	0.37	B
27-1981	OR	S2	1979	1	116	293	340	2.9	0.35	B
27-1981	OR	S3	1980	2	147	368	340	2.4	0.34	B
20-1982	NY	51	1973	2	130	310	1540	11.8	2.18	B
"	NY	52	1980	2	160	380	220	1.4	0.22	B
"	NY	53	1977	2	200	490	590	2.9	0.47	B
20-1982	NY	54	1973	2	140	350	980	6.8	1.16	B
"	NY	55	1980	2	100	240	510	5.0	0.87	B
"	NY	56	1980	2	160	380	500	3.2	0.56	B
"	NY	57	1974	2	150	360	910	6.1	1.14	B
"	NY	58	1974	2	130	310	780	6.0	1.04	B
20-1982	NY	59	1967	SL	190	440	870	4.7	0.82	B
"	NY	60	1978	2	210	520	580	2.7	0.47	B

TABLE 6

Correction Factors for $X \neq 0$

X	Q_s/L_o factor
0.0	1.000
0.1	0.993
0.2	0.973
0.3	0.941
0.4	0.895
0.5	0.838

TABLE 7

Correction Factors for $R \neq 0.5$

R	Q_{wind}/L_o factors	Q_{stack}/L_o factors
0.0	1.260	0.80
0.1	1.216	0.840
0.2	1.170	0.880
0.3	1.119	0.920
0.4	1.063	0.960
0.5	1.000	1.000
0.6	0.928	1.040
0.7	0.843	1.080
0.8	0.737	1.120
0.9	0.585	1.160
1.0		1.200

TABLE 8

Correction Factors for Shielding Coefficients ≠ 0.25

Shielding Class	C'	Q_{wind}/L_o Factors
1	0.34	1.360
2	0.30	1.200
3	0.25	1.000
4	0.19	0.760
5	0.11	0.440

TABLE 9

Correction Factors for Height ≠ 2.5 m and Terrain Class ≠ III

	Q_{wind}/L_o factors for terrain classes					
Height (m)	I	II	III	IV	V	$Q_{stack}L_o$ factors
2.0	1.718	1.219	0.956	0.696	0.415	0.894
2.5	1.757	1.261	1.000	0.735	0.449	1.000
3.0	1.789	1.296	1.037	0.770	0.479	1.095
3.5	1.817	1.326	1.070	0.800	0.505	1.183
4.0	1.841	1.353	1.099	0.827	0.529	1.265
4.5	1.863	1.377	1.125	0.852	0.552	1.342
5.0	1.883	1.399	1.149	0.875	0.572	1.414
5.5	1.901	1.1419	1.171	0.896	0.592	1.483
6.0	1.918	1.438	1.191	0.915	0.610	1.549
6.5	1.933	1.455	1.211	0.934	0.627	1.612
7.0	1.947	1.471	1.229	0.951	0.644	1.673
7.5	1.961	1.487	1.246	0.968	0.660	1.732
8.0	1.974	1.501	1.262	0.984	0.675	1.789

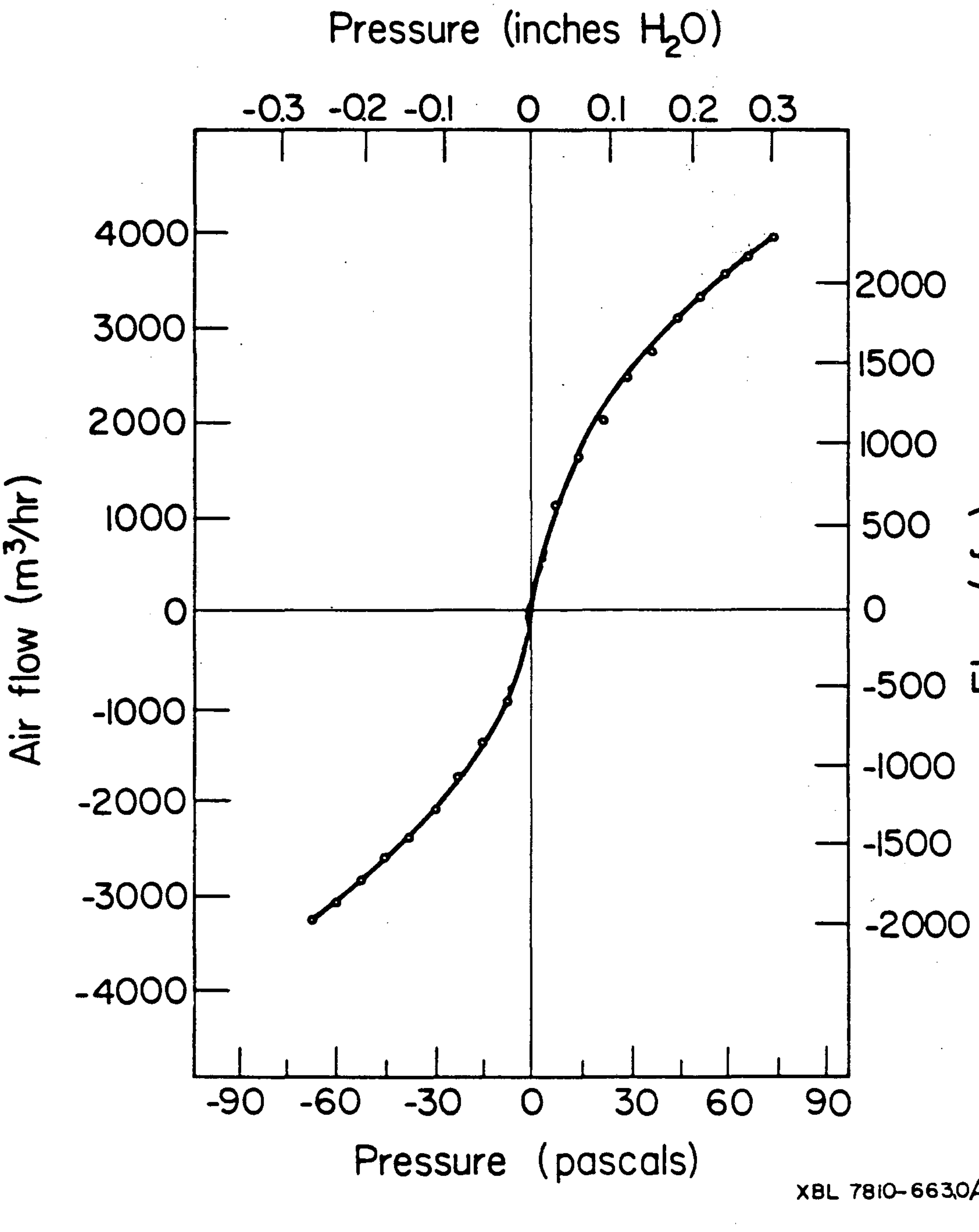
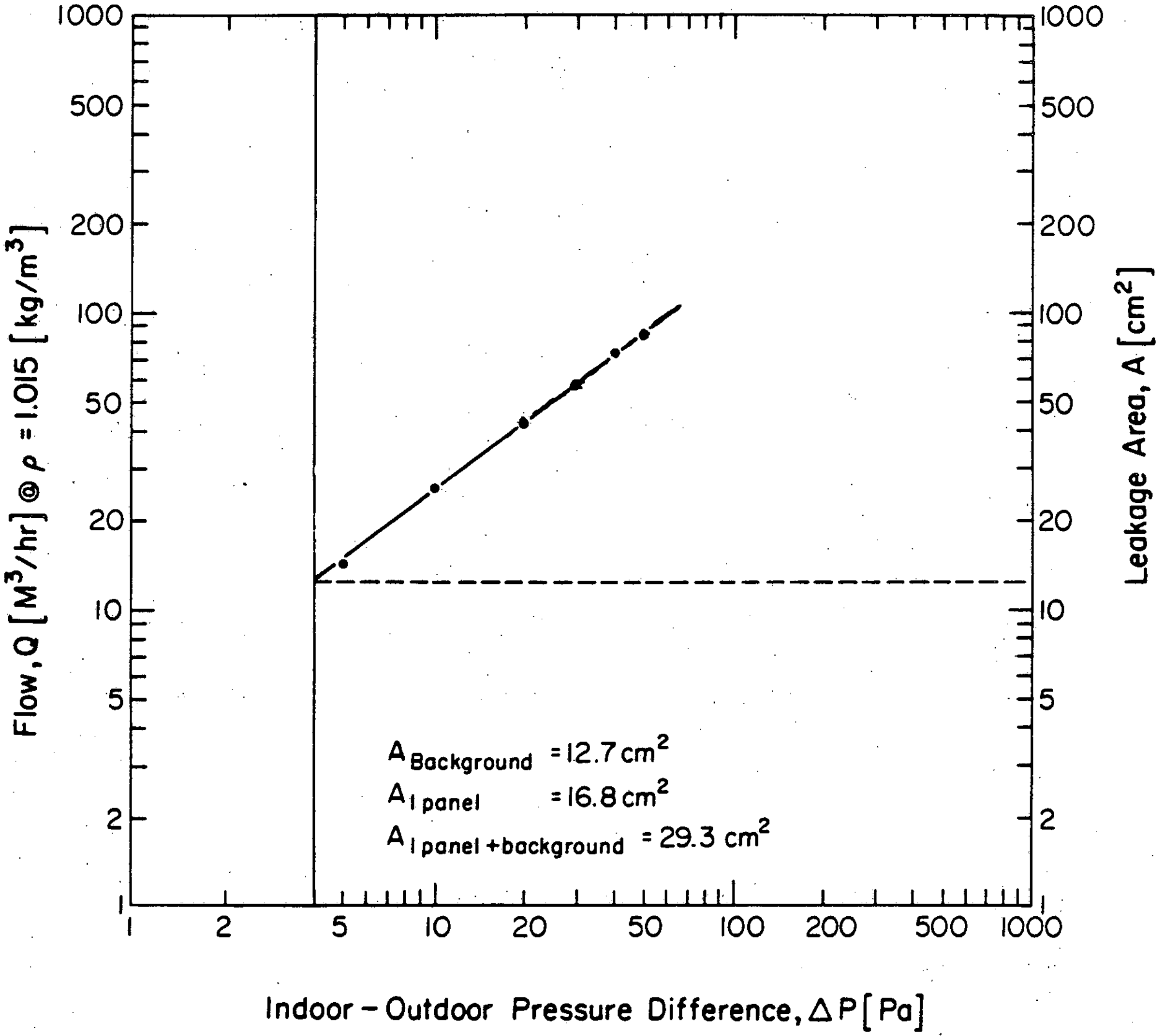
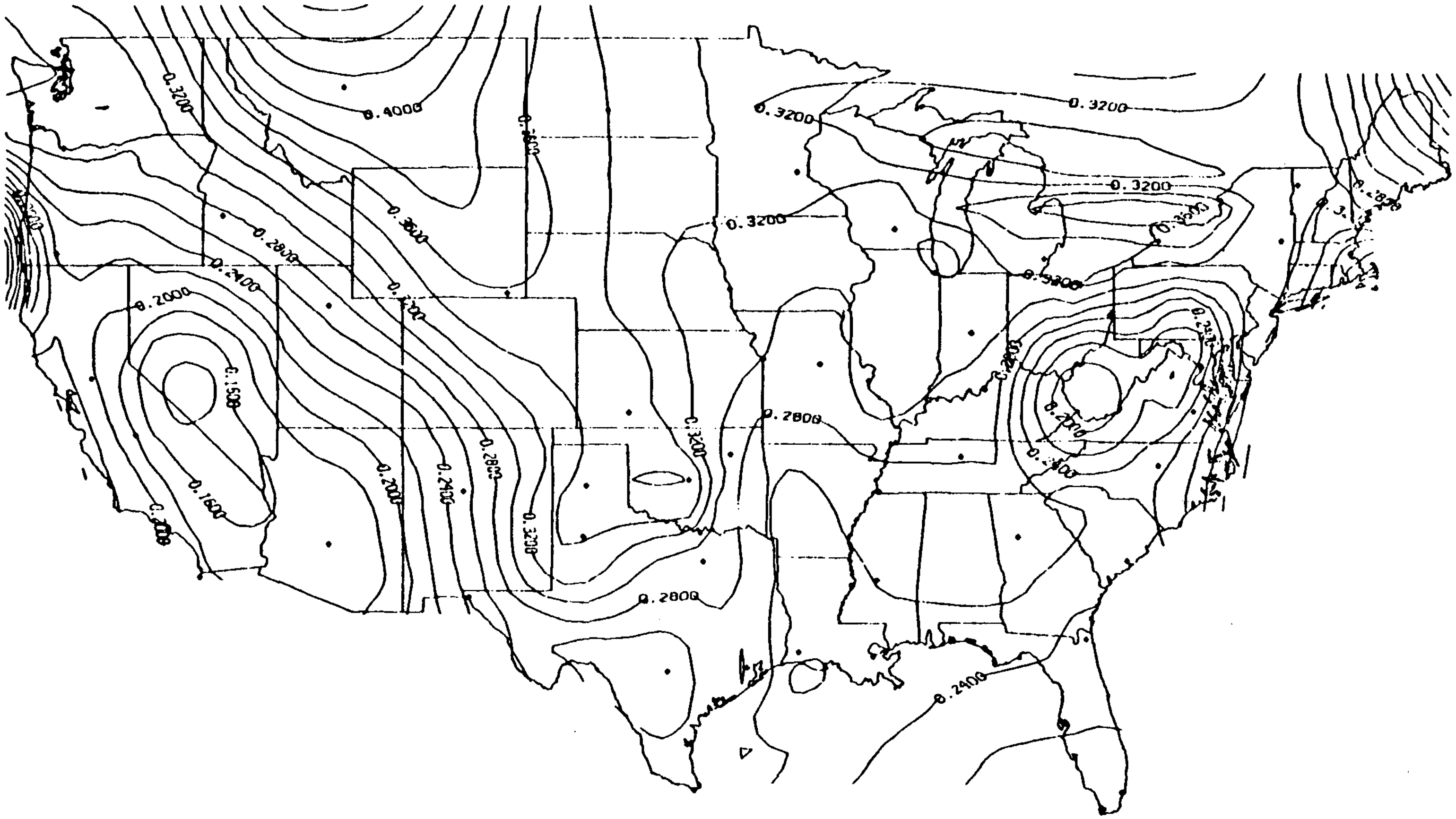


Figure 1 Typical flow versus pressure characteristic obtained using fan pressurization.



XBL 811-2109

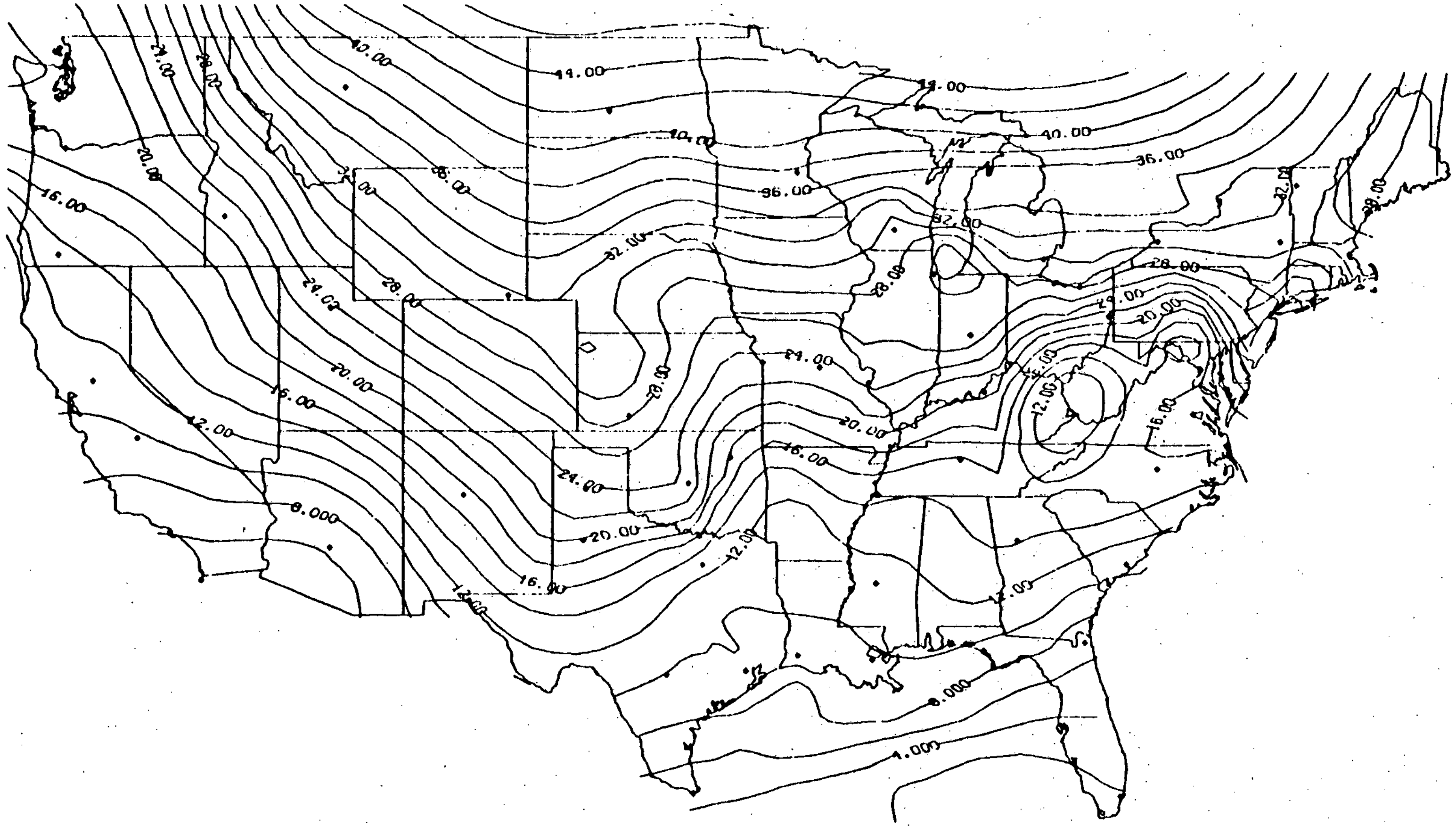
Figure 2 Pressure versus flow monograph that can be used to obtain the leakage area. Extrapolate to find the flow at 4 Pa; follow the dashed line to the right scale to read the leakage area.



Heating Season Infiltration (m^3/hr-cm^2)

XBL 8212-12076

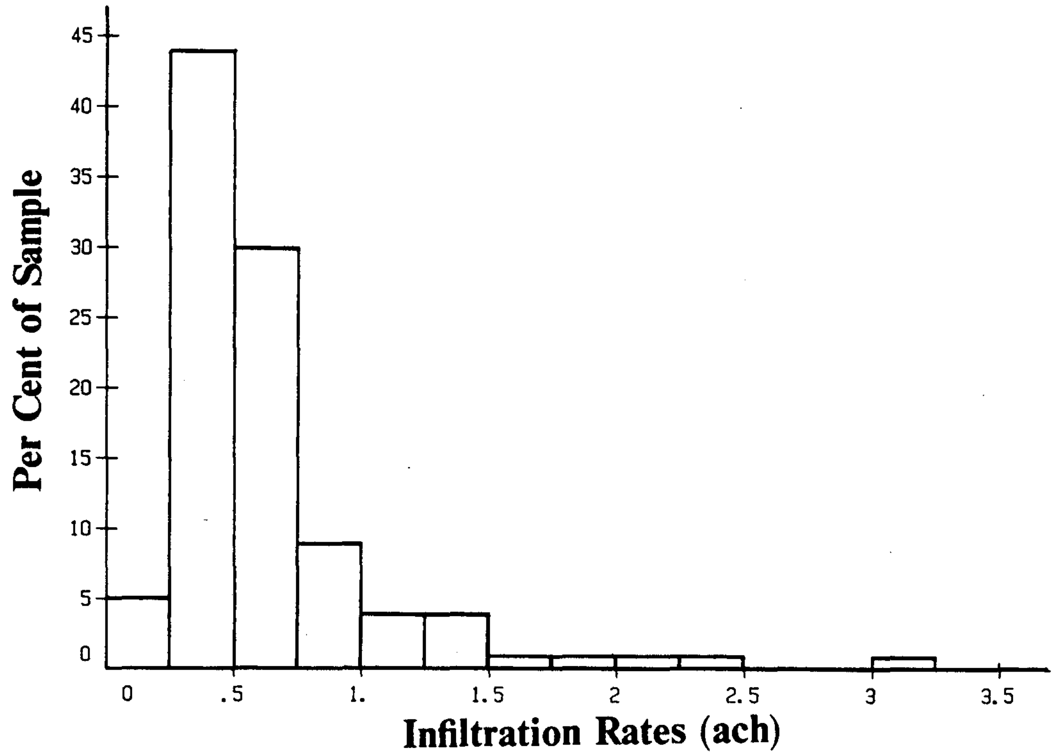
Figure 3 Heating season average infiltration [m^3/h.cm^2]. The contour interval is 0.02 m^3/h.cm^2 (0.076 ft^3/min.in.^{2}).



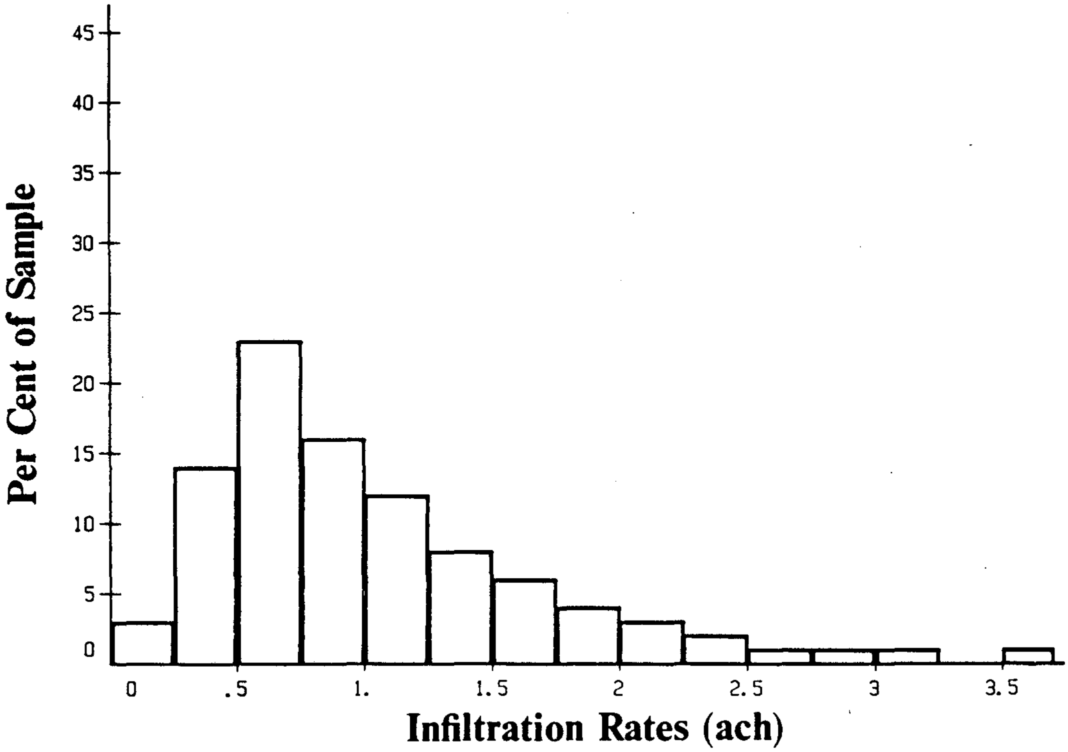
Heating Season Infiltration Load (Mjoules/cm^2)

XBL 8212-12077

Figure 4 Heating season infiltration load [Mjoules/cm^2]. The contour interval is 2.0 Mjoules/cm^2 (12.24 kBtu/in.^{2}).



XBL 8212-12078



XBL 8212-12079

Figure 5 Histogram of infiltration values from the data sample contained in Tab. 5. The lower histogram is another sample reported by Grot and Clark (Ref 28). The two sample distributions represent the difference that may be observed among new construction (top) and low income housing (bottom).

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