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Infiltration Modeling Guidelines for Commercial Building Energy Analysis

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Executive Summary

This report presents a methodology for modeling air infiltration in EnergyPlus to account for envelope air barrier characteristics. Based on a review of various infiltration modeling options available in EnergyPlus and sensitivity analysis, the linear wind velocity coefficient based on DOE-2 infiltration model is recommended. The methodology described in this report can be used to calculate the EnergyPlus infiltration input for any given building level infiltration rate specified at known pressure difference. The sensitivity analysis shows that EnergyPlus calculates the wind speed based on zone altitude, and the linear wind velocity coefficient represents the variation in infiltration heat loss consistent with building location and weather data. EnergyPlus infiltration input is calculated to be 0.2016 cfm/sf of exterior wall area, assuming that uncontrolled air leakage through the building envelope can be specified by a baseline leakage rate of 1.8 cfm/sf (@ 0.30 in. w.c) of exterior above grade envelope area (based on ASHRAE SSPC-90.1 Envelope Subcommittee recommendation).

Contents

List of Figures

List of Tables

1. Introduction

Air infiltration through the building envelope has a significant impact on the space heating energy use in buildings [1]. Energy simulation tools can be used to determine the impact of air infiltration through the building envelope. Although there are very detailed and complex approaches available to model air infiltration using air flow networks (AFN) and computation fluid dynamics (CFD), typically building energy simulation tools use a simplified approach to estimate air change rate based on building air tightness measured by pressurization tests [2]. Several field surveys and test methods have been developed to specify building level air infiltration rates for a known standard pressure difference across the envelope [3]. In an effort to specify air-barrier requirements, the ASHRAE 90.1 Envelope Subcommittee has developed a list of component infiltration rates that can be used to calculate the overall building air infiltration rate. This air infiltration rate is a critical input to represent envelope air tightness in energy simulation. This report summarizes the methodology used to calculate the total building infiltration rate and recommendations for modeling infiltration in EnergyPlus.

2. Building Infiltration Rate

During the development of air barrier requirement changes to 90.1-2004 (Addenda ‘z’), ASHRAE SSPC 90.1 Envelope Subcommittee developed recommendations of baseline and advanced infiltration levels for building components, as shown in Table 1. These recommendations were provided for each opaque element of the envelope such as walls, windows, roof, etc. The total infiltration for a building can be calculated by aggregating the component infiltration rates. Though the component infiltration rates specify the infiltration rate of the materials and components, leakage through interfaces between components and workmanship need to be accounted for in calculating the total building infiltration rate. The Envelope Subcommittee recommended a baseline infiltration rate of 1.8 cfm/sf (@ 0.3 in. w.c.) of exterior above grade envelope surface area, based on the average air tightness levels summarized in the National Institute of Science and Technology (NIST) report [4]. This baseline infiltration rate is used to establish a ‘construction quality adjustment’ (CQA) factor by subtracting the total component infiltration rates. Further, the Envelope Subcommittee recommended that the CQA calculated based on the baseline infiltration rate for each building be used to determine the total building infiltration rate for advanced requirements based on Addenda ‘z’ to ASHRAE 90.1-2004.

Table 1: Envelope Component Infiltration Rates

Component Infiltration Rate Summary Table
(SSPC 90.1 Envelope Subcommittee)

Opaque Elements	**Baseline Infiltration Rate (@ 0.30 in. w.c.)**	**Addenda 'z' Infiltration Rate (@ 0.30 in. w.c.)**	**Unit**	**Area calculation notes**	**Reference**
Roofs	0.12	0.04	cfm/sf	Net opaque area of roof	Envelope Subcommittee
Above Grade Walls	0.12	0.04	cfm/sf	Net opaque area of above grade walls	Envelope Subcommittee
Below Grade Walls	-	-	-	*Not used in infiltration calculations*	-
Floor	0.12	0.04	cfm/sf	Net opaque area of floor over unconditioned space	Envelope Subcommittee
Slab	-	-	-	*Not used in infiltration calculations*	-
Opaque Doors	0.40	0.40	cfm/sf	Area of opaque doors	90.1-2004 Section 5.4.3.2
Loading Dock Doors	0.40	0.40	cfm/sf	Area of door, applicable only for warehouses	90.1-2004 Section 5.4.3.2
Fenestration Elements					
Swinging or Revolving Glass Doors	1.00	1.00	cfm/sf	Area of swinging or revolving glass doors	90.1-2004 Section 5.4.3.2
Vestibule	1.00	1.00	cfm/sf	Area of door	90.1-2004 Section 5.4.3.2
Sliding Glass Doors	0.40	0.40	cfm/sf	Area of sliding glass doors	90.1-2004 Section 5.4.3.2
Windows	0.40	0.40	cfm/sf	Area of windows	90.1-2004 Section 5.4.3.2
Skylights	0.40	0.40	cfm/sf	Area of skylights	90.1-2004 Section 5.4.3.2
Construction Quality Adjustment (CQA[1])	CQA=Total Building Leakage –(∑ component infiltration rates)		cfm/sf	To be calculated for each building type	Envelope Subcommittee
Total Building Leakage[2]	**1.8**	**CQA + component infiltration rates**	**cfm/sf**	***exterior above grade envelope surface area***	NIST REPORT NISTIR 7238

Note 1: Construction quality adjustment **(**CQA) will be calculated for each prototype initially at the baseline conditions and will remain constant for advanced case building models.

Note 2: The total building infiltration schedule fraction will be 1.0 when all heating, ventilation and air-conditioning (HVAC) systems are off and 0.25 when the HVAC systems are in operation.

3. EnergyPlus Infiltration Input Requirements

Modeling air infiltration in EnergyPlus requires the following two sets of input:

1. Design infiltration rate (I_{design}): The design infiltration rate is defined as a volumetric flow rate for each conditioned zone in the thermal model. In addition to design infiltration rate, an infiltration schedule can be specified to indicate the variation in infiltration rate based on time of day.
2. Infiltration model coefficients: The infiltration models coefficiencts are used to calculate the thermal loads based on the volume flow rate, temperature and wind speed.

EnergyPlus calculates infiltration load based on design infiltration rate (I_{design}), schedule fraction ($F_{schedule}$), temperature difference between the zone and outdoor air, and wind speed, using the following equation:

$$\text{Infiltration} = I_{design} * F_{schedule} * (A + B*|(T_{zone}-T_{odb})| + C*\mathit{Wind\ speed} + D*\mathit{Wind\ speed}^2) \qquad (1)$$

There are four coefficients A, B, C and D that can be defined by users to take into account the effect of micro climate conditions of temperature and wind speed at each simulation time step. EnergyPlus reference manual [5] provides coefficients shown in Table 2for three infiltration models commonly used in handling the building infiltration.

Table 2: EnergyPlus Infiltration Model Coefficients

Model Name	**Constant Coefficient (A)**	**Temperature Coefficient (B)**	**Wind Speed Coefficient (Linear term) (C)**	**Wind Speed Coefficient (Quadratic term) (D)**	**Reference Wind Speed**
Constant Infiltration (EnergyPlus default)	1.0	0	0	0	N.A.
DOE-2 Infiltration Methodology	0	0	0.224	0	10 mph
BLAST Infiltration Methodology	0.606	0.03636	0.1177	0	7.5 mph

The DOE-2 infiltration methodology uses a reference wind speed of 10 mph and the BLAST methodology uses a reference wind speed of 7.5 mph (with no temperature differential across the envelope). Under these conditions for both models, the infiltration into the building is equal to I_{design}.

4. Design Infiltration Rate Calculation

This section discusses the methodology used to convert a known leakage rate at a fixed building pressure to a corresponding input for the Energy Plus wind-driven infiltration model. The starting point for this analysis is the baseline infiltration rate of 1.8 cfm/ft^2 (@ 0.30 in w.c.) discussed in Section 2.

When the wind strikes perpendicular to a building face, it creates a positive pressure on the windward building surface with respect to ambient pressure. It also results in a negative pressure on the leeward building surfaces, and generally a negative pressure on the building surfaces parallel with the wind, again with respect to ambient. The pressure developed on the windward wall surface is not the stagnation pressure (P_u) of the wind (i.e., the wind pressure developed when the wind perpendicular to an infinite plane surface). Instead, air slips around the sides and over the top of the building in a somewhat complicated fashion generally resulting in a surface pressure somewhat lower than the stagnation pressure. A modifying factor (Cp) is used to account for the deviation between the stagnation pressure and the wind pressure at a particular point on the surface.

$$\text{Stagnation Pressure } (P_u) = \tfrac{1}{2}\,\rho\, U_{ref}^2 \qquad (2)$$

$$\text{Local Pressure } (P_x) = C_p\, P_u \qquad (3)$$

Where

U_{ref} is the wind velocity at the point of impingement
ρ is the density of air
C_p is the local wind pressure coefficient at the point of impingement.

Studies of the variation in the local wind pressure coefficient have been made [6], however, integrating the product of the local wind pressure coefficient and the stagnation pressure across surfaces in real buildings is difficult. Engineering solutions of surface-averaged wind pressure coefficients have been developed for characteristic building shapes and as a function of the angle of impingement relative to the normal of a particular building face [7, 8]. ASHRAE uses the nomenclature C_s for the calculated average surface pressure coefficient on a wall due to wind effects.

While all infiltration is subject to the pressure maintained by the building HVAC system, in most cases the windward face will experience wind-driven infiltration. The other faces will generally exhibit increased exfiltration because the leeward pressures are characteristically lower than the building pressure. The C_s parameter thus varies from positive to negative as the angle of impingement varies from 0 to 180°. The basic variation in C_s and rough order of magnitude as a function of angle of incidences are similar for both high-rise and low-rise buildings based on the studies reported by Akins,et.al.[7], and Swami and Chandra [8]. The EnergyPlus infiltration model uses wind *speed* to vary infiltration and does not have a wind direction component to the infiltration model. Hence, the effective average infiltration rate for the building need to be calculated using an average of the positive surface pressure coefficient to account for the average wall pressure coefficient around all sides of the building that would result in wind-driven infiltration (ignoring the roof, and assuming higher air speeds across the roof surface generate a low pressure region and are not expected to increase infiltration).

An average wind pressure coefficient can be developed for infiltration calculation applicable to all surfaces in the building by integrating all the *positive* values of surface average (C_{p_avg}) for the angles from 0-360° around the entire building. Positive values are used because only they result in wind-driven infiltration. For this purpose, the analysis is simplified by assuming that the buildings have a 1:1 aspect ratio (L/W = 1 in Figure 1). For simplicity, the C_s coefficients as a function of angle were calculated using the Swami and Chandra [8] correlation for the medium office building from the DOE commercial benchmark building models [9]. A numerical integration was achieved by extracting the average surface pressure coefficients for all angles based on the Swami and Chandra model [8] and using the NIST CONTAM tool at 15° intervals. NIST Curve fit 2 was used (a cubic spline curve fit) and integrated over the 360° around the building. The resulting average positive surface pressure coefficient (C_{s_avg}) was 0.1617.

In general, the use of the average surface pressure coefficients, as described above, require the use of a reference point for the wind velocity because the wind is impinging on the whole surface and not on a defined point. By convention, the reference wind speed used to determine pressure coefficients is usually the wind speed at the eaves height for low-rise buildings (where pitched roofs are commonly used) and the building height for high-rise buildings (where flat roofs are more common) [10]. Assuming the building height as the reference point, the average *positive* surface pressure on all wall surfaces can be calculated as:

$$P_{avg} = 0.5\, C_s\, \rho\, U_H^2 \qquad (4)$$

where

U_H is the wind speed at the building height
$C_s = 0.1617$

Starting from the known leakage rate at 0.3 in w.c. (75 Pa), the leakage rate at the average positive building surface pressure P_{avg} (measured in Pa) can be calculated as

$$I_{Pavg} = I_{75\,pa}\left(\frac{P_{avg}}{75}\right)^n \qquad (5)$$

where n is a flow exponent, assumed to be 0.65 for this analysis.

Using the above equations and a starting building leakage rate at 75 Pa, the infiltration rate at an arbitrary wind speed, as measured at the building roof height, can be calculated.

Energy Plus calculates the wind speed as a function of height (y position on the building face) using the input or default wind speed profile coefficients. It does this to facilitate more accurate calculations of wind-driven convection coefficients, but also applies this variation to the wind speed used for the calculation of wind-driven infiltration. This was confirmed by observing variation in infiltration rate by floors when a constant infiltration value was used for all floors. This is briefly described in the Surface Heat Balance Manager section of the EnergyPlus engineering reference manual. It was confirmed by conversation with the Energy Plus Support team member[1]. The following excerpt is from the EnergyPlus Engineering Reference manual[5]:

> *"To accommodate atmospheric variation EnergyPlus automatically calculates the local outdoor air temperature and wind speed separately for each zone and surface that is exposed to the outdoor environment. The zone centroid or surface centroid are used to determine the height above ground. Only local outdoor air temperature and wind speed are currently calculated because they are important factors for the exterior convection calculation for surfaces (see Exterior Convection below) and can also be factors in the zone infiltration and ventilation calculations. Variation in barometric pressure, however, is considered when using the Airflow Network objects"*

---

[1] Email exchange between David Winiarski and Peter Ellis, May 27, 2008

Thus, the actual wind-driven infiltration rates at the different floors of the building calculated by Energy Plus should sum to equal that calculated using a surface average pressure coefficient and the building roof height. For infiltration models, where the infiltration rate varies linearly with the wind speed, it is possible to apply an adjustment factor to the wind-driven infiltration component in EnergyPlus equal to the ratio of the wind speed (U_H) at building roof height to the average wind speed impinging on the building face (U_{avg}). The latter can be found by integrating the wind profile with respect to height (up to the building roof height) and then dividing by the building roof height.

The base wind profile used by EnergyPlus is of a power law form

$$\frac{U_H}{U_{met}} = \left(\frac{\delta_{met}}{H_{met}}\right)^{\alpha_{met}} \left(\frac{H_{bldg}}{\delta_{bldg}}\right)^{\alpha_{bldg}} \tag{6}$$

where U_H and U_{met} are the wind speed at building height H and measured at the weather station, and α and δ are parameters describing the wind boundary layer height and a corresponding exponent--both a function of terrain of the weather station and the building in question.

Integrating the above equation with respect to height from 0 to the building height H and then averaging over building height H provides an average wind speed on the building face equal to:

$$\frac{U_{avg}}{U_{met}} = \frac{1}{H_{bldg}} \frac{1}{(\alpha_{bldg}+1)} \left(\frac{1}{\delta_{bldg}}\right)^{\alpha_{bldg}} \left(\frac{\delta_{met}}{H_{met}}\right)^{\alpha_{met}} (H_{bldg})^{\alpha_{bldg}+1} \tag{7}$$

While EnergyPlus calculates the wind speed at the centroid of each exterior surface, use of the average wind speed across the building height top to bottom is a simplifying assumption.

From Equation 6 and 7, the ratio of the building average wind speed impinging on a vertical wall surface to the wind speed at the building roof line is then

$$\frac{U_{avg}}{U_H} = \frac{1}{(\alpha_{bldg}+1)} \tag{8}$$

Examples of the difference in wind speeds for a 39 ft high office building in an Urban/Suburban terrain ($\alpha_{bldg} = 0.22$, $\delta_{bldg} = 1200$ ft) are shown in Figure 3.

Equations (2) through (5) are used to calculate infiltration as a function of U_H. Because U_H is greater than the average wind speed impinging on the surface U_{avg} (the value used by EnergyPlus in the infiltration calculation) by the ratio shown in Equation (8), an infiltration rate referenced to the wind speed at roof height must be multiplied by the factor (α_{bldg} +1) for use in EnergyPlus.

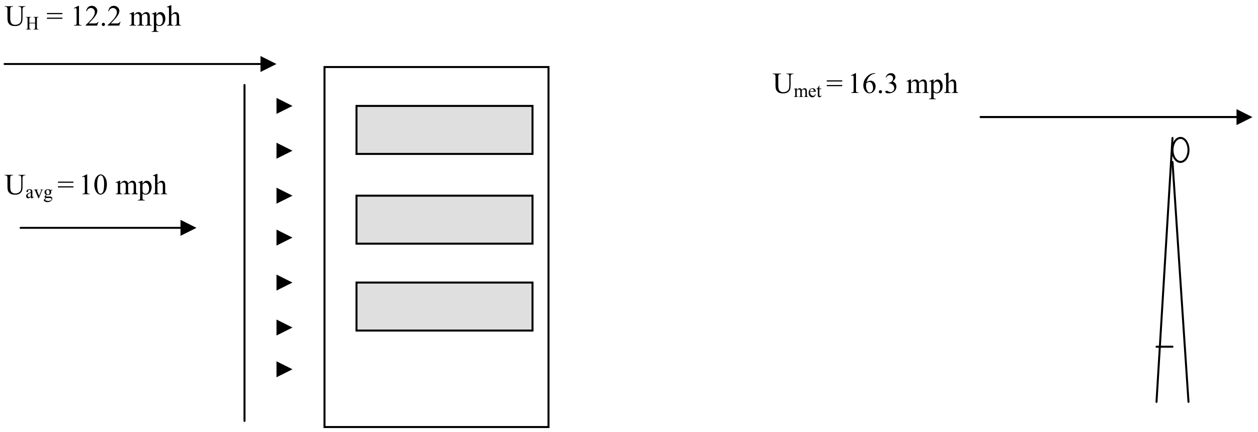

Figure 1: Examples of Wind Speed Variation

For the situation where the DOE-2 method and coefficients are used in EnergyPlus and where infiltration is correlated only with wind speed and the reference wind speed (the average wind speed on a building face, assumed to be same from top to bottom of wall) is 4.47 m/s:

$$I_{design} = (\alpha_{bldg} + 1) \cdot I_{75pa} \left(\frac{0.5\, C_s\, \rho U_H^{\;2}}{75} \right)^n \qquad (9)$$

where

U_H = 4.47 m/s
ρ = 1.18 kg/m^3
C_s = 0.1617
n = 0.65

Based on input from the DOE Commercial Benchmark Modeling team, an “urban” terrain environment is assumed. The α_{bldg} for that terrain is 0.22.

Since DOE-2 wind velocity coefficient is based on the reference wind speed of 10 mph (4.47 m/s), I_{design} is dependent only on I_{75pa}. Using a baseline value of I_{75pa} = 1.8 cfm/ft^2 (@ 0.30 in. w.c.) for all buildings as a starting point makes I_{design} the same for all buildings, and total infiltration is simply a function of the building envelope area. All building height-related impacts on wind speed and subsequent wind-driven infiltration in the building are handled within EnergyPlus simulation software based on the linear wind velocity coefficient.

The calculated value for I_{design} on a per square foot basis for each benchmark building is then 0.2016 cfm/ft^2 for all above ground envelope area. This is equal to 0.001024 $m^3/s\text{-}m^2$.

5. Sensitivity Analysis

To assess the impact of infiltration coefficients, a sensitivity analysis was performed using the medium office model EnergyPlus idf files available from the DOE Commercial Benchmark Building models [9]. A summary of the building characteristics are below:

Total conditioned floor area: 53, 628 ft^2
Number of floors: 3
Aspect ratio: 1.5
Window-wall ratio: 33%
Number of zones: 15 (four perimeter zones and a core zone, on each floor)
Wall type: Steel frame walls
Roof type: Insulation entirely above deck
Floor/Basement: Concrete slab-on-grade, no basement
Envelope insulation levels: As per ASHRAE 90.1-2004 Tables 5.5-1 to 8
HVAC system: Packaged DX cooling and gas furnace heating, single duct VAV system with electric reheat

For the sensitivity analysis, the following six locations were selected: Baltimore, Chicago, Helena, Miami, Minneapolis and Phoenix. This set of locations were selected to represent warm, humid, hot and cool climates to identify the impact of infiltration coefficients. The sensitivity analysis includes three approaches of specifying infiltration air flow rate in the core and perimeter zones: (i) uniform flow rate in all zones, (ii) core flow rate represented as half of the perimeter and (iii) all infiltration assigned only to perimeter zones. Tables 3 through 5 show the summary of building level air change and volume flow rates for the three approaches. In addition, the sensitivity analysis includes a comparison of the infiltration rates used in the DOE Commercial Benchmark, ASHRAE 90.1-1989 Section 13.7.3.2 [11], and DOE-2/BLAST coefficients with the 1.8 cfm/sf (@ 0.30 in. w.c.) exterior envelope surface area baseline recommended by the Envelope Subcommittee.

After comparing the results for all locations, further analysis of results focused on Chicago and Minneapolis because infiltration modeling details affected only the heating zones significantly. The total sensible infiltration heat loss, electric heating energy and total building energy-use index (EUI) are shown in Figures 4 and 5. The total electric heating energy and total building infiltration heat loss for perimeter only modeling of infiltration are comparable to other methods of distributing infiltration between perimeter and core zones. Among the three infiltration methodologies considered, it is observed that the 90.1-1989 based infiltration rates are most conservative, and the BLAST coefficients model was highly sensitive to the temperature coefficient and included a constant term that tended to predict higher total infiltration heat loss in most cases by a factor of three or larger when compared to DOE-2 coefficients model.

Figures 6 and 7 show the infiltration air change rates in the various zones of the building. From the variation of air change rates per floor, it is observed that the DOE-2 methodology accounts for wind effect based on the floor height, whereas the BLAST coefficients result in little variation in air change rate in all the three floors.

Further sensitivity analysis of the impact of infiltration was evaluated using the DOE-2 coefficients model for four levels of increased air tightness. Figures 8 and 9 show the trends in total infiltration rate and electric heating energy consumption. It is observed that reducing the infiltration by half results in a relatively proportional reduction in total sensible infiltration heat loss, however, the total electric heating energy savings is not consistent with the change in infiltration heat loss. It is possible that the building HVAC system and the lower set back thermostat may contribute to using the gas heating system in certain circumstances, resulting in the variation. Further analysis needs to be done with other building types to investigate the reason for this difference.

Table 3: Uniform Perimeter and Core - Infiltration flow rate input for all zones assuming the building level air change is distributed equally in all zones

Model Id	Model Name	Building infiltration rate basis	Building ACH	Perimeter flow rate (cfm/sf of floor area)	Core volume flow rate (cfm/sf of floor area)
BM	Constant Infiltration (DOE Benchmark)	0.3 ACH perimeter, 0.15 ACH core	0.2115	0.035	0.035
90.1-1989	Constant Infiltration (90.1-1989)	0.038 cfm/sf of exterior wall area	0.0697	0.012	0.012
DOE-2	DOE-2 Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)	0.4024	0.067	0.067
BLAST	BLAST Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)	0.2766	0.046	0.046

Table 4: Perimeter Only - Infiltration flow rate input for all zones assuming the building level air change is distributed only in perimeter zones

Model Id	Model Name	Building infiltration rate basis	Building ACH	Perimeter flow rate (cfm/sf of floor area)	Core volume flow rate (cfm/sf of floor area)
P-BM	Constant Infiltration (DOE Benchmark)	0.3 ACH perimeter, 0.15 ACH core	0.2115	0.086	0.0
P-90.1-1989	Constant Infiltration (90.1-1989)	0.038 cfm/sf of exterior wall area	0.0697	0.028	0.0
P-DOE-2	DOE-2 Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)	0.4024	0.165	0.0
P-BLAST	BLAST Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)	0.2766	0.113	0.0

Table 5: Core Flow Rate – Half of Perimeter - Infiltration flow rate input for all zones assuming the building level air change in core is half that of the perimeter zones

Model Id	Model Name	Building infiltration rate basis	Building ACH	Perimeter flow rate (cfm/sf of floor area)	Core volume flow rate (cfm/sf of floor area)
PC-BM	Constant Infiltration (DOE Benchmark)	0.3 ACH perimeter, 0.15 ACH core	0.2115	0.05	0.025
PC-90.1-1989	Constant Infiltration (90.1-1989)	0.038 cfm/sf of exterior wall area	0.0697	0.016	0.008
PC-DOE-2	DOE-2 Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)	0.4024	0.095	0.048
PC-BLAST	BLAST Methodology	1.8 cfm/sf of above grade envelope area @ 0.3 in. w.c. (75 Pa)	0.2766	0.065	0.033

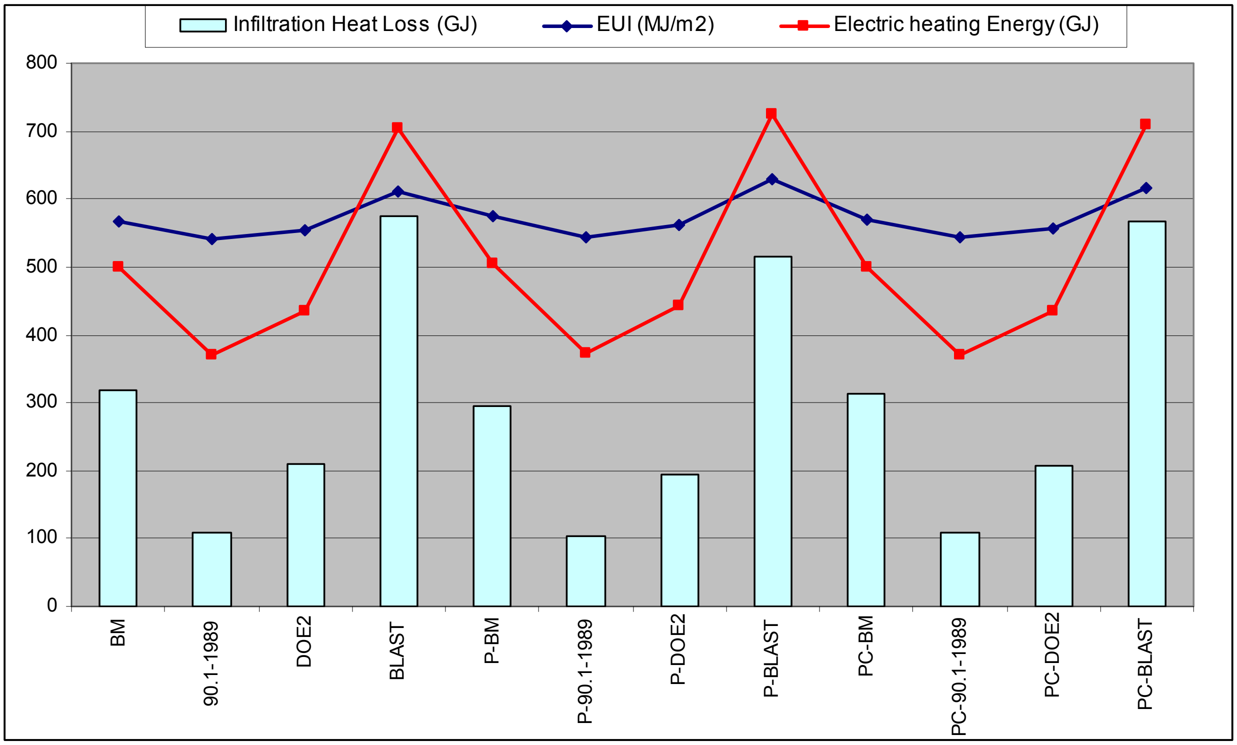

Figure 2: Impact of Infiltration Model Coefficients – Chicago

(Reference values for no infiltration case: EUI – 530.35 MJ/m^2, Electric Heating Energy – 309.76 GJ)

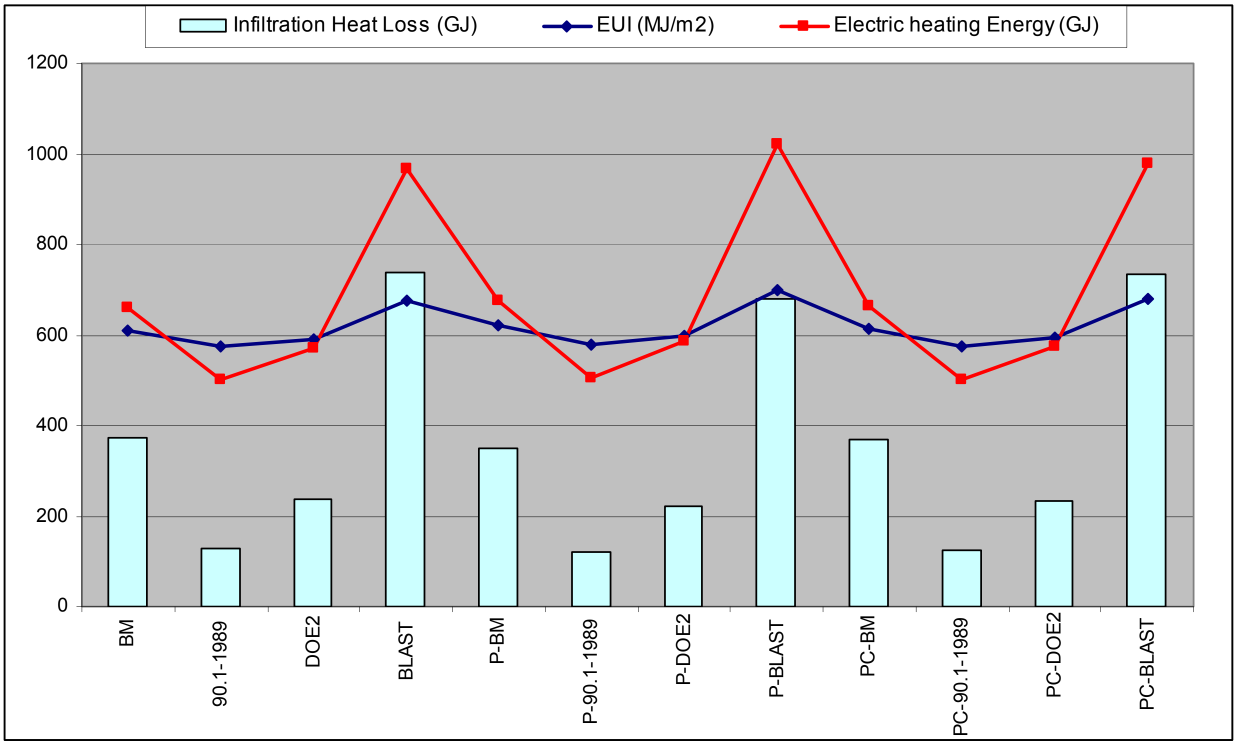

Figure 3: Impact of Infiltration Model Coefficients - Minneapolis

(Reference values for no infiltration case: EUI – 558 MJ/m^2, Electric Heating Energy – 421.27 GJ)

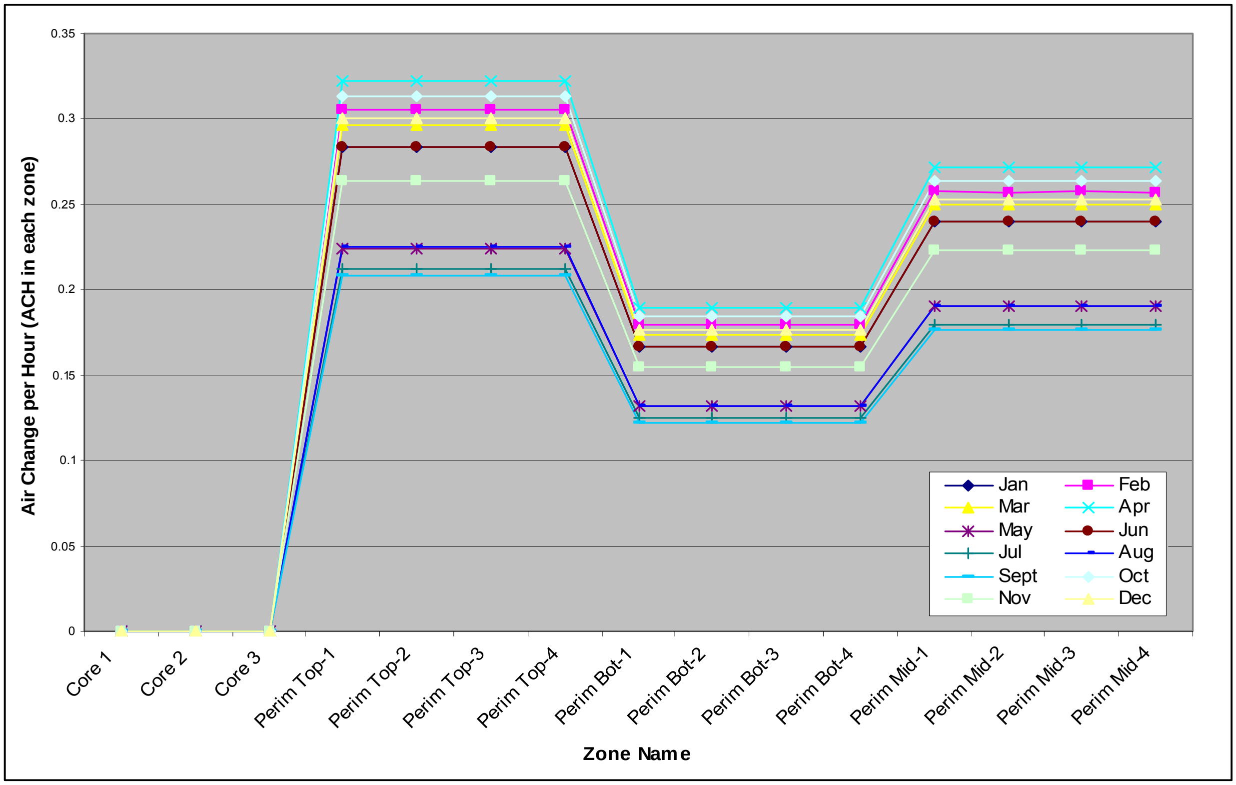

Figure 4: Annual Variation of Air Change Rates (DOE-2 Methodology)

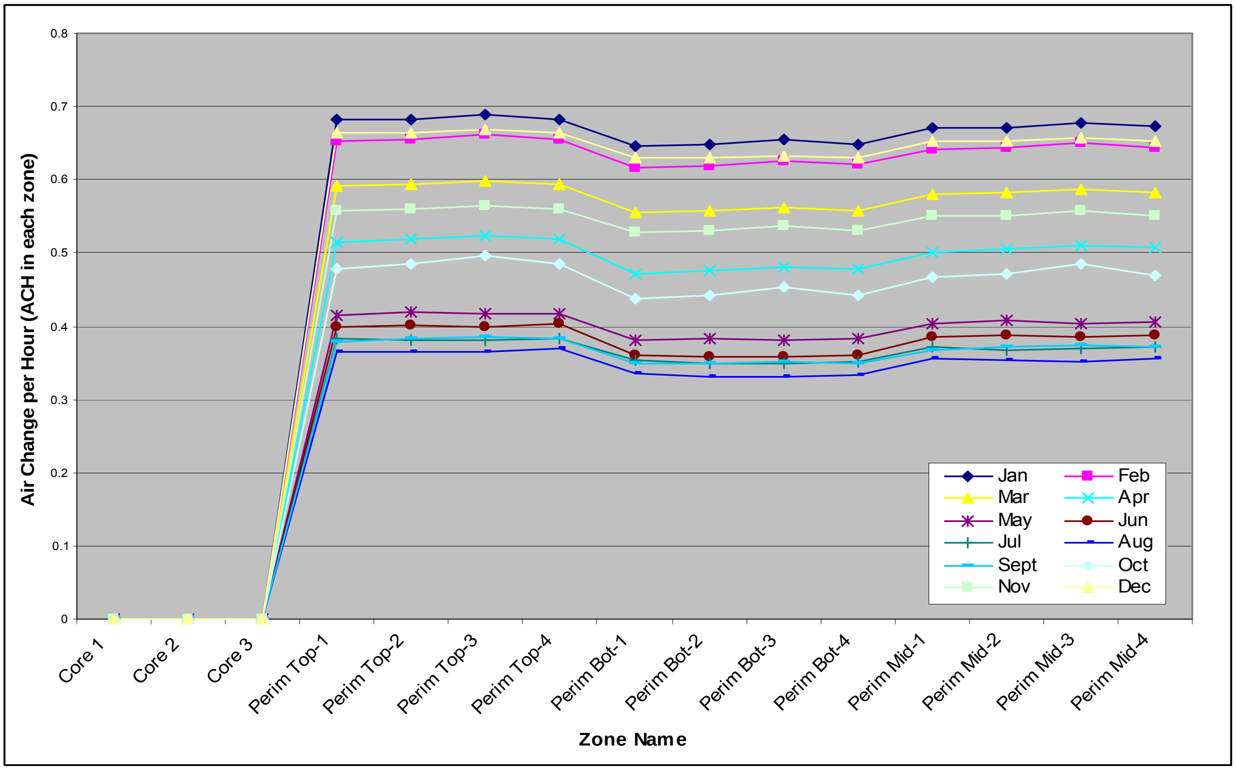

Figure 5: Annual Variation of Air Change Rates (BLAST Methodology)

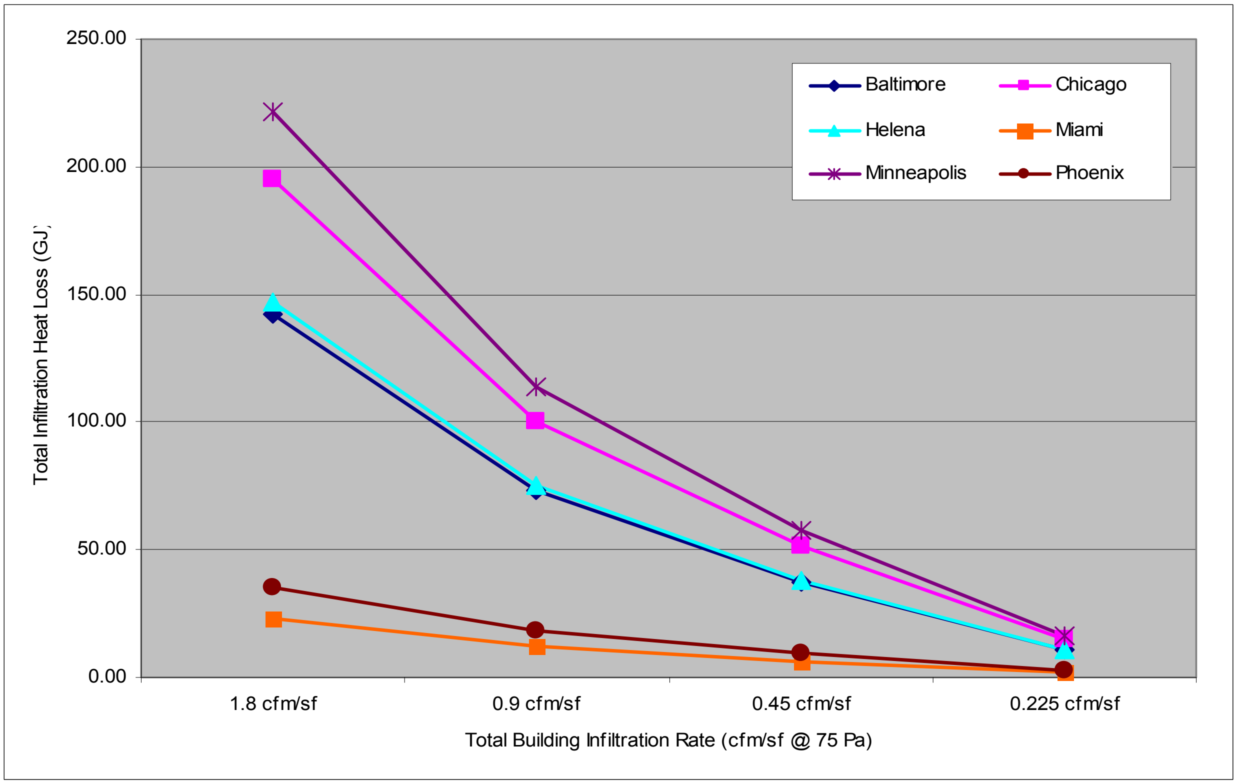

Figure 6: Impact of Infiltration Rate on Total Sensible Heat Loss

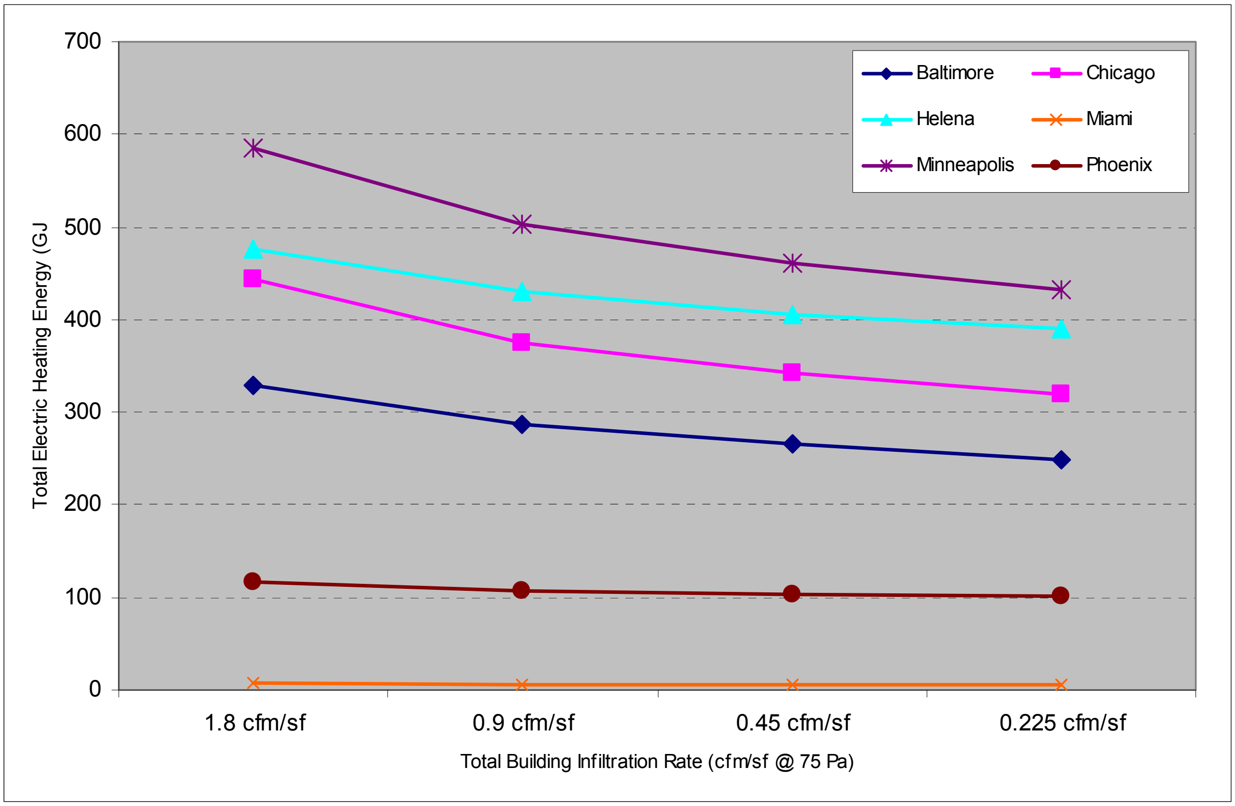

Figure 7: Impact of Infiltration on Total Electric Heating Energy

6. Conclusions and Recommendations

Based on the literature review and sensitivity analysis, PNNL recommends the use of DOE-2 coefficients to model infiltration in EnergyPlus and recommends the following steps to calculate the design infiltration rate input for EnergyPlus:

Step 1: Calculate the average wind-driven building pressure on all walls of a building of height H with a wind velocity of U_H calculated at the roof line and normal to one wall of the building using existing wind pressure formulations [8].

Step 2: Integrate the positive wind-driven building pressure for all angles of wind to get an average positive wind pressure across all wall surfaces as a function of U_H. (This step is necessary because wind speed correlations in EnergyPlus are independent of direction)

Step 3: Calculate the infiltration in the building at an average surface pressure from Step 2 and a reference wind speed at the roof line (e.g., 10 mph) by multiplying the infiltration at 0.3 in. w.c. (75 Pa) whole building pressure difference by the ratio of the average wind-driven pressure from Step 2 to 0.3 in. w.c. (75 Pa), as modified using a flow exponent 0.65. This provides the average infiltration rate across the wall surfaces based on the wind speed measured at the roof line.

Step 4: Adjust the calculated infiltration rate from Step 3 so that it can be correctly used as EnergyPlus input by multiplying it by the ratio of the wind speed at the roof line to the average wind speed impinging on a building wall with outward surface normal opposite to the wind direction. This ratio can be calculated using a power-law wind profile based on the same site terrain as in the EnergyPlus model. (This is necessary because the infiltration calculations in EnergyPlus use the wind speed at the center height of each exterior wall above ground)

Following the above methodology, the EnergyPlus input design infiltration (I_{design}) was calculated as 0.2016 cfm/ft² (0.001024 $m^3/s/m^2$) of above grade exterior wall surface area, equivalent to the base infiltration rate of 1.8 cfm/ ft² (0.00915 $m^3/s/m^2$) of above-grade envelope surface area at 0.3 in. w.c. (75 Pa). The calculated design infiltration rate can be specified in EnergyPlus using the ‘Flow per Exterior Surface Area’ option (available since Version 3.1). Though the current approach addresses modeling wind-driven infiltration, further research is needed to model infiltration due to stack effect. EnergyPlus provides the option to define multiple infiltration objects for each zone and this option could be used to specify the infiltration due to wind and stack effects separately.

7. References

1. Woods, T. and A. Parekh, A. 1992. *Identification, Assessment and Potential Control of Air-Leakage in High-Rise Buildings*. Proceedings of Sixth Conference on Building Science and Technology, University of Waterloo, Waterloo, Ont. pp.68-82.

2. Djunaedy, E., J.L.M.Hensen, and M.G.L.C.Loomans. 2003. *Development of a Guideline for Selecting a Simulation Tool for Airflow Prediction*. Eighth International IBPSA Conference, Eindhovan, Netherlands.

3. Genge, C. 2009. *Controlling Air Leakage in Tall Buildings*. ASHRAE Journal, Vol. 51, No. 4, pp.50-60.

4. Emmerich, S.J., T. McDowell, and W. Anis. 2005. *Investigation of the Impact of Commercial Building Envelope Airtightness on HVAC Energy Use*. NISTIR-7238. National Institute of Standards and Technology, Gaithersburg, MD.

5. EnergyPlus Manual, Documentation Version 3.0, Department of Energy, Washington, D.C. November 2008.

6. Davenport, A.G. and H.Y.L. Hui. 1982. *External and Internal Wind Pressures on Buildings.* BLWT-820133. Boundary Layer wind Tunnel Laboratory, University of Western Ontario, London, Ontario, Canada.

7. Akins, R.E., J.A. Peterka and J.E. Cermak. 1979. *Averaged Pressure Coefficients for Rectangular Buildings*. Proceedings of the Fifth International Wind Engineering Conference, Fort Collins, U.S., Vol. 1, pp. 369-380.

8. Swami, S.V. and S. Chandra. 1987. *Procedures for Calculating Natural Ventilation Airflow Rates in Buildings.* FSEC-CR-163-86. Florida solar Energy Center, Cape Canaveral, FL.

9. Commercial Benchmark Building Models, http://www1.eere.energy.gov/buildings/commercial_initiative/benchmark_models.html, accessed September 2009.

10. ASHRAE. 1995. *Handbook of Fundamentals.* ASHRAE Inc., Atlanta, GA.

11. ASHRAE. 1989. *Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*. ASHRAE Standard 90.1-1989, ASHRAE Inc., Atlanta, GA.