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ABSTRACT

The mechanism of air infiltration is reviewed as background for introducing a procedure that yields more reliable estimates of average infiltration rates through a window unit than do methods currently employed. The procedure is applied to estimating the average winter heat losses through windows in low-rise residential buildings variously located throughout the United States. It is concluded that, regardless of climate, the heat loss attributable to infiltration through the window unit is small compared with that incurred as a result of direct transmission of heat through the window.

Methods of Estimating Air Infiltration through Windows

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INTRODUCTION

As interest in improving the thermal performance of windows has grown, the need to develop methods for estimating the heat transfer due to air infiltration through the window has become apparent. The reason is simple: heat loss (or gain) by direct transmission through a window and by air infiltration are parallel processes, and one must know the magnitude of both in order to identify the most effective strategy for improvement.

The methodology currently used to estimate air infiltration rates is in considerable disarray. Extensive research on the total air infiltration rate in buildings has shown that any one of the conventional methods for predicting air infiltration rates on the basis of meteorological data may be in error by more than 300%.[1-4] The only relatively reliable method for determining air infiltration rates is direct *in-situ* measurement by tracer-gas techniques; however, this method measures whole-building air infiltration and does not give the air infiltration rate through a single component such as a window. It can be fairly said, therefore, that *at present there exists no widely accepted technique, either experimental or computational, for determining the actual air infiltration rate through a window*. Nevertheless, the need for estimates persists, and those who require them will continue to use available methods despite their drawbacks. The method most frequently used is the ASHRAE crack method.[5] The failings of this procedure for residential buildings are well documented in the research literature, and we expect that over the next few years it will be replaced by one treating the components of the building envelope in terms of their equivalent leakage areas. The purpose of this report (aside from stressing the riskiness of any estimating procedure) is to point out the limitations of the ASHRAE method and to present an expanded procedure which, in our judgement and in the light of current research, is a useful interim solution.

In this report, we first discuss the mechanism of air infiltration and the parameters that must be measured or estimated for its determination. Next we present our method of estimating air infiltration through windows and the ways in which it differs from the ASHRAE procedure. If the estimates resulting from application of this method are such that accuracy and reliability are necessary (i.e., if heat losses due to air infiltration are comparable to those due to direct transmission) it is strongly recommended that the estimate be experimentally checked. We briefly discuss limitations on the validity of the estimating procedure and then apply it to a calculation of winter heat loss due to air infiltration through windows at various urban locations around the United States.

THE MECHANISM OF AIR INFILTRATION

Air flow through orifices or channels is a well studied phenomenon and is known to obey the following relation:

$$Q = K(\Delta P)^n, \tag{1}$$

where

- Q = the flow rate through the channel or orifice
- K = a parameter characterizing the effective area of the orifice or channel
- ΔP = the pressure difference across the orifice or channel
- n = an exponent, $\frac{1}{2} \leq n \leq 1$, which characterizes the flow.

For flow at fixed ΔP through a single channel, n=1 for a very long, thin channel in which the flow is laminar. As the smallest transverse dimension of the channel increases, transition to turbulent flow takes place and n decreases to $\frac{1}{2}$. Thereafter, further increases in the channel dimensions have no effect on n. Conversely, for a channel of given dimensions the flow is laminar (n=1) below a characteristic pressure difference and turbulent ($n=\frac{1}{2}$) above a second (somewhat higher) pressure difference. Between these two values of pressure difference is a transition region for which one can say only $\frac{1}{2} \leq n \leq 1$.

If the channel is shorter than a critical length, called the entrance length, there will be insufficient time for laminar flow to develop, even for a very narrow channel. In this case, it is quite possible to have turbulent flow even for the narrow cracks found in a tightly-fitting window. If they are sufficiently short, these cracks behave as orifices whose effective size, however, is smaller than their geometric size by a ratio known as the discharge coefficient.

Careful measurements on simple windows with fixed crack size[6] show that at pressure differences above 24.9 Pa (0.1 in. H_2O) cracks of 1/16" or larger have essentially turbulent flow. Because any real window will have leaks of varying sizes, however, it is not possible to predict the dependence of the flow rate on the pressure difference. This dependence is typically measured using a technique described in ASTM Standard E-283[7] in which a pressure differential is placed across the window and the resulting flow rate through it is measured as a function of the pressure difference. From these measurements, K and n can then be determined. Once the value of K and n are determined, it is necessary to know only the (average) value of ΔP in order to predict the air infiltration. It is in calculating this quantity that all of the current methods fail. A brief description of the origins of ΔP will make it clear why the calculation is a difficult one.

Two separate effects, temperature differences and wind, each produce a pressure difference between the interior and exterior of a building. We consider first the case where there is no wind. Air at equilibrium at a given temperature has a pressure that varies approximately linearly with height, with a slope proportional to the density of the air. Since the density is, in turn, (inversely) proportional to the temperature, it follows that two volumes of air at different temperatures will have a pressure difference between them that varies linearly with height and is proportional to temperature. This is termed the "stack effect". The inside and outside pressures can equalize at only one height, called the neutral level. This pressure difference drives the air flow through leaks in the building envelope, outward (exfiltrative) above the neutral level and inward (infiltrative) below. This flow, in turn, reduces the pressure differences (i.e., changes the height of the neutral level). The net result is that ΔP is given by

$$\Delta P = \Delta P_o - \rho g h \frac{\Delta T}{T}, \qquad (2)$$

where

ΔP_o	= the internal pressure shift
ρ	= the outside air density
g	= the gravitational acceleration
h	= the height above grade
T	= the inside temperature
ΔT	= the inside-outside temperature difference

The only unknown in this equation is ΔP_o, the difference between the internal and external pressure at grade level, which depends on the sizes and locations of leaks in the building envelope.

A similar situation occurs in the case of wind. A wind blowing on a building exerts a static pressure on the center of the windward wall equal to

$$P_s = \tfrac{1}{2}\rho v^2,$$

where v is the local wind velocity. At other points the pressure exerted on the building shell depends on the air-flow pattern around the building; in general, a pressure above the static ambient pressure is exerted on the windward face(s) of the building and a pressure below static ambient is exerted on the side and leeward faces. Therefore, a flow through the building envelope occurs -- infiltrative in the region where there is a net overpressure on the shell and exfiltrative elsewhere. The interior pressure adjusts itself such that the infiltrative and exfiltrative flows are equal. Thus, again, the pressure difference across the building envelope depends on the sizes and distribution of leaks in the envelope.

In the case where both wind and an inside-outside temperature difference are present, the height of the neutral level and ΔP_o (the internal pressure shift at grade level) adjust themselves so that the total inward flow through leaks on the upwind side is equal to the total outward flow through leaks on the downwind side. The pressure difference ΔP across the envelope varies with height as given by Eq. (2) and drives a flow, as given by Eq. (1), through any given leak. In other words, the value of ΔP_o results from a complicated equilibrium process that depends on the sizes and distribution of leaks in the building envelope, the magnitude (and direction) of the wind velocity, the actual flow pattern of wind around the building envelope, and the internal and external temperatures.

Two additional effects complicate the calculation of wind-dominated infiltration. Unless directly measured, the local wind speed must be calculated from measurements taken by a weather station at some other location. This reading will correspond to the wind speed at a set height (generally 10m) and adjustment must be made for the fact that wind is a boundary layer flow, in which speed increases significantly with height. Specifically,

$$v(H) = v_o \alpha \left[\frac{H}{10}\right]^{\gamma}, \tag{3}$$

where

v_o	= the wind speed under standard conditions
H	= the height above grade
α and γ	= constants that depend on the type of terrain.

Values of α and γ for various classes of terrain are listed in Table 1.

Equation 3 enables one to estimate the mean wind speed at a given height from the recorded wind speed at a different height and possibly a different class of terrain. (The reliability of the estimate decreases, however, if the recording station is far from or in a different type of terrain from the location for which the estimate is made, and the estimate cannot be used if there are major geological features such as mountains or ranges of hills between the two locations.) The value of the speed that results from the equation represents the free-stream speed. The local velocities in the vicinity of the building walls, which determine the pressures exerted on the walls, depend on the pattern of wind flow around the building and the presence of objects in its immediate neighborhood (trees, other buildings, etc.). Both of these effects modify the pressure exerted on the walls. Letting

$$P_s = \frac{1}{2}\rho[v(H)]^2$$

be the static-pressure equivalent of the free-stream wind velocity, the pressure on the i^{th} building face (i = roof, wall 1, etc.) is

$$P_i = C_i \, P_s. \tag{4}$$

The constants C_i are called shielding coefficients and are determined from wind-tunnel measurements.[8] They depend both on the shape and orientation of the building (relative to the wind) and on the nature of its surroundings.

ESTIMATING WINDOW INFILTRATION RATES

We are now in a position to outline the proper method for estimating the air infiltration through a window.

Two kinds of estimates may be made. One may calculate the average infiltration through a particular window or the total infiltration through an average window--that is, the net impact on the house of the air leakage, considering all the windows in a given story to be identical. In the following calculation we consider the latter case. For the case of a particular window one would do step (8) below differently (omitting the factor of $\frac{1}{2}$) and might also treat the effects of shielding differently (since a particular window may have a specific orientation relative to the prevailing wind direction).

(1) Determine the pressurization curve. For windows in low-rise buildings, this curve should be determined by making measurements in the range 1 - 10 Pa, which is characteristic of the pressure differences induced by weather variations, rather than the 26 - 75 Pa range suggested in the ASTM standard and by ASHRAE. The measurements should be done in-situ [9] because the leakage rate of installed windows may differ substantially from their pre-installation values.[10] In the absence of detailed low-pressure measurements, the curve of Eq. (1) can be estimated on the basis of a single pressurization measurement to determine K and by assuming that n=0.65, as suggested by whole-building research.[14] In this case, however, the sensitivity to this assumption should be tested by repeating all calculations, first assuming $n=\frac{1}{2}$ and then assuming n=1.

Test data on air leakage of windows is often expressed as a ratio of the leakage rate measured at a particular pressure to the nominal crack length of the window. While this may be a convenient way of specifying performance standards, it should be clear from our previous discussion that the nominal crack length bears no physical relationship to the number or dimensions of leaks in the window. This is particularly true of weatherstripped windows, where the major leaks occur at discontinuities in the weatherstripping.[10] Therefore, measurements on one window should not be extrapolated to another window of different size or shape on the basis of nominal crack length.

The next step is to compute the pressure difference. To do this we use the fact that in typical buildings the air infiltration through windows is a small part of the total leakage (on the order of 20%).[11] We therefore assume that the pressure differences are determined by the overall leakage of the building envelope and compute them following the approach developed by M.H. Sherman and D.T. Grimsrud[12] on whole-building infiltration rates.

(2) Separate the infiltration rates into stack-dominated and wind-dominated components. We denote the stack-dominated infiltration rate by Q_s and the wind-dominated by Q_w and compute them separately. If both are important, we assume (following Ref. 12) that the total is estimated by

$$Q = \sqrt{Q_s^2 + Q_w^2} \ . \tag{5}$$

(3) Determine the height of the neutral level. Denote this height by h_o. Then

$$\Delta P_o = \rho g h_o \frac{\Delta T}{T} . \tag{6}$$

(4) Calculate the stack-driven infiltration. Once ΔP_o is determined, the pressure difference can be computed as a function of height from Eq. (2) and the infiltration (or exfiltration) rate at that height from Eq. (1). This infiltration (exfiltration) rate should then be summed over the portion of the window below (above) the neutral level. One should first calculate the order of magnitude of the stack-driven infiltration by assuming that h_o is half the building height. If the

infiltration rate turns out to be important, a more accurate value of h_o can then be obtained either by the calculation procedure described by ASHRAE or by direct measurement. (The treatment of the stack effect presented here is equivalent to that of the ASHRAE method.)

(5) Estimate the local wind speed. Using Eq. (3) and the constants given in Table 1, we estimate the free-stream wind speed at ceiling height, given by

$$v_R = v_M \frac{\alpha_R \left[\frac{H_R}{10}\right]^{\gamma_R}}{\alpha_M \left[\frac{H_M}{10}\right]^{\gamma_M}} \tag{3A}$$

where

v_R = free-stream wind speed at ceiling height

v_M = wind speed at measuring station

H_R = ceiling height

H_M = height of measurement sensor

α_M, γ_M = constants from Table 1 appropriate to location of measurement station

α_R, γ_R = constants from Table 1 appropriate to location of building.

(For a multistory structure, we make a separate estimate of v_R for each story.) We denote

$$P_R = \tfrac{1}{2} \rho v_R^2 \tag{6A}$$

as the static pressure equivalent to the free-stream wind.

(6) Use angle-averaged shielding coefficients. In Ref. 12, the whole-house infiltration problem is solved by using the wind-tunnel measurements of Ref. 8 for isolated buildings, equating the infiltrative and exfiltrative flows to determine the interior pressure level and estimating the effects of surrounding structures from separate wind-tunnel measurements.[13] We use their result here:

$$\Delta P_W = \Omega \; P_R \tag{7}$$

where ΔP_W is the magnitude of the average wind-induced pressure difference across the building envelope and Ω is an averaged shielding coefficient.

The values of Ω for various conditions of local shielding of the building by objects of comparable height are given in Table 2, and are derived from the infiltrative shielding coefficients in Ref. 2. (Note that for multistory buildings, "comparable height" means height comparable to the height of the story under consideration.)

The quantity ΔP_W is the mean pressure difference between the interior and exterior of the exfiltrating (or infiltrating) portion of the building envelope; i.e., the exfiltrating portion is driven, on the average, by a pressure difference $+\Delta P_W$ and the infiltrating portion, by $-\Delta P_W$. For each building face, the average of ΔP_W is computed over all angles for which that face is exfiltrating.

Steps (5) and (6) constitute the major difference between this procedure and the ASHRAE methodology, which, because it makes no height correction and uses a shielding coefficient that is never smaller than $1/2$, results in a great overestimate of ΔP_W for low-rise structures.

(7) Separate the infiltrating and exfiltrating roles of the window. Calculation of the wind-driven air infiltration, Q_W, can now proceed by inserting ΔP_W into Eq. (1); this use of ΔP_W replaces the actual infiltration (which varies with time) by an average situation in which all windows are under a pressure difference of the same absolute magnitude.

In this situation half the windows will be infiltrating and half exfiltrating; therefore,

$$Q_w = \tfrac{1}{2}\ \dot{K}\ (\Delta P_w)^n \ . \tag{8}$$

This equation is analogous to the ASHRAE stipulation that half the crack length be used in the calculation.

ACCURACY AND LIMITATIONS OF THE METHOD

Any general estimating procedure will yield only approximate results when applied to specific situations. The procedure described here is intended to provide a more reliable estimate of the relative magnitude of air infiltration rates through windows than the ASHRAE procedure. In most situations this method produces estimates that are considerably smaller than those produced by the ASHRAE method and, generally, the uncertainties in the estimate will be small relative to those associated with other heat losses in the building. If accurate values of air infiltration rates are needed, however, there is no substitute for direct measurements, for which one should measure both the low-pressure leakage characteristic of the window and the value of ΔP_w. The measurements of ΔP_w should then be correlated with measurements of wind speed taken at a weather station as a check on the estimate of the seasonal average of ΔP_w calculated from weather data and shielding coefficients. One should also check that the neutral level height is not too far from the mid-height. These measurements are quite difficult to make.

Although the estimation procedure presented here--an application of the whole-house method of Sherman and Grimsrud to the prediction of single-component infiltrations--has not been tested, its chief uncertainities are the same as for the whole-house case and should have comparable accuracy. In Ref. 12 a comparison between predicted whole-house infiltration rates and measured rates for fifteen different houses showed an RMS deviation of about 5%, with the largest single deviation an underprediction of 60%. Subsequent work has suggested uncertainties varying from 25% for a one-hour estimate to 10% for a one-week average.*

*D. Grimsrud. 1981. Private communication.

In specific situations, several general assumptions of the procedure could lead to incorrect results. First, our method assumes that wind conditions are isotropic when averaged over a season. For locations where there is a strong prevailing wind direction, the averaging procedure used would be incorrect. Sherman and Grimsrud believe this effect to be responsible for the few large deviations they observed between measured and predicted values. For these weather conditions it is possible to construct a different procedure from that given by Eq. (7) by using information contained in Ref. 12, 8 and 13. Second, it is necessary to bear in mind that the shielding coefficients in Table 2 are based on the measurements in Ref. 8 which, because they are for rectangular, flat-roofed buildings, could produce inaccurate results for buildings of markedly different shape. Third, it is assumed that leaks in the building envelope are relatively uniformly distributed. The presence of a single large leak, such as an open flue or fireplace, could produce large inaccuracies.

We note also that using the mean wind speed and the Sherman and Grimsrud results implicitly assumes $n = 1/2$. A more accurate averaging of wind pressures and shielding coefficients, however, would yield only slightly different numeric results and, considering the uncertainty in the estimates arising from other sources, one can hardly justify the labor involved in a more detailed calculation.

EXAMPLE CALCULATIONS

To illustrate how the parameters and assumptions enter the estimating procedure, we calculate the air infiltration for two hypothetical residential-sized windows; one, a reasonably tight double-hung, double-glazed window with $7.7 \times 10^{-4} m^2/s$ (0.5CFM/ft) leakage at 69 Pa and the other an unweatherstripped, single-glazed, loosely fitting window with $2.0 \times 10^{-3} m^2/s$ (1.3 CFM/ft) at 25 Pa. These examples are chosen to contrast the type of "worst-case" loosely fitting window with $2.0 m^2/s$ (1.3 CFM/ft) at 25 Pa that is commonly found in older houses with the type of "tight" window that might be found in energy-conscious new construction. We assume indoor and outdoor temperatures of 20 °C and 0 °C, respectively, and a 6.7 m/s (15 MPH) wind at a nearby weather station of 10-m height. We assume the terrain to be suburban (class III), the weather station to be located at an airport (class II), and the window to be located in a one-story structure (ceiling height, 4m) with light local shielding. The results of this calculation are given in Table 3.

ESTIMATING WINTER HEAT LOSS DUE TO AIR INFILTRATION

We next apply our method to estimating the winter heat loss rate due to air infiltration. We consider a double-hung window of the same dimensions as in the previous example (1.25m high by 0.8m wide) placed in a one-story building of the same characteristics, i.e., suburban (class III), light local shielding, and ceiling height 4m above grade. We then calculate the heat loss through this window at a number of locations around the United States. The heat loss rate is expressed as a fraction of the loss rate incurred by direct thermal transmission through the window (i.e., U-value), allowing us to present a number that is relatively independent of outside temperature.

We consider both single- and double-glazed windows and treat four levels of air leakage: "very leaky" (corresponding to the ASHRAE case of a "loosely fitting window, much worse than average"[5]), "leaky" (corresponding to either an unweatherstripped window with average fit or a weatherstripped window with loose fit--$7.0 \times 10^{-4} m^2/s$ (0.45 CFM/ft) at 24.8 Pa), "tight" (characterized by a leakage of $7.7 \times 10^{-4} m^2/s$ (0.5 CFM/ft) at 75 Pa, a common standard specified by many manufacturers of weatherstripped windows), and "very tight" (taken to be half the "tight" leakage rate and corresponding to the best performance reported in Ref. 10 for double-hung windows). The extreme cases of a "very tight" single-glazed window and a "very leaky" double-glazed window were omitted from the calculation.

Stack-induced infiltration was omitted from this calculation since it is smaller than wind-induced infiltration (on the order of 30%) for single-story structures. It increases to 67% in the worst case for two-story structures and becomes increasingly important in multistory structures. The mean winter wind speed was computed for each location from compiled data on seasonal wind-speed distributions.[15] (Winter is taken to be the months of December through February.)

The results of the calculation, shown in Table 4, are striking. The heat loss due to air infiltration is a rather constant percentage of the direct transmission loss through the window, and this percentage depends relatively weakly on location. Air infiltration is always less than 30% of the direct transmission loss, more typically less than 20% and, for reasonably well weatherstripped windows, often less than 10%. For comparison, at the bottom of the table we list the values which would result from applying the ASHRAE method, i.e., assuming a 6.7 m/s wind speed at the window.

The situation is somewhat different if one considers instantaneous rather than average conditions. In the case of Minneapolis, for a wind speed that is exceeded 10% of the time, for example, the (instantaneous) infiltrative heat loss increases to about 40% of the conductive loss for the very leaky window presented in Table 4. If we bear in mind that this is an average between infiltrating and exfiltrating windows, we see that for an infiltrating window (where the heat loss actually appears as cold air) the effect is to approximately double the heat-loss rate of the window. It becomes clear, then, that air infiltration has a much greater effect on thermal comfort and the peak load of the heating system than on seasonal energy consumption.

SUMMARY AND CONCLUSIONS

We have discussed the mechanisms of air infiltration and attempted to show why the ASHRAE procedure may produce inaccurate estimates of seasonal average air infiltration rates through windows. We have then applied recent research results to produce a more reliable estimating procedure for predicting these rates. After a discussion of limitations of the method and a brief sample calculation, we applied our procedure to estimating the winter seasonal heat loss due to air infiltration through windows at various urban locations around the United States.

These estimates show quite strikingly that for low-rise residential buildings the winter energy loss due to air infiltration through the window unit is small compared to the energy loss attributable to the direct transmission of heat through the window. This relationship was consistently observed, regardless of the location or window leakage rate considered. Because this result is quite different from that obtained when instantaneous rates under extreme or design conditions are considered, it is clearly important that seasonal average performance be correctly treated if the impact of conservation measures for dynamic building elements such as windows is to be properly evaluated.

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TABLE 1. 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, trees, etc.
IV	0.25	0.67	Urban, industrial, or forest areas
IV	0.35	0.47	Center of large city (e.g., Manhattan)

TABLE 2. Generalized Shielding Coefficient vs. Local Shielding		
Shielding Class	Ω	Description
I	0.420	No obstructions or local shielding whatsoever
II	0.325	Light local shielding with few obstructions within two house heights
III	0.230	Moderate local shielding, some obstructions within two house heights
IV	0.137	Heavy shielding, obstructions around most of perimeter
V	0.042	Very heavy shielding, large obstructions surrounding perimeter within two house heights

TABLE 3. Sample Evaluation for Two Windows

Quantity	Value	Source
Interior Temperature	20 ^oC	Assumed
Exterior Temperature	0 ^oC	Assumed
h_o	2 m	Assumed
ΔP_o	1.7 Pa	Eq. 6
Height of window center	2 m	Assumed
$\langle \Delta P_{stack} \rangle$	0.3 Pa	Average Eq. 2 over upper half of window
v_m	6.7 m/sec (15 MPH)	Assumed
v_R	4.7 m/sec (11 MPH)	Eq. 3A
P_R	14.2 Pa	Eq. 6A
Ω	0.33	Table 2
ΔP_w	4.7 Pa	Eq.7
LEAKY WINDOW		
Area	1. m^2	Assumed
Crack Length	4.9 m	Assumed
Leakage/ft crack	$2.0 \times 10^{-3} m^2/s$ (1.3 CFM/ft)	Assumed
n	0.65	Assumed
K	$1.20 \times 10^{-3} m^3 s^{-1}/(Pa)^{.65}$	Eq. 1
Q_s	$5.2 \times 10^{-4} m^3/s$	Eq. 1
Q_w	$1.6 \times 10^{-3} m^3/s$	Eq. 8
$\left[\frac{\text{Heat Lost thru Infiltration}}{\text{Conductive heat loss}}\right]$	33%	Assume single glazing, no humidification
TIGHT WINDOW		
Area	1.0 m^2	Assumed
Crack Length	4.9 m	Assumed
Leakage/ft crack	$7.7 \times 10^{-4} m^2/s$ (0.5 CFM/ft)	Assumed
n	0.65	Assumed
K	$2.2 \times 10^{-4} m^3/s/(Pa)^{.65}$	Eq. 1
Q_s	$9.4 \times 10^{-5} m^3/s$	Eq. 1
Q_w	$3.0 \times 10^{-4} m^3/s$	Eq. 8
$\left[\frac{\text{Heat Lost thru Infiltration}}{\text{Conductive heat loss}}\right]$	13%	Assume double glazing, no humidification

TABLE 4. Infiltrative Heat Loss for Windows in Various U.S. Locations

CITY	WINTER MEAN WIND SPEED (M/S)	Infiltrative Heat Loss / Conductive Heat Loss (%) SINGLE GLAZING VERY LEAKY	SINGLE GLAZING LEAKY	SINGLE GLAZING TIGHT	DOUBLE GLAZING LEAKY	DOUBLE GLAZING TIGHT	DOUBLE GLAZING VERY TIGHT
Altanta	3.7	16.5	5.8	3.0	13.0	6.7	3.3
Baltimore	4.5	14.4	5.1	2.6	11.4	5.8	2.9
Boston	6.1	30.4	10.6	5.5	23.9	12.3	6.1
Chicago	4.9	23.1	8.4	4.2	18.9	9.4	4.7
Dallas	4.6	21.5	7.5	3.9	17.0	8.7	4.3
Denver	4.3	15.2	5.3	2.7	12.0	6.1	3.1
Detroit	5.0	17.8	6.6	3.2	14.1	7.2	3.6
Los Angeles	2.8	5.3	1.9	0.9	4.2	2.1	1.1
Minneapolis	4.4	19.8	7.0	3.6	15.6	8.0	4.0
New Orleans	4.0	17.7	6.2	3.2	14.0	7.1	3.6
New York	5.6	27.7	9.7	5.0	21.7	11.1	5.6
St. Louis	4.4	20.0	7.0	3.6	15.8	8.1	4.0
Seattle	4.0	17.5	6.2	3.2	13.9	7.1	3.5
San Francisco	2.6	8.7	3.1	1.6	6.9	3.5	1.8
ASHRAE METHOD, 6.7 M/S AT WINDOW		103.	36.	18.	81.	42.	21.

REFERENCES

1. H. D. Ross and D. T. Grimsrud. 1978. Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda, Lawrence Berkeley Laboratory report, LBL-7822.

2 D.T. Grimsrud, M.H. Sherman, R.C. Diamond, P.E. Condon, and A.H. Rosenfeld. 1978. Infiltration-Pressurization Correlations: Detailed Measurement on a California House, Lawrence Berkeley Laboratory report, LBL-7824.

3. D.T. Grimsrud, M.H. Sherman, R.C. Diamond, and R.C. Sonderegger. 1979. Air Leakage, Surface Pressures and Infiltration Rates in Houses, Lawrence Berkeley Laboratory report, LBL-8828.

4. D.T. Grimsrud, M.H. Sherman, A.K. Blomsterberg, and A.H. Rosenfeld. 1979. Infiltration and Air Leakage Comparisons: Conventional and Energy-Efficient Housing Designs. Lawrence Berkeley Laboratory report, LBL-9157.

5. ASHRAE Handbook of Fundamentals, 1977. American Society of Heating, Refrigerating and Air Conditioning Engineers, Philadelphia, PA

6. H.J. Sabine, M. B. Lacher, D. R. Flynn, and T. L. Quindry. 1975. Acoustical and Thermal Performance of Exterior Residential Walls, Doors and Windows. Washington, DC., National Bureau of Standards, NBS-BSS-77.

7. Annual Book of ASTM Standards. 1980. American Society for Testing and Materials, New York, NY.

8. R.E. Akins, J.A. Peterka, and J.E. Cermak. 1979. Average Pressure Coefficients for Rectangular Buildings, in Proceedings of the Fifth Int. Conf. on Wind Energy Engineering, Boulder, Colorado.

9. A method for measuring air flows at low pressures in the presence of weather fluctuations is given in M.H, Sherman, D.T. Grimsrud, and R.C. Sonderegger. 1979. The Low Pressure Leakage Function of a Building, Lawrence Berkeley Laboratory report, LBL-9162.

10. J.L. Weidt, J. Weidt, and S. Selkowitz. 1979. Field Air Leakage of Newly Installed Residential Windows. Lawrence Berkeley Laboratory report, LBL-9937.

11. G.T. Tamura. 1975. Measurement of Air Leakage Characteristics of House Enclosures. ASHRAE Trans. 81, 202.

12. M.H. Sherman and D.T. Grimsrud. 1980. Measurement of Infiltration Using Fan Pressurization and Weather Data, in Proceedings of 1st Annual Air Infiltration Centre Symposium on Instrumentation and Measurement Techniques, International Energy Agency, Windsor, United Kingdom. October, 1980. In revised form: Lawrence Berkeley Laboratory report, LBL-10852.

13. B.E. Lee, M. Hussain, and B. Soliman, 1980. Predicting Natural Ventilation Forces Upon Low-Rise Buildings. ASHRAE Journal Feb., p. 35.

14. R.K. Beach. June 1979. Relative Tightness of New Housing in the Ottawa Area. Division of Building Research, National Research Council of Canada, Ottawa. Building Research Note No. 149.

15. C. G. Justus, W. R. Hargraves, and A. Mikhail. 1976. Reference Wind Speed Distributions and Height Profiles for Wind Turbine Design and Performance Evaluation Applications. School of Aerospace Engineering, Georgia Institute of Technology. Technical Report ORO/5108-76/4.