THE USE OF BLOWER-DOOR DATA*

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The role of ventilation in the housing stock is to provide fresh air and to dilute internally-generated pollutants in order to assure adequate indoor air quality. Blower doors are used to measure the air tightness and air leakage of building envelopes. As existing dwellings in the United States are ventilated primarily through leaks in the building shell (i.e., infiltration) rather than by whole-house mechanical ventilation systems, accurate understanding of the uses of blower-door data is critical. Blower doors can be used to answer the following questions:.

- What is the Construction Quality of the Building Envelope?
- Where are the Air Leakage Pathways?
- How Tight is the Building?
- How Much Ventilation Does the Air Leakage Supply?
- How Much Energy Does the Air Leakage Lose?
- Is this Building Too Tight?
- Is this Building Too Loose?
- When Should Mechanical Ventilation be Considered?

Various ASHRAE Standards (e.g., 62, 119, and 136) are used to determine acceptable ventilation levels and energy requirements

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INTRODUCTION

Virtually all knowledge about the air tightness of buildings comes from field measurements using *Blower Door* technology. Blower Doors measure air tightness which, in turn, is the prime building factor in determining infiltration and air leakage. Blower Doors can be used in a variety of ways for a variety of purposes that span the range of energy, air quality, comfort and safety. This report summarizes what is and what can be done with Blower-Door data in helping to answer these kinds of questions.

This report does not intend to cover issues related to the (fan pressurization) measurements themselves. As the AIVC (1990) has shown, there exist many measurement standards throughout the world, but the two used by the ASHRAE Standards discussed below are the ASTM (1991) Standard (E779-87) and the CGSB (1986) Standard (149). Issues of measurement uncertainty as described by Sherman and Palmiter (1994), and reproducibility, as shown by Murphy et al (1991), while important, will not be discussed. Both technical (e.g. ASTM 1990) and popular (e.g. Nissan 1985 and Meier 1994) articles are available to familiarize the reader with some of the relevant issues.

This report focuses on single-zone buildings. While Blower Doors are sometimes used for component or multizone leakage measurements, the vast majority of measurements have been made for whole-building, single-zone situations, such as single-family homes. Similarly, the simplified models and consensus standards have focussed on these types of buildings.

BACKGROUND

"*Blower Door*" is the popular name for a device that is capable of pressurizing or depressurizing a building and measuring the resultant air flow and pressure. The name comes from the fact that in the common utilization of the technology there is a fan (i.e. blower) mounted in a door; the generic term is "Fan Pressurization". Blower-Door technology was first used in Sweden around 1977 as a window-mounted fan (as reported by Kronvall, 1980) and to test the tightness of building envelopes (Blomsterberg, 1977). That same technology was being pursued by Caffey (1979) in Texas (again as a window unit) and by Harrje, Blomsterberg and Persily (1979) at Princeton University (in the form of a Blower *Door*) to help find and fix the leaks.

During this period the diagnostic potentials of Blower Doors began to become apparent. Blower Doors helped Harrje, Dutt and Beya (1979) to uncover hidden *bypasses* that accounted for a much greater percentage of building leakage than did the presumed culprits of window, door, and electrical outlet leakage. The use of Blower Doors as part of retrofitting and weatherization became known as *House Doctoring* both by Harrje and Dutt (1981) and the east coast and Diamond et al. (1982) on the west coast. This in turn led Harrje (1981) to the creation of instrumented audits and Sonderegger et al. (1981) to computerized optimizations.

While it was well understood that Blower Doors could be used to measure air tightness, the use of Blower-Door data could not be generally used to estimate real-time air flows under natural conditions or to estimate the behavior of complex ventilation systems. When compared with tracer-gas measurements, early modeling work by Caffey (1979) was found wanting. There was a rule of thumb, which Sherman (1987) attributes to Kronvall and Persily that seemed to relate Blower-Door data to seasonal air change data in spite of its simplicity:

$$ACH \approx \frac{ACH_{50}}{20} \qquad \text{(EQ 1)}$$

That is, the seasonal amount of natural air exchange could be related to air flow necessary to pressurize the building to 50 Pascals.

To overcome the physical limitations of such rules of thumb, it is necessary to model the situation physically which, in this case, means separating the leakage characteristics of the building from the (weather) driving forces. As the early versions of the ASTM Standard show, leakage is described conventionally as a power law, Equation 7, which was found to be valid empirically but without theoretical substantiation (recent work by Sherman (1992a) has provided the theoretical basis for the expression). Using orifice flow (Equation 8) as a physical model, the Blower-Door data can be used to estimate the Effective Leakage Area (*ELA*) Equation 9.

Using this orifice-flow paradigm, Sherman and Grimsrud (1980) developed the LBL Infiltration model (Equation 14) which was then validated by Sherman and Modera (1984) and incorporated into the ASHRAE Handbook of Fundamentals (1989). Much of the subsequent work on quantifying infiltration is based on that model, including ASHRAE (1988) Standard 119 and ASHRAE (1993) Standard 136. The important equations are summarized in "APPENDIX: MODELING TOOLS" on page 13.

ISSUES

Blower Doors are still used to find and fix the leaks, but more often the values generated by the measurements are used to estimate infiltration for both indoor air quality and energy consumption estimates. These estimates in turn are used for comparison to standards or to provide program or policy decisions. Each specific purpose has a different set of associated blower-door issues.

Compliance with standards, for example, requires that the measurement protocols be clear and easily reproducible, even if this reduces accuracy. Public policy analyses are more concerned with getting accurate aggregate answers than reproducible individual results. Measurements that might result in costly actions are usually analyzed conservatively, but "conservatively" for IAQ is diametrically opposed to "conservatively" for energy conservation.

Complicating any analysis is the fact that infiltration, being weather dependent, is not constant. Because of the non-linearities involved, the equivalent constant infiltration rate is not simply related to the average of the instantaneous values. Sherman and Wilson (1986) have determined that the equivalent constant infiltration rate is generally higher than the average for energy-related purposes and lower for indoor air quality purposes, indicating that infiltration is not a particularly efficient ventilation strategy. As shown in the appendix special purpose quantities are required to take these effects into account.

To clarify the importance of these issues as well as provide operational guidance to those wishing to use Blower-Door data, we have posed and then provided the means to answer a set of questions commonly addressed with Blower Doors:

What is the Construction Quality of the Building Envelope?

As mentioned earlier this semi-quantitative function was the original use for blower-door technology. The goal here is to assure that the envelope is of sufficiently good (i.e. tight) construction that leakage is not an important liability in energy, comfort or air flow; that is, prime consideration was devoted to reducing drafts and uncontrolled air movement. As such intentional openings are normally sealed in the test method and the test may even be done prior to the completion of construction to, for example, find penetrations in vapor barriers.

As the tightness value is an indicator only, and is not intended to be used in further calculations, a single, simple measurement is appropriate: usually air changes at 50 Pascals. Examples of this kind can be found in the standards from Sweden (1989) and Norway (1987) among others. For these types of standards it is sufficient to assure that the fabric of the envelope is tight (e.g. below 3 air changes at 50 Pa) and that ventilation must be provided through some other (i.e. mechanical) mechanism.

Where are the Air Leakage Pathways?

This question often follows the first when the building envelope is found not to be sufficiently tight either because of excessive energy complaints or, more likely, because of discomfort due to draft. The Blower Door is used as a means of inducing flow through the leaks which can be detected by a variety of means as indicated by an ASTM (1991) standard (E116) including smoke movement, sound propagation, and thermography. The flow measuring part of the Blower Door is not needed.

Supertight construction makes use of these detection means to reduce or eliminate leakage paths during the construction phase. As described by Gettings (1989), House Doctoring makes use of these detection means to retrofit existing buildings. Many types of air leakage paths, such as *bypasses*, can only be identified this way.

How Tight is the Building?

While this question may appear to be similar to the first question, there are several significant difference. This question seeks to *quantify* the air tightness in such a way that it can be used to calculate the contribution of air leakage/infiltration towards ventilation and energy requirements. Thus it needs to be more quantitative and to reflect the leakage in normal operating conditions; that is, it must reflect accurately that amount of air leakage through all leakage paths exposed to environmental driving forces.

As described in the Appendix (Equation 10), Blower-Door data can be reduced to an Effective Leakage Area (*ELA*) and a flow exponent. The ELA quantifies the equivalent amount of holes in the (given configuration of the) building and can be used with the LBL model to estimate the flow rate of infiltrating air (Equation 13).

For most purposes it is desirable to normalize leakage (and ventilation) by the size of the building, either for comparison or standardization purposes. Standard 119 defines the Normalized Leakage (*NL,* in Equation 11) for this purpose and also uses NL to define leakage classes. (See Table 1, "CHARACTERIZATION BY BUILDING LEAKAGE," on page 7.)

It is interesting to note that for a typical single-story house the normalized leakage is simply related to the air changes at 50 Pascals using (the climate-independent) approximation of Equation 12:

$$NL = \frac{ACH_{50}}{20} \qquad \text{(EQ 2)}$$

Sherman's (1987) correction factors must be applied if the leakage exponent or building height are different from the default assumption.

How Much Ventilation Does the Air Leakage Supply?

If we are concerned about the pollutant-dilution capabilities of infiltration it is important to take into account when and how varied the instantaneous infiltration is as indicated by Sherman and Wilson (1986). As is done for Standard 136 these details can be incorporated into a (annual) weather factor, *w*, to describe the ventilation potential of each climate*. Equation 17 describes the equivalent amount of air exchange derived from infiltration:

$$ACH_{Std136} = 1.44 \cdot w \cdot NL \qquad \text{(EQ 3)}$$

The factor *1.44w* ranges between two-thirds and unity for most climates in the U.S. and slightly higher in Canada. In addition to weather variations, *w* is a function of height, leakage distribution and wind sheltering. (See Equation 14.) When combined with Equation 2 this expression comes close to approximating the "divide by 20" rule.

This air change rate is a good estimate of the equivalent amount of ventilation produced by infiltration, but it is not a good estimate of the average air change rate or an air change rate suitable for making energy estimates.

*. ASHRAE has interpreted the method of standard 136 to be acceptable for meeting the requirements of Standard 62. Since Standard 136 uses an annual evaluation, one can infer that only long-term values are important.

How Much Energy Does the Air Leakage Lose?

If we are concerned about the thermal loads imposed by infiltration, it is important to take into account when infiltration occurs (e.g. the energy impact, as well as the driving forces, for infiltration are larger when the outdoor temperatures is at $0^{o}C$ than at $15^{o}C$). Infiltration-related climate can be expressed using the concept of Infiltration Degree-Days (*IDD*s) as developed by Sherman (1986b). In the units of kJ/m^2, Equation 22 approximates the infiltration load (per unit floor area) and can be explained as

$$75 \cdot IDD \cdot NL \ . \qquad \text{(EQ 4)}$$

Typical values of IDD run between $2000^{o}C$-day and $7000^{o}C$-day according to ASHRAE Standard 119, which makes a particular assumption about heating and cooling limits. Standard 119 contains a table of IDD values for many cities as well as a calculation method.

Although Standard 119 makes a certain set of assumptions about degree-days, they can be recalculated for different purposes (e.g. heating-only) and the equation still applies.

Is this Building Too Tight?

This question has embedded in it an assumption about the definition of “too tight”. For our purposes we will define it as meaning too tight to meet ASHRAE’s (1989) Ventilation Standard (62)of 0.35 ach using Equation 17 and assuming no significant contribution from mechanical ventilation. Thus the building is too tight if

$$NL < \frac{0.24}{w} \qquad \text{(EQ 5)}$$

The building may be too tight for other considerations. For example, Dumont and Snodgrass (1990) have shown that buildings with naturally-aspirated fossil-fuel appliances may *backdraft* if there is insufficient air leakage. Although air leakage can be an important factor in backdrafting, other factors such as the characteristic of the combustion appliances and the amount of mechanical exhaust must also be considered. Such considerations are beyond the scope of this report.

Is this Building Too Loose?

The implied definition here is to minimize drafts and energy consumption, which will depend on climate. If we use Equation 23 as an approximation to Standard 119, then the building will be too loose if

$$NL < \frac{2000}{IDD} \qquad \text{(EQ 6)}$$

In the background to the formation of Standard 119 Sherman (1986a) shows that this criterion is based on 150 MJ/m^2 as the maximum allowed infiltration load, which is a value believed to cut off the highest energy users without undue hardship for the typical building under typical efficiency and fuel cost assumptions. As the desire for energy conservation increases, energy standards may wish to strengthen this requirement.

Other looseness considerations include draft which can lead to poor thermal comfort as per ASHRAE's (1992) Thermal Comfort Standard (55) and moisture accumulation which can lead to material problems.

When Should Mechanical Ventilation* Be Considered?

The decision when and how to use mechanical ventilation depends somewhat on climate, but it depends primarily on building tightness. If we use the leakage classification of Standard 119 and apply our criteria for the range of weather factors found in Standard 136 we can summarize the need for mechanical ventilation in Table 1 using the guidance Standard 62 and Equation 3.

TABLE 1. CHARACTERIZATION BY BUILDING LEAKAGE

LEAKAGE CLASS	Minimum NL	Maximum NL	Typical ACH_{50}	Ventilation Requirement	Recommended Ventilation Type
A	0	0.10	1	Full	Balanced Only
B	0.1	0.14	2	Yes	Balanced
C	0.14	0.20	3	Yes	Either
D	0.20	0.28	5	Some	Either
E	0.28	0.40	7	Likely	Unbalanced
F	0.40	0.57	10	Possible	Unbalanced Only
G	0.57	0.80	14	Unlikely	Unbalanced Only
H	0.80	1.13	20	None	None
I	1.13	1.60	27	*Buildings in this range may be too loose and should be tightened.*	
J	1.60				

Table 1 summarizes the need for mechanical ventilation for different building leakages. It contains recommendations about which leakage classes require some sort of whole-house mechanical ventilation and recommends the type. The flow addition principles described by Sherman (1992b) indicate that balanced ventilation (e.g. an air-to-air heat exchanger) is best for the tighter classes because it does not affect the internal pressure and unbalanced (e.g. exhaust fan) systems are best for the looser classes because they minimize variations in total ventilation. For those buildings in which large depressurizations will not cause problems, unbalanced systems can be used regardless of tightness.

This table can be used either as a guide to selecting ventilation for a new or existing house whose tightness is known. Alternatively it can be used to guide construction quality for a house where the ventilation system (or lack thereof) has been designed.

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*. The term "mechanical ventilation" refers to whole-house, purpose-provided ventilation systems operating for substantial parts of the day. Because of the normally low duty cycles, local exhaust in kitchens and bathrooms are not generally included.

Equation 3 can be used to estimate the impact that leakage will have towards meeting the 0.35 ach requirement of ASHRAE Standard 62, but the equations in Standard 136 must be used to combine both infiltration and mechanical ventilation.

A building of Leakage Class A is sufficiently tight that no credit can be taken for infiltration towards meeting a ventilation requirement; such a house should be considered *airtight* and all ventilation and pressure relief must be designed through the mechanical system. Classes B and C represent looser, but still quite tight construction. While infiltration may be non-negligible for energy concerns in some climates, its contribution towards ventilation will be too small to count on and there is still a ventilation system requirement. Classes D and E begin to be leaky enough that the infiltration may become a significant part of the ventilation requirement. It may be possible to meet the requirement with natural ventilation or intermittent mechanical ventilation. Leakage Classes F and G will usually be sufficiently leaky that in all but sheltered and mild climates explicit mechanical ventilation is probably not needed. Leakage Classes H and above would not be expected to require purpose-provided ventilation and usually represent opportunities for cost-effective tightening.

DISCUSSION

Equation 2 through Equation 6 have a set of default assumptions embedded in them regarding some of the details of the buildings. In the aggregate we would expect these assumptions to lead to reasonable averages, but for a single structure the details can be important. Thus, for the purposes such as setting energy standards we might use Equation 4 to get a robust estimate of the impacts of certain options.

An aggregate analysis by Sherman and Matson (1993) using existing databases has estimated the loads associated with residential infiltration for the U.S. stock, and shows that the requirements for the current stock to meet the ASHRAE ventilation requirement through ventilation are about 3EJ, but that about 2EJ could be saved if those houses were tightened to meet ASHRAE Standard 119.

It may not always be possible to meet both standards through infiltration. In more extreme climates there may be no airtightness level that would simultaneously allow that, or the allowed range of tightness values would be so narrow as to preclude designing for it.

Using over 200 weather sites, we have generated a map of the continental U.S. (See Figure 1, ”Air Tightness Levels”.) showing four different zones regarding air tightness requirements and the range of air tightness levels that can meet energy and ventilation standards.

Zone 1 represents the severe climates of the Northern tier in which designing to meet the air tightness standards for energy conservation would make it practically impossible to reliably get sufficient ventilation from infiltration to meet the ventilation standard. Thus in Zone 1 good design should include mechanical ventilation.

Zone 2 represents the moderate climates in which careful design and control of building air tightness can allow buildings to be designed to simultaneously meet energy and ventilation standards. Zone 3 represents the mild climates ranging from the Puget Sound through Texas to the Southeast. In these climates there is a substantial range of air tightness that would meet both standards.

In Zone 4, coastal California and some of the Southwest, there is a large range of acceptable leakage, but the climate is so mild that it is necessary to have very leaky houses to meet the ventilation standard, leakier in fact than new construction tends be built. Mechanical ventilation may need to be considered in this zone (and some of Zone 3) because of insufficiently low construction quality.

The issue of whether these standards are set at appropriate levels is a valid one, but the expressions presented above can be used to help understand the implications of a variety of standards and levels. The equations are at a degree of simplicity that rivals the rule of thumb in Equation 1, but contains significantly more usable information. It is interesting to note that with the correct interpretations Equation 2 and Equation 3 can be combined to yield that rule for certain circumstances.

Summary

Infiltration and ventilation in dwellings is conventionally believed to account for 1/3 to 1/2 of the space conditioning energy. As energy conservation improvements to the thermal envelope continue, the fraction of energy consumed by the conditioning of air may increase. Air-tightening programs, while decreasing energy requirements, have the tendency to decrease ventilation and its associated energy penalty at the possible expense of adequate indoor air quality. In this report we have demonstrated how data collected from Blower Doors can be used to address these issues and have indicated some of the limitations thereon.

FIGURE CAPTION

FIGURE 1. Air Tightness Levels. Each of the four zones represents an increasingly larger range of airtightness that would be meet both ASHRAE Standard 119 and ASHRAE Standard 62. Zone 1 buildings cannot meet both standards; Zone 2 and 3 buildings can. Zone 4 (not labeled) has a large acceptance range, but requires very leaky construction.

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LIST OF SYMBOLS

A	stack coefficient [-]
A_f	building floor area [m^2]
ACH	air change rate (ach) [h^{-1}]
ACH_{50}	air change rate at 50 Pascals pressure difference (ach) [h^{-1}]
B	wind coefficient [-]
C'	generalized shielding coefficient [-]
C_p	heat capacity of air [1.022 kJ/kg-°K]
E	annual load [kJ]
ELA	effective leakage area [m^2]
f_s	stack factor [$(m/s)(°K)^{1/2}$]
f_w	wind factor [-]
g	gravity [9.8 m/s^2]
H	building height [m]
HI	inside enthalpy [kJ/kg]
HO	outside enthalpy [kJ/kg]
IDD	infiltration degree days [°C-day]
n	power-law exponent [-]
N	number of hours [h]
NL	normalized leakage area [-]
P	pressure [Pa]
Q	air flow rate [m^3/s]
R	fraction of total leakage area in the floor and ceiling [-]
s	specific infiltration [m/s]
s_o	average specific infiltration [0.71 m/s]
ΔT	inside-outside temperature difference [°C]
T_o	absolute temperature used for reference [298 °K]
κ	leakage coefficient [$m^3/s/Pa^n$]
v	measured wind speed [m/s]
X	difference in ceiling/floor fractional leakage area [-]
w	air change rate factor accounting for effect of local weather (m/s)*
ρ	density of air [1.2 kg/m^3]
[h]	indicates hourly value

*. Note that in ASHRAE Standard 136 the units are expressed in air changes per hour. For a single-story structure the conversion factor between ach and m/s is 1.44.

APPENDIX: MODELING TOOLS

Blower doors can generate sets of fan flow, and house pressure pairs. Sherman (1992a) has shown that these data can be expressed empirically as a power law:

$$Q_f = \kappa P_f^n \qquad \text{(EQ 7)}$$

where the subscript, *f*, relates to fan-induced pressure or flow. For ease of use and understanding this two-parameter characterization of flow is reduced to the one-parameter characterization of the effective leakage area of an orifice:

$$Q_f = ELA \cdot \sqrt{\frac{2P_f}{\rho}} \qquad \text{(EQ 8)}$$

If we assume that these two expression characterize the flow at some reference pressure, P_r, then we calculate ELA from the blower door data:

$$ELA = \kappa \cdot P_r^{n-1/2} \cdot \sqrt{\frac{\rho}{2}} \qquad \text{(EQ 9)}$$

which leads to

$$Q_f = ELA \cdot \sqrt{\frac{2P_r}{\rho}} \cdot \left(\frac{P_f}{P_r}\right)^n . \qquad \text{(EQ 10)}$$

While 10 Pa is sometimes used as the reference pressure in Canada, ASHRAE Standards and Handbooks normally use 4 Pa for the reference pressure. Accordingly, 4 Pa has been used as the reference pressure throughout this report.

The effective leakage area, *ELA*, quantifies the absolute size of the openings in the building and for the LBL infiltration model is determined by summing the respective component leakage areas of a specific building. (Blower doors directly measure the total leakage.) A better measure of the relative tightness, however, is the normalized leakage as defined in ASHRAE Standard 119:

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3} \qquad \text{(EQ 11)}$$

If we combine this expression with Equation 10 for typical conditions found in a single-story house we find that

$$NL = \frac{ACH_{50}}{20} \qquad \text{(EQ 12)}$$

where ACH_{50} is the number of air changes through the house induced by a 50 Pascal pressure from blower door operation. Note that as air tightness is independent of the driving forces, there is no need for climate-dependent factors.

LBL INFILTRATION MODEL

The fundamental relationship between the infiltration and the house and climate properties is expressed by the LBL infiltration model as described in Sherman and Modera (1984), which is incorporated into the ASHRAE (1989) Handbook of Fundamentals. While Palmiter and Bond (1991) have suggested potentially valuable improvements to the model for certain circumstances, the current version is widely used.

The LBL infiltration model is used to generate, on an hourly basis, specific infiltration and air flow rates. The hourly infiltration rate is calculated using the following relationship:

$$Q[h] = ELA \cdot s[h] \qquad \text{(EQ 13)}$$

The LBL infiltration model calculates specific infiltration rate, *s[h]*, as:

$$s[h] = \sqrt{f_s^2 \cdot \Delta T[h] + f_w^2 \cdot v^2[h]} \qquad \text{(EQ 14)}$$

where the stack and wind factors (f_s and f_w respectively) are a function of building properties

The stack factor is calculated as shown in Equation 15

$$f_s = \left(\frac{1 + \frac{R}{2}}{3}\right)\left(1 - \frac{X^2}{(2-R)^2}\right)^{\frac{3}{2}}\left(\frac{g \cdot H}{T_o}\right)^{\frac{1}{2}} \qquad \text{(EQ 15)}$$

where R and X are measures of leakage distribution, H is the height of the building and T_o is the outside drybulb temperature.

The wind factor is calculated as shown in Equation 16.

$$f_w = C'(1-R)^{\frac{1}{3}} A\left(\frac{H}{10m}\right)^B \qquad \text{(EQ 16)}$$

where C′ can be found from Table 2, “Shielding Parameters,” as a function

Table 2: Shielding Parameters

Class	*I* *None*	*II* *Light*	*III* *Moderate*	*IV* *Heavy*	*V* *Very Heavy*
C’	0.34	0.30	0.25	0.19	0.11

of shielding class.

A and B can be found from Table 3, “Terrain Parameters,” as a function of terrain class.

Table 3: Terrain Parameters

Class	*I* *None*	*II* *Light*	*III* *Moderate*	*IV* *Heavy*	*V* *Very Heavy*
A	1.30	1.00	0.85	0.67	0.47
B	0.10	0.15	0.20	0.25	0.35

ANNUAL AVERAGES

The LBL model allows estimation of instantaneous air change rates. As shown by Sherman and Wilson (1986) a simple average of these values has, unfortunately, little physical significance. In order to use the hourly values to find out more physically interesting information it is necessary use the appropriate type of weighted average over the appropriate period.

The appropriate period may be all of the occupied hours or it may be a heating or cooling season. The appropriate type of weighted average depends on the physical process involved.

In using the LBL model below, a default set of assumptions have been made about heights, sheltering and leakage distribution. While believed appropriate for estimating impacts of large populations, corrections for these affects could be significant in individual cases.

Effective Air Change Rate

The *effective* air change rate is defined as the constant air change rate which would supply the same amount of pollution dilution (or, equivalently, the same average pollution level) as the actual hourly time series under consideration. It can be calculated by a process similar to that used in ASHRAE Standard 136-93:

$$ACH = 1.44 \cdot w \cdot NL \qquad \text{(EQ 17)}$$

where *w* is the equivalent value of *s* that would yield the same pollution levels under constant conditions. If we are careful to assume a minimum value for the specific infiltration, we can approximate the exact expression as follows:

$$w = \frac{N}{\sum_{h=1}^{N} \frac{1}{s[h]}} \quad \text{(EQ 18)}$$

This harmonic average can never be more than the normal arithmetic mean.

Seasonal Energy Use

The energy used to condition air depends on the temperature or enthalpy difference between the infiltrating and exfiltrating air. Since the driving forces for infiltration also depend on the temperature difference, the relationship is non-linear.

A simplified method for treating this non-linearity is to create a statistic that quantifies the infiltration-related climate. The Infiltration-Degree Day (IDD) method of Sherman (1986b) creates such a statistic. During the heating season the IDDs can be calculated by summing over each heating hour:

$$IDD_{heating}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot (TH - T[h]) \quad \text{(EQ 19)}$$

where *TH* is the indoor heating temperature setpoint (19 °C), *T[h]* is the outside drybulb temperature and s_o=0.71 m/s.

For the cooling season, as latent cooling loads may be quite important, both latent and sensible cooling loads must be considered. The IDDs for each hour should be taken as the larger of the two values:

$$IDD_{cooling(sensible)}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot (T[h] - TC) \quad \text{(EQ 20)}$$

where *TC* is the cooling setpoint temperature (25°C).

$$IDD_{cooling(latent)}[h] = \frac{1}{24} \cdot \frac{s[h]}{s_o} \cdot \frac{HO[h] - HI}{C_p} \quad \text{(EQ 21)}$$

where *HO* is the enthalpy of the outside air and *HI* is the enthalpy of the indoor air.

Hours of heating, cooling and ventilation are determined based on outside temperature conditions. The total number of IDDs (both heating and cooling) is a good estimate of the energy intensity of the climate with respect to infiltration. The annual energy intensity, reflecting heating and cooling energy consumption, can be calculated from the normalized leakage and the number of infiltration degree days:

$$E/(Af) = 86.4 \cdot s_o \cdot \rho C_p \cdot NL \cdot IDD \quad \text{(EQ 22)}$$

where the coefficient 86.4 has the units of s/day.

Compliance with ASHRAE Standards

Compliance is checked with the two relevant ASHRAE standards: Standard 119, the tightness standard, and Standard 62, the ventilation standard.

ASHRAE Standard 119 relates normalized leakage to infiltration degree-days. The standard can be expressed in the following form:

$$2000 \geq IDD \cdot NL \quad \text{(EQ 23)}$$

A building is considered to be in compliance with the tightness standard when the above relationship is true. This expression only guarantees compliance if the definitions and classes are used as defined, but it will be used herein as a reasonable approximation.

The effective air change rate, as calculated using Equation 17, is the value of the air change rate that should be used in determining compliance with minimum ventilation requirements. ASHRAE Standard 62 sets minimum air change rate requirements, for residences, of 0.35 air changes per hour. If we use Equation 17 to represent the effective minimum air change rate then the requirement becomes:

$$w \cdot NL \geq 0.24 \quad \text{(EQ 24)}$$

A building may be considered to be in compliance with the ventilation standard when the above relationship is true. It should be noted, for smaller residences, that the additional requirement of a minimum of 7.5 l/s per occupant must also be met in order to meet compliance.

Equation 17 through Equation 24 are true assuming that infiltration is the only contributor to the total ventilation. While this is true for most U.S. houses, incorporation of mechanical ventilation must be considered as an option. To do so requires that Q, s, w be recalculated. The equations can be found in Sherman (1992b). Similar considerations are required for combustion-induced ventilation.

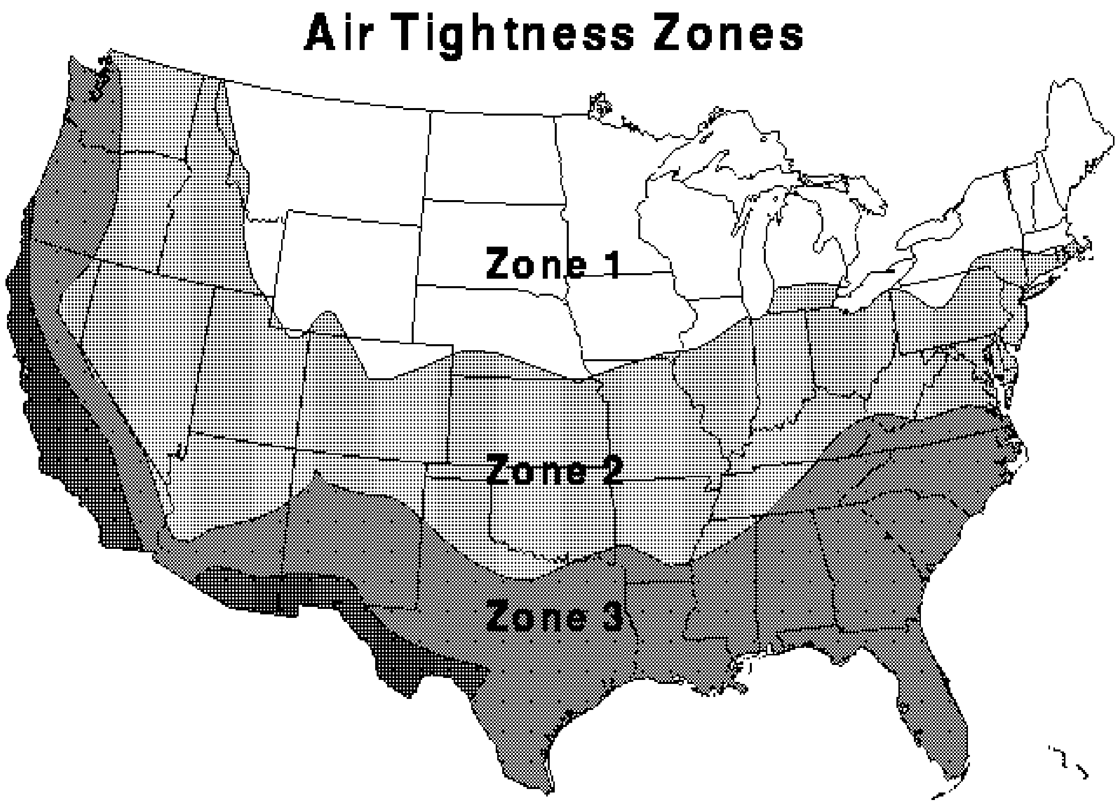

FIGURE 1. Air Tightness Levels. Each of the four zones represents an increasingly larger range of airtightness that would be meet both ASHRAE Standard 119 and ASHRAE Standard 62. Zone 1 buildings cannot meet both standards; Zone 2 and 3 buildings can. Zone 4 (not labeled) has a large acceptance range, but requires very leaky construction.