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Infiltration as Ventilation: Weather-Induced Dilution

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ABSTRACT

*The purpose of outdoor air ventilation is to dilute or remove indoor contaminants to which occupants are exposed. It can be provided by mechanical or natural means. In most homes, especially older homes, weather-driven infiltration provides the dominant fraction of the total ventilation. As we seek to provide good indoor air quality at minimum energy cost, it is important to neither over-ventilate nor under-ventilate. Thus, it becomes critically important to evaluate correctly the contribution infiltration makes to the total outdoor air ventilation rate. Because natural ventilation is dependent on building air leakage and weather-induced pressure differences, a given amount of air leakage will provide different amounts of infiltration. Varying rates of infiltration will provide different levels of contaminant dilution and hence effective ventilation. This report derives these interactions and then calculates the impact of weather-driven infiltration for different climates. A new "*N-factor*" is introduced to provide a convenient method for calculating the ventilation contribution of infiltration for over 1,000 locations across North America. The results of this work could be used in indoor air quality standards (specifically ASHRAE 62.2) to account for the contribution of weather-driven infiltration towards the dilution of indoor pollutants.*

Keywords: Infiltration, Mechanical Ventilation, Ventilation Effectiveness, Residential Ventilation, Indoor Air Quality

NOMENCLATURE

ACH	Air Changes per Hour [$1/h$]
ACH_{eff}	Effective air change rate [$1/h$]
A_{floor}	Building floor area [m^2]
c	Building flow coefficient [$m^3/(s/Pa^n)$]
C_D	Discharge coefficient [-]
C_s	Stack coefficient [$(Pa/K)^n$]
C_w	Wind coefficient [$(Pa{\cdot}s^2/m^2)^n$]
ELA	Effective Leakage Area [m^2]
G	Wind speed multiplier [-]
H	Total building height [m]
H_o	Height of a single story [m]
i	Turnover time period [h]
IAQ	Indoor Air Quality
n	Pressure exponent [-]
n_H	Updated pressure exponent [-]
N	Leakage-infiltration ratio [-]
$N_{62.2}$	Leakage-infiltration ratio for use in ASHRAE Standard 62.2
NL	Normalized Leakage [-]
N_{story}	Number of stories of the house
Q	Airflow rate [m^3/s]
Q(50Pa)	Airflow rate at 50 *Pa* of pressure [m^3/s]
Q_{eff}	Effective airflow rate [m^3/s]
Q_I	Infiltration airflow rate [m^3/s]
Q_s	Infiltration airflow rate due to stack effect [m^3/s]
Q_w	Infiltration airflow rate due to wind [m^3/s]
s	Shelter factor [-]
t	Time [h]

T	Air temperature [$°C$]
U	Wind speed at house site location [m/s]
V_{house}	Building volume [m^3]
VOC	Volatile Organic Compound
W_{136}	Weather factor for ASHRAE 136 [$1/h$]
WSF	Weather and Shielding Factor [$1/h$]
$W_{n\text{-}story}$	Weather factor for an n-story home [1/h]
ε	Ventilation efficiency (efficacy) [-]
ρ	Air density [kg/m^3]
ΔP_{ref}	Reference pressure difference [Pa]
τ_e	Turnover time [h]

INTRODUCTION

The purpose of ventilation is to provide outdoor air to ensure healthy indoor air quality (IAQ) by diluting or removing internally-generated contaminants. Historically, people have ventilated buildings to provide source control for both combustion products and objectionable odors (Reid, 1844).

Weather-driven infiltration is the flow of air through cracks and other unintentional openings in the building envelope (ASHRAE 2009), caused by naturally occurring pressure differences due to indoor-outdoor temperature differences and wind. It can contribute significantly to the overall heating or cooling load of a building via the exchange of indoor and outdoor air. The magnitude of infiltration depends on many factors including environmental conditions, building design, construction quality and operation. A building envelope that it too loose, coupled with the variable nature of weather-driven infiltration, can result in over-ventilation with a subsequent energy penalty. Conversely, a building envelope that is too tight can result in under-ventilation and poor IAQ.

The majority of existing U.S. homes have no mechanical ventilation, instead relying on infiltration combined with the occasional opening of windows. Studies such as Price and Sherman (2006), Offermann (2009) and Breen et al. (2010) have shown that window opening as ventilation is highly unreliable as a strategy because it is often used inappropriately. Infiltration is therefore a dominant mechanism for providing ventilation in U.S. residences.

Recent residential construction methods have yielded tighter building envelopes that can save energy, but also can create a potential for under-ventilation (Sherman and Dickerhoff, 1994, Sherman and Matson, 2002). As a result, new homes often need mechanical ventilation systems to meet current ventilation standards. McWilliams and Sherman (2005) reviewed codes, standards and related factors that helped facilitate the adoption of mechanical ventilation requirements in some jurisdictions (e.g. California).

Ignoring weather-driven infiltration can lead to excess ventilation and unnecessary energy expense, while over-estimating the contribution of infiltration can lead to poor IAQ and contaminant exposure. This report proposes analytical and simulation methods to help determine how infiltration can be valued correctly in the context of residential ventilation.

ASHRAE Standards

A key motivation for understanding the role of infiltration in ventilation is the development and application of energy and/or IAQ standards. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is the key organization in this regard in the United States and the only one to have American National Standards on residential ventilation and infiltration. Currently the three key standards are Standards 62.2, 136 and 119.

ASHRAE Standard 62.2 (2010) sets requirements for residential ventilation and acceptable IAQ. There are source control requirements and minimum local and continuous mechanical ventilation requirements. The standard mostly concerns mechanical ventilation systems, but incorporates a default infiltration credit that allows mechanical ventilation rates to be reduced based on annual average infiltration rates when determined using ASHRAE Standard 136.

Standard 136 (1993, 2003) uses pre-calculated weather factors and measured air tightness represented as normalized leakage (using Standard 119) to estimate the impact that infiltration would have on IAQ and thus determine the equivalent ventilation. This concept will be described in more detail in a later section of this report.

Standard 119 (1988, 2005) defines normalized leakage (NL) and also specifies envelope air tightness levels based on energy conservation concerns. Henceforth, we are only concerned with the NL definition in 119.

We will look at the impacts of infiltration towards providing acceptable IAQ and examine the need to change these standards, particularly Standard 136, accordingly.

Energy vs. Indoor Air Quality (IAQ)

This report is focused on determining the role that air tightness and weather-driven infiltration play in providing the dilution of indoor contaminant sources, but not on their role in increasing the space conditioning load. Therefore, we have made decisions in our modeling and analysis choices that are more appropriate to an IAQ analysis than to an energy analysis. An example is the assumption of a constant indoor air temperature of 22°C all year, rather than using different temperatures for heating and cooling seasons. This assumption was to simplify both the simulations and data analysis. Consequentially, it is important to recognize that the use of these results would not be appropriate for estimating energy impacts.

More importantly, we have made modeling choices that are *conservative* with respect to IAQ but likely liberal with respect to energy. The simple models we are using do not allow (nor do we fully know) the complete range of parameters including leakage distributions, wind sheltering and house shapes. While we have tried to be as accurate as possible, we have erred on the side of under-prediction of the air change rates so that our results would be more protective of the indoor environment.

As will be described in detail below, we have elected to use an infiltration model that is known to under-predict slightly the magnitude of infiltration. Similarly we have chosen to use wind sheltering that is conservative. Our simulations do not include other forms of passive or natural ventilation such as the opening of windows.

BACKGROUND

To understand the contribution of infiltration towards ventilation we review the role of air tightness and weather in driving infiltration and the role ventilation has in providing acceptable IAQ. Weather is a time-varying phenomenon that affects airflow through leaks in the building envelope; the specific weather-driven forces include indoor-outdoor temperature differences (often referred to as the 'stack effect') and wind. Ventilation standards implicitly assume constant ventilation (and often a constant contaminant source). To determine the impact that a time varying situation will have that would be equivalent to a time invariant one requires that we understand the time dependency of the quantity of interest— IAQ. This requires numerical modeling. The Sherman-Wilson (1986) approach to effective ventilation can be used to determine the steady-state ventilation rate that would provide the same dilution as the physically occurring, time-dependent infiltration. In this study we calculated hour-by-hour infiltration rates using simplified models and weather data. These infiltration rates were then used to calculate effective ventilation rates that accounted for the dilution of pollutants. Finally, we determined weather and building related factors that could be used in ventilation standards to account for the effects of infiltration on the dilution of pollutants.

Air Tightness

Air tightness is the fundamental building property that impacts infiltration. There are a variety of definitions of infiltration, but essentially infiltration is the movement of air through leaks, cracks, or other adventitious openings in the building envelope. The modeling of infiltration (and thus ventilation) requires a measure of air tightness as a starting point. More extensive information on air tightness can be found in Sherman and Chan (2006), who review the state of the art. This information is also part of a broader state of the art review on ventilation compiled by Santamouris and Wouters (2006).

Sherman and Chan (2006) also discuss the topics of metrics, reference pressures, and one versus two-parameter descriptions of airtightness in some detail. There are various airtightness metrics one could use other than NL. For example, airflow at a fixed pressure is the easiest one to measure but does not account for house size and suffers from accuracy issues due to extrapolation errors when the reference pressure is outside of the measured range. Similarly, leakage per unit of exposed surface area is a good estimate of the porosity of the envelope, but does not scale correctly for either energy or IAQ purposes.

ASHRAE Standard 119 (1988, 2005) currently uses the metric of NL to describe air tightness of houses because it reduces the influence of house size and height, and because it scales with house size. NL is defined in Standard 119 as follows:

$$NL = 1000 \cdot \frac{ELA}{A_{floor}} \cdot \left(N_{story}\right)^{0.3} \tag{1}$$

where *ELA* is the 'Effective Leakage Area' measured by methods such as ASTM E779 (2003) in the same units as the floor area, A_{floor} and the number of stories of the house, N_{story} (or the ratio of total house height to individual story height). In the current study we revisit the 0.3 exponent used for the height effect (N_{story}) but retain the general formulation.

To link NL (or any other air leakage metric) to the total ventilation we must use an infiltration model. This link was previously provided by a weather factor, *W*, that was calculated using a version of the Basic Infiltration Model, also known as the LBL or Sherman and Grimsrud model, found in the ASHRAE Handbook of Fundamentals (ASHRAE, 2009). To avoid confusion with the updated *W*-factor outlined in this report, the older weather factor described in Standard 136 will henceforth be referred to as W_{136}.

Infiltration Model

In this study we used the enhanced model from the ASHRAE Handbook. This is based on the Alberta Infiltration Model (AIM2), developed by Walker and Wilson (1993, 1998), with assumptions made for leakage distribution and wind shelter to reduce the number of required inputs. The enhanced model improves on the basic model by:

i. Using a pressure exponent that is not fixed to be 0.5. A summary of several studies by Orme et al. (1994) found an average exponent of 0.65 (and reported that 0.66 be assumed for ventilation modeling). Additional field measurements and analytical approaches by Walker et al. (1997) found a similar result with a typical exponent of two-thirds. Therefore, in this study we assume a pressure exponent of 0.67
ii. Allowing there to be a flue in the house (typically this is from a vented combustion appliance or fireplace). The enhanced model includes sub-models for predicting infiltration in a house with and without an open flue
iii. Using improved definitions of building shelter
iv. Using two different types of house construction: basement slab and crawlspace floors.

Separate terms describe the stack, Q_s and wind Q_w airflow rate [m^3/s] components:

$$Q_s = c \cdot C_s \Delta T^n \quad (2)$$

$$Q_w = c \cdot C_w (sU)^{2n} \quad (3)$$

Where C_s is the stack coefficient [$(Pa/K)^n$], C_w is the wind coefficient [$(Pa \cdot s^2/m^2)^n$] and s is the shelter factor [dimensionless]. To account for reduced wind speeds at house site location, U [m/s] compared to weather measurement location, v [m/s], the enhanced model uses a dimensionless wind speed multiplier, G:

$$U = v \cdot G \quad (4)$$

This converts the wind speed recorded in weather data files (typically measured at 10 m high airport towers) to the height of the building under study. G varies with the height of the house and accounts for atmospheric boundary layer effects. Tabulated values of C_s, C_w and G can be found in the ASHRAE Handbook of Fundamentals.

The building flow coefficient, c [$m^3/(s/Pa^n)$] and pressure exponent, n, are calculated from multi-point pressurization testing of the building envelope, typically using procedures from standard techniques such as ASTM E779 and CGSB 149.10 (1986). They can be calculated directly using E779 or related to the ELA calculated from E779 as follows:

$$c = C_D \cdot ELA\sqrt{\frac{2}{\rho}\Delta P_{ref}}(4Pa)^{0.5-n} \qquad (5)$$

Where C_D is the dimensionless discharge coefficient (defined as 1.0 in E779 but has other values in some standards, such as 0.611 in CGSB 149.10), ρ is the air density [kg/m^3], ΔP_{ref} is the reference pressure difference [Pa] (in E779 this is 4 Pa, but other standards use other pressures, such as 10 Pa in CGSB 149.10). The original AIM2 used pressure addition and a correction term to account for wind and stack interactions. For simplicity and because the methods are approximately equivalent (Walker and Wilson, 1993, and Sherman, 1992), we use the procedure used in the ASHRAE Handbook of Fundamentals where the stack and wind infiltration components are combined in quadrature to give the overall infiltration airflow rate, Q_I [m^3/s]:

$$Q_I = \sqrt{Q_s^2 + Q_w^2} \qquad (6)$$

The air change rate in air changes per hour can be found from the infiltration airflow rate and the building volume V_{house} [m^3] as follows:

$$ACH_I = 3600[s/hr] \cdot \frac{Q_I}{V_{house}} \qquad (7)$$

Superposition

The calculated infiltration airflow rate can be combined with the mechanical ventilation rate via 'Superposition'. Sherman (1992) examined the topic in some detail for a variety of cases. The simplest, most robust method (and the method used in the ASHRAE Handbook of Fundamentals and Standard 136), is to combine the unbalanced mechanical ventilation (such as a simple exhaust fan) and infiltration ventilation in quadrature, then add balanced systems linearly:

$$Q_{combined} = Q_{balanced} + \sqrt{Q_{unbalanced}^2 + Q_I^2} \tag{8}$$

Ventilation Effectiveness

From the perspective of acceptable IAQ, the purpose of ventilation is to dilute the concentration of internally-generated contaminants. We generally seek to control the average concentration of these contaminants over some period of interest. With constant emission strength and constant total ventilation this is a trivial calculation. Since pollutant concentration is non-linear with respect to ventilation rate, a simple average of the ventilation rate cannot be used when the ventilation varies over time. Instead, the term 'effective ventilation' is defined as the steady-state ventilation that would yield the same average pollutant concentration over some time period as the actual time varying ventilation would in that same time period.

ASHRAE Standard 136 (1993) was a first attempt to determine the contribution of infiltration towards providing ventilation. The algorithm used was based on approximations made by Yuill (1986) and used a variety of weather sources available at the time. The result was a table of weather related 'W_{136}' values that linked the effective ventilation due to infiltration to the normalized leakage:

$$ACH_{eff} = NL \cdot W_{136} \tag{9}$$

In this report we use the approach of effective ventilation developed by Sherman and Wilson (1986) to quantify the contributions of time varying ventilation. It is important to note that the contaminant source strength was assumed to be constant over the period of interest. This holds for many building contaminants where the source emission varies slowly with time or operates in a stepwise fashion, *and* is unaffected by ventilation rate. Some important exceptions are radon or formaldehyde, where in some circumstances the emission rate can be dependent on the ventilation rate of the building. If such cases are relevant, such as the exposure to episodic emissions from activities like cleaning and cooking, more detailed techniques may be required.

Effective ventilation is calculated by first finding the inverse or turnover time, τ_e [h] for the pollutant concentration to reach steady state. For the hourly time series data generated by the infiltration model, for time period i, the turnover time is given by:

$$\tau_{e,i} = \frac{1 - e^{-ACH_i \Delta t}}{ACH_i} + \tau_{e,i-1} \cdot e^{-ACH_i \Delta t} \quad (10)$$

where Δt is the time period (in hours). The mean ventilation efficiency is a non-dimensional quantity which is defined as the ratio of the mean effective ventilation to the mean instantaneous ventilation. It is shown in terms of the characteristic time. The closer the actual ventilation rate is to steady state over the period of interest, the higher the ventilation efficiency, ε (sometimes called *efficacy*), will be:

$$\varepsilon = \frac{1}{\overline{ACH} \cdot \overline{\tau_e}} \quad (11)$$

The overbars indicate an average over time. The effective ventilation for that period will be the average ventilation for that period multiplied by the mean (temporal) ventilation efficiency for that period:

$$ACH_{eff} = \overline{ACH} \cdot \varepsilon = \frac{1}{\overline{\tau_e}} \quad (12)$$

Exposure Period

The ventilation effectiveness derivation above requires the averages of the quantities involved over some period of time. Since we are conducting this analysis using annual weather data the nominal time period over which to average is one year. This would be appropriate if the relationship between the impact of the contaminants were dependent only on the average concentration of the contaminants. This may not always be the case. Therefore we need to determine the relevant *exposure period*.

Contaminants in the indoor environment may interact with the body in different ways. This means their relevant exposure metric can be quite different. There are two time scales we can use to evaluate health effects: chronic and acute. For the chronic case, when the risk of disease is related to the total dose we consider the integrated concentration over time. Many types of pollutants are assumed to behave this way such as carcinogens like radon or volatile organic compounds (VOCs) like formaldehyde.

For the acute case, the concentration over a comparatively short time period is important. For example, carbon monoxide poisoning occurs due to elevated levels over a time period of minutes to hours and so long-term dose is unimportant. Another example includes exposure to chlorine gas which exhibits a non-linear dose-response relationship between concentration and health end points.

These issues can be handled by presuming there is a relevant *exposure period* for each contaminant of concern. For those contaminants where long-term averaging or *dose* is the key metric, the annual average is appropriate. Previous work by Logue et al. (2010) and Sherman et al. (2010) has shown that the contaminants of concern for whole house mechanical ventilation, i.e. those contaminants that are continuously emitted from diffuse sources throughout the home such as formaldehyde and acrolein, have sufficiently high acute exposure health standards (relative to chronic health standards) that the annual average concentration is the appropriate metric given current intermittent ventilation standards. This means the exposure period can be set to one year.

Infiltration is weather dependent. Due to the availability of hourly weather data files we typically consider variations from hour-to-hour over the course of a year. To evaluate the net benefits of infiltration towards controlling indoor contaminants, we need to apply the temporal ventilation effectiveness concept to infiltration. To do so requires the use of an infiltration model and typical weather data for an entire year.

We define infiltration efficiency as a special case of ventilation efficiency. Generalized ventilation efficiency as defined by Sherman and Wilson (1986) is based on the simple average over the time period in question. The reference for our infiltration efficiency will be the longest term (i.e. annual) average. So the effective ventilation becomes defined through the following expression:

$$ACH_{eff} = \varepsilon_I \cdot \overline{ACH}_{I,annual} = \frac{1}{\overline{\tau}_e} \quad (13)$$

where the characteristic time is averaged over the relevant exposure period of the contaminant(s) of concern.

Concentration fluctuations are damped out by the volume of the indoor space and the air change rate. This effect was not included in the original Yuill approach, but is in the Sherman-Wilson approach. Thus there is some indirect dependency on the total ventilation rate and the air tightness.

In this study, we applied Equation (13) to calculate the infiltration efficiency for all TMY3 (Wilcox and Marion, 2008) locations in the USA (1,020 locations) and 80 locations in Canada.

INFILTRATION CALCULATIONS

ASHRAE Standard 62.2 gives a ventilation credit for infiltration that may affect the sizing of mechanical ventilation equipment. This is why it is important to remain conservative in any description of the magnitude of the weather-induced infiltration. Currently, Standard 62.2 allows for the calculation of expected air change due to infiltration and then applies a conservative reduction by halving the infiltration. The infiltration credit is applied linearly in 62.2, however, the infiltration and mechanical ventilation should be combined using superposition. Unbalanced mechanical ventilation and infiltration combine sub-linearly. In one way, the reduction by halving could be seen as a simplistic approach to account for the non-linear sub-additive nature of combing infiltration and unbalanced mechanical ventilation. This halving of infiltration should be unnecessary given suitable conservative considerations for the infiltration model and its input parameters.

Previous studies (Palmiter et al., 1991, Walker and Wilson, 1998, Wang et al., 2009) have shown that the enhanced infiltration model predicts smaller airflows than the basic LBL model. Therefore, the new analysis performed for the current study will result in lower infiltration estimates, and will be conservative in terms of providing good IAQ. For this study we used the enhanced model with a building shelter class of 4, representing typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away (ASHRAE, 2009) with a flue (based on Walker et al., 1996) and a basement slab floor. The ASHRAE Standard 136 used a less conservative shelter class of 3. Twenty percent of the envelope leakage was assumed to be in the flue, representing natural draft combustion appliances and fireplaces. An inside design temperature of 22°*C* was chosen for both summer and winter. The minimum instantaneous wind speed allowed was 1 *m/s* to account for the number of false zeros in weather data files arising from the start-up wind velocity required for some anemometers. Building leakage was assumed to be an ELA of 0.074 m^2 (this corresponds to a NL of 0.4 or about 8 Air Changes per Hour (ACH) at 50 Pa) with an envelope pressure exponent of 0.67 and a floor area (A_{floor}) of 185 m^2. The effect of building height (that influences the stack and wind effects) was evaluated by modeling one, two and three story homes. The floor area was the same in each case; however the envelope leakage distribution was varied to account for changes in building geometry (see Table 1) – with proportionally more leakage in the walls with increasing number of stories. The height of each story was 2.5 *m* and the building volume was kept constant. The hourly calculated infiltration rates were used in Equation (12) to determine the hourly turnover times.

Table 1: Envelope leakage distribution used in the simulations

Envelope Leakage Distribution			
Number of Stories	1	2	3
Fraction of Leakage in the Walls	0.5	0.66	0.75
Fraction of Leakage in the Ceiling	0.25	0.165	0.125
Fraction of Leakage at Floor Level	0.25	0.165	0.125

The following figures illustrate some of the variability in hourly, annual average, and effective ventilation rates. Figure 1 shows how Miami, Florida has low ventilation rates all year, with an average ventilation rate (caused by infiltration) of 0.184 ACH and an *effective* ventilation rate of 0.167 ACH– a reduction of 10%. The hourly ventilation rates for the year vary by a factor of 10 from 0.050 to 0.500 ACH. However, Miami's mild climate does not automatically lead to the smallest differences between mean and effective ventilation rates. Figure 2 shows that Oakland, California has a higher average ventilation rate of 0.226 ACH and an effective ventilation rate of 0.217 ACH but the effective ventilation rate is only 4% lower than the annual average because weather is more consistent throughout the year in Oakland. At the other end of the weather spectrum, Helena, Montana has large diurnal variations that drive major differences between average and effective ventilation rates. Helena, has a larger difference of 12% between the average ventilation rate of 0.286 ACH and effective ventilation of 0.252 ACH. Helena also has large seasonal variations, compared to Oakland or Miami, with higher rates in the winter when temperature differences are larger, as shown in Figure 3.

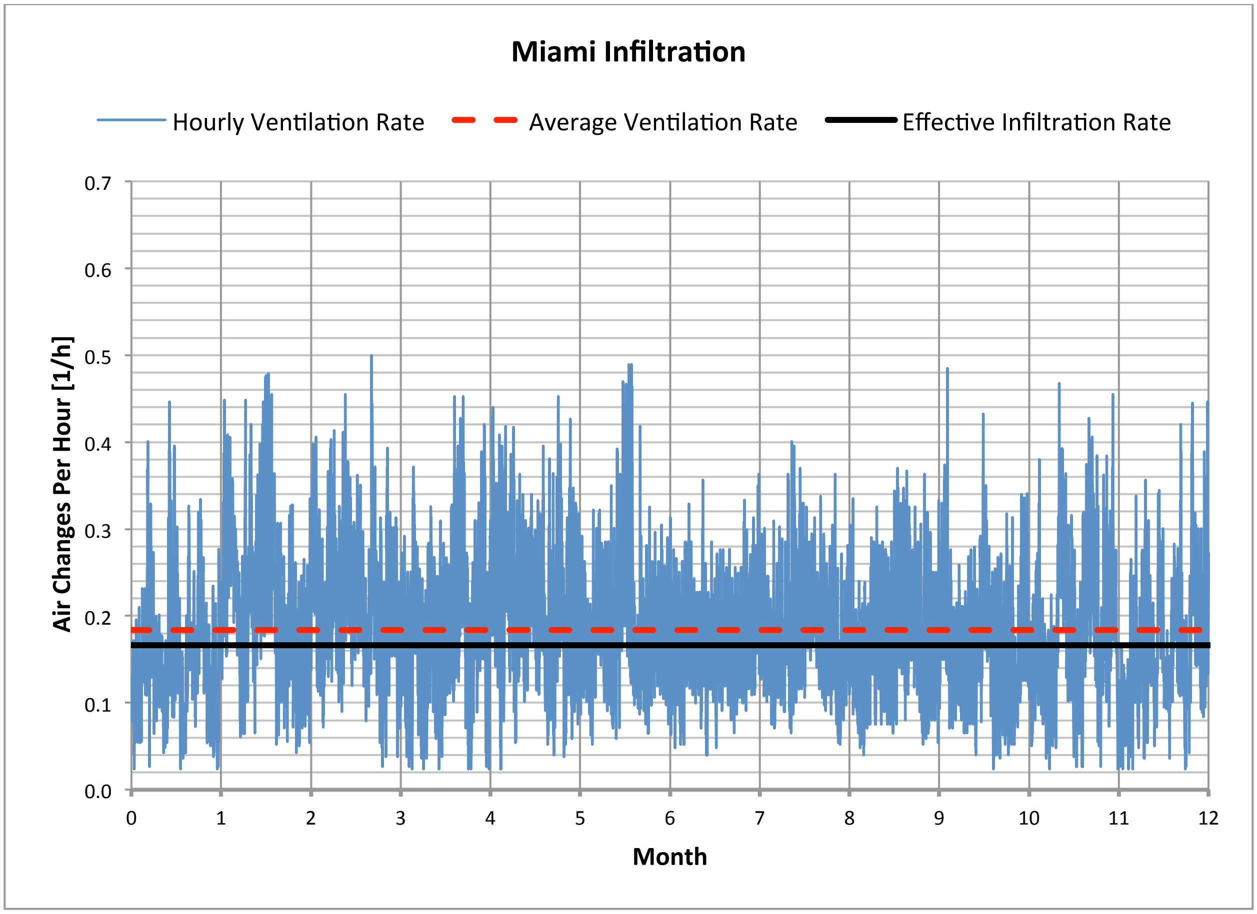

Figure 1: Hourly calculated infiltration rates for Miami, Florida with the average ACH and the effective ventilation calcultaed from the updated *W*-factor.

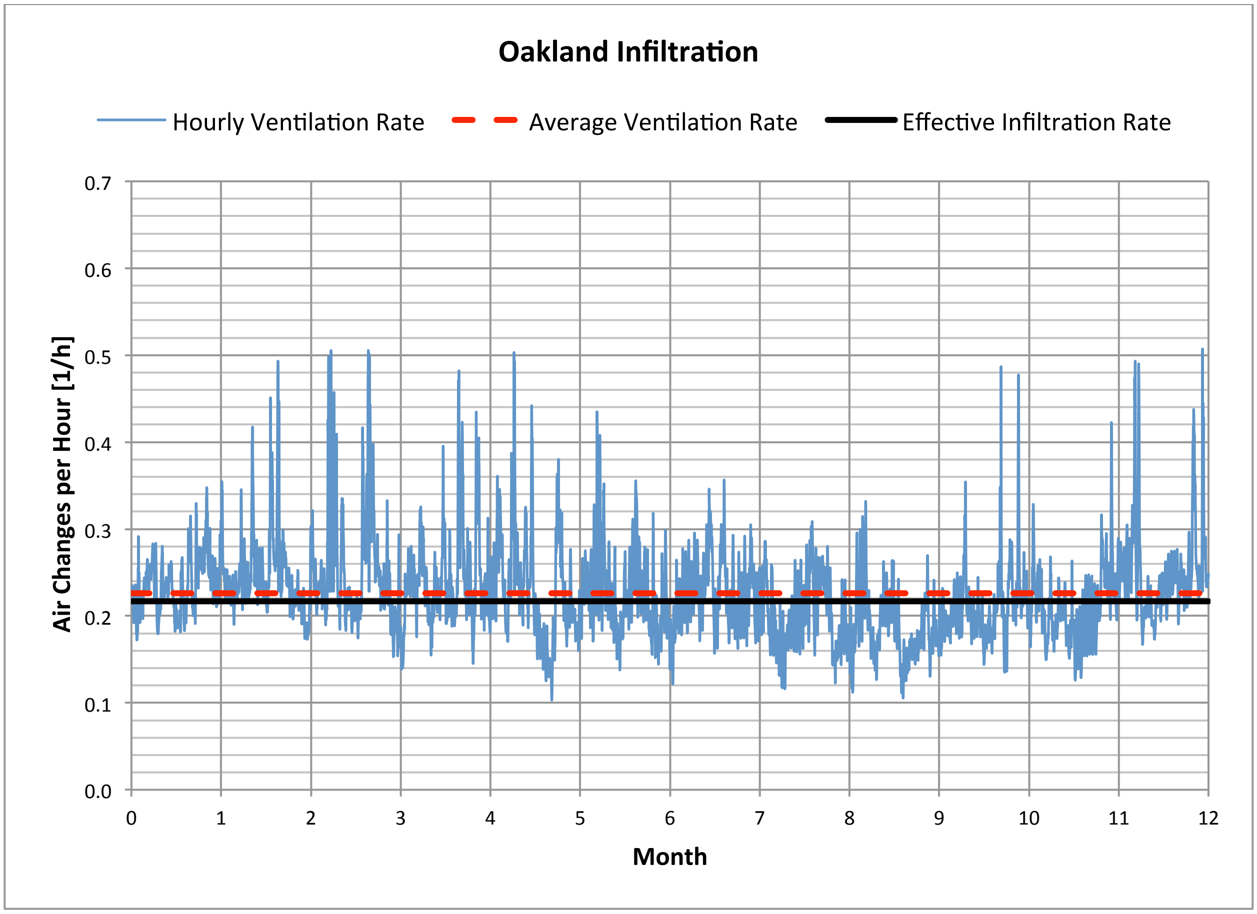

Figure 2: Hourly calculated infiltration rates for Oakland, California with the average ACH and the effective infiltration calcultaed from the updated *W*-factor.

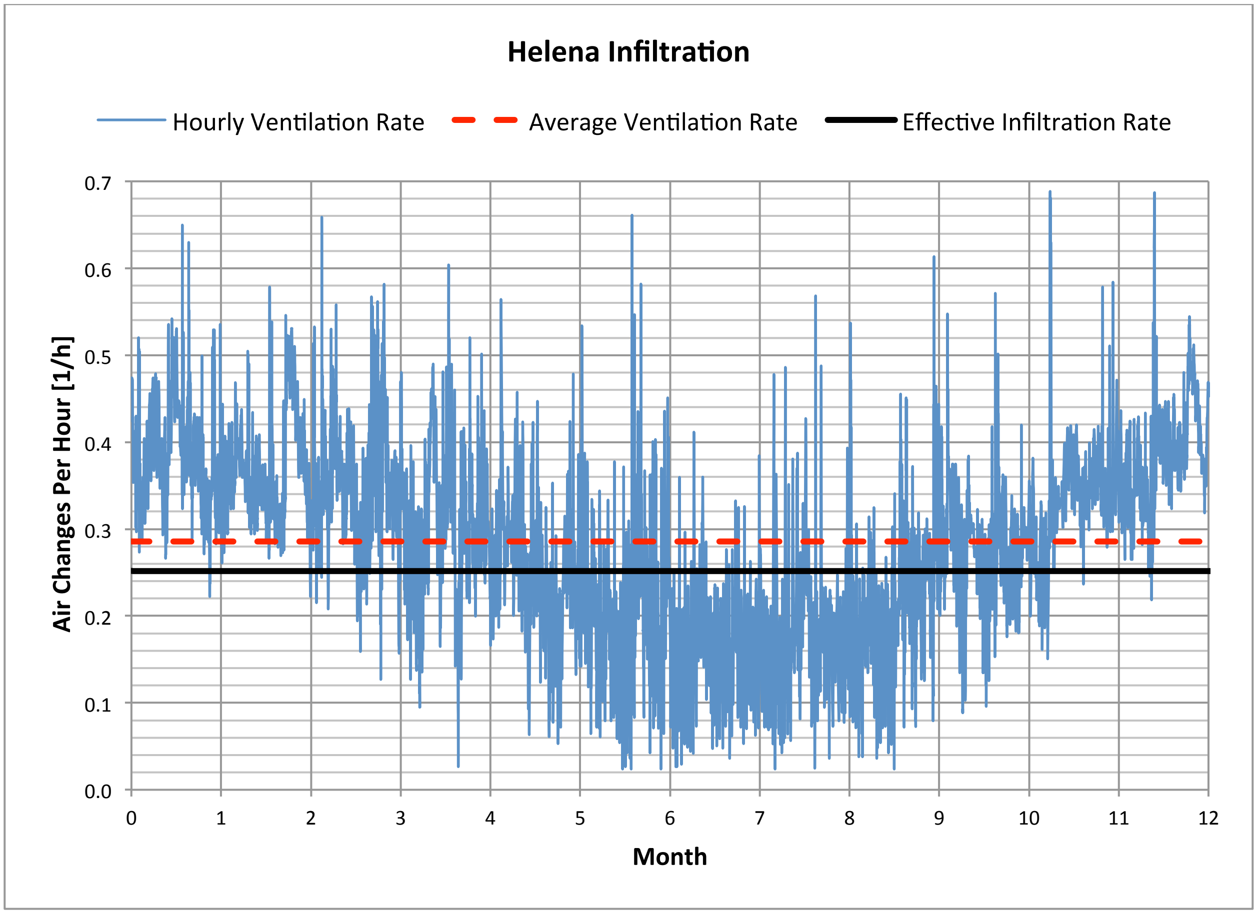

Figure 3: Hourly calculated infiltration rates for Helena, Montana. Note the higher variability in infiltration rates due to higher variability in weather conditions.

CALCULATION OF *W* AND HEIGHT EFFECTS

To calculate new values of *W* in the current study, hour-by-hour simulations were carried out for 1,020 TMY3 U.S. weather sites and 80 CWEC (Canadian Weather for Energy Calculations) weather sites (Numerical-Logics, 1999). First, the hourly outdoor airflow rate due to infiltration was calculated using the enhanced infiltration model and the weather data for each site. This was then used to calculate the mean annual turnover time using Equation (10) which in turn yielded the *W* weather factor, defined as:

$$W = \frac{1}{1000(\frac{ELA}{A_{floor}})\cdot\overline{\tau_e}} \quad (14)$$

The effect of the building height (number of stories) was determined by the ratio of W for the two and three stories cases to that of the one story case. This ratio was raised to an exponent, n_H, that was determined empirically using the results from all 1,100 weather sites. The metric used to determine the value of the exponent was the root mean square (RMS) error comparing the ratio of W using the exponent approach to the actual ratios. The RMS error induced by the exponent fit was under 1.5%. The optimal exponent was 0.378. The best exponent having one significant digit is 0.4, which still has less than 1.5% RMS error. Using 0.3 would increase the error by a few percent.

The weather factor for two and three story houses, $W_{n\text{-}story}$ can then be calculated from:

$$W_{n-story} = W_{one-story}\left(\frac{H}{H_0}\right)^{n_H} \quad (15)$$

where $W_{one\text{-}story}$ is the weather factor for a single story home, H_o is the height of a single story, and H is the total building height in the same units as H_o. Finally, the average annual air changes per hour from infiltration can be calculated by combining the NL and the W-factor using Equation (9).

DERIVATION OF $N_{62.2}$

The current ASHRAE Standard 136 calculations using W_{136} have an inherent problem for non-standard ceiling heights. This is intrinsic to the definition of W and comes from it being based on ACH when the house size metric is floor area. To get away from this issue we use the concept of a leakage-infiltration ratio, N, sometimes called the 'N-factor'. This has been developed analytically by Sherman (1987) based on initial empirical work by Kronvall (1978). In this study we advance the concept of $N_{62.2}$, which does not explicitly use ELA, but instead uses a measured airflow at a fixed pressure.

The vast majority of building air leakage tests do not follow ASTM E779 or similar multi-point pressurization and/or depressurization tests. Instead, a single test is performed at 50 *Pa* and the resulting airflow, Q(50Pa) is reported. To allow for use of this simpler test data we can derive an alternative weather factor ($N_{62.2}$) that uses Q(50Pa) instead of ELA to estimate natural infiltration:

$$Q_{eff} = \frac{Q(50Pa)}{N_{62.2}}\left(\frac{H}{H_0}\right)^{n_H}\left(\frac{50Pa}{4Pa}\right)^{n-0.65} \tag{16}$$

Where *n* is the exponent measured from the blower door test.

To determine $N_{62.2}$ we need to relate it to ELA by assuming a fixed value for the pressure exponent of 0.65 (Orme et al. 1994). This pressure exponent is used to convert Q(50Pa) to ELA at 4 *Pa* (the reference pressure used in the definition of ELA in ASTM E 779 and in the definition of NL).

$$ELA = Q(50Pa)\left(\frac{4Pa}{50Pa}\right)^{n}\sqrt{\frac{\rho}{8}} = 0.194Q(50Pa)\sqrt{\frac{\rho}{8}} \tag{17}$$

Q_{eff} using W is given by:

$$Q_{eff} = ACH_{eff}\frac{V_{house}}{3600} = \frac{W \cdot NL \cdot V_{house}}{3600} = \frac{W \cdot ELA \cdot 1000 \cdot V_{house}}{3600 A_{floor}}\left(\frac{H}{H_0}\right)^{n_H} \tag{18}$$

Substituting Equation (17) into Equation (18), we can eliminate the direct use of ELA:

$$Q_{eff} = \frac{W \cdot 0.194Q(50Pa)\sqrt{\frac{\rho}{8}} \cdot 1000 \cdot V_{house}}{3600 A_{floor}}\left(\frac{H}{H_0}\right)^{n_H} \tag{19}$$

Equating Equations (16) and (19):

$$N_{62.2} = \frac{3600}{W \cdot 0.194 \cdot \sqrt{\frac{\rho}{8}} \cdot 1000 \cdot H_0} \tag{20}$$

Using typical values of air density, ρ = 1.2 kg/m^3 and story height, H_o = 2.5 m, gives us:

$$N_{62.2} = \frac{19.2}{W} \quad (21)$$

Equation (21) was used to convert the values of W for each site to $N_{62.2}$. Hence, we can have a table of $N_{62.2}$ values for each weather station that allows the direct use of Q(50Pa) (and the leakage exponent) instead of ELA to estimate effective infiltration rates.

RESULTS

We have calculated the W and N-factor for 1,100 sites in North America: 1,020 TMY3 weather sites for the United States and its territories and 80 CWEC sites for Canada. Supplementary data to this report includes tables of all the results. In this section we will only show N-factors as they are more likely to be used in the field by practitioners.

Figure 4 shows all the sites we have simulated in the United States. Figure 5 is a similar plot but for the U.S., its territories and Canada. The dots on the map show the location of the weather measurement sites. The color indicates the magnitude of $N_{62.2}$, from low (blue) to red (high). A higher N-factor indicates less ventilation contribution from infiltration. This occurs in U.S. coastal regions, areas with a smaller day/night temperature swing, and those at latitudes closer to the equator such as the southern states of Florida and Alabama. The lower N-factors (more weather-induced infiltration) occur in regions with more extreme weather conditions i.e. stronger wind speeds and larger temperature differences. These are typically exposed locations, inland and at higher latitudes. The lowest $N_{62.2}$ for the dataset is the exceptionally severe climate of Mount Washington, NH with an $N_{62.2}$ of 12. The weather station at Mount Washington is at an altitude of nearly 2 *km* (6,500 feet) and has an annual average indoor/outdoor temperature difference and wind speed (from the TMY3 dataset) of 23.8 *K* and 15.1 *m/s* respectively.

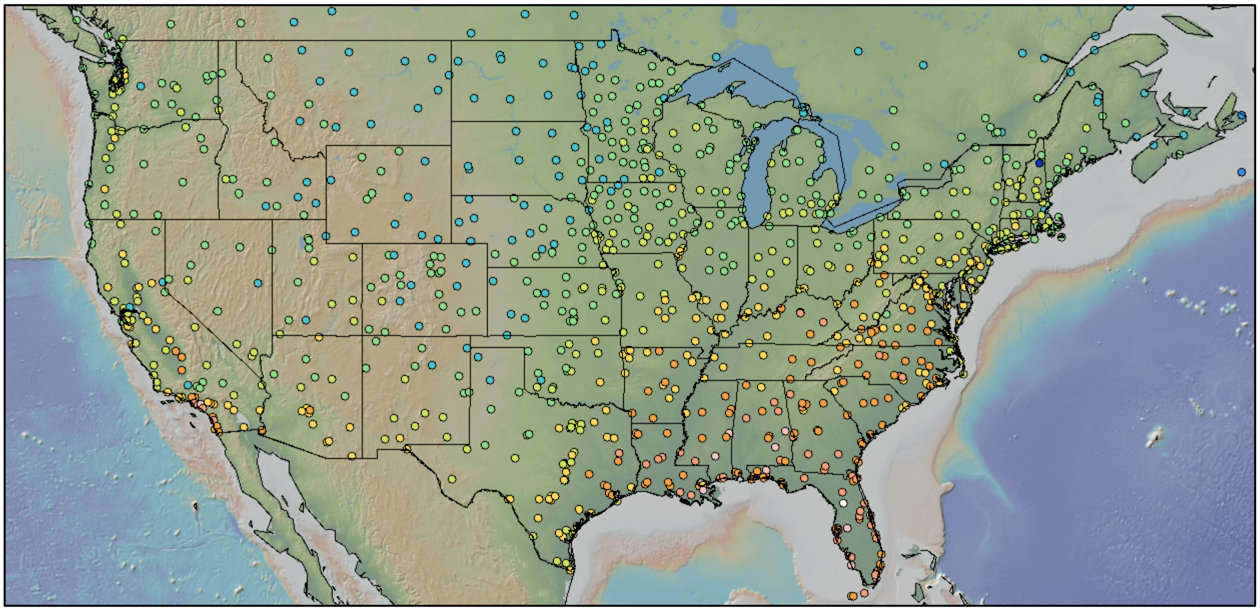

Figure 4: *$N_{62.2}$* factors for the continental United States.

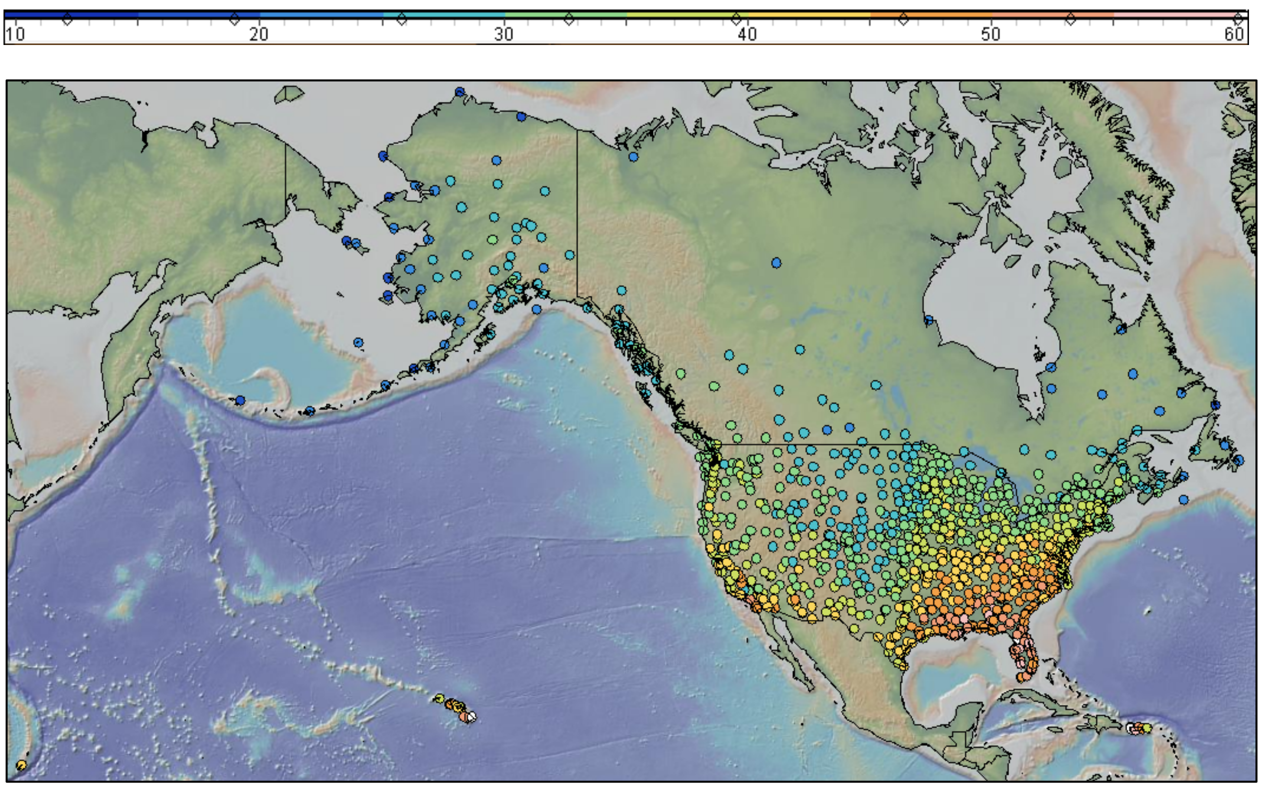

Figure 5: *$N_{62.2}$* factors for the United States, its territories and Canada. Maps from Ryan et al. (2009), data points plotted using *GeoMapApp* (Haxy, 2011).

The data has also been summarized by the IECC climates zones (Briggs et al., 2003) to give a general indication of the magnitude of infiltration over broader geographical areas. Table 2 shows the minimum, maximum and median $N_{62.2}$ values for each climate zone, its representative city, and Canada. A is 'moist', B is 'dry' and C is 'marine'. Climate zone 1 includes Hawaii, Guam, Puerto Rico and the Virgin Islands. Climate zone 7 can be split into A, B and Alaska, or considered all together. There are no representative cities for 7B, 7 Alaska or Canada. The representative city for zone 1B is Luxor, Egypt (since there is no equivalent city in the U.S.) and was therefore omitted from the simulations. We see that climate zones 1 to 3 experience less weather-induced infiltration compared to the more extreme climate zones 4 to 8. There is also a clear distinction between the dry and moist climate zones, with more infiltration occurring in the dry zones.

Table 2: $N_{62.2}$ Values for the USA by IECC Climate Zone and Canada.

Climate Zone	Min. $N_{62.2}$	Max. $N_{62.2}$	Median $N_{62.2}$	CZ Representative City $N_{62.2}$	City, State
1A	35	67	47	47	Miami, FL
2A	36	60	47	45	Houston, TX
2B	35	47	43	44	Phoenix, AZ
3A	29	56	45	42	Memphis, TN
3B	28	56	40	40	El Paso, TX
3C	32	44	39.5	32	San Francisco, CA
4A	26	51	41	39	Baltimore, MD
4B	28	38	31	35	Albuquerque, NM
4C	31	41	35	35	Salem, OR
5A	26	45	35	32	Chicago, IL
5B	27	43	32	34	Boise, ID
6A	12	42	33	32	Burlington, VT
6B	25	35	29	31	Helena, MT
7A	26	35	30	27	Duluth, MN
7B	26	30	29	-	-
7 (Alaska)	19	32	27	-	-
7 (All)	19	35	29	27	Duluth, MN
8 (Alaska)	17	30	22.5	27	Fairbanks, AK
Canada	15	35	27	-	-

The $N_{62.2}$ values range from 12 for Mount Washington, NH to 67 for Hilo International Airport, HI. The maximum continental $N_{62.2}$ value is 60 for Ocala Municipal Airport, FL. For the whole of the U.S. the median $N_{62.2}$ is 35. In Canada the lowest $N_{62.2}$ is 15 for Resolute, Nunavut, the maximum is 35 for Abbotsford, B.C., while the median is 27.

IMPLICATIONS FOR ASHRAE STANDARDS

The updated values of W and $N_{62.2}$ can be used in ASHRAE Standard 62.2 in the calculation of credit for infiltration. The effect of this infiltration credit in ASHRAE 62.2 is to reduce the fan size required in mechanical ventilation systems compared to the prescriptive tables. The revised W values (and corresponding $N_{62.2}$ values) result in lower effective natural infiltration rates than the current ones (35% lower on average) due to changes in the infiltration model used and assumptions about wind shelter. Some differences may be due to the different weather files. These new values of W are therefore conservative compared to the old values. Figure 6 shows the current W's (W_{136}) and new W's (called $W_{62.2}$ when considered in the context of ASHRAE standards) ranked by order of climate severity. The difference between them is about 0.3 across the full range of W. Thus the change is proportionally greater in mild climates.

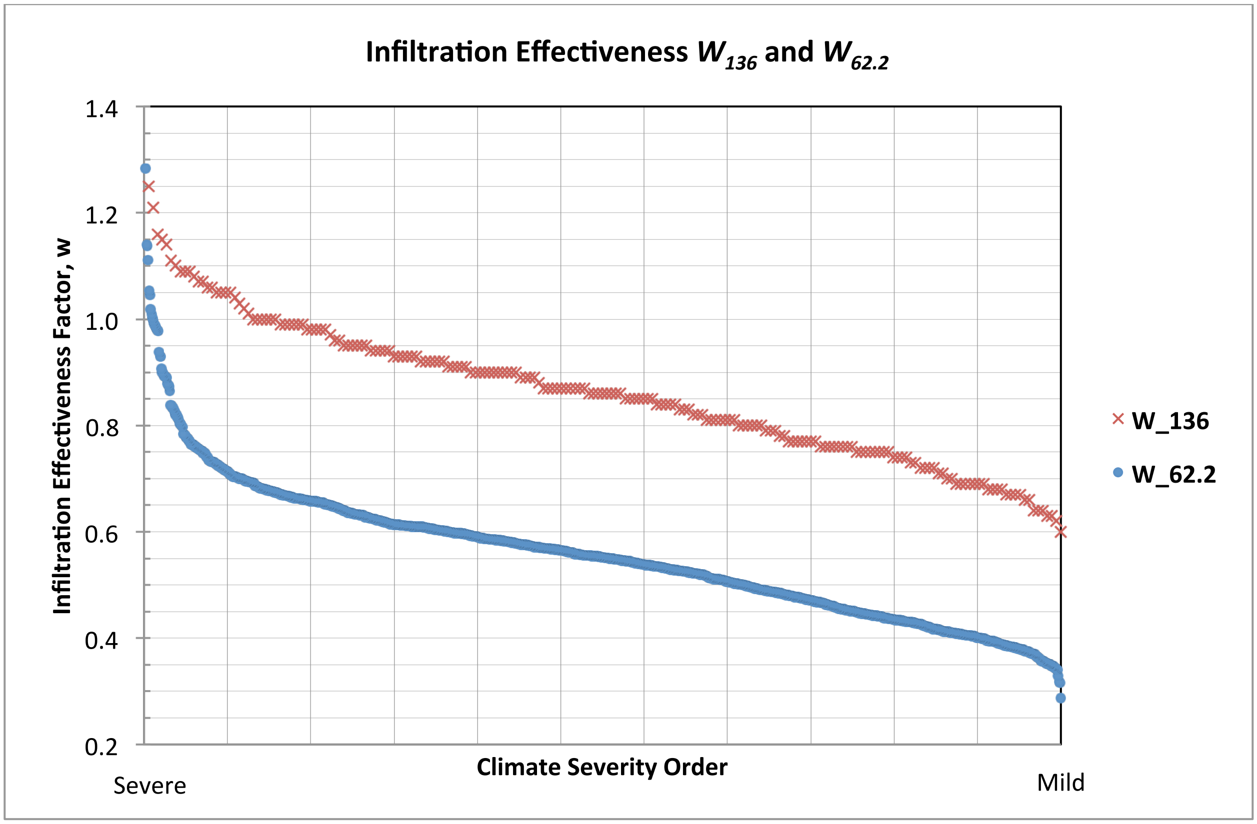

Figure 6: Current (*W_{136}*) and updated (*$W_{62.2}$*) values of *W* ranked by climate severity.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In this study, the principles of effective ventilation were used to determine the effect of infiltration on indoor pollution dilution and determine the equivalent steady-state ventilation. The effective ventilation is related to house envelope air leakage parameters using two weather factors that were developed in this study: the *W*-factor that is equivalent to that currently used in ASHRAE Standard 136 and a revised *N*-factor '$N_{62.2}$' introduced to correct for issues when using *W* for non-standard ceiling heights and to allow the use of Q(50Pa) house pressurization data rather than the ELA used in calculations using *W*. Higher $N_{62.2}$ values indicate a smaller weather-induced ventilation contribution and are characterized by lower wind speeds and smaller inside-outside temperature differences.

The height correction term currently used in ASHRAE Standard 136 was also estimated for all 1,100 weather stations across the U.S. and Canada and a different height exponent of 0.4 (replacing 0.3) was found to be more accurate. The low value of RMS error (less than 1.5%)

indicated that using the height ratios raised to an exponent is a good method to account for house height.

The enhanced infiltration model and shelter class selection used for the calculations resulted in conservative values of infiltration compared to those using current *W*-factors. These assumptions make the use of the derived values directly appropriate for applying to equivalent ventilation calculations and IAQ, but they would significantly underestimate energy impacts and so are not appropriate for that use.

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