AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 16

COMPONENT LEAKAGE AREAS IN RESIDENTIAL BUILDINGS

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SYNOPSIS

To predict air infiltration in single-zone, residential buildings, some air infiltration models rely on measured values of the effective leakage area and on its distribution within the building envelope. The easiest method of measuring air leakage is a blower door, but, where such a device is not available, leakage areas can be estimated by adding leakage areas of all envelope components. In this paper we first review the published data on component air leakage and, from them, compile a set of component leakage figures for use in estimating leakage areas and their distribution in buildings. These calculations of leakage areas based on component leakages are compared with measurements of leakage areas in 36 houses in different locations in the United States. The model appears to predict leakage area accurately for the average of the 36 houses, while for individual houses the standard deviation is about 20%. In addition to describing the methods used to calculate building leakage areas based on component information, we discuss the assumptions and methods to convert other types of component leakage data to component leakage areas. Where several independent data exist for the same components (e.g., windows), we discuss the quantitative differences in terms of possible differences in construction practices. In addition to understanding the relative importance of each component, the methods and data presented can be used to estimate building leakage areas based simply on drawings.

LIST OF SYMBOLS

Q	total air infiltration rate or air flow through blower door [m^3/s]
Q_s	stack-driven infiltration [m^3/s]
Q_w	wind-driven infiltration [m^3/s]
f_s, f_w	structural infiltration factors
ΔT	indoor-outdoor temperature difference [°C]
v	wind speed from a weather tower [m/s]
C'	shielding class coefficient
α, γ	coefficients describing terrain class near the building
α', γ'	coefficients describing terrain class near the weather tower
H, H'	heights of the building and the weather tower, respectively
ΔP	pressure difference across envelope [Pa]
Q_P	air flow rate measured at pressure difference ΔP [m^3/s]
n, K	flow exponent and proportionality constant found from regression of measured leakage data
ΔPr	reference pressure difference [Pa]
Q_{Pr}	flow through the building or building component at the pressure difference ΔPr [m^3/s]
ρ	density of air [kg/m^3]

L	effective leakage area of building at ΔPr [cm^2]
L_c	ceiling leakage area [m^2]
L_f	floor leakage area [m^2]
L_i	leakage area per unit dimension of the i-th component [cm^2/m^2 or cm^2/m or cm^2 per component]
D_i	dimension of the i-th component [m^2 or m or number of components]
i	index denoting all building components
i_f	index denoting the floor components
i_c	index denoting the ceiling components
ΔL	uncertainty of the overall building leakage area [cm^2]
ΔL_i	uncertainty of the i-th component leakage area per unit component dimension [cm^2/m^2 or cm^2/m or cm^2/each]
L_C	calculated leakage area [cm^2]
L_M	measured leakage area [cm^2]
R^2	correlation coefficient squared

1. INTRODUCTION

Several air infiltration models have been developed to predict air infiltration in residential buildings. Some of these models rely on measured values of the effective leakage area and its distribution within the building envelope. The effective leakage area is a quantity that characterizes the air leakage of a structure. In 1980, Sherman and Grimsrud introduced the "LBL infiltration model"[1] in which the leakage area is combined with local weather data to predict average seasonal air exchange rates. The model predicts the air exchange through the building envelope on the basis of a few measurable parameters:

- the leakage area of the structure and its distribution
- the geometry of the structure
- the inside-outside temperature difference
- the wind speed
- the terrain class of the structure location
- the shielding class of the structure

For purposes of calculating air infiltration in a building using the LBL model, the single most important parameter is its leakage area, defined as the equivalent area of an orifice with a unit discharge coefficient that would allow the same volume of air flow as the actual building, assuming it is exposed to the same pressure difference. The easiest method of measuring the leakage area is by using a blower door.[2,3] An alternate method, called AC-Pressurization, is being developed by our group at Lawrence Berkeley Laboratory.[4]

Where a blower door is not available, leakage areas can, in principle, be estimated by adding component leakage areas of all the envelope components. There are two drawbacks to this method. First, finding all air leakage sites in the building envelope is difficult without a direct inspection assisted by specialized instrumentation (e.g., building pressurization with smoke tracers or thermographic equipment, or high-frequency acoustic methods). The second difficulty is the lack of data on air leakage through such leakage sites.

In this paper we addressed these drawbacks as follows. First, we only considered a fixed set of leakage sites that have been found by direct measurement to be significant. The frequency of occurrence or physical quantity of these leakage sites (i.e., number of pipe penetrations or overall window area) were determined solely by inspection of architectural drawings or sketches, not by information from direct visual inspection during a field visit, although such information is available for some of the houses used to validate the model and would have helped improve the model accuracy. Second, we compiled leakage areas measured for such leakage sites from the published literature. For some building components, other investigators have measured component leakage areas by methods similar to blower door pressurization.[5,6] In general, however, component leakage tests, although used for many years, have been used for slightly different purposes: consequently, the figures published in the literature reported component leakage in different formats, as best suited to their separate purposes:

- air changes per hour
- air flow in m^3/s or cfm
- leakage areas or effective leakage areas in cm^2 or square inches.

Regardless of the format, leakage can be expressed per component, per unit surface area, or per unit length of crack, and it can be quoted at a fixed pressure difference (usually 4 Pa, 50 Pa or 75 Pa) or over a given range of pressures.

The variety of reporting formats and the lack of coordination among different measurements have been the main obstacles to using such measured component leakages as a basis for deriving the leakage area and the air infiltration rate of a building. Accordingly, part of our emphasis is on the standardization of the component leakage areas reported by others into leakage areas per unit length, per unit area, or per unit component (e.g., leakage area per fireplace). The building leakage areas estimated from the component leakage areas may be used as input to the LBL infiltration model to predict the infiltration in the building.

From the methods and values reported in this paper, designers and architects can estimate component and building leakage areas based simply on drawings and their knowledge or decisions about such important details as whether the structure has weatherstripping around windows, or dampers in ventilation ducts and fireplaces. The better the knowledge about construction details, the more accurate the resulting estimate of building leakage area. On the other hand, no amount of sleuthing will be better than direct measurement by pressurization techniques. That is, this paper should not be construed as an invitation to replace blower doors with mindless crack counting, but it should help those who, for institutional or practical reasons, are not in a position to make actual leakage area measurements.

2. OVERVIEW OF THE LBL MODEL

The LBL-model[7] is a single-zone calculation method to predict the weather-induced infiltration of a residential or small commercial building. The model also predicts the impact of retrofits or other changes in the building envelope on the basis of performance changes effected in a few measurable parameters:

1) The leakage area(s) of the structure and its distribution. This parameter describes the tightness of the structure (obtained by pressurization and depressurization). Most retrofits will affect the leakage area or the leakage distribution.

2) The geometry of the structure. The height and other geometric quantities are usually known or can be directly measured.

3) The inside-outside temperature difference. The temperature difference controls the infiltration caused by thermal buoyancy commonly called stack effect. It is also necessary for calculating the heating and cooling loads due to infiltration.

4) The wind speed. The wind speed is required to calculate the wind-induced infiltration, usually called "wind effect."

5) The terrain class of the structure. Standard wind-engineering practice has established five "classes" for characterizing the terrain surrounding a structure: they range from open terrain, as on a prairie, to the completely obstructed terrain typical of a large city.

6) The shielding class of the structure. Similar to terrain class is the concept of shielding class, which, however, applies only to the structure's immediate vicinity (within two house heights). For any particular calculation, the shielding class, also in five categories, is assigned on the basis of the density of surrounding buildings and obstructions, such as trees, fences and sheds.

Of these parameters, the distribution of leakage area is the most difficult to measure directly. To measure ceiling leakage area, the building should be pressurized and depressurized with walls and floors well sealed. Conversely, walls and ceiling should be sealed to measure floor leakage area. In practice, ceiling and floor leakage areas are estimated from leakage areas of light fixtures, floor penetrations, and similar components in ceiling and floor. The effect of the apparent inconsistency of this method is minimized when one considers the comparatively weak sensitivity (0 - 15%) of the model to the leakage distribution for average houses. Still, one of the purposes of this paper is to put the estimation of the leakage area distribution on a more scientific basis.

The principal equations of the LBL infiltration model are summarized below. A cardinal assumption of the model is the addition of stack and wind effects in quadrature:

$$Q = \sqrt{Q_s^2 + Q_w^2} \tag{1}$$

Both stack- and wind-driven infiltration terms have similar forms:

$$Q_s = L\, f_s \sqrt{\Delta T} \tag{2.1}$$
$$Q_w = L\, f_w\, v \tag{2.2}$$

The structural factors, f_s and f_w are:

$$f_s = \frac{(1 + R/2)}{3} \left[1 - \frac{X^2}{(2-R)^2} \right]^{3/2} \sqrt{\frac{gH}{T}} \tag{3.1}$$

$$f_w = C' \, (1 - R)^{1/3} \left[\frac{\alpha (H/10)^{\gamma}}{\alpha' (H'/10)^{\gamma'}} \right] \tag{3.2}$$

The building leakage area distribution parameters, R and X, are:

$$R = \frac{L_c + L_f}{L} \quad \text{and} \quad X = \left| \frac{L_c - L_f}{L} \right| \tag{4}$$

Knowing the terrain class and the shielding class of the structure allows the use of off-site weather data for calculating wind-induced pressures on the building surfaces. Thus, even though on-site weather data collection greatly improves the results obtainable in a research setting, it is not necessary. The only requirement when using off-site weather data is that the measured wind data is for the "same wind", i.e., that there be no mountains or other major disturbances in terrain between the site and the wind tower.

Drawings of a building are generally sufficient for determining the building height, H. For the leakage area and the leakage area distributions, R and X, direct measurements should be used or, alternatively, component leakage areas in conjunction with drawing details. In other words, air infiltration can be calculated for a building as early as in the planning stage. Moreover, the consequences of different design details can be evaluated immediately. For existing buildings, direct information from an on-site visit would complement the information gathered from any drawings available.

3. CALCULATION OF LEAKAGE AREAS

The leakage area values presented in this paper conform to the definition used in the LBL model:

$$L = 10{,}000\ Q_{Pr} \sqrt{\frac{\rho}{2\ \Delta Pr}} \qquad (5)$$

In accordance with the LBL infiltration model, we use a reference pressure difference of 4 Pa. The component leakage areas presented in this paper are given in cm^2 per unit, where the "unit" could be:

- linear meters of house perimeter
- square meters of window area
- number of penetrations through the envelope
- number of components of one type (e.g., fireplace).

The component leakage areas per unit are found in the tables in Appendix A. To calculate the total leakage area of a building, we multiply the overall dimensions or the number of occurrences of each building component by the appropriate table entry; by adding the resulting products we obtain the building leakage area. If we do the sum separately for ceiling or floor, using the entry for leakage location -- "Walls," "Ceiling," or "Floor" -- at the bottom of each table, we can estimate ceiling and floor leakage areas to be used in calculating the parameters R and X. That is

$$L = \sum_i D_i\ L_i \qquad (6.1)$$

$$L_f = \sum_{i_f} D_i\ L_i \qquad\qquad L_c = \sum_{i_c} D_i\ L_i \qquad (6.2)$$

Note that the component "dimension," D_i, refers to <u>all</u> components of the i-th kind. For example, D_i may refer to the overall window area, to the overall length of floor joint, or to the overall number of plumbing penetrations.

The amount of care used in determining the size and number of leakage sites directly affects the accuracy of the estimates obtained by this method. For instance, based on reference to drawings alone, a window frame would likely be considered "average" and assigned an average leakage-area-per-unit-surface area. An on-site inspection, however, may reveal that the cracks around the frame have been carefully caulked, a finding that would be reflected in a lower value in the component leakage table. Finally, a direct test with a smoke-stick could distinguish between "well caulked" and "average caulked." An example of an actual leakage area calculation is shown in Table 1. The calculated leakage area is 810 cm^2 with an uncertainty of ± 128 cm^2. The measured leakage area is 770 cm^2. Of course, in general, we would not expect such good agreement.

TABLE 1
Example of Calculation of Building Leakage Area Based on Component Leakage Areas and Comparison to the Measured Leakage Area.

Component	Description	D_i	L_i	ΔL_i	$D_i L_i$	$(D_i \Delta L_i)^2$
Sills	Uncaulked	43.2 m	4.0 cm^2/m	2.0	173	7,482
Elec. outlets		20	0.5 cm^2 ea	0.5	10	100
Windows Framing	Sliding	13.1 m^2	4.0 cm^2/m^2 1.7 cm^2/m^2	2.0	75	676
Exterior doors Framing	Single	5.7 m^2	7.7 cm^2/m^2 1.7 cm^2/m^2	7.0	54	1,592
Fireplace	Without damper	1	350.0 cm^2 ea	30.0	350	900
Penetrations	Pipes	7	6.0 cm^2 ea	3.0	42	441
Heating ducts	Ducts untaped, in basement	1	144.0 cm^2 ea	72.0	144	5,184
						16,375
Calculated Building Leakage Area, L_C (cm^2):					810	± 128
Measured Building Leakage Area, L_M (cm^2):					770	

Note: Refer to symbol list for explanation of column headings

3.1 Estimation of Uncertainty

In general, the leakage of any component depends on a number of factors, such as quality of workmanship or type of fireplace damper. Other variables have to do with differences in the way the literature reports leakage area values for the same component. Whenever such differences could not be correlated with observable features, or when, in our experience, the leakage area of a particular component was especially susceptible to construction quality, we entered a range of leakage areas to reflect the uncertainty. In Appendix A, we use "Max" to describe the leakiest and "Min" to describe the tightest components reported in the literature. Harrje and Born[9] indicate their component leakage areas in a similar but graphical form, but do not include the discharge coefficient of each component in their definition of leakage area.

An overall building leakage area derived from individual component leakage areas with individual uncertainties must, of course, have a similar uncertainty associated with it. We suggest that the uncertainty of the overall building leakage area be determined by following the rules for error propagation used in analyzing measurements;[10] that is, by assuming the error in each individual component leakage area to be independent of that of any other component in magnitude and in sign. Then, the uncertainty in overall building leakage area can be estimated from the square root of the sum of squares of individual uncertainties:

$$\triangle L = \sum_i (D_i \triangle L_i)^2 \quad (7)$$

Calculating the leakage area and its uncertainty from drawings or sketches can be an aid in deciding whether more time-consuming measurements or surveys are necessary or warranted. Suppose that the calculation in Table 1 had been done on an actual house before the survey. It would then have been known that concentrating on a careful inspection of the sill, the doors, and the fireplace would reduce the uncertainty of the total leakage area. The calculation also shows that an extensive survey to ascertain the quality of the sealing of electric outlets is not warranted: decreasing the uncertainty of the leakage area of each electrical outlet from 0.5 to 0.2 would decrease the uncertainty of the total leakage by less than 0.3%.

4. REVIEW OF EXISTING DATA FOR COMPONENT LEAKAGES

A review of the component leakage data found in the literature listed in Appendix A,[11-23] and shown in Table 2 reveals that:

- most of the data used pertain to residential houses in North America only;
- most data are for windows and doors of various types;
- there are some data for leakages around pipes and wires;
- there are some data for fireplaces and heating systems;
- there are no data for leakages of windows and doors where weatherstripping was installed several years prior to test;
- there are very few data for leakage of sills and wall-ceiling joints, and those available are not detailed;
- there are no data for leakages through walls, floors, and ceilings except for penetrations;
- the Scandinavian references contain results from laboratory tests only, but all test samples represent current Scandinavian building technology.

TABLE 2
Synopsis of Measured Component Leakage Areas Reported in Literature.

Component	Ref. 11*	Ref. 12*	Ref. 13*	Ref. 14*	Ref. 15*	Ref. 16*	Ref. 17*	Ref. 18*	Ref. 19*	Ref. 20*	Ref. 21*	Ref. 22*	Ref. 23*
Sill (wall foundation)		Caulked and not caulked	3 types		6 types				2 types			8 x 2 types	
Ceiling/roof									1, not described				21 types w/vapor barrier
Wall/ceiling joints		Internal walls											
Floor													
Windows		18 types			Older types	5 types of newer windows	2 calibrated plastic	1 with and w/out storm	2 types				
Doors		15 types			Swinging door								
Penetrations in walls and ceilings	Electrical outlets	Electrical outlets, pipes, ducts	Electrical outlets	17 types							Electrical installations		
Heating systems	Ductwork	9 types											
Exhaust fans	2 types	9 types											
Fireplaces	With and without insert	8 types											
Natural ventilation										21 types			
TEST	Field measurement		Lab test	Lab test	Standard	Field measurement of 192 windows	Lab test			Lab test		Lab test	
DATA	Leakage area at 4 Pa	Leakage area at 50 Pa	Curve airflow/pressure	Curves	Airflow at 4 diff. pressures	Airflow at 75 Pa	cfm vs. in. H_2O curves	Leakage area	Airflow at 75 Pa	Curves m^3/h vs. 0-200 Pa		Curves m^3/h 0-150 Pa	Curves m^3/h 0-150 Pa

*Column Headings Refer to References in Paper.

We used the data from the Scandinavian references[13-14,20-23] to determine the lower limits of the uncertainty range for the leakage areas of some components.

4.1 Transformation of air leakage data into effective leakage area

Whenever the data in the literature were not given in units of effective leakage area at $\Delta Pr = 4$ Pa, one of the two transformation formulae shown below was used.

Pressure curve: If the leakage results were reported as a series of flow rates through the component at several different reference pressures, the data was fitted to the following empirical form:

$$Q = K \Delta P^n \tag{8}$$

The equation was then evaluated at $\Delta P = 4$ Pa to obtain the air flow needed in Eq. (5) determining effective leakage area.

Fixed pressure data: Where the air flow was given at a fixed difference pressure, usually 50 Pa or 75 Pa, the leakage area was calculated by assuming a value for the flow coefficient n, usually

$$n = 0.65, \tag{9}$$

since this value appears to be a good estimate for many houses.[24] The equation used to calculate the leakage area then becomes:

$$L = 10{,}000\, Q_P \left[\frac{\Delta Pr}{\Delta P} \right]^n \sqrt{\frac{\rho}{2 \Delta Pr}} \tag{10}$$

5. COMPARISON OF CALCULATED AND MEASURED BUILDING LEAKAGE AREAS

To test the method outlined above, we calculated effective leakage areas from component leakage information for a sample of 36 houses from various areas of the United States for which we had both detailed drawings and measured values of overall effective leakage area.[25-28] These were all single-family residential houses, some of which have leakage area measurements available for before and after certain air-tightening retrofits had been carried out. The locations were: Rochester (New York), Midway (Washington), Eugene (Oregon) and Davis and Walnut Creek (California).

In addition to drawings or sketches of the houses, ranging from simple sketches done by house doctors to detailed architectural drawings, we relied upon notes about window types, weatherstripping, etc. However, we only used information that was or would have been available without an on-site inspection. The calculation presented in Table 1 was performed on each of the 36 houses.

5.1 **Comparison on Full Set of Houses**

In Fig. 1 we show the comparison of calculated and measured leakage areas for the 36 houses in our sample. Each point represents one comparison, with the measured value as the abscissa and the calculated value as the ordinate. The uncertainty calculated for each leakage area is shown as a vertical bar and is in the range of ±10% to ±20%. For a few of the tighter houses, the uncertainty was as high as ±40%. The error in the measurement of leakage area is estimated to be between ±10% and ±15%. The solid diagonal line represents perfect correspondence between calculated and measured values, while the dotted lines show the limits of ±20% discrepancy with respect to measured leakage areas.

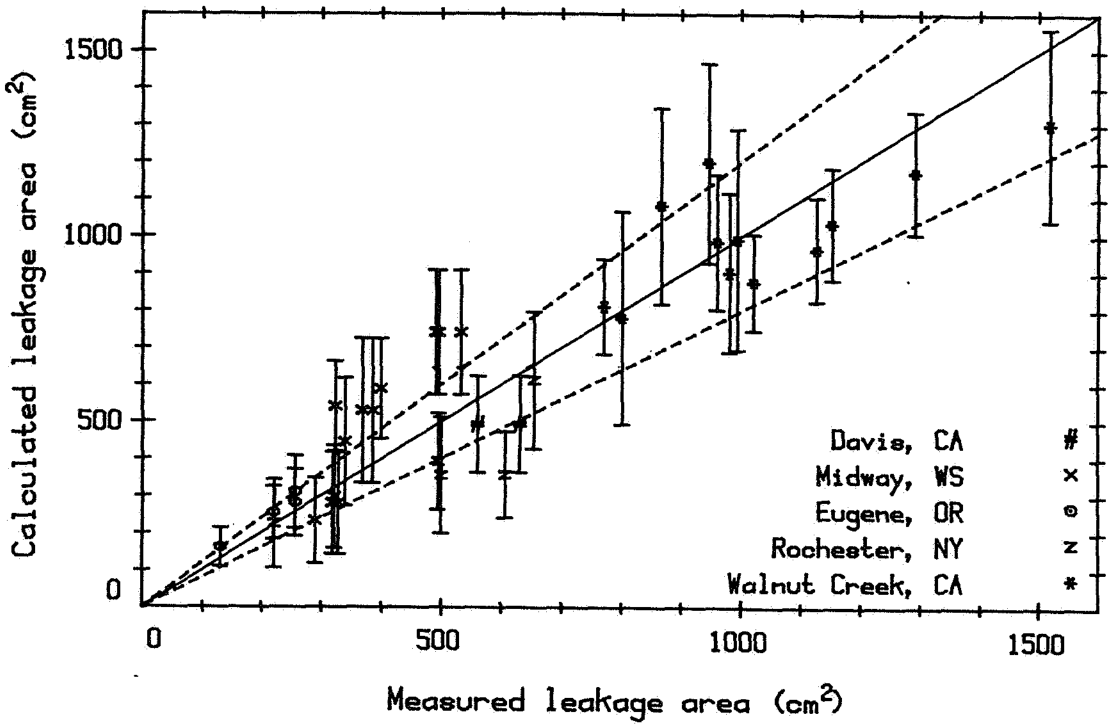

Fig. 1: Comparison of measured and calculated leakage areas for 36 houses; vertical bars represent uncertainty of calculation; solid diagonal line indicates perfect agreement; dashed lines indicate ±20% discrepancy.

A simple linear regression of the points in Fig. 1 yields a best-fit line of:

$$L_C = \underset{(0.06)}{0.84}\, L_M + \underset{(46.3)}{111.5} \qquad (R^2 = 0.84) \tag{11}$$

The figures in parentheses indicate the standard deviation of the estimated regression coefficients. The R-squared value of 0.84 indicates that 84% of the variation in calculated leakage area is explained by the measured leakage area, with only 16% of the variation due to lack of fit of the model.

The apparent correlation between calculated and measured leakage areas is encouraging. In most cases, calculated values fall within the ±20% range, with the greatest outliers at ±40%. For this particular sample, it appears that the calculations overpredict for tight houses and underpredict for very leaky houses. A comparison of the drawings of tight and leaky houses might reveal systematic differences in building construction details. For example, most of the tight houses had continuous vapor barriers, while the leakier ones did not.

5.2 Continuous Vapor Barrier

One component of great importance to the overall leakage area is a continuous polyethylene vapor barrier. Although its effect on the overall tightness of a building is undisputed, we could not find quantitative results in the literature, except for ceiling and wall joints (Table A-2), and ducts through walls or ceiling (Table A-8). Moreover, because it acts in series to other envelope components, a vapor barrier can not be characterized as an additive leakage area.

As an interim solution, we propose to use the "Min" values in the tables in Appendix A for window and door frames, sills and wall joints, electric outlets and light fixtures, and pipes and ducts through the envelope. The application of this rule to the tight houses for which our method overpredicts leakage area would improve the correspondence between prediction and measurement. Because of the arbitrary nature of such a "rule," however, we did not use those results and thus, as an interim solution, ignored the effect of a continuous vapor barrier. In any case, any premature conclusions with regards to continuous vapor barriers or to the calculation method presented here should be tempered by the current paucity of component leakage data and by the fact that the tightest and the leakiest sets of houses in our comparison are each located on a single site and are each reported in a single reference.

5.3 Comparison of "Unique" vs. "Replicated" Houses

Some of the houses in the sample were replicated from the same set of drawings and some of the houses were evaluated both before and after retrofits. In the first case, of course, the calculations will predict the same leakage areas for all houses, and in the second case the calculated leakage areas, although different, will be strongly interdependent. If we eliminate the repetitions, there are only 22 physically distinct houses in our data set. Fig. 2 shows the comparison of calculated and measured leakage areas for these 22 "unique" cases.

In these cases, a linear regression yields:

$$L_C = \underset{(0.07)}{0.89}L_M + \underset{(50.5)}{49.5} \qquad (R^2 = 0.90) \tag{12}$$

with the same nomenclature and conventions as in Eq. (11).

Based on the comparison shown in Figs. 1 and 2, it appears that the uncertainties of 20% to 40% calculated with the method described earlier and quantified by Eq. (7) are too conservative. If the vertical error bars are to symbolize standard errors and if the error distribution for each prediction is assumed to be normal, then we would expect only about two-thirds of the vertical error bars to intersect the diagonal line. In fact, 28 out of 36 do so for the full sample of 36 houses (Fig. 1) and 19 out of 22 do so for the subset of 22 "unique" houses (Fig. 2). A casual inspection of the two figures suggests that vertical error bars in the range of 20% would better satisfy the criteria for standard deviations.

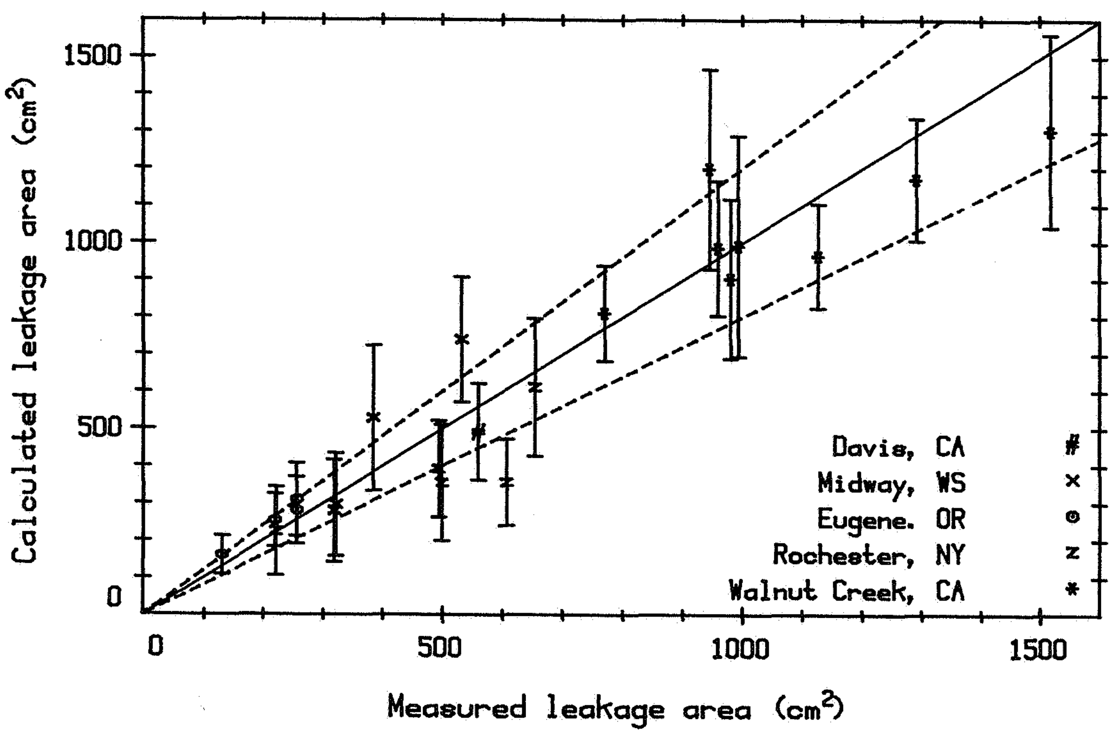

Fig. 2: Comparison of measured and calculated leakage areas for 22 "unique" houses; vertical bars represent uncertainty of calculation; solid diagonal line indicates perfect agreement; dashed lines indicate ±20% discrepancy.

For each of the 22 unique calculations, we computed the ratio of calculated to measured leakage areas -- a ratio of 1.0 indicating perfect correspondence, a ratio of 1.2 translating to 20% overprediction, and so on. Fig. 3 shows a histogram of the 22 ratios calculated in this manner. The average is 1.005 with a standard deviation of 0.20, suggesting that the calculation method generally produces accurate predictions. Thus, based on this limited data set, and assuming that the error distribution is normal, the leakage area of a house, calculated on the basis of its drawings alone, falls within 80% and 120% of the actual value with a probability of 68%. If the limits are relaxed to 60% to 140% of actual value, the probability increases to 95.5%.

The standard deviation of 20% should be compared with two related quantities: the error of 10% to 15% inherent in leakage area measurements, and the uncertainty of about 20% resulting from the uncertainty in component leakage areas. If we make the hypothesis that these results would hold over a significantly larger set of houses, we would conclude that the simple method for calculating leakage area, as described in this paper, is of a quality comparable to that of our data. In other words, few refinements to the method are warranted until the large uncertainty is reduced that presently exists in the values reported for component leakage areas.

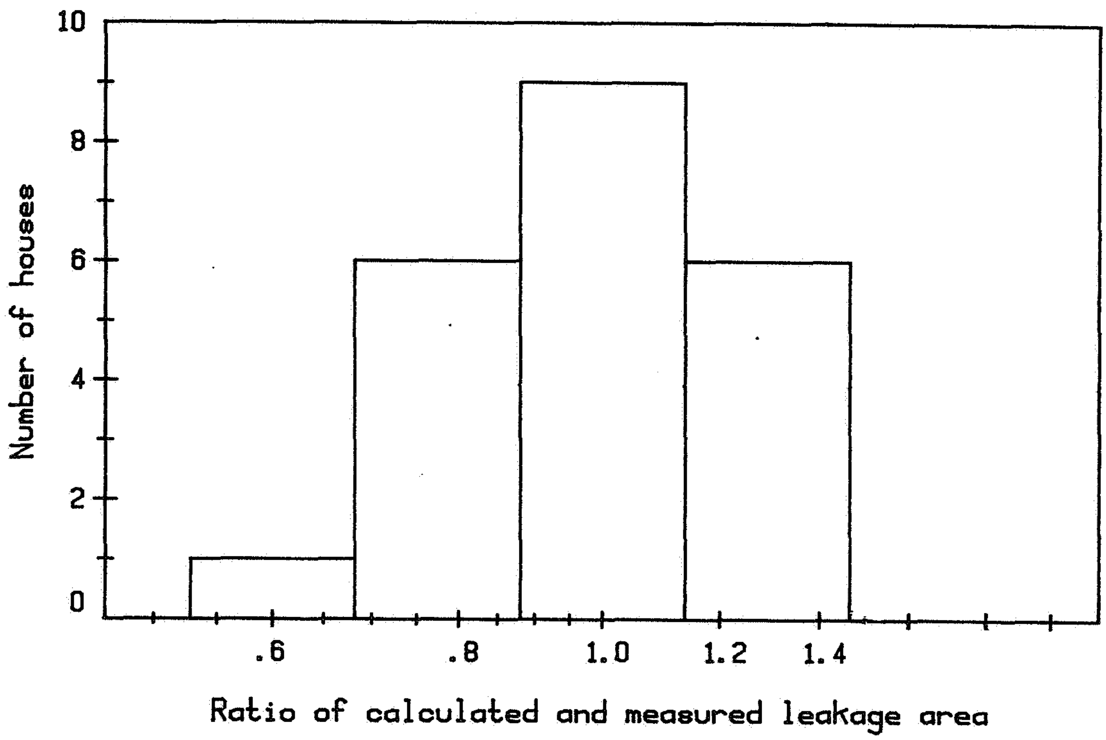

Fig. 3: Histogram of ratios of calculated to measured leakage areas for 22 "unique" houses.

On a different level, the small predictive bias of our model based solely on architectural drawings may appear to be contradictory to the findings widely reported in the literature and consistent with our experience that only on-site inspection can accurately reveal location and size of air leaks in buildings. In reality, the sizeable standard deviation of the predictions indicates the existence of inaccuracies of the model. The small bias implies only that the errors committed in omitting leakage sites or in assigning improper leakage areas are uncorrelated and, thus, tend to cancel each other. Nevertheless, it is important to recognize that this model, as any deterministic method, is inherently best suited for design calculations on new buildings and for predictions of energy savings in sets of existing buildings. When predicting the savings from retrofitting an individual building on the basis of drawings alone the model, obviously, can only be as good as its assumptions, namely, the identification and the sizing of all leakage sites.

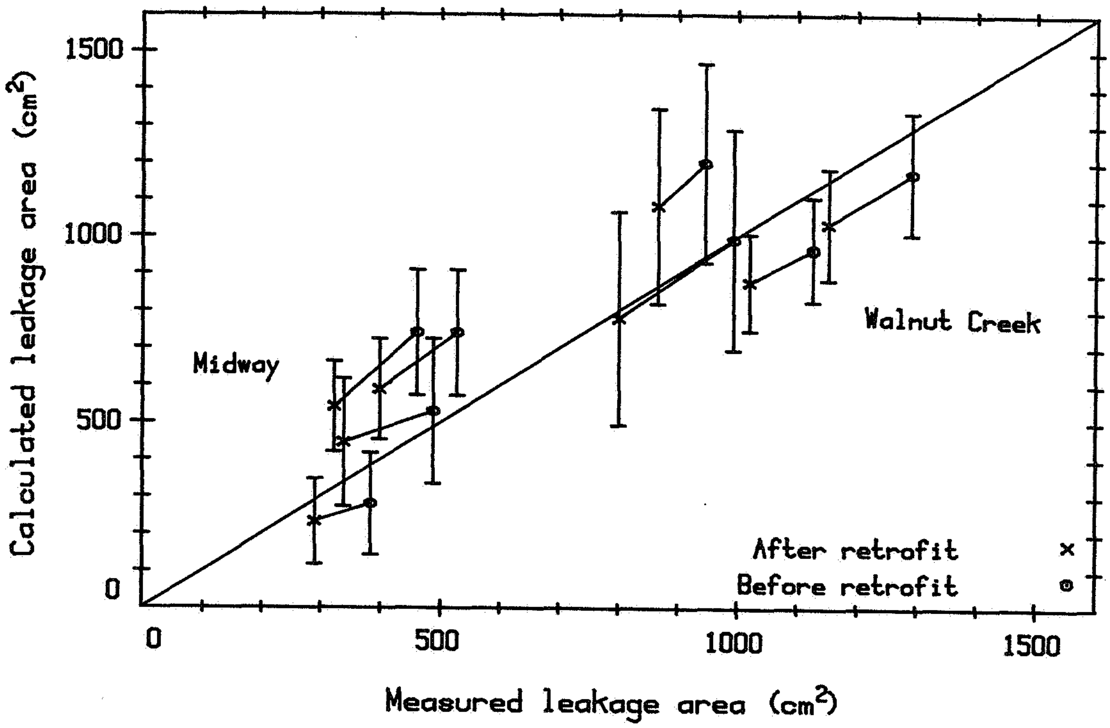

Fig. 4: Comparison of measured and calculated leakage areas of 8 houses before and after air-tightening retrofits; the solid line indicates perfect agreement.

5.4 Comparison of Air-Tightening Retrofits

Figure 4 shows the results of calculations on the eight houses in which leakage area had been measured before and after air-tightening retrofits were carried out. Four houses are located in Midway and four in Walnut Creek. The calculations on these eight houses are based on sketches and notes done by house doctors since no detailed architectural drawings were available. Each house is represented by a line connecting the two points indicating the leakage areas before and after retrofit. A connecting line parallel to the solid diagonal indicates perfect agreement between calculation and measurement of the change in leakage area. This comparison is possibly the most encouraging thus far. It shows that for six of the eight houses, the change in leakage achieved by retrofit was calculated to much greater accuracy than the absolute leakage areas either before or after retrofit. In light of our earlier discussion on the relative benefits of on-site visits and calculations based on drawings, one might conclude that our knowledge of the values of individual component leakage areas (at least those affected by the retrofits in these eight houses) is better than our awareness of the existence of all leakage sites in the shell.

5.5 Comparison of Calculations with Measured System Leakage Areas

Several previous studies have reported measurements of component leakage areas aggregated by groups of components (e.g., all electric outlets and recessed light fixtures) and by large discrete components (e.g., fireplaces). In the pie charts in Figs. 5a and 5b we aggregate in a similar manner the component leakage areas of a subset of houses formed by the "unique" houses, including both the before and after configurations of the eight retrofitted houses. Partly because of the reporting format of the previous studies, we considered the 19 houses with fireplaces separately from the 11 houses without. The percentages in each sector -- windows, for example -- were obtained by dividing the average window leakage area of all houses by the average total leakage area.

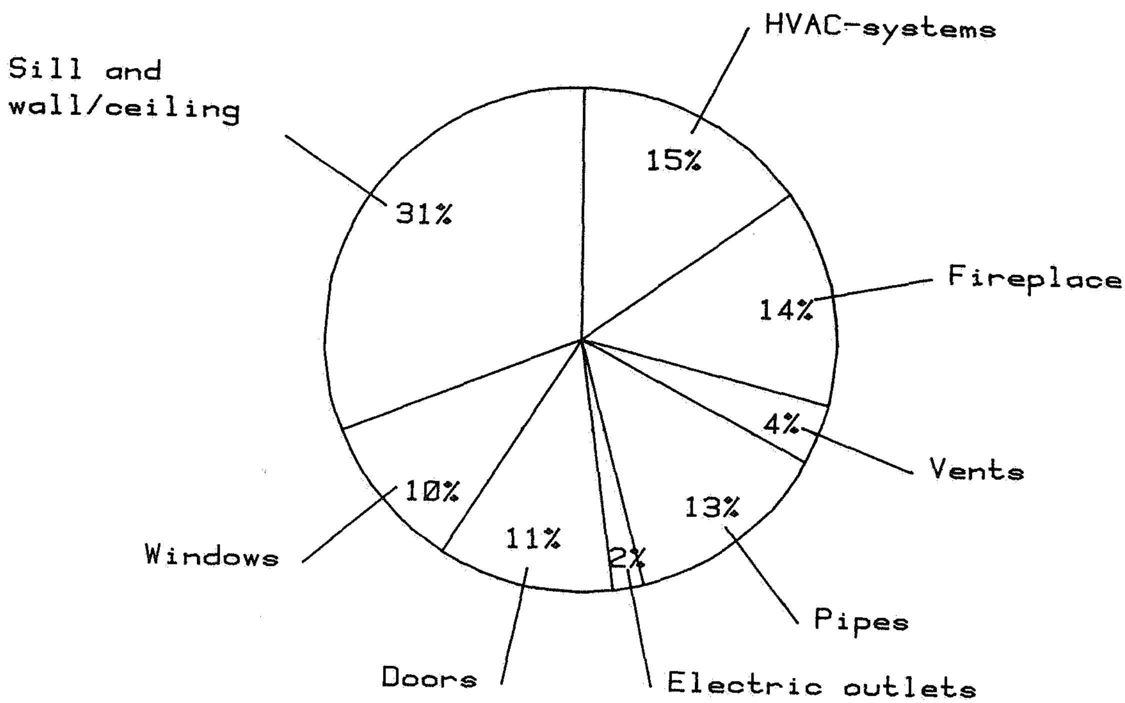

Fig. 5a: Distribution of leakage areas by major component systems for 19 houses with fireplace.

Our calculation of 14% as the contribution of a fireplace to total leakage area (see Fig. 5a) compares favorably with the 16%

measured in a previous study by Dickerhoff et al.[29] The leakage attributable to forced air heating and cooling ducts was calculated to be 15% and 13%, respectively. Caffey found duct leakage to be 14% of the total,[30] while the study by Dickerhoff et al. found 13%; similar measurements by Lipschutz et al. reported 15% and 21%, respectively.[31-33]

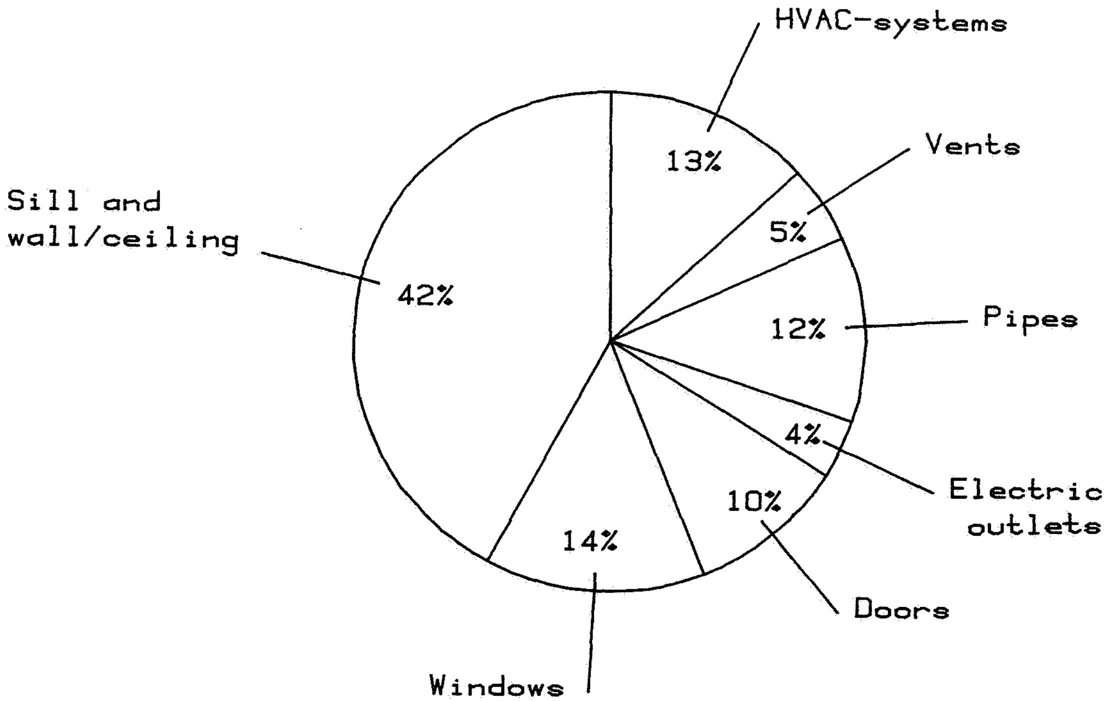

Fig. 5b: Distribution of leakage areas by major component systems for 11 houses without fireplace.

The leakage associated with kitchen fans, bathroom fans, and clothes dryers is indicated by the sectors marked "Vents." Here, we found average values of 4% and 5% for houses with and without fireplaces, respectively, while Dickerhoff et al. measured 3% to 6%.[34]

Our calculations show that electric outlets and recessed light fixtures contribute 2% and 4%, respectively. Values reported in the literature display dramatic variations for this component. While Dickerhoff et al. determined this contribution to be 1%,[35] Caffey reported 25%.[36] Swedish laboratory tests measured leakage areas for electric outlets to be between 0.00 cm^2 and 0.33 cm^2 each, depending on how well they were sealed.[37] No recessed light fixtures were tested. In our calculations, we used 0.5 cm^2 per outlet and 10 cm^2 for each recessed light fixture. While they did not address recessed light fixtures, the Swedish tests thus appear to confirm the range found by Dickerhoff et al. and by our calculations.

6. CONCLUSIONS

Leakage areas predicted for 36 building plans using component leakage areas appear to be in good agreement with direct measurements using a blower door. Care was taken to use only architectural drawings of the buildings and to ignore additional information from prior on-site visits. The weakness of this comparison, of course, is that we had prior knowledge of the buildings and their measured leakage areas. Although we strived to prevent such knowledge from biasing our judgments when interpreting the building plans, our results might have been stronger if the leakage areas had been calculated before any on-site visit had been made.

With these caveats in mind, we still feel that calculating building leakage areas from component information provided by architectural drawings appears to be a sound alternative to direct measurement by blower door. Although calculations without site visits will never yield the accuracy obtainable by direct measurement, they may prove more cost-effective when planning large numbers of retrofits. For new houses, the availability of an accurate and exhaustive list of component leakage areas may be crucial for evaluating the energy efficiency of a proposed design as a basis for suggesting alternative air tightness strategies or trade-offs when necessary.

To be sure, more than the air tightness of a building is involved in estimating air infiltration, but it is air tightness that so far has been least amenable to desk calculations. With the understanding that the values reported in this paper are far from definitive, and that we may have involuntarily omitted some data on measured values of leakage areas of components, we regard this paper as the first in a series of periodic updates. A format for data collection -- component leakage areas at a reference pressure of 4 Pa -- is suggested, but not mandatory for inclusion in this data base. For purposes of transforming other reporting formats to leakage areas we have included appropriate conversion formulae.

New information on component leakage areas does not emanate solely from direct measurements on a component-by-component basis. As in the studies reviewed in this paper, selective systems of components can also be measured. A sufficient number of such aggregate data could be transformed into component leakage areas through multiple linear regression. Indeed, a similar analysis of a large number of measured whole-building leakage areas could yield accurate estimates of component leakage areas, provided that the architectural details of the buildings relevant to air leakage are reported in a consistent format, one of which is suggested in our paper. Of course, it is probable that such a format, even if agreed upon by all air infiltration researchers today, would evolve as new measurements were reported. More window types would likely be added, with more consideration given to international differences in component details. Similarly, fireplaces may be generalized to wood-burning appliances but characterized by a much greater variety of design than the present four entries -- with and without fireplace insert, with and without damper.

Aside from allowing air tightness and air infiltration to be calculated on the basis of drawings alone, the reporting of component leakage areas in a consistent format would be of great assistance in analyzing international differences in building practices. For example, are all Scandinavian houses built tighter than all United States houses, or is this difference less pronounced in new houses? If there are large differences, how do they break down by component or how do they relate to building style? These and similar questions could be addressed more rationally if more component leakage areas were known and reported in a format allowing comparison.

ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and by a grant to Claus Reinhold by the Danish Building Research Institute.

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APPENDIX A
COMPONENT LEAKAGE AREAS

TABLE A-1
SILL FOUNDATION - WALL

Component	Best Estimate	Max	Min	Unit
SILL, caulked per m of perimeter	0.8	1.2	0.4	cm^2/m *
SILL, not caulked per m of perimeter	4	4	1	cm^2/m *

Leakage location: "Walls" if sill is open to outdoors or if slab-on-grade construction;
"Floor" if sill open to crawlspace or basement.

TABLE A-2
JOINTS BETWEEN CEILING AND WALLS

Component	Best Estimate	Max	Min	Unit
JOINTS per m of wall Only if not taped or plastered and no vapor barrier.	1.5	2.5	0.5	cm^2/m *

Leakage location: "Ceiling"

Note: * indicates that Max and Min are not found in the literature. The given values of Max and Min are our estimates.

TABLE A-3
WINDOWS

Component	Best Estimate	Max	Min	Unit
CASEMENT Weather stripped per m^2 window area	0.8	1.2	0.4	cm^2/m^2
Same, not weatherstr.	1.6	2.4	0.8	cm^2/m^2.
AWNING Weather stripped per m^2 window	0.8	1.2	0.4	cm^2/m^2
Same, not weatherstr.	1.6	2.4	0.8	cm^2/m^2
SINGLE HUNG Weather stripped per m^2 window	2.2	2.9	1.8	cm^2/m^2
Same, not weatherstr.	4.4	5.8	3.6	cm^2/m^2
DOUBLE HUNG Weather stripped per m^2 window	3.0	4.4	1.6	cm^2/m^2
Same, not weatherstr.	6.0	8.8	3.2	cm^2/m^2
SINGLE SLIDER Weather stripped per m^2 window	1.8	2.7	0.9	cm^2/m^2
Same, not weatherstr.	3.6	5.4	1.8	cm^2/m^2
DOUBLE SLIDER Weather stripped per m^2 window	2.6	3.8	1.4	cm^2/m^2
Same, not weatherstr.	5.2	7.6	2.8	cm^2/m^2

Leakage location: "Walls"

TABLE A-4
DOORS

Component	Best Estimate	Max	Min	Unit
SINGLE DOOR Weather stripped Per m^2 door	8	15	3	cm^2/m^2
Same, not weatherstr.	11	17	6	cm^2/m^2
DOUBLE DOOR Weather stripped Per m^2 door	8	15	3	cm^2/m^2
Same, not weatherstr.	11	22	7	cm^2/m^2
ACCESS TO ATTIC OR CRAWL-SPACE Weather stripped Per access	18	18	8	cm^2 each *
Same, not weatherstr.	30	30	10	cm^2 each *
Leakage location: "Walls"				

TABLE A-5
WALL - WINDOW FRAME

Component	Best Estimate	Max	Min	Unit
WOOD FRAME WALL With caulking. Per m^2 window	0.3	0.5	0.3	cm^2/m^2
Same, no caulking	1.7	2.7	1.5	cm^2/m^2
MASONRY WALL With caulking Per m^2 window	1.3	2.1	1.1	cm^2/m^2
Same, no caulking	6.5	10.3	5.7	cm^2/m^2
Leakage location: "Walls"				

TABLE A-6
WALL - DOOR FRAME

Component	Best Estimate	Max	Min	Unit
WOOD WALL With caulking Per m^2 door	0.3	0.3	0.1	cm^2/m^2
Same, no caulking	1.7	1.7	0.6	cm^2/m^2
MASONRY WALL With caulking Per m^2 door	1.0	1.0	0.3	cm^2/m^2
Same, no caulking	5	5	1.7	cm^2/m^2
Leakage location: "Walls"				

TABLE A-7
DOMESTIC HOT WATER SYSTEMS

Component	Best Estimate	Max	Min	Unit
GAS WATER HEATER (only if in conditioned space)	20	25	15	cm^2 each *
Leakage location: "Ceiling" (see note at end of appendix).				

TABLE A-8
ELECTRIC OUTLETS AND LIGHT FIXTURES

Component	Best Estimate	Max	Min	Unit
ELECTRIC OUTLETS AND SWITCHES Gasketed	0	0	0	each
Same, not gasketed	0.5	1.0	0	cm^2 each *
RECESSED LIGHT FIXTURES	10	20	10	cm^2 each *

Leakage location: "Walls" for outlets or fixtures in walls;
"Ceiling" for fixtures in ceiling.

TABLE A-9
PIPE AND DUCT PENETRATIONS THROUGH ENVELOPE

Component	Best Estimate	Max	Min	Unit
PIPE PENETRATIONS Caulked or sealed	1	2	0	cm^2 each *
Same, not caulked	6	10	2	cm^2 each *
DUCT PENETRATIONS Sealed or with contin. vapor barrier	1.6	1.6	0	cm^2 each *
Same, unsealed and without vapor barrier	24	24	14	cm^2 each *

Leakage location: "Walls" for penetrations of outside wall surfaces;
"Ceiling" for penetrations of the ceiling;
"Floor" for penetrations going from the living space to crawlspace or basement.

TABLE A-10
FIREPLACE

Component	Best Estimate	Max	Min	Unit
FIREPLACE W/O INSERT Damper closed	69	84	54	cm^2 each
Same, damper open	350	380	320	cm^2 each
FIREPLACE WITH INSERT Damper closed	36	46	26	cm^2 each
FIREPLACE WITH INSERT Damper open or absent	65	90	40	cm^2 each

Leakage location: "Ceiling" (see note at end of appendix).

TABLE A-11
EXHAUST FANS

Component	Best Estimate	Max	Min	Unit
KITCHEN FAN Damper closed	5	7	3	cm^2 each
Same, damper open	39	42	36	cm^2 each
BATHROOM FAN Damper closed	11	12	10	cm^2 each
Same, damper open	20	22	18	cm^2 each
DRYER VENT Damper closed	3	6	0	cm^2 each *

Leakage location: "Walls" for wall fans;
"Ceiling" for ceiling fans (see note at end of Appendix.

TABLE A-12
HEATING DUCTS AND FURNACE

Component	Best Estimate	Max	Min	Unit
FORCED AIR SYSTEMS				
DUCTWORK (only if in unconditioned space)				
Duct joints taped or caulked	72	72	32	cm^2 per house
Duct joints not taped or caulked	144	144	72	cm^2 per house
FURNACE (only if in conditioned space)				
Sealed combustion furnace	0	0	0	each
Retention head burner furnace	30	40	20	cm^2 each *
Retention head plus stack damper	24	30	18	cm^2 each *
Furnace with stack damper	30	40	20	cm^2 each *

Leakage location: "Floor" for ducts in basement or crawlspace;
"Ceiling" for ducts in attic;
"Ceiling" for furnace (see note at end of Appendix.

TABLE A-13
AIR CONDITIONER

Component	Best Estimate	Max	Min	Unit
AIR CONDITIONER Wall or window unit	24	36	0	cm^2 each *

Leakage location: "Walls"

Note on ceiling leakage areas:

In this paper we assign to "Ceiling Leakage" the leakage area of all ducts, fans, stacks, chimneys, and exhaust vents that pierce the ceiling regardless of whether they also cross the roof. Strictly speaking, only leakage paths from the living space to the attic are part of the ceiling leakage area. Air flows from the living space through the roof directly to the outdoors should be calculated separately and added in quadrature to natural infiltration. See, for example, M.H. Sherman and D.T. Grimsrud, "A Comparison of Alternate Ventilation Strategies" in Proc. 3d AIC Conference on Energy Efficient Domestic Ventilation Systems for Achieving Acceptable Indoor Air Quality (The Air Infiltration Centre, Old Bracknell Lane West, Bracknell, Berkshire, RG12 4AH, England, 1982).

When using a blower door to measure leakage area, one should therefore seal all stacks, chimneys and vents in direct communication with the outdoors and calculate the airflow through those openings separately. As in the measurements reported in this paper, this procedure is not always followed in practice. In such cases the ceiling leakage area refers to all air flows, including those through the roof which are then implicitely lumped with natural air infiltration. The error in the resulting air infiltration calculation is usually small, except for houses with large chimneys without dampers.