A PREDICTIVE METHOD TO DETERMINE THE LEAKAGE AREA NEEDED IN RESIDENCES FOR IAQ CONTROL BY INFILTRATION

Donald G. Colliver, Ph.D., P.E., Fellow ASHRAE
University of Kentucky

ABSTRACT

A technique has been developed to estimate the equivalent leakage area needed in residences to provide a quantity of infiltration-driven air exchange which exceeds a design value for a desired level of frequency of occurrence. The technique presented applied an air infiltration simulation model to hourly long term weather data to provide hourly estimates of the infiltration weather factor. Cumulative frequency distributions (CFD) were then used to describe the distribution of these data when 1-, 3-, 6-, 8-,12-, 24-, and 48-hour time periods were grouped together. The CFDs were developed for ten locations in North America. An example is presented to determine the necessary equivalent leakage area required to provide a minimum level of infiltration over various time periods. Comparisons between the leakage area required to provide 0.35 ACH on the average as opposed to at least 95% of the 1-, 8-, 12-, and 24-hour time periods are also presented.

INTRODUCTION

There has been a tremendous push toward reducing the energy usage in buildings. It is estimated that 30-50% of the energy used to provide heating and cooling in residences is used to condition the outside air infiltrating into buildings. Thus reducing the amount of infiltrating air has the potential to greatly to reduce the energy usage in residences.

As a repercussion, problems arose concerning the reduction of the fresh outside air which diluted the indoor air which had become polluted from the occupants and contents of the interior spaces. Indoor Air Quality (IAQ) has become extremely important as the houses have become tighter and tighter.

There are obvious tradeoffs involved as the indoor environment designers attempt to minimize the infiltration values while maximizing the outdoor air exchange to provide for adequate indoor air quality. In summary the tradeoffs can be simplified to: “How tight should my house be to reduce energy costs and how loose should it be to provide a healthy environment?” or “How tight is too tight?”

Several standards have been developed to attempt to indirectly respond to this question. In North America the primary response has been the development of ASHRAE Standard 62-1999, *Ventilation for Acceptable Indoor Air Quality* (ASHRAE 1999). Several states and building code organizations have incorporated earlier versions of this standard (ANSI/ASHRAE Standard 62-1989 or ASHRAE Standard 62-1981) into their building codes.

Standard 62-1999 has a general requirement for outdoor ventilation of residential facilities at a rate of 0.35 air changes per hour (ACH). However there are no specifications concerning if this is the average ACH over some time period or if 0.35 ACH has to be provided for each hour of the entire year. Specific airflow (or installation of openable window) requirements are given for kitchens, bath/toilets and garages. The problem with this approach for the large majority of residential structures in North America is that infiltration is relied on to provide the ventilation. Mechanical outside air intake ventilation is not commonly used. Mechanical ventilation is usually found in larger commercial, industrial and/or high rise residential buildings containing central air handling units. It should be recognized that mechanical ventilation could be used to provide the necessary ACH in residences, however for simplification of this work and also recognizing that many residences do not used ducted heating and cooling systems, it is assumed that mechanical fresh air ventilation is not provided.

The infiltration rate varies with weather and is not constant. As the wind speed and/or the inside-outside temperature difference changes there is a corresponding change in the infiltration rate. Therefore determining the amount of leakage in the house needed to provide 0.35 ACH is impossible since there are no time references to the ACH requirement. That is, there are no indications if the specified ACH must be provided every hour of the year or if this is an average ventilation over some specified time window such as a year, month, day, or even an 8 hour occupancy time period. While ANSI/ASHRAE Standard 136-1993 (ANSI/ASHRAE 1993) has been used to determine the effective air change rates in detached dwellings (Interpretation IC 62-1989-15 of ANSI/ASHRAE Standard 62-1989), Standard 136 describes the annual average values and doesn’t address the variability of infiltration due to actual long term weather conditions.

A need therefore exists to be able to predict the variability of the ACH or amount of time a structure will have various levels of infiltration driven ventilation. If this variability is known, then a level of leakage may be established which will provide a minimum (or average) level of infiltration over a given number of hours for a specified probability.

The goal of the research reported in this paper is to develop a technique to determine the necessary leakage area in a residence (a measure of leakiness) to provide a minimum (or average) value of infiltration at a specified frequency of occurrence. The objective of this paper is to present the background and development of this technique along with some of the simplifying assumptions which were used and then demonstrate its use.

BACKGROUND

Pollutant Concentration:

The concentration of air pollutants inside a building can be described by the mass balance governing equation:

$$\left(\frac{dC}{dt}\right) * V = \left(\frac{dG}{dt}\right) + \left(\frac{dS}{dt}\right) + Q\left(C_o - C_i\right)\left(\frac{dQ}{dt}\right) \qquad (1)$$

where:

C = pollutant concentration
V = effective volume
G = pollutant generation
S = pollutant storage
Q = indoor to outdoor air movement
$_{i,o}$ = subscripts representing indoor and outdoor locations

It is assumed that:

a) the pollutant generation/source is constant,
b) the change and absolute value of storage of pollutants is insignificant,
c) the pollutant concentration in the outdoor air is insignificant (or if it is, then we are looking at the pollutant levels above the outdoor levels), and
d) the enclosure is fully mixed,

then the mass balance equation reduces to:

$$\left(\frac{dC}{dt}\right) = \left(\frac{G}{V}\right) - \left(\frac{QC}{V}\right) \qquad (2)$$

Integrating this equation yields the pollutant concentration:

$$C = \left[G - (G - QC_o)e^{(\frac{-Qt}{V})}\right] / Q \qquad (3)$$

where:

C_o = initial pollutant concentration.

It can be seen from this equation that the pollutant concentration is directly related to the airflow across the building envelope. For residential structures this is typically supplied by infiltration.

Airflow Across the Building Envelope:

The air movement through a building skin can be the result of three different modes of air exchange: *forced ventilation, natural ventilation, and infiltration.* Forced ventilation is the air movement across the building envelope due to a mechanical or forced-air moving system such as air distribution and/or exhaust fans. The use of forced ventilation systems is the most typical technique to provide fresh air ventilation for commercial, industrial and high-rise residential structures. The exclusive use of a constant, forced ventilation system to provide fresh air is not typically utilized in North American low-rise residential structures.

Natural ventilation is the air movement through intentional operable openings such as open windows and doors and is the result of pressure differences due to wind and indoor-outdoor temperature differences. Opening windows and doors to provide natural ventilation is commonly used and provides large amounts of fresh air. However it is not efficient to use during times with large inside-outside temperature differences and is often not used at all by individuals with allergy problems.

Infiltration is the air movement due to wind and stack pressure differences across non-intentional openings in the building envelope. It is the primary method of providing outdoor ventilation when mechanical ventilation does not contribute and operable openings are closed. Historically there was sufficient quantity of infiltration air exchange to provide adequate indoor air quality. However as the non-intentional openings have been reduced due to better construction materials and techniques, the quantity of outdoor air is not sufficient to provide adequate IAQ.

The infiltration rate can be thought of as the airflow rate necessary to provide for the exchange of one complete volume of air in the space being considered. It is defined as:

$$I = \frac{Q}{V} \tag{4}$$

where:

I = Infiltration rate, m^3 /m^3-hr
Q = Air flowing across the building envelope (direction from outside to inside is positive), m^3/hr
V = Volume of the building, m^3

The mass of the air flowing into the building (infiltration) is the same as the air flowing out of the building (exfiltration) so by continuity (neglecting the change in density due to temperature effects):

$$Q_{in} = Q_{out} = Q \qquad (5)$$

and the subscripts do not need to be considered. However it should be noted that the airflow being discussed as necessary for IAQ is one-half of the total airflow across the building envelope (i.e. Only the inward-bound air is being considered.).

Thus the airflow needed for ventilation can be described by:

$$Q = I * V \qquad (6)$$

This airflow is proportional to the pressures driving the airflow through the openings in the building skin:

$$Q \propto f\text{ (stack pressure, wind pressure, mechanically induced pressure)} \qquad (7)$$

where:

stack = pressure due to the difference in the densities of the air due to the different inside and outside temperatures
wind = pressure due to the kinetic energy of the wind around the building
mechanically induced = pressure due to the pressurization (intake) and/or suction (exhaust) fan(s).

Because of the reasons previously mentioned, it will be assumed for this study that mechanical ventilation does not contribute to bringing in outdoor air and the last term of (7) may be neglected. The functional form of the airflow then reduces to:

$$Q \propto f(\text{stack, wind}) \qquad (8)$$

A considerable amount of research worldwide has been conducted to develop this functional relationship into an “infiltration model”. Techniques for calculating building air exchange rates have improved in recent years (ASHRAE 1997, Liddament 1996, Orme 1999). Several empirical, single-cell and multi-cell models have been developed (Allard et al 1990, Cole *et al.* 1980, Etheridge and Alexander 1980, Feustel and Smith 1997, Liddament 1989, Sherman and Grimsrud 1980). Orme (1999) and Liddament (1996) provide good reviews of the various models.

The LBL Model (Sherman and Grimsrud 1980) is a single cell infiltration model which has been used widely and is used in example calculations in the ASHRAE *Handbook - Fundamentals* (1997). Single cell models are appropriate to buildings with little or no internal resistance to airflow and are commonly used to describe residential ventilation. This model uses information about the amount and distribution of leakage in the structure, building height, local terrain and shielding characteristics to describe the airflow due to the stack and wind effects. It can be simplified to:

$$Q = L\,(C_1 * \Delta T + C_2 * v^2)^{½} \qquad (9)$$

where:

L = Effective leakage area of the building, cm^2
ΔT = Absolute value of the inside - outside temperature difference for the time interval of the calculation, ^oC
v = Average wind speed for the time interval of the interest, m/s
C_1 = Stack coefficient, $(L/s)^2(cm)^{-4}(^oC)^{-1}$
C_2 = Wind coefficient, $(L/s)^2(cm)^{-4}(m/s)^{-2}$

The effective leakage area (ELA) has been commonly used as a measure of the “tightness” of the structure. It is the area of a sharp-edged orifice with a unity discharge coefficient which would provide a similar response to the flow versus applied pressure differential curves of the sum of unintentional openings in the structure. The ELA of a structure is commonly found via blower door tests for whole house measurements (ASTM 1987, Murphy et al. 1991). It can also be estimated by summing the individual leakage from the various building components using tables of typical ELA values (ASHRAE 1997, Colliver et al. 1992).

It will be assumed that the ELA remains constant over time for this analysis. This means that it is assumed that the seasonal variation in ELA due to shrinking/ swelling of structural components is small compared to the total leakage of the structure. It is also assumed that the natural ventilation from the intentional opening of windows and doors is insignificant.

The stack coefficient is an semi-empirically derived coefficient which accounts for the height of the inside and outside columns of air with different densities and the distribution of the leakage within the building envelope. Values of the stack coefficient for one, two and three stories of house height are given in ASHRAE (1997).

The wind coefficient is another semi-empirically derived coefficient which accounts for the effect of the local terrain, local shielding, house height and the distribution of leakage within the building skin. Wind coefficient values are also given in ASHRAE (1997), for one, two and three stories of house height and the five classes of local shielding. The local shielding classifications are also presented.

DEVELOPMENT OF TECHNIQUE

It has been shown that the air infiltration rate into the structure is a function of the weather parameters and the leakage area. If it is assumed that the amount of leakage remains constant over time, the changing air infiltration rate, Q_i, is defined by:

$$Q_i = \text{Leakage} * W_i \tag{10}$$

where:

Q_i = infiltration rate for the time interval of the calculation, L/s
Leakage = effective leakage area (ELA) of building envelope, cm^2
W_i = weather and structure interaction factor for the time interval of the calculation, $(L/s)(cm)^{-2}$

i = time interval of the calculation.

Therefore the varying air infiltration rate can be described by a constant times some changing function which is dependent upon the weather. This weather factor, W_i, can be determined at *i* intervals with an infiltration model by using the model with time intervals consistent with the time intervals of the weather data collection (e.g. hourly).

The effective leakage area required to provide the necessary infiltration rate can then be found from:

$$I = \frac{Q}{V} = \frac{L * W_i}{V} \qquad (11)$$

or

$$L = \frac{(I * V)}{W_i} \qquad (12)$$

Since the weather is a continuous variable with data collected at fixed intervals, the weather factor, W_i, can also be considered a continuous variable. If it is calculated on an hourly basis using a long time period of weather data as input, a histogram of the frequency of occurrence of W within a given range can be determined. If these bins are small and of a sufficiently large number, this histogram can be converted to a continuous function, f(W) as in Figure 1.

This continuous function is representative of the frequency of occurrence of the weather factor, W_i.

The Cumulative Frequency Distribution (CFD) of the weather factor as illustrated in Figure 2 can then be determined from:

$$CFD = F(W) = \int_{\circ}^{\infty} f(W)dW \qquad (13)$$

The probability of an occurrence can then be described as:

$$p(a \le W \le b) = \int_{a}^{b} f(W)dW \qquad (14)$$
$$= F(b) - F(a)$$

For example, if it is desired to know the value of the weather factor which is exceeded 50% of the time, $W_{50\%}$, it may be obtained from $p(0 \le W \le 0.5)$,

$$\int_{o}^{w} f(W) = 0.5 \tag{15}$$

if the equation for f(W) is known, or from a graph of the CFD by:

$$W_{50\%} = CFD\big|_{0.5} - CFD\big|_{0.0} \tag{16}$$

Since the second term is theoretically zero, the value of $W_{50\%}$ can be obtained directly from the CFD curve.

This value of W can then be used to determine the ELA which must be present to provide at least the required air change rate for the time specified.

Thus far the development has involved looking at the weather factor on an individual time period increment. That is, the CFD has been calculated for the weather factor on an hourly basis, treating each hour as an independent observation. The weather factor calculated in this manner would have the probability associated with the occurrence of having the level selected occur during a percentage of the single-hour time periods during the year.

It is recognized that the air distribution in a residence does not occur like plug flow and the well mixed assumption used in the pollutant concentration mass balance equations is not appropriate in many cases. This can be taken into account by lumping some number of multiple hours together. In order to account for this unknown “mixing time constant”, it would be beneficial to determine the effects of lumping adjacent hours together into a multiple-hour weather factor:

W^k_j = Multiple-hour weather factor

where:

k = the number of time increments (e.g. hours) being included in the time period of interest (mixing time constant),
j = the jth element in the weather factor series, integers only.

There are $j_{max} = i_{max} - k + 1$ elements in a series of data where i_{max} is the number of weather observations. For instance, for 175,320 hourly observations (20 years), j_{max}= 175,273 observations of W^{48}.

A philosophical/engineering judgement decision is involved in the selection of the appropriate multiple-hour weather factor. There are at least two ways of considering this parameter when the time periods being considered are longer than the time increment used in the infiltration model:

Case 1: *Average Value,* W^k_{avg}- The average of each of the k individual hourly W_i values over the time period selected (similar to moving average):

$$W^{k}_{j,avg} = \frac{1}{k}\sum_{l=1}^{k} W^{1}_{j+l-1} \qquad (17)$$

for $1 \le j \le i_{max} - k + 1$

Case 2: *Minimum Value,* W^{k}_{min} - The minimum value of the k individual hourly W_i values calculated over the time period selected:

$$W^{k}_{j,min} = Minimum\left(W^{1}_{j}, W^{1}_{j+1,\ldots}, W^{1}_{j+k-1}\right), \qquad (18)$$

for $1 \le j \le i_{max} - k + 1$

It should be noted that when only one hour is considered:

$$W^{1}_{avg} = W^{1}_{min} = W^{1} \qquad (19)$$

DEVELOPMENT OF CUMULATIVE FREQUENCY DISTRIBUTIONS OF WEATHER FACTOR, W_i

A set of cumulative frequency distributions (CFDs) of the W_i were developed using the technique described and long term hourly weather data for several locations and time periods.

Hourly weather data for nine locations in North America were obtained for 15 years (1976-90) from the SAMSON dataset (NCDC 1991) and five additional years (1991-1995) were obtained from the HUSWO dataset (NCDC 1997). One additional location (Brownsville, TX) only used data from 19 years since only three-hourly data were available for 1976 for this location. The dry-bulb temperature data had been previously filled by NCDC during their development of the datasets and there were very few missing wind speeds. When there was a missing wind speed the weather factor for the missing hour was set equal to the value for the previous hour. The analysis used 175,295 hours of dry bulb and wind speed data for locations other than Brownsville which had 166,511 hours of data.

It is assumed that this time series was sufficiently long to be representative of the long-term conditions and there was not a significant long-term change in the weather influencing infiltration. Plots of the data did not indicate any apparent long-term drift of the data.

The single-hour weather factor, W_i, was calculated for each hour using the LBL air infiltration model. The weather/structure interaction constants used in the model were for a two-story house with Class 3 shielding (moderate local shielding; some obstructions within two house heights, thick hedge, solid fence or one neighboring house). Other simplifying assumptions were:

- The leakage was equally distributed around the structure
- The leakage was symmetric with respect to wind direction.
- Half of the leakage was in the walls, remainder in floor and ceiling.
- There were equal amounts of leakage in the floor and ceiling.
- The leakage area remained constant over time and window/door openings were negligible.
- The inside temperature was kept between 20° and 25°C (68° and 77°F). Therefore there was no infiltration stack effect when the outside temperature was between 20-25°C.
- The pollution generation rate was constant over time.
- The ceiling height was 2.4m (8').

An example of the hourly weather factor for five years (1/1/91-12/31/95) for Atlanta is presented in Figure 3. The seasonal variation in the weather factor is readily apparent. The winter months are higher due to the larger influence of the stack effect. The occurrence of Wi=0 during the spring to fall seasons is due to the outside temperature being between the heating and cooling setpoints and calm wind conditions.

The multiple-hour weather factor, W^k_j; the frequency of occurrence (using bins with $\Delta W = 0.005$); and the CFDs for the average and minimum value cases were then determined using time increments of k = 1, 3, 6, 8, 12, 24, and 48 hours for all ten locations.

RESULTS AND DISCUSSION

Case 1 - Averaging W_i Over Time Period, W^k_{avg}

The CFDs for W_i determined for Atlanta using the averaging case are presented in Figure 4. The general shape and relationship between the curves were similar for all other locations. As expected, the 1-hr W_i was smaller than the 48-hr W_{avg} for the lower probabilities and greater for the higher probability of occurrence while approximately equal near the center.

Three examples of the use of the CFDs illustrates how the curves can provide an estimation of the ELA needed to provide specified levels of infiltration over certain time periods.

Example 1: It is desired to calculate the necessary ELA for a 450 m^3 structure (2000 ft^2 with 8 ft ceilings) in Atlanta in which the air infiltration rate will be less than 0.35 ACH for 5% of the number of hours.

From Figure 4: $W^1 @_{0.05} = 0.033$ (l/s)(cm)$^{-2}$

From Eqn 12:

$$\begin{aligned} \text{ELA} &= 0.35 \text{ AC/h} * 450 \text{ m}^3\text{/AC (1000l/m}^3\text{//3600 s/h) / 0.033 (l/s)(cm)}^{-2} \\ &= 1326 \text{ cm}^2 \end{aligned}$$

Example 2: It is desired to determine the necessary ELA for the same structure when the air infiltration rate will average less than 0.35 ACH for 5% of the 8-hr periods.

From Figure 4: $W^8_{avg} @_{0.05} = 0.038$ (l/s)(cm)$^{-2}$

From Eqn 12:

$$\begin{aligned} \text{ELA} &= 0.35 \text{ AC/h} * 450 \text{ m}^3\text{/AC (1000 l/m}^3\text{//3600 s/h) / 0.038 (l/s)(cm)}^{-2} \\ &= 1151 \text{ cm}^2 \end{aligned}$$

Example 3: It is desired to calculate the necessary ELA for the same structure when the air infiltration rate will be less than 0.35 ACH for 50% of the time (i.e. the mean hourly rate).

From Figure 4: $W^1 @_{0.5} = 0.072$ (l/s)(cm)$^{-2}$

From Eqn 12:

$$\begin{aligned} \text{ELA} &= 0.35 \text{ AC/h} * 450 \text{ m}^3\text{/AC (1000 l/m}^3\text{//3600 s/h) / 0.072 (l/s)(cm)}^{-2} \\ &= 608 \text{ cm}^2 \end{aligned}$$

These examples indicate that the house must have a ELA of at least 1326 cm^2 if air infiltration is to provide a minimum of 0.35 ACH for at least 95% of the hours and would only need 1151 cm^2 if the air infiltration was averaged over an 8-hr time period. However if only an average of 0.35 ACH was required, the house would need an ELA of only 608 cm^2.

The 5% W_{avg} values for the locations and time periods investigated are presented in Table 1. This table also includes the ratio of W^1/W^8_{avg} at the 5% level. These ratios indicate that only 0.77 to 0.92 of the leakage area required by the single hour value would need to be provided if the criterion specified the ACH should be averaged over an 8-hour time period.

Table 1. W_{avg} Values for 5% (averaged over time period), (l/s)(cm)$^{-2}$

	1 hr	3 hr	6 hr	8 hr	24 hr	48 hr	W^1/W^8_{avg}
Atlanta, GA	0.033	0.035	0.037	0.038	0.045	0.047	0.868
Bismarck, ND	0.042	0.044	0.046	0.047	0.053	0.056	0.894
Boston, MA	0.051	0.053	0.055	0.056	0.062	0.065	0.911
Brownsville, TX	0.024	0.026	0.029	0.031	0.046	0.048	0.774
Los Angeles, CA	0.030	0.033	0.036	0.037	0.047	0.048	0.811
Miami, FL	0.023	0.026	0.028	0.030	0.041	0.043	0.767
Phoenix, AZ	0.025	0.027	0.030	0.031	0.039	0.040	0.806
Seattle, WA	0.046	0.048	0.049	0.050	0.054	0.056	0.920
Salt Lake City, UT	0.043	0.047	0.051	0.052	0.058	0.061	0.827
St Louis, MO	0.036	0.038	0.040	0.041	0.046	0.049	0.878

The 50% W_{avg} values for the locations are presented in Table 2. There were little differences in the values for the different time periods so only the 1-hr values are presented. These values represent the median W_i and can be used to determine the median infiltration rate over the time period considered.

Table 2. Median W^1_i Values (i.e. 50% value)

	W^1_i (l/s)(cm)$^{-2}$	Ratio to 5% W^1_i
Atlanta, GA	0.072	2.18
Bismarck, ND	0.093	2.21
Boston, MA	0.098	1.92
Brownsville, TX	0.075	3.12
Los Angeles, CA	0.061	2.03
Miami, FL	0.065	2.83
Phoenix, AZ	0.059	2.36
Seattle, WA	0.076	1.65
Salt Lake City, UT	0.083	1.93
St Louis, MO	0.083	2.31
Average		2.25

The ratio of the 50% to 5% values for each location are also included in Table 2. This ratio means that for the given set of assumptions, the structure requires from 1.65 to 3.12 times as much equivalent leakage area to provide the same level of air infiltration for at least 95% of the single hour readings as would be required for 50% of the single hour readings.

Case 2 - Selecting Minimum Value of W_i *Occurring During Time Period,* W^k_{min}

The W^k_{min} CFDs for Atlanta when the minimum value is selected from each time period are presented in Figure 5. The curve shapes were similar for the other locations and time periods. As expected, the longer time period blocks provided for a smaller W_i. Thus, larger ELAs are required when the minimum value is selected from a longer block because the smaller values would have a longer lasting effect. The CFDs were nearly linear and parallel in the 20% to 80% range.

The CFDs did not start at 0 for the longer time blocks because there were some time periods in which the ΔT was zero and the wind was calm. Therefore, $W_i = 0$. This gives an indication that regardless of the amount of leakage area there are hours in which infiltration would not supply sufficient ventilation. In these cases, natural or mechanical ventilation would be required. It should be noted however that most of these time periods are due to the outside temperature being between the heating and cooling setpoints and the wind was calm. These typically are the time periods in which operable windows could be open.

The percentage of time the W_{min} was zero for the various locations and time periods are presented in Table 3.

Table 3. Percent of Time $W_{min} = 0$

(Using minimum value occurring during time period)

	1 hr	3 hr	6 hr	8 hr	12 hr	24 hr	48 hr
Atlanta, GA	0.9	2.1	3.5	4.4	6.2	11.0	18.1
Bismarck, ND	0.4	0.9	1.7	2.2	3.2	5.8	10.0
Boston, MA	0.1	0.1	0.2	0.3	0.4	0.8	1.5
Brownsville, TX	2.6	5.0	8.0	9.9	13.7	23.1	33.6
Los Angeles, CA	0.8	1.9	3.4	4.4	6.3	11.4	18.6
Miami, FL	1.4	3.0	5.0	6.2	8.6	15.1	23.8
Phoenix, AZ	1.7	3.8	6.6	8.4	11.9	21.3	31.1
Seattle, WA	0.1	0.2	0.4	0.5	0.7	1.4	2.6
Salt Lake City, UT	0.2	0.6	1.2	1.6	2.4	4.6	8.5
St Louis, MO	0.9	2.0	3.5	4.4	6.1	10.8	17.6

It appears as though the milder climates had a larger percentage of the time when the W_i was zero however this trend needs further investigation.

The 5% W^k_{min} values for all locations and time periods are presented in Table 4. There are no differences between Case 1 and Case 2 for the one hour calculations since there is no averaging or selection of minimum values. Some of the time periods for many of the locations do not have a W^k_{min} value at the 5% level because greater than 5% of the values were zero.

Table 4. W^k_{min} Values for 5% (minimum during time period), $(l/s)(cm)^{-2}$

	1hr	3hr	6 hr	8 hr	12 hr	24 hr	48 hr
Atlanta, GA	0.033	0.024	0.021	0.015	-	-	-
Bismarck, ND	0.042	0.034	0.028	0.024	0.021	-	-
Boston, MA	0.051	0.044	0.037	0.036	0.033	0.027	0.021
Brownsville, TX	0.024	-	-	-	-	-	-
Los Angeles, CA	0.030	0.022	0.017	0.012	-	-	-
Miami, FL	0.023	0.017	0.001	-	-	-	-
Phoenix, AZ	0.025	0.018	-	-	-	-	-
Seattle, WA	0.046	0.039	0.035	0.034	0.031	0.025	0.021
Salt Lake City, UT	0.043	0.034	0.028	0.024	0.021	0.011	-
St Louis, MO	0.036	0.030	0.021	0.016	-	-	-

Example 4: It is desired to determine for the house previously described the ELA required to assure that 95% of the occurrences ($0<p<5\%$) of the minimum hourly infiltration rate will be greater than 0.35 ACH during any adjacent 8-hour time frame.

From Table 4: $W^8_{min}@_{5\%} = 0.015\ (l/s)(cm)^{-2}$

$$\begin{aligned} ELA &= 0.35 * 450\ (1000/3600) / 0.015 \\ &= 2917\ cm^2 \end{aligned}$$

It should be noted that this ELA is 2.53 times the size required if the infiltration rate were averaged over the 8-hour period.

The 50% W^k_{min} values for the locations are presented in Table 5. These numbers represent the median of the smallest value of W_i occurring during each time period and can be used to determine the minimum infiltration rate which occurred 50% of the time periods.

Table 5. W^k_{min} Values for 50% (minimum during time period), (l/s)(cm)$^{-2}$

	1 hr	3 hr	6 hr	8 hr	12 hr	24 hr	48 hr
Atlanta, GA	0.072	0.064	0.058	0.055	0.051	0.044	0.035
Bismarck, ND	0.093	0.085	0.080	0.077	0.073	0.066	0.059
Boston, MA	0.098	0.089	0.083	0.080	0.076	0.068	0.062
Brownsville, TX	0.075	0.064	0.054	0.050	0.044	0.034	0.025
Los Angeles, CA	0.061	0.052	0.046	0.043	0.038	0.032	0.027
Miami, FL	0.065	0.055	0.048	0.045	0.038	0.031	0.023
Phoenix, AZ	0.059	0.052	0.046	0.043	0.037	0.030	0.024
Seattle, WA	0.076	0.070	0.066	0.064	0.061	0.056	0.051
Salt Lake City, UT	0.083	0.075	0.068	0.065	0.061	0.053	0.046
St Louis, MO	0.083	0.075	0.069	0.066	0.062	0.054	0.046

When a 48 hour time period is considered, W^{48}_{min}, the average (for the 10 locations used) ELA required is 2.08 times as large (range of 1.49 to 3.0) as required when only one hour is considered. Since the CFDs were nearly linear and parallel in the 20% to 80% range this is applicable over the $W_{20\%}$-$W_{80\%}$ range.

CONCLUSIONS

A technique has been developed to determine the equivalent leakage area (ELA) needed in residences to provide a quantity of air infiltration which exceeds a design value for a desired level of frequency of occurrence. The technique presented applies an hourly air infiltration simulation model to long-term weather data sets to provide hourly values for the infiltration weather factor. A Cumulative Frequency Distribution (CFD) was then used to describe the distribution of the values of these data when 1-, 3-, 6-, 8-, 12-, 24-, and 48- hour time periods were grouped together.

It was determined that for the simplifying assumptions and the locations used, there were significant differences in the ELA required based upon identified design criterion options. A structure requires from 1.65 to 3.12 times as much ELA to provide the same (or greater) amount of air infiltration for 95% of the single-hour readings as would be required for 50% of the single-hour readings. It was also found that at the 5% minimum frequency of occurrence (i.e. 95% of the ACH values would be greater), only 77 to 92% of the single-hour ELA requirement would need to be provided if the criterion specified the ACH should be averaged over an 8-hour time period.

When the design criterion specifies that the air infiltration should exceed a minimum value every hour during the time period rather than an average rate over the time period, the ELAs required were much larger. The ELA required for a 48-hour time period was 2.08 (range 1.49 to 3.0) times the ELA required when only one hour was considered. In several locations the infiltration weather factor was zero for more than 5% of the periods when the minimum value for the time period was the selected criterion. This was due to low temperature differences and no wind.

Examples have been provided which demonstrate the use of the technique for Atlanta, GA.

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Figure 1. Distribution of Weather Factor, W_i

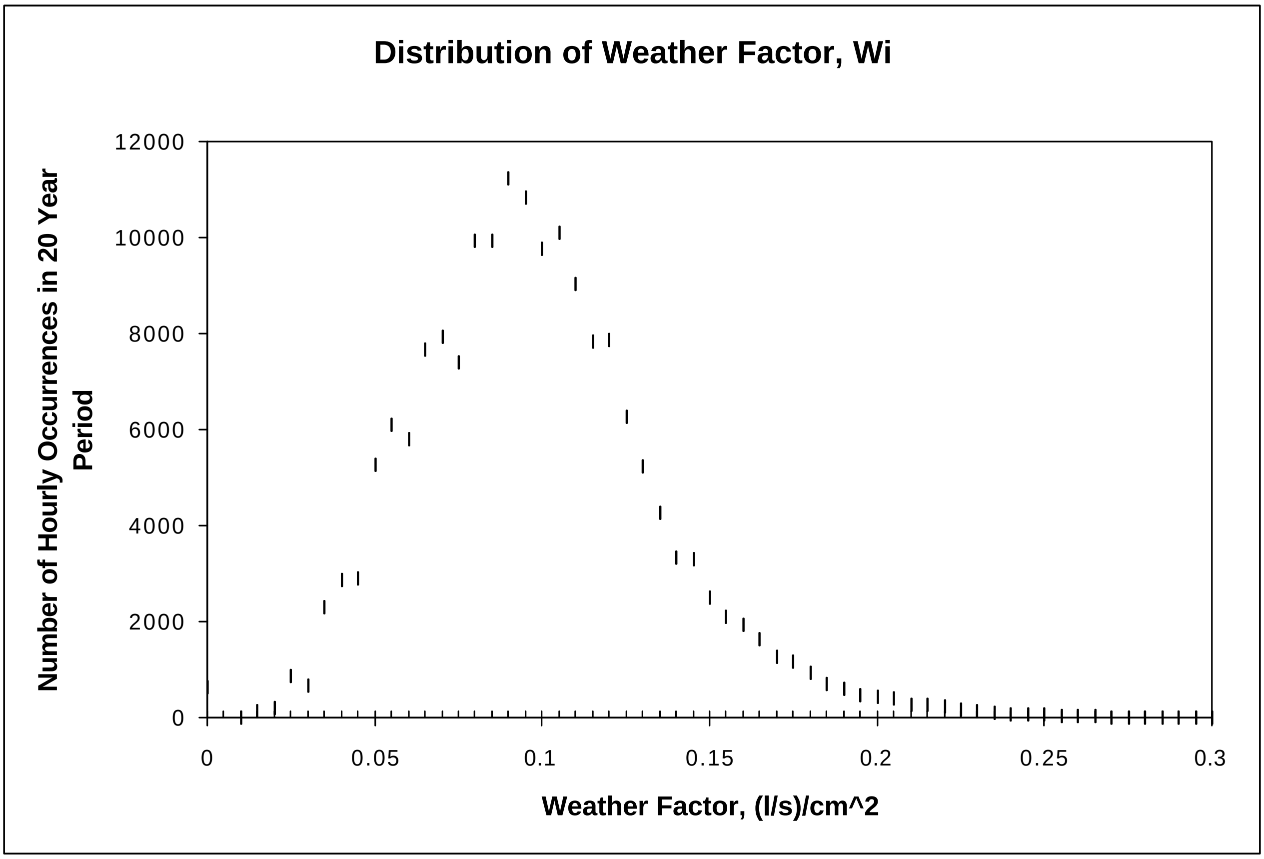

Figure 2. Cumulative Frequency Distribution of Weather Factor

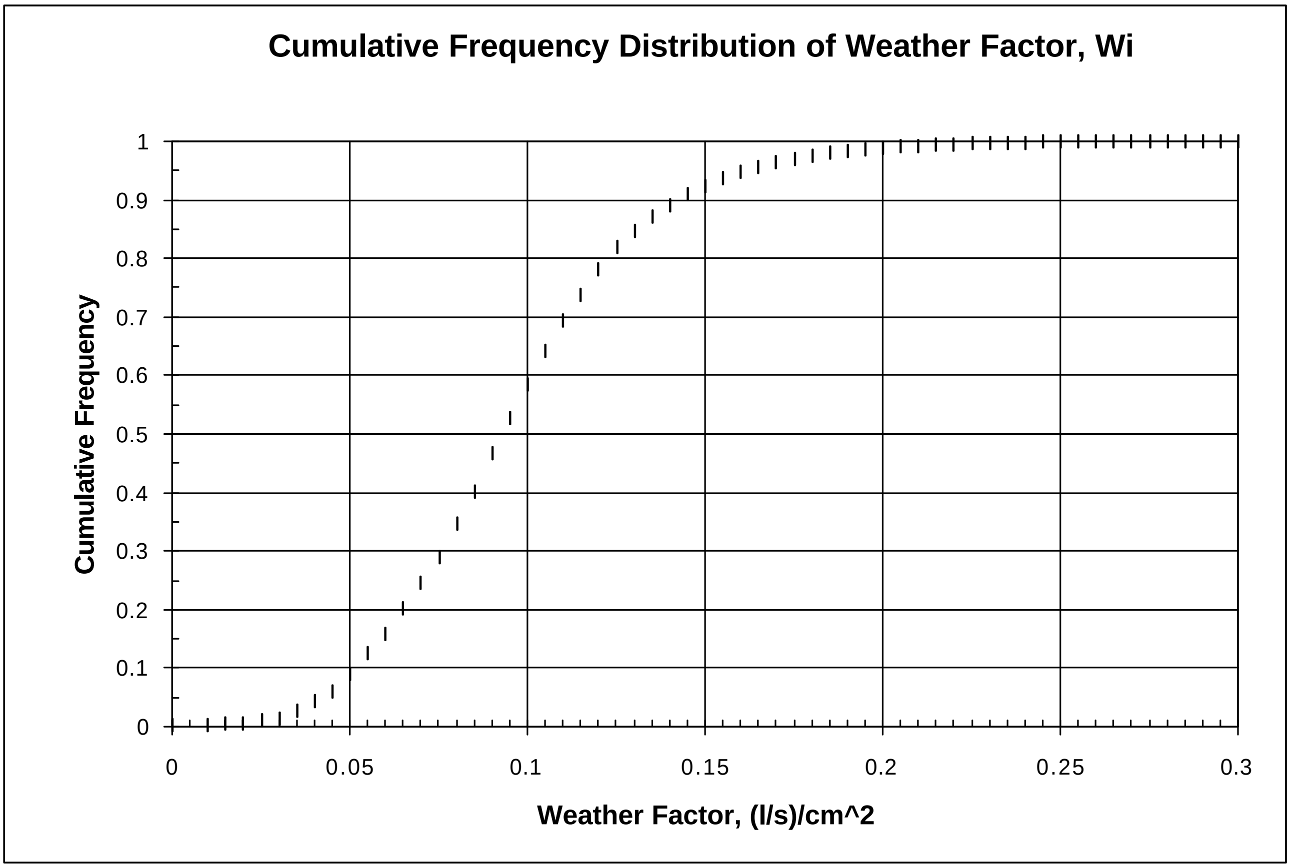

Figure 3. Example of Single Hour Weather Factor for Atlanta, GA

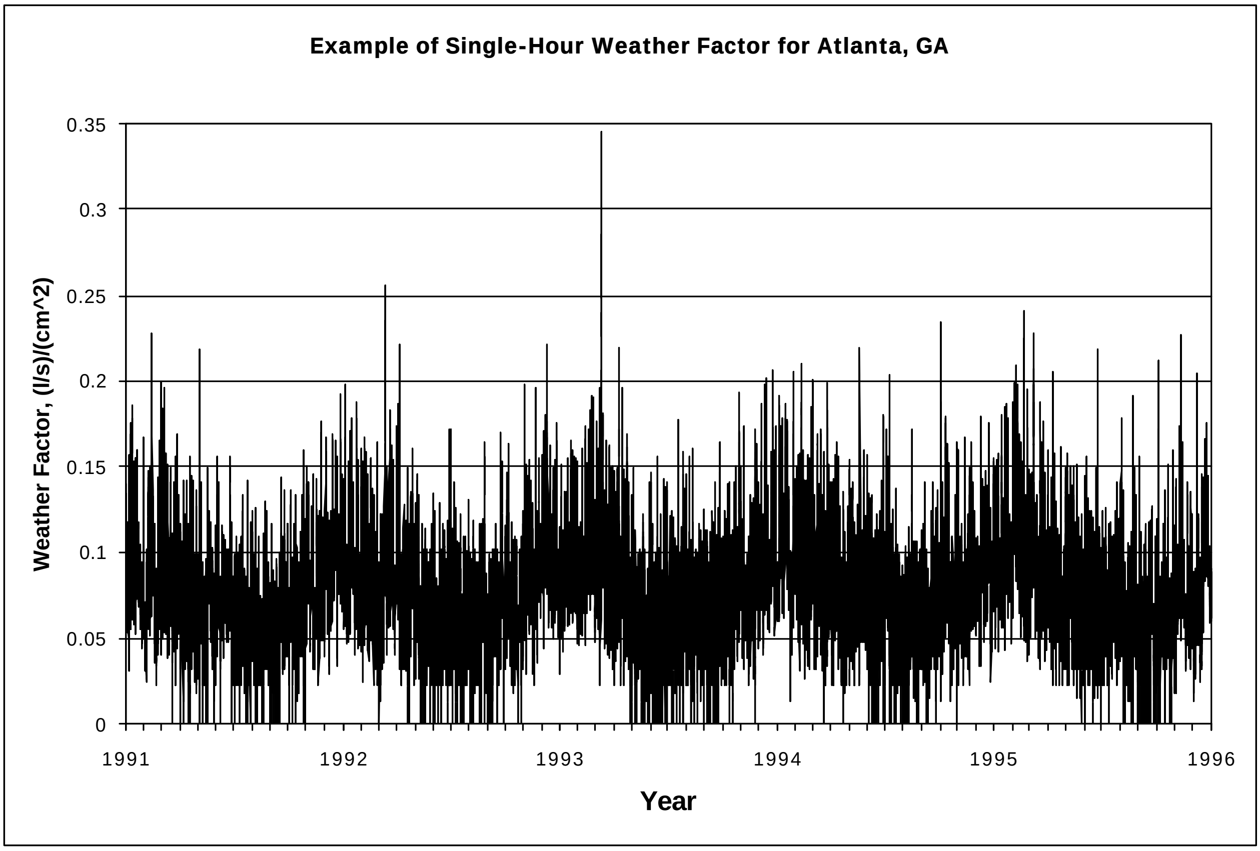

Figure 4. Cumulative Frequency Distribution of W_{avg} for Atlanta, GA – Average Value during Time Period

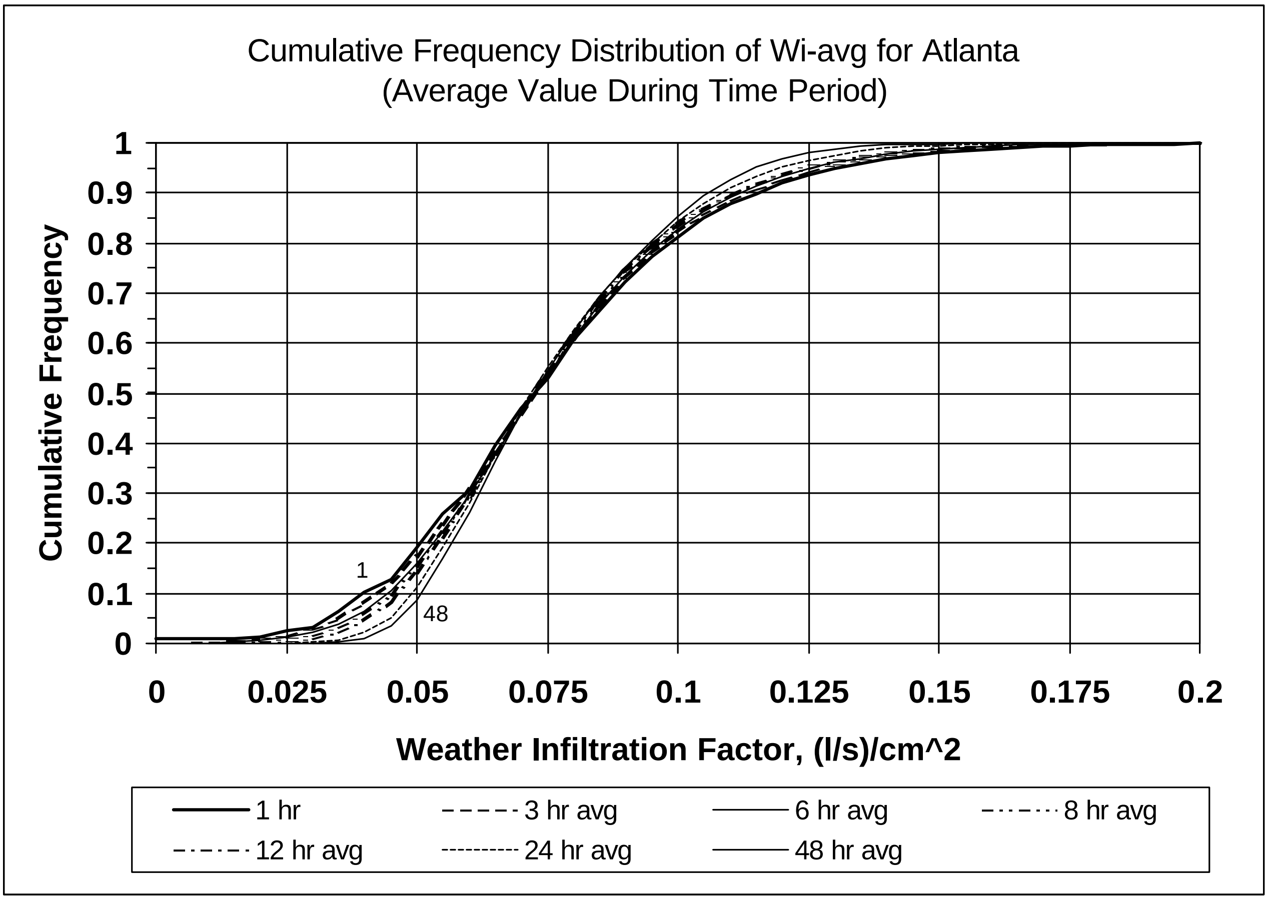

Figure 5. Cumulative Frequency Distribution of W_{min} for Atlanta, GA – Minimum Value during Time Period