ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Infiltration Effects on Residential Pollutant Concentrations for Continuous and Intermittent Mechanical Ventilation Approaches

M. H. Sherman, J.M. Logue, B.C. Singer

Environmental Energy Technologies Division

June 2010

Funding was provided by the U.S. Dept. of Energy Building Technologies Program, Office of Energy Efficiency and Renewable Energy under DOE Contract No. DE-AC02-05CH11231; by the U.S. Dept. of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control through Interagency Agreement I-PHI-01070, and by the California Energy Commission through Contract 500-08-06.

Disclaimer

ABSTRACT

The prevailing residential ventilation standard in North America, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2, specifies volumetric airflow requirements as a function of the overall size of the home and the number of bedrooms, assumes a fixed, minimal amount of infiltration, and requires mechanical ventilation to achieve the remainder. The standard allows for infiltration credits and intermittent ventilation patterns that can be shown to provide comparable performance.

Whole-house ventilation methods have a substantial effect on time-varying indoor pollutant concentrations. If alternatives specified by Standard 62.2, such as intermittent ventilation, are used, short-term pollutant concentrations could exceed acute health standards even if chronic health standards are met.

The authors present a methodology for comparing ASHRAE- and non-ASHRAE-specified ventilation scenarios on relative indoor pollutant concentrations. We use numerical modeling to compare the maximum time-averaged concentrations for acute exposure relevant (1-hour, 8-hour, 24-hour) and chronic exposure relevant (1-year) time periods for four different ventilation scenarios in six climates with a range of normalized leakage values. The results suggest that long-term concentrations are the most important metric for assessing the effectiveness of whole-house ventilation systems in meeting exposure standards and that, if chronic health exposure standards are met, acute standards will also be met.

INTRODUCTION

Indoor air quality affects occupant health (Jacobs et al. 2007). Exposures in the residential environment are important to the total air pollutant exposure an individual experiences, as demonstrated in numerous studies (Edwards et al. 2001; Weisel et al. 2005). As outdoor air pollutant concentrations decrease and residential air exchange rates are lowered with improved air tightness (Sherman and Matson 2002), the contribution of indoor pollutant sources to overall exposure is expected to become increasingly more significant. The California Air Resources Board recently published a report showing that pollution risks indoors often exceed risks in the outdoor environment (CARB 2005). According to the American Lung Association (ALA 2010), a number of factors within homes are increasingly recognized as threats to respiratory health. Construction-defect litigation and damage are also on the increase in new houses; some of this increase is related to indoor air quality problems such as moisture. Appropriate residential ventilation can address many of these indoor air quality problems.

Many hazardous pollutants have been measured in the indoor residential environment. Several organizations both within the United States and abroad have established exposure standards and guidelines for exposure to these pollutants. These standards are often compared to pollutants concentrations outdoors, but have only sparingly been compared to indoor concentrations to identify hazards and risks indoors. The main organizations that publish standards and guidelines are the World Health Organization (WHO), the United States Environmental Protection Agency (USEPA), and the California EPA (CalEPA) (WHO 2005; EPA 2008; OEHHA 2010). These groups publish both chronic and acute standards that are thought to represent "safe" levels. Acute standards are set at levels that are thought to prevent immediate health effects for short-term exposure. These standards are set for 1 hour, 8 hours, or 24 hours. Chronic standards are set at levels that are thought to prevent long-term health effects from a lifetime of exposure. These standards are usually set for a time period of 1 year to life, and the total exposure is the time-averaged exposure over the relevant time frame, meaning that variability in concentration is ignored. Residential ventilation standards focus, at most, on chronic effects even though variations in concentrations over shorter time periods due to varying ventilation scenarios may exceed acute standards.

The dominant standard for residential ventilation system design is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2-2010. Most implementations of Standard 62.2 use constant mechanical ventilation and assume that infiltration is high enough to meet the standard.

There are economic and energy-efficiency rationales for reducing total residential mechanical ventilation and for designing and operating ventilation systems with variable amounts of ventilation airflow (Concannon 2002; Russell et al. 2005). Benefits of reduced and variable mechanical ventilation include reducing energy use during peak load periods, avoiding the intake of outside air during high-pollution events, and reducing the energy used to heat or cool inside air.

Standard 62.2 allows for the use of infiltration credits and intermittent operation in residential buildings to accommodate innovative ventilation systems and variable outdoor conditions. However, these ventilation strategies increase the magnitude of fluctuations in indoor pollutant concentrations because they result in periods of reduced and/or no mechanical ventilation. Weather-induced changes in infiltration and the allowable variability in time-scheduled operation of mechanical ventilation can both substantially affect indoor pollutant concentrations. Thus, when ventilation systems are designed to maximize the benefits of infiltration credits and intermittent operation, steps must be taken to ensure that indoor air quality is not compromised. Designers and decision makers need a method to determine how intermittent ventilation and varying infiltration will impact indoor concentrations for both acute-exposure-relevant and chronic-exposure-relevant time frames. ASHRAE does not directly address these issues.

Ventilation system design and the time-variability of infiltration (described henceforth as “ventilation scenarios”) can affect indoor pollutant concentrations in various ways. Whole-house ventilation aims to keep indoor pollutant concentrations at safe levels for long-term (i.e., chronic) exposure.

This study presents a methodology to quantify the effect of ventilation scenario on short-term concentration fluctuations for continuously emitted indoor pollutants. This paper does not assess whether the rates specified in ASHRAE Standard 62.2 are sufficient to control chronic exposures to contaminants of concern. Rather, our study focuses on quantifying the magnitude of short-term fluctuations relative to long-term average pollutant concentrations. The result of this analysis informs the relative level of concern for acute versus chronic health effects for continuously emitted pollutants that have exposure standards for both time frames. One particular application is the question of whether fluctuations could lead to exceedance of an acute standard when chronic standards are being met.

Our approach uses a physics-based model to track infiltration, mechanical ventilation and pollutant emissions to determine the time-varying pollutant concentration profile for a representative single-family house placed through simulation in various climate zones and having varying air tightness levels (expressed as normalized leakage area). We determine the ratio between the highest short-term concentrations in each simulation to the non-varying pollutant concentrations that result from a reference simulation using a continuous steady ventilation rate. The continuous ventilation rate is set by the air flows specified in Standard 62.2, including both mechanical ventilation and an assumed steady natural infiltration rate. We then compare these ratios to ratios of acute to chronic pollutant concentrations from various health standards.

BACKGROUND

For most of the existing U.S. housing stock, ventilation is provided by uncontrolled infiltration combined with occupant use of windows, doors, and bath and kitchen exhaust fans. Sometimes this results in over-ventilation and corresponding excess energy consumption or under-ventilation and poor indoor air quality (Orme 2001). Residential construction methods designed to produce energy-efficient buildings have created tight building envelopes that can result in under-ventilation (Sherman and Dickerhoff 1994; Sherman and Matson 2002). Thus, new homes often need mechanical ventilation systems to meet ventilation standards.

ASHRAE Standard 62.2 has requirements for source control ventilation in kitchens and baths, and for whole house ventilation. The required whole-house mechanical ventilation rate is based on the assumption that infiltration contributes 2 cubic feet per minute (cfm) per 100 square feet (ft^2) or 0.1 L s^{-1} m^{-2}. In addition to this infiltration, the standard prescribes the whole-house mechanical ventilation rate given by Equation 1:

$$Q(cfm) = 0.01A_{floor}(ft^2) + 7.5(N + 1) \quad \textbf{(1a)}$$

$$Q\left(\frac{L}{s}\right) = 0.05A_{floor}(m^2) + 3.5(N + 1) \quad \textbf{(1b)}$$

where Q is the required ventilation rate, A_{floor} is the house floor area, and N is the number of bedrooms. The size of the house is a surrogate for pollutants from materials intrinsic in the building, and the number of bedrooms is a surrogate for home-occupancy dependent activities and associated emissions. Standard 62.2 also allows for specific infiltration credits and for intermittent operation of mechanical ventilation systems with some restrictions.

Standard 62.2 requires source control, including local kitchen and bath exhausts, but a large part of the standard focuses on the requirements for continual mechanical whole-house ventilation. Standard 62.2's whole-house ventilation requirement implicitly assumes a constant, additive infiltration rate. However, infiltration is highly variable and dependent on the air-tightness of the building envelope as well as on fluctuating driving conditions such as wind and indoor-outdoor temperature differences. The metric for air-tightness is Normalized Leakage (NL), defined by ASHRAE Standard 119 (1988) as:

$$NL = 1000\frac{ELA}{FloorArea}(N_{story})^{3}, \quad \textbf{(2)}$$

where *ELA* is the effective leakage area. *N* is the number of stories in the home and *FloorArea* is the floor area of the home. Normalized leakage is a dimensionless term that represents the fraction of the home that is open to airflow normalized for the effects of house size and height. *NL* typically ranges from 0.1 to 1.0; the former is exceptionally tight with very little infiltration, and the latter is very loose with excessive infiltration. Chan et al. (2005) found that the median NL value in US homes was 0.52 with the central 50% of homes having values that range from 0.33 to 0.84.

McWilliams and Sherman (2005) reviewed ventilation standards and studied the impacts of intermittent mechanical ventilation and ventilation credits for infiltration. The studies major finding was that ventilation is increasingly becoming an important component of a healthy dwelling and occupants generally think ventilation is important, even if their understanding of ventilation systems is low.

METHOD AND APPROACH

This study used numerical modeling to compare indoor concentrations across a variety of ventilation scenarios for a typical single-family dwelling: a 2,000 ft^2 (185 m^2) 3-bedroom single-story detached house with 8 ft (2.5 m) ceilings. Time-dependent outdoor air exchange rate for the house was calculated for various mechanical ventilation approaches, envelope leakages, and climates. The effect of weather-driven temporal variations on infiltration was examined by simulating placement of the house in six U.S. cities located in distinct climates: Long Beach CA; Phoenix AZ; Miami FL; Chicago IL; Boston MA; and Bethel AK. These climates range from mild (Long Beach CA) to extreme (Chicago IL) and are the same cities studied by Sherman (2008).

Hourly pollutant concentrations were calculated by mass balance assuming a constant whole-house emission rate with dilution and pollutant removal varying with total outdoor air exchange (ventilation). Pollutant concentrations were examined over averaging times relevant to chronic (annual) and acute (1-hour, 8-hour, and 24-hour) exposures and health-based standards. All results were compared to the pollutant concentrations calculated for a reference case meeting all constant airflow assumptions of ASHRAE Standard 62.2.

Reference Case

The reference case to which we compare alternate ventilation scenarios is the typical house described above ventilated in compliance with ASHRAE Standard 62.2; the whole-house mechanical ventilation is set to the value specified in the standard, and infiltration is set to the level assumed in the standard. The mechanical ventilation is assumed to be constantly running, and infiltration is assumed to be constant, non-varying, and adding linearly to the mechanical ventilation to give the total air change rate. The Standard 62.2 reference case of adding a constant infiltration contribution is an idealized case, because in reality infiltration varies hour by hour and over the year. We explore that issue further below when we look at the default scenario.

Standard 62.2 specifies that local mechanical exhaust shall be installed to be operated as needed by the occupant in each bathroom and kitchen. The standard specifies kitchen range hood exhaust fan airflow of at least 100 cfm or a whole kitchen exhaust rate of 5 ach or more. Bathroom fans are specified at 50 cfm or more. This ventilation is user operated and is presumed to run to exhaust the intermittent and local pollutants generated by the activities in those rooms. Because we are focusing on pollutants with constant emissions, we assume that local ventilation is not used in either the reference case or in the different scenarios. For the reference case in this study, the total ventilation (i.e., the combined air exchange rate from mechanical ventilation and infiltration) is a constant 0.3375 air changes per hour.

Modeling Indoor Concentrations

We simulated the combined hourly infiltration and mechanical ventilation using the method described by Sherman (2008), which is based on the ASHRAE (2009) *Handbook of Fundamentals*, a mass balance model approach. We treated the home as a perfectly well mixed space with a constant pollutant emission rate. The derivative form of a mass balance of the home is:

$$V_{house}\frac{dC}{dt} = S - A * C * V_{house} \tag{3}$$

where C is the concentration in the home (mass/volume), S is the emission rate of the pollutant (mass per unit time), A is the air exchange rate (1/time), and V_{house} is the volume of the house. We assumed negligible outdoor concentrations of the pollutant of interest.

We wrote a script to determine the hourly pollutant concentration for each of the climates and each of the ventilation scenarios. We used a simple time-step modeling approach to calculate indoor concentrations as a function of mechanical and natural ventilation. Since the derivative form of the mass balance equation is unstable for a 1 hour time step for many of the simulations we explored, we used the integrated form of the equation. In order to integrate Equation 3, we assumed that *A* was steady over the course of a given time step. The integral form of Equation 3, assuming *A* is constant, is:

$$C(t) = C_o \exp(-At) + \frac{S(1-\exp(-At))}{AV_{house}} \quad (4)$$

This form of the equation can only be applied from one time step to another in our scenarios and cannot be used continuously. The discretized form of equation 4 is:

$$C_i = C_{i-1}\exp(-A_i\Delta t) + \frac{S(1-\exp(-A_i\Delta t))}{A_iV_{house}} \quad (5)$$

We compared solutions using the integrated and derivative versions of the mass balance equation and found no difference in the calculated solution. A time step, ΔT, of 1 hour was found to be small enough to keep the Equation 5 calculations stable. For each run, initially $C_{i=0}$ was set to zero, and the first month of results was discarded as spin-up time after which a full year of simulations was completed. Spin-up time is the time it takes the model to reach dynamic equilibrium and to eliminate the effect of the initial conditions on the solution.

Both infiltration and mechanical ventilation contribute to the air exchange rate, A_i. ASHARE Standard 136 (1993) gives a reference method of combining mechanical ventilation and natural infiltration:

$$A_i = A_{bal,i} + \sqrt{A^2_{unbal,i} + A^2_{inf,i}} \quad (6)$$

Where $A_{bal,i}$ is the air exchange rate at time step *i* due to balanced mechanical ventilation alone, $A_{unbal,i}$ is the air exchange rate at time step *i* due to unbalanced mechanical ventilation alone, and $A_{inf,i}$ is the air exchange rate at time step *i* due to natural infiltration alone. Balanced mechanical ventilation uses mechanical equipment to provide both supply and exhaust air flow at equal rates. When mechanical equipment is used to provide only supply or exhaust airflow, airflow in the other direction through the building envelope is induced through the resulting pressure differential and the system is described as unbalanced. Infiltration is natural ventilation that is driven by the indoor-outdoor temperature difference and outdoor wind speed through envelope leaks.

For the reference case, mechanical ventilation was assumed to be balanced. For the remaining cases, the mechanical ventilation was assumed to be unbalanced.

Infiltration is dependent on the air tightness of the building envelope. Tightness is quantified using *NL*, which is a non-dimensional value that represents the area of the leaks and cracks in a home that allow for airflow, normalized by home size. There are several methods of modeling air infiltration rates ranging from multi-zone indoor air quality models (Emmerich 2001) to simple numerical models based on building and meteorological properties. For this work, the relationship between *NL* and A_{inf} used was described in detail by Sherman (2008) as:

$$A_{inf,t} = k_i * NL * s_t \tag{7}$$

$$s_t = \sqrt{f_s^2 * \Delta T_t + f_w^2 * v_t^2} \tag{8}$$

Here k_i (1.44 s $hr^{-1}m^{-1}$), f_s (0.12 m s^{-1} $K^{-1/2}$), and f_w (0.132) are all constants, f_w is dimensionless, ΔT is the difference between the outdoor and indoor temperatures, and v is wind speed. The values for k_i, f_s, and f_w were taken from ASHRAE Standard 119 (1988). The combined infiltration and mechanical ventilation rate will vary diurnally and seasonally. The outdoor temperature and wind velocity data were taken from the Typical Meteorological Year Version 3 (TMY3) Database (NREL 2008). The TMY3 database provides hourly wind and outdoor temperature data for a representative year for each climate explored. The database is intended for use in computer simulations of building systems. An indoor temperature of 22 °C was used for all of the simulations.

The analysis assumes a constant whole-house pollutant emission rate that is unaffected by air exchange rate or home conditions. The analysis focuses on the relative concentration, which is independent of *S* and allows us to assess the effect of ventilation scenario on indoor concentrations for any constant indoor source strength.

Description of Ventilation Scenarios

For all of the ventilation schemes we modeled, we calculated indoor concentrations based on combined mechanical ventilation and natural infiltration. The amount and delivery method of mechanical ventilation varied among scenarios and was specified in each run of the model. Unlike in the reference case, the amount of infiltration was not specified in each scenario. Rather, the total air change rate was calculated based on the mechanical ventilation rate, *NL*, and weather parameters for each climate using Equations 6 and 7. Hourly concentrations were then calculated, and any appropriate averages taken. For each scenario, we calculated the time-varying indoor pollutant concentration for the reference house using weather data for each city and for *NL* values ranging from 0.1 to 1. The ventilation scenarios are:

Constant Default. The Constant Default scenario is what is currently implemented in most new homes. Mechanical ventilation is set to the value specified by ASHRAE Standard 62.2-2010, Equation 1 (or Table 1). For our simulations, the total ventilation was calculated based on weather conditions and leakage as described above.

Constant with Infiltration Credit. Standard 62.2-2010 allows the required mechanical ventilation rate to be reduced under certain circumstances when the air leakage has been measured. The Constant with Infiltration Credit scenario sets an assumed constant infiltration airflow rate based on NL and a *w* value provided in ASHRAE Standard 136. The *w* value is a representation of localized weather conditions. Based on this credit, the airflow rate of the designed mechanical ventilation system can be reduced by half of the calculated increase in infiltration above the assumed 62.2 infiltration of 2 cfm/100 sq. ft (from Section 4.1.3 of Standard 62.2) . For each climate and each NL value, we reduced the mechanical ventilation flow rate based on this credit.

Constant Optimized. The Constant Optimized ventilation scenario looks at optimizing the amount of constant mechanical ventilation to reduce the total air exchange rate to the lowest level possible while still achieving an annual average concentration that is no higher than the reference case. This can be viewed as an alternative infiltration credit approach that achieves the most efficient constant ventilation rate. Although ASHRAE Standard 62.2 does not state a maximum relative chronic exposure, it sets the minimum ventilation for acceptable air quality. This scenario implicitly assumes that the rate and assumptions specified in 62.2 would provide “acceptable indoor air quality” as intended.

We executed a set of simulations for each climate and NL value in which we adjusted the mechanical ventilation system across a wide range of values from zero to a value high enough that concentrations were reduced to nearly zero. For each level of mechanical ventilation, we calculated hourly indoor concentrations as described above and determined the annual average concentration. For each *NL* and climate, we identified the lowest mechanical ventilation flow rate that resulted in an annual average concentration that was the same or lower than the reference case. This value was used to calculate hourly concentrations for the representative year.

Intermittent Optimized. The Intermittent Optimized scenario looks at the effect of intermittent mechanical ventilation on indoor concentrations but is otherwise similar to the Optimized Ventilation scenario. The ventilation scenarios above assumed that mechanical ventilation operated continuously. Standard 62.2, however, supports the use of intermittent ventilation, i.e., shutting off the ventilation system during a certain portion of a day and increasing the ventilation during the rest of the day to provide the same average indoor concentration as if the system ran continuously. The intermittent ventilation equations in ASHRAE 62.2 are based on Sherman (2004), using the concept of *relative dose.* The general idea of *relative dose* is that if the time-averaged concentration over a given period is the same as it would be for a constant concentration over that same time period, then the chronic health effects for those two ventilation scenarios may be considered equivalent.

Intermittent ventilation increases the range of concentrations occurring over shorter averaging times because overall ventilation rates are reduced during periods without mechanical ventilation. This in turn leads to higher short-term concentrations relative to constant ventilation. The highest concentrations occur during the longest periods without mechanical ventilation. We selected the case in which the mechanical ventilation is off for 12 continuous hours and on for 12 continuous hours, as might occur with night ventilation or an economizer. As with the previous scenario, the mechanical ventilation is set to the minimum value to keep the annual average concentration at the reference level or below. This value was determined in the same way as in the previous case, by conducting simulations for a range of mechanical ventilation values and determining, for each climate and *NL*, the minimum mechanical ventilation rate that resulted in a annual average concentration as low as the reference case.

RESULTS

The Effect of Infiltration on Air Exchange Rate

Figure 1 presents the calculated daily-average ventilation rate over one year for the modeled house using climate data from Bethel AK and Long Beach CA. Results in the left panel were calculated for a tight envelope (*NL*=0.125) whereas the results in the right panel are for a moderately leaky condition (*NL*=0.5). Also shown in each panel is the air exchange rate for the reference case used in our analysis, namely the home where infiltration airflow is fixed and additive to mechanical airflow as assumed in the Standard 62.2.

Figure 1 shows the effect of weather (as a driving force) and *NL* on infiltration and the resulting overall air exchange rate. When *NL*=0.125 both cities have daily averaged air exchange rates lower than the reference case for most days. A higher *NL* leads to higher air exchange rates in both locations; with *NL*=0.5, the daily values are generally on par with or higher than the reference case. Daily fluctuations are driven by local weather conditions; however, the overall annual average concentration depends strongly on *NL*. Bethel has a much less temperate climate than Long Beach, resulting in more fluctuations in concentration over the year. Infiltration is higher in Bethel than in Long Beach because of greater indoor-outdoor temperature differences. As *NL* increases, the magnitude of the day-to-day fluctuations increases for both cities. For a constantly emitted pollutant, variations in ventilation cause variations in indoor concentration.

The Effect of Varying Infiltration on Relative Indoor Concentration

Figures 2 through 5 present results for the simulated ventilation scenarios in relation to the reference case. The scenarios all include time-varying infiltration resulting from time-varying weather conditions, and each ventilation scenario was simulated for a range of leakages in each climate. All of the figures are formatted in the same manner to allow for easy comparison. In each subfigure, results are presented for each city, with air leakage (NL) values ranging from 0.1 to 1.0. In all of the figures, Subfigure A shows the normalized annual average concentration, Subfigure B shows the normalized maximum 24-hour averaged concentration, Subfigure C shows the normalized maximum 8-hour averaged concentration, and Subfigure D shows the normalized maximum 1-hour concentration. The maximum concentration is defined as the highest concentration for the stated averaging time over the 1-year simulation. In all of the subfigures, the concentrations are normalized by the same value as for the comparable concentrations in the reference case. Because the ventilation is constant in the reference case, the indoor concentration was constant, and the normalizing values are all the same and equal to the annual average concentration in the reference case.

Constant Mechanical Ventilation. Figure 2 shows the concentration ratios as a function of air tightness for the Constant Default mechanical ventilation scenario. With more leakage, infiltration increases, and concentrations decrease for the analyzed conditions relative to the 62.2 reference case (balanced constant mechanical and constant infiltration). The peak ratios for each of the graphs and for each of the cities occurs at the minimum *NL* value considered. For tight houses, infiltration airflow is less, and concentrations are higher than in the 62.2 reference case. For each climate, the annual average concentration is reduced below the reference value when infiltration airflow exceeds the value assumed in Standard 62.2. For each case, we can identify the critical value of *NL* at which this occurs. For the locations examined in this analysis, the critical *NL*s for annual average ventilation were in the range of 0.23 to 0.4. However, the maximum hourly concentrations for Miami, Phoenix, and Chicago are higher than the reference case for *NL* values up to 1.

Figure 2 shows, not surprisingly, that, for constant mechanical ventilation, increasing air leakage leads to lower indoor concentrations. It also shows that the damping effect of increased air leakage is reduced for shorter averaging times because infiltration varies over the year; air leakage is less effective than mechanical ventilation at reducing concentration peaks.

Figure 3 displays simulation results for the Constant with Infiltration Credit scenario. For low *NL* values, there is no difference between the results in Figure 2 and the results in Figure 3 because the air leakage is too low to allow for much of a reduction in mechanical ventilation. Again, the annual average concentration reaches a maximum value when there is no leakage. As *NL* increases, the maximum concentrations for 1-hour, 8-hour, and 24-hour averaging times increase until a peak is reached at *NL* values of 0.2 to 0.5. As *NL* increases further, the mechanical ventilation is reduced in favor of natural infiltration until a critical *NL* value where mechanical ventilation reduces to zero. Before the critical value, air-leakage-induced ventilation is replacing constant mechanical ventilation, and the short-term averages increase because temporal variations in infiltration lead to temporal variations in overall ventilation rates. At leakage areas above the critical *NL*, mechanical ventilation is no longer required by the standard and thus not included in the simulation. Beyond this point, higher *NL*s lead to higher air exchange rates that, even with variability, produce lower peak short-term concentrations.

Figure 4 displays the results for the Constant Optimized scenario, in which mechanical ventilation is set at the minimum level needed to achieve annual average concentrations that are the same as the reference case. Sub-panel A indicates that consistent with the proposed mechanical ventilation scenario, the annual average concentration is kept at the same level as in the reference case until the *NL* value is large enough to turn off mechanical ventilation altogether. The value of this critical *NL* varies from climate to climate. As mechanical ventilation is reduced with increasing *NL*, short-term maximum average concentrations increase. At some point in each climate, the envelope becomes sufficiently leaky that no mechanical ventilation is required. At this point, the maximum 1-hour, 8-hour, and 24-hour concentrations reach a peak value. As the house gets even leakier, the maximum short-term ratios decrease as does the annual average concentration ratio. The maximum short-term concentrations ranged from 1.9 to 2.7 compared to 1.8 to 2.4 for the Standard 62.2 infiltration credit.

Intermittent Mechanical Ventilation. Figure 5 shows results for the Intermittent Optimized scenario in which mechanical ventilation is provided on a 12 hour on, 12 hour off cycle. The mechanical ventilation was set at the minimum level to achieve an annual average concentration that was at least as low as in the reference case. This scenario is compliant with Standard 62.2 (i.e. mechanical ventilation rates are higher or equal to the value determined by equation 4.2 in section 4.4 of Standard 62.2:

$$Q_f = \frac{Q_r}{\varepsilon f} \qquad (9)$$

where

Qf is the fan flow rate, *Qr* is the ventilation rate required by equation 1a,b,

ε is the ventilation effectiveness and *f* is the fractional on time of the system) at low *NL* values, 0.125-0.2 based on climate. Since this is an optimized simulation, as *NL* increases beyond those levels, the mechanical ventilation rate drops below the value specified by the standard.

There are two competing effects going on in this case. Sub-figures A and B are very similar to their counterparts in Figure 4 because the averaging times for those sub-figures are long enough to encompass an entire 24-hour ventilation cycle. Variability in these graphs is due to variability in infiltration alone. In Sub-figures C and D, the maximum short-term concentrations are at the lowest *NL* value, indicating the importance of the ventilation cycle for determining the maximum time-averaged concentration over smaller integrating periods. As the *NL* increases, the effect of intermittent ventilation becomes a less important contributor to indoor concentration fluctuations. Beyond the critical *NL* at which mechanical ventilation is no longer needed to achieve the same annual average concentration as in the reference case, there is a second maximum because of the influence of infiltration on concentrations. At low *NL*, the mechanical ventilation cycle is the dominant contributor to concentration fluctuations. As *NL* increases, the importance of the mechanical ventilation cycle decreases, and fluctuations in infiltration are the dominant contributor to concentration fluctuations. As *NL* increases beyond that second maximum, the graphs overlay exactly with Figure 4 because the total air change rate becomes completely dependent on infiltration.

DISCUSSION

The Effect of Ventilation Scenarios on Concentrations

Figure 2 shows the variability in pollutant concentrations that would result from climate- and house-specific leakage variations under the assumptions in the current prescriptive path of ASHRAE Standard 62.2. While the assumptions of constant infiltration and balanced mechanical ventilation are unrealistic, the calculated pollutant concentrations associated with these assumptions are the appropriate reference against which to compare pollutant concentrations resulting from other ventilation scenarios. The analysis of the idealized 62.2 scenarios shows that in general, tighter homes have lower infiltration and thus higher pollutant concentrations over both shorter and longer averaging times. As leakage increases, infiltration airflow varies more over time, and indoor pollutant concentrations will therefore vary more over shorter averaging times, resulting in larger differences between the highest short-term concentrations and annual average concentrations. The more infiltration controls time-varying air exchange rates, the larger the spread between the annual average and short-term average concentrations.

Annual average indoor concentrations will be higher than the reference case for homes with low *NL*. The *NL*s required to achieve annual average concentrations comparable to those of the reference case ranged from 0.2 for Bethel AK to 0.4 for Long Beach CA. Sherman and Dickerhoff (1994) and Chan et al. (2005) found that the median *NL* of the existing housing stock for states where data were available was higher than this range. However, as noted previously, Chan et al. (2005) found that more than 25% of the homes they studied had *NL* values less than 0.4 and newer homes have *NL* significantly lower than older housing stock. Thus, while most older homes may well meet the intent of Standard 62.2 with prescriptive ventilation rates, newer, tighter homes may not.

Our analysis of mechanical ventilation systems assumed unbalanced, exhaust only ventilation. With an unbalanced system, additional leakage-driven airflow increases total airflow and air change rate by quadrature, not by addition, therefore it has a greater effect at low natural infiltration and decreasing effect at infiltration increases. This means that increased infiltration will have a greater effect on whole-home ventilation than when the ventilation system is balanced. This difference is insignificant for very tight and very leaky houses, but at some point, the *NL* becomes large enough in both balanced and unbalanced systems that the annual average concentration will decrease below the reference case value. To be more conservative in our analysis we have presented only the unbalanced case. The only impact of considering the balanced case would be to lower the *NL* at which the relative dose became equal to unity.

As Figure 2 shows, homes with weather-driven infiltration and constant mechanical ventilation, as specified by Equation 1 with *NL* below that critical value, will have higher pollutant concentrations than would be predicted using the assumed (constant) infiltration rate. Applying the infiltration credit (Figure 3) effectively lowers the mechanical ventilation requirement for any *NL* above that critical value[1]. Above that critical value the Figure 3 values are somewhat higher than Figure 2 values.

The Constant Optimized scenario achieves long-term indoor concentrations that are at or below the reference case level. At low *NL* values, when the minimum required mechanical ventilation specified by Standard 62.2 is provided, the total ventilation rate will be insufficient to dilute the contaminants whether the Section 4.1.3 infiltration credit is applied or not (compare Figures 2 and 3). Adding the credit at low *NL* values will increase indoor pollutant concentrations even more. If the *NL* is higher than the critical value where there is enough infiltration to reduce annual average concentrations to the reference case level, then adding the infiltration credit will reduce home thermal-conditioning costs without compromising indoor air quality. Knowing the *NL* value for a home could give an indication of whether applying Section 4.1.3 would lead to under-ventilation or over-ventilation.

Potential Health Concerns from Indoor Concentrations

Table 1 presents the maximum indoor pollutant concentration ratios for various averaging times; these values are the highest concentrations calculated over the stated averaging time divided by the non-varying concentration calculated for the reference case. These ratios represent the degree to which short-term concentrations in the various ventilation scenarios deviate from the long-term (annual average) concentrations for the reference case. The ratios in Table 1 can be used to assess the degree to which acute health standards are of concern in relation to chronic health standards.

While this analysis was done for the idealized case of a constant indoor emission rate and negligible outdoor concentration, the results are more generally relevant to any pollutant with continuous indoor source(s) and outdoor concentrations that are much lower than indoor levels. The analysis does not, necessarily apply to pollutants with intermittent or episodic emissions or pollutants that predominately enter the indoor space via infiltration.

There is substantial uncertainty regarding whether the whole-house ventilation assumptions in Standard 62.2 leads to concentrations that are below relevant chronic

[1] There is some ambiguity around this critical NL; 62.2 calculates it using ASHRAE Standard 136, while we simulate it more exactly.

health standards for all indoor pollutants. In particular, it has been shown that formaldehyde concentrations can exceed chronic standards in new homes meeting ASHRAE 62.2 (Offermann 2009).

It is important to note that our focus is on demonstrating a methodology for understanding the effect of ventilation approach on the relationship between short-term peaks and annual average concentrations. We use this approach to investigate whether ventilation approaches that achieve chronic health standards are also adequate to meet acute health standards. Specifically, we use the results of this analysis to explore three important questions. 1) If the ASHRAE reference case meets the chronic exposure standard for some identified contaminant of concern, do the ventilation scenarios explored here meet both chronic and acute health standards for that same contaminant? 2) If a given ventilation scenario meets a chronic health standard for some contaminant can we safely assume that an acute standard for the same contaminant will be met as well?

To answer the questions indicated above, we must first establish what are the maximum acceptable ratios of short-term to long-term indoor concentrations when chronic standards are met. For simplicity, these ratios will be referred to in the rest of the text as the acute-to-chronic standards ratios (ACSR). We do this by dividing the most conservative acute standards for 3 different time frames (1-h, 8-h, and 24-h) by the most conservative chronic standard for lifetime exposure for pollutants identified as hazards in the indoor residential environment. We then compare the ACSRs to the maximum concentration ratios calculated for each of the ventilation scenarios (Table 1).

Logue et al. (2010) identified 23 pollutants[2] that are chronic hazards in US homes. Table 2 lists the most health-protective chronic and acute standard and guidelines put forth by each institution (WHO 2005; EPA 2008; OEHHA 2010). For a detailed descriptions of how these levels were developed and chosen, see Logue et al. (2010). While some of these pollutants have substantial or even primarily intermittent or outdoor sources, we include them all here to provide a larger pool of acute to chronic ratios against which to evaluate the approach we have demonstrated.

Considering the idealized case in which Standard 62.2 most efficiently achieves the objective of providing acceptable indoor air quality, the reference case will have an annual average concentration equal to the controlling chronic health standard(s). For each ventilation scenario, an annual average concentration ratio of 1.0 in our calculations indicates acceptable indoor air quality with regard to chronic health standards.

The first two ventilation scenarios (Constant Default and Constant with Infiltration Credit) result in long-term concentration ratios greater than unity for low *NL* values, indicating potential chronic exposure concerns for tighter homes.

For all of the ventilation scenarios, maximum ratios of short-term to annual average concentrations for 1-hour and 8-hour time frames are well below the ACSR values, independent of whether annual average concentrations exceed unity. The maximum 24-hour concentrations are closer to this limit than is the case for the other acute time frames but are still lower than the ASCRs. This indicates that weather-induced variability in infiltration does not lead to excessive peak concentrations for constantly emitting pollutants with negligible outdoor concentrations in these ventilation scenarios as long as

[2] Logue et al further reduced this list to 9 key contaminant that are present more broadly, but for this study we use the larger list of 23.

the ventilation scenario meets the chronic health standards. This holds true for intermittent ventilation. However, if chronic standards are not met, intermittent ventilation could lead to concentrations above acute standards.

For ventilation scenarios that result in long-term concentrations at or below the chronic standards, we can assume that acute exposures to continuously emitting contaminants with negligible outdoor sources will not have to be addressed separately from the chronic exposures as long as the scenario keeps the maximum concentrations below the following levels: the 1-hour indoor concentration at less than 4.7 times the reference case, the maximum 8-hour average at less than 5.4 times the reference case, and the maximum 24-hour concentration average at less than below 2.5 times the reference case. This is the case for the scenarios presented here.

SUMMARY, CONCLUSIONS, AND RECOMMENDATION

We developed and demonstrated an approach to assess the effects of air leakage and intermittent ventilation on the ratio of peak short-term to time-averaged pollutant concentrations for various ventilation strategies. We applied this approach to assess ratios of the highest short-term indoor concentrations (averaged over 1-hour, 8-hour, and 24-hour periods) to annual average exposures for four ventilation scenarios: Default (constant ventilation as specified in ASHRAE 62.2), Infiltration Credit, Constant Optimized, and Intermittent Optimized. The reference scenario was the (physically unrealistic) condition of constant infiltration airflow, as assumed in ASHRAE 62.2. The other scenarios examine potential alternative applications of Standard 62.2.

Infiltration and intermittent ventilation can increase maximum, short-term indoor pollutant concentrations relative to constant ventilation; however, we find that if the ventilation scenario meets long-term chronic standards, the maximum short-term concentrations are below acute standards.

Our results indicate that chronic exposure is the most relevant metric for assessing indoor air quality of different whole-house ventilation scenarios for constantly emitting pollutants with negligible outdoor concentrations. Two of the scenarios presented here had annual average concentrations higher than the reference case; however, none had concentrations that exceed acute-to-chronic standards ratios.

Ventilation scenarios that incorporate air leakage as part of the design can provide equivalent indoor air quality. That is, it is possible to provide adequate indoor air quality without any mechanical ventilation at high *NL* values. The energy efficiency and cost effectiveness of such a strategy may not make it desirable to do so, but that issue was not investigated.

Providing sufficient ventilation to keep chronic concentrations of continuously emitted pollutants at safe levels should be the goal of whole-house ventilation. Although research is needed to determine whether application of Standard 62.2 in fact keeps indoor concentrations below chronic exposure standards, our results show that, when the chronic levels *are* met, the concept of relative dose (i.e., average annual relative exposure) can be a guiding principle for ensuring that residential ventilation standards meet acute exposure standards.

REFERENCES

American Lung Association (ALA. (2010, 2010). "American Lung Association: Indoor Air Quality." 2010, from http://www.lungusa.org/associations/charters/mid-atlantic/air-quality/indoor-air-quality.html.

ASHRAE (1988). Air Leakage Performance for Detached Single Family Residential Buildings". Atlanta, GA, American Society of Heating, Refrigerating, and Air Conditioning Engineers. **Standard 119**.

ASHRAE (1993). A Method of Determining air Change Rates in Detached Dwellings. Atlanta, GA, American Society of Heating, Refrigerating and Air Conditioning Engineers. **Standard 136**.

ASHRAE (2009). 2009 ASHRAE Handbook - Fundamentals. Atlanta, GA.

ASHRAE (2010). Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta, GA, American Society of Heating, Refrigerating and Air Conditioning Engineers. **Standard 62.2**.

CARB (2005). Indoor air pollution in California, California Air Resources Board Report to the California Legislaturehttp://www.arb.ca.gov/research/indoor/ab1173/rpt0705.pdf

Chan, W. R., W. W. Nazaroff, P. N. Price, M. D. Sohn and A. J. Gadgil (2005). "Analyzing a database of residential air leakage in the United States." Atmospheric Environment **39**(19): 3445-3455.

Concannon, P. (2002). Technical Note AIVC 57: Residential Ventilation. Brussels, Air Infiltration and Ventilation Center (AIVC)

Edwards, R. D., J. Jurvelin, K. Koistinen, K. Saarela and M. Jantunen (2001). "VOC concentrations measured in personal samples and residential indoor, outdoor and workplace microenvironments in EXPOLIS-Helsinki Finland." Atmospheric Environment **35**: 4531-4543.

Emmerich, S. J. (2001). "Validation of Multifzone IAQ Modeling of Residential-Scale Buildings: A Review." ASHRAE Transactions **107**(Pt. 2).

EPA. (2008, 06/04/2008). "Integrated Risk Information System." 2007, from http://www.epa.gov/ngispgm3/iris/index.html.

Jacobs, D. E., T. Kelly and J. Sobolewski (2007). "Linking public health, housing, and indoor environmental policy: Successes and challenges at local and federal agencies in the United States." Environmental Health Perspectives **115**(6): 976-982.

Logue, J. M., T. E. McKone, M. H. Sherman and B. C. Singer (2010). "Hazard Assessment of Chemical Air Contaminants Measured in Residences." Submitted to Indoor Air.

McWilliams, J. and S. M. (2005). Review of Literature Related to Residential Ventilation Requirements. Berkeley, CA, Lawrence Berkeley National Laboratory**:**LBNL 57236

NREL. (2008). "Typical Meteorological Year." from http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

OEHHA. (2010, 2007). "Air Toxicology and Epidemiology: Hot Spots Guidelines." 2010, from http://www.oehha.org/air/hot_spots/index.html.

Offermann, F. J. (2009). Ventilation and indoor air quality in new homes, California Air Resources Board and California Energy Commission, PIER Energy-Related Environmental Research Program. Collaborative Report. CEC-500-2009-085.

Orme, M. (2001). "Estimates of the energy impact of ventilation and associated financial expenditures." Energy and Buildings **33**(3): 199-205.

Russell, M., M. H. Sherman and A. Rudd (2005). Review of Residential Ventilation Technologies. Berkeley, CA, Lawrence Berkeley National Laboratory

Sherman, M. H. (2004). "ASHRAE's New Residential Ventilation Standard (LBNL 53776) " ASHRAE J. **46**(1): S149-156.

Sherman, M. H. (2008). On the valuation of infiltration towards meeting residential ventilation needs. Berkeley, CA, Lawrence Berkeley National Laboratory**:**LBL-

Sherman, M. H. and D. Dickerhoff (1994). Air-Tightness of U.S. Dwellings (LBNL-35700). 15th AIVC Conference: The Role of Ventilation, Coventry, Great Britain:Air Infiltration and Ventilation Centre, 225-234.

Sherman, M. H. and N. E. Matson (2002). Air tightness of new U.S. houses: A preliminary report. Berkeley, Ca, Lawrence Berkeley National Laboratory, LBNL-48671.

Sherman, M. H. and N. E. Matson (2002). Air Tightness of New U.S. Houses: A Preliminary Report. Berkeley, CA, Lawrence Berkeley National Laboratory**:**LBNL 48671

Weisel, C. P., J. Zhang, B. J. Turpin, M. Morandi, S. Colome, T. Stock and D. M. Spektor (2005). Relationships of Indoor, Outdoor, and Personal Air (RIOPA) Part I. Collection Methods, Health Effects Institute, Mickely Leland National Urban Air Toxics Research Center and Descriptive Analysis**:**HEI Research Report 130 http://pubs.healtheffects.org/getfile.php?u=25

WHO (2005). Air quality guidelines: Global update 2005, Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. Copenhagen, Denmark, World Health Organization http://www.euro.who.int/Document/E90038.pdf

TABLES

Table 1. Maximum concentration ratio of indoor concentrations for different averaging times compared to the reference case for each ventilation scenario.

Maximum Concentration Ratio				
Ventilation Scenario	**Annual**	**24 hour**	**8 hour**	**1 hour**
Constant-Default	1.7	1.8	1.8	1.8
Constant with Infiltration Credit	1.7	1.8	2.2	2.3
Constant Optimized	1.0	2.1	2.6	2.8
Intermittent Optimized	1.0	2.1	2.6	3.4

Table 2. Concentration standards and guidelines for pollutants that present hazards in the indoor residential environment.

Table 2. Concentration Standards and Guidelines (μg/m^3)[a]				
COMPOUND	**Chronic**	**24 Hr**	**8 Hr**	**1Hr**
Acetaldehyde*	3.7		300	470
Acrolein*	0.02		0.7	2.5
Acrylonitrile	0.03			
Benzene*	0.34			1300
Benzyl chloride	0.2		5174	240
Butadiene, 1,3-*	0.06			
Cadmium	0.0024			
Carbon tetrachloride	0.24			1900
Chloroform	1.98			150
Chromium	6.7E-5			
Dichlorobenzene, 1,4-*	0.91		45000	
Dichloropropane,1,2-	4		350000	
Ethanol			1900000	
Ethylbenzene	4			
Formaldehyde*	1.67		9	55
Hexachlorobutadiene	0.45			
Methylene chloride	10			14000
Naphthalene*	0.29		50000	
NO2*	40			189
PM2.5*	10	25		
Tetrachloroethane, 1,1,2,2-	0.17		35000	
Tetrachlorothene	1.69			20000
Vinyl chloride	0.13			1800000
Lowest Acute to Chronic Ratio [-]		**2.5**	**5.4**	**4.7**

[a] micrograms per square meter * Compounds identified by Logue et al (2010) as key contaminants

FIGURES

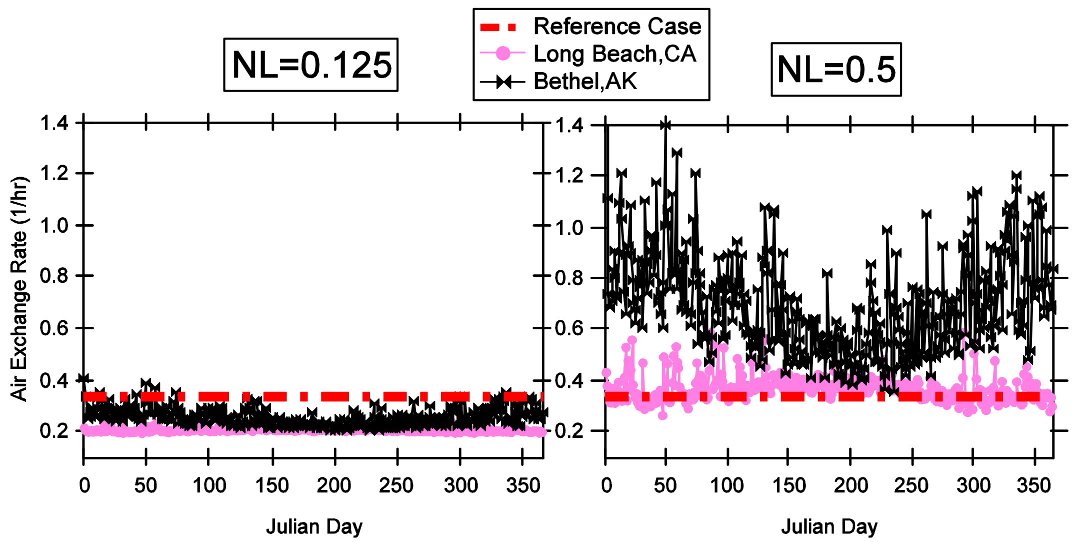

Figure 1. Daily averaged air exchange rates for Long Beach CA and Bethel AK compared to the reference case for normalized leakage (NL) values of 0.125 and 0.5. The *NL* value has a large effect on the average air exchange rate values, but the high infiltration and low infiltration days are functions of weather only.

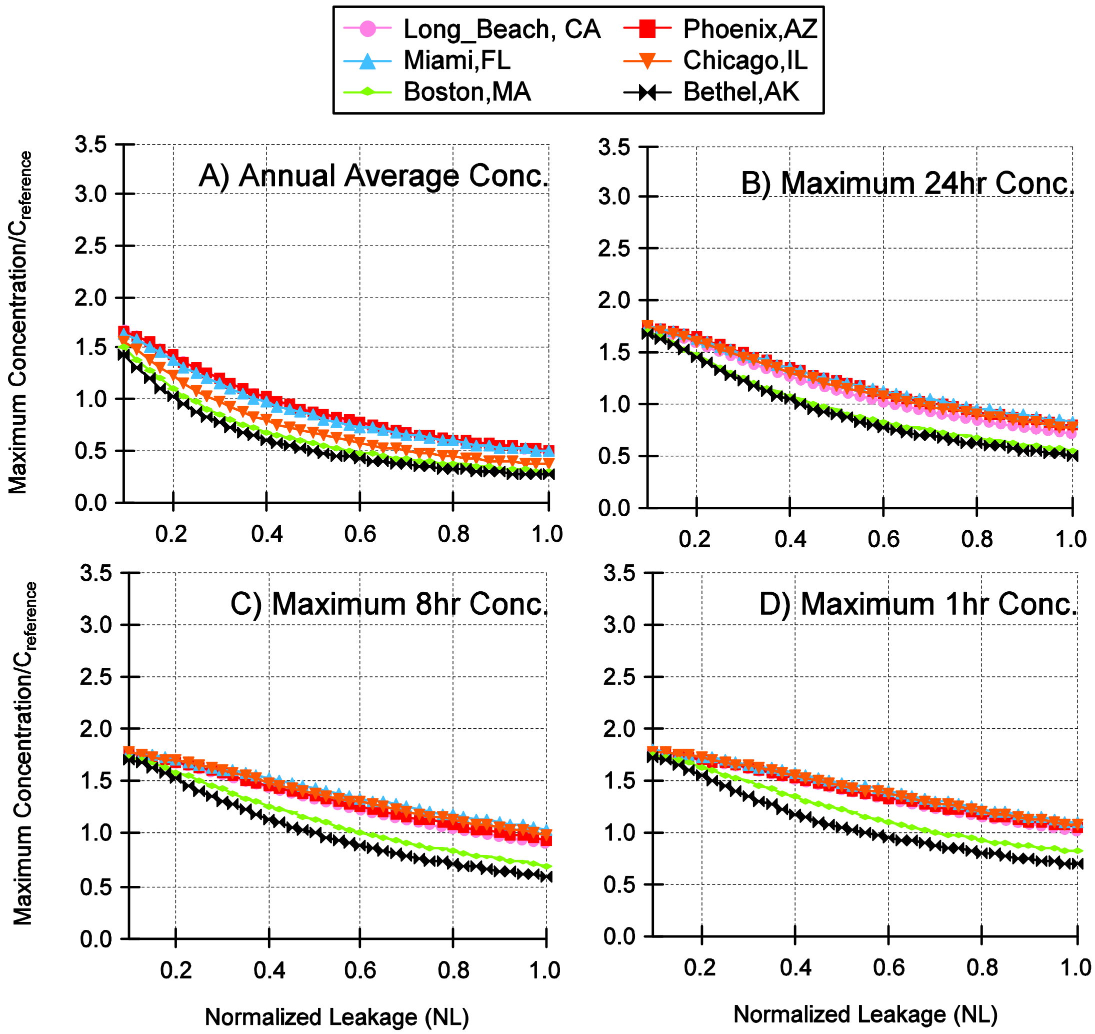

Figure 2. Results for Constant Default scenario; mechanical ventilation reduced for conditions of higher normalized leakage (NL) as allowed by ASHRAE 62.2-2010. Displayed in each panel are the highest concentrations for the stated averaging time and *NL*, divided by the non-varying concentrations that would result if infiltration airflow were constant and at the rate assumed in 62.2: A) normalized annual average concentration B) normalized maximum 24-hour average concentration, C) normalized maximum 8-hour averaged concentration, and D) normalized maximum 1-hour concentration modeled for a 2,000 ft^2, 3-bedroom home meeting the ASHRAE Standard 62.2-2010 mechanical ventilation requirement.

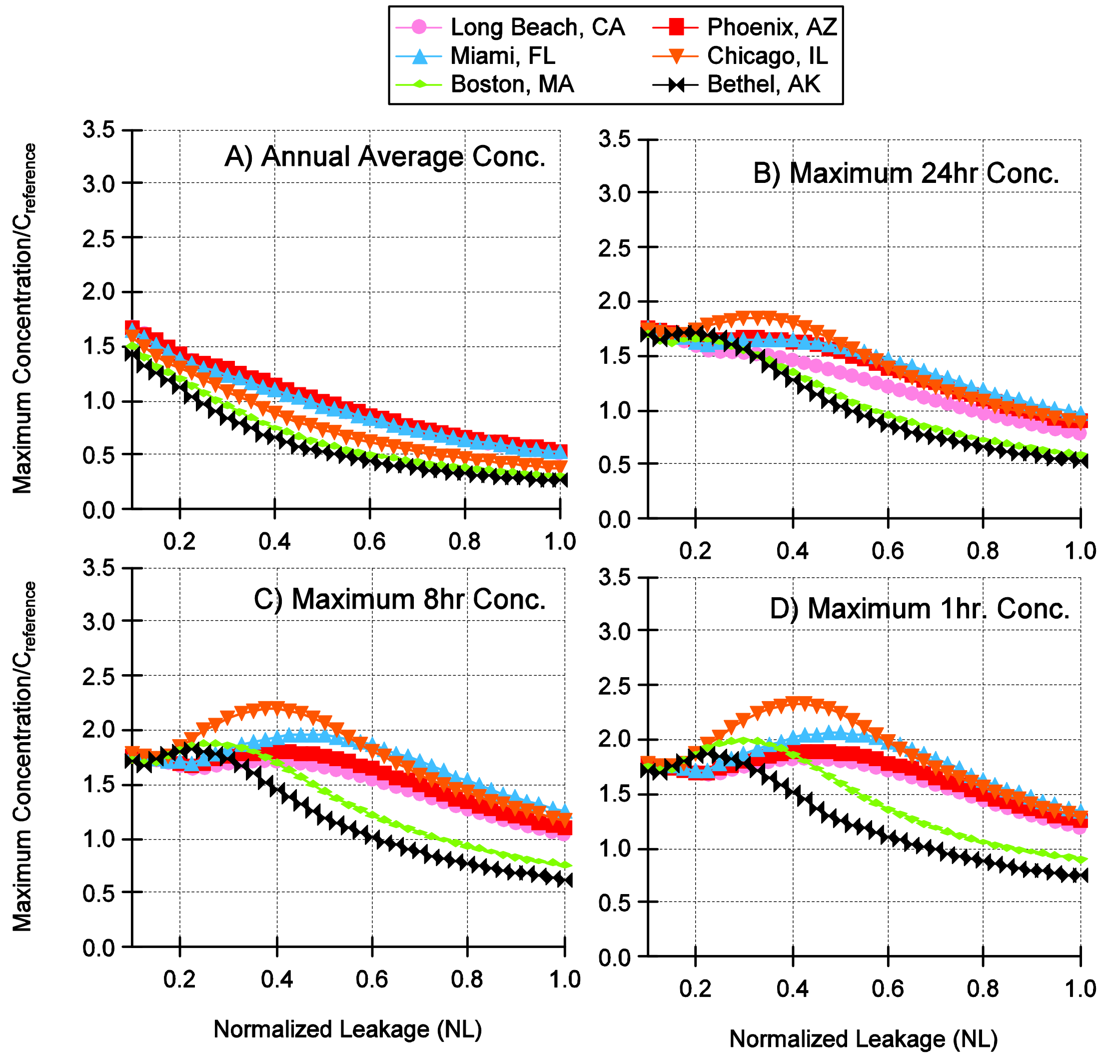

Figure 3. Results for Constant with Infiltration Credit scenario; mechanical ventilation reduced for conditions of higher normalized leakage (NL) as allowed by ASHRAE 62.2-2010. Displayed in each panel are the highest concentrations for the stated averaging time and *NL*, divided by the non-varying concentrations that would result if infiltration airflow were constant and at the rate assumed in 62.2. See text for additional details

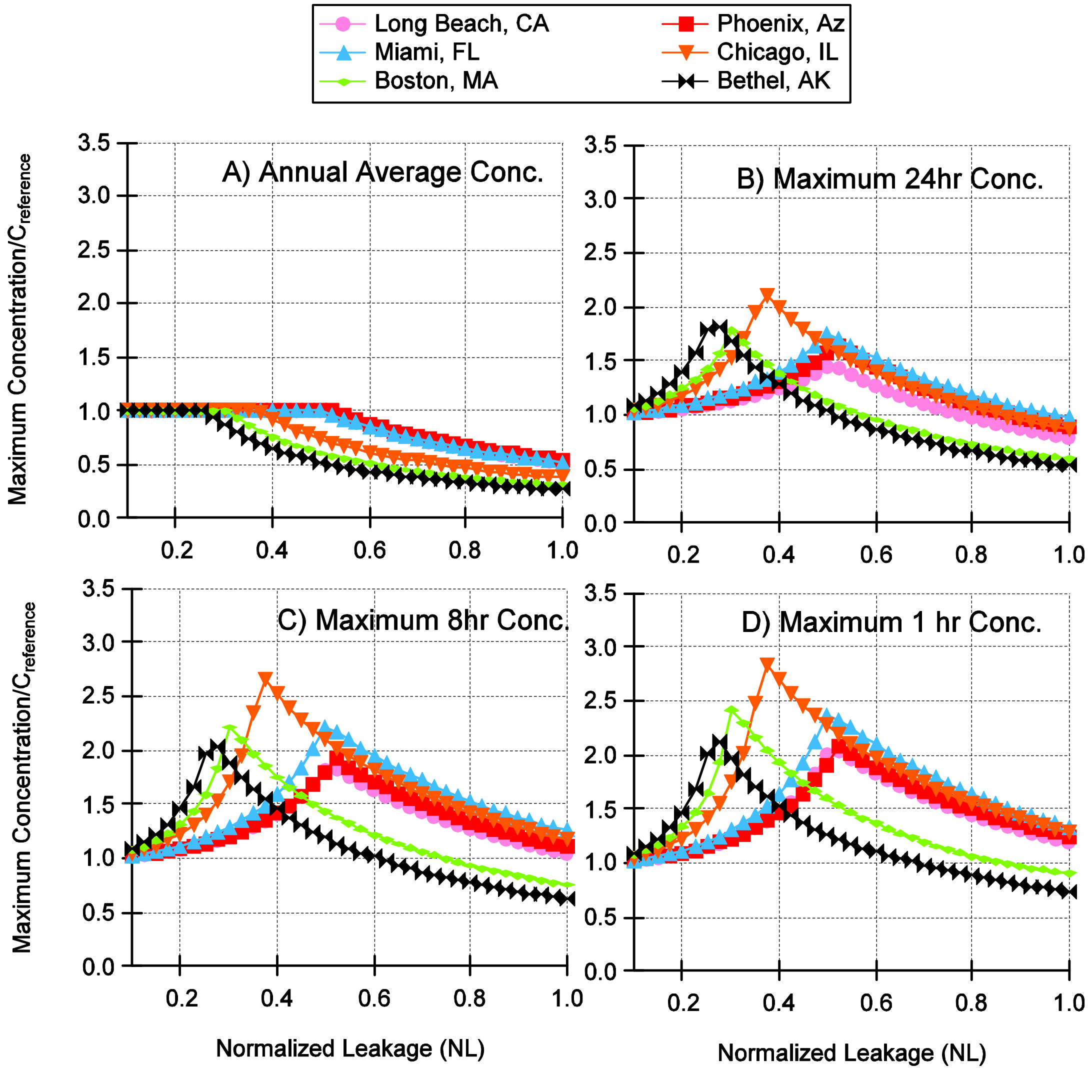

Figure 4. Results for Constant Optimized scenario; mechanical ventilation set to the lowest level possible while still achieving an annual average concentration that is at least as low as that of the reference case set by ASHRAE 62.2-2010. Displayed in each panel are the highest concentrations for the stated averaging time and normalized leakage, divided by the non-varying concentrations that would result if infiltration airflow were constant and at the rate assumed in 62.2. See text for additional details.

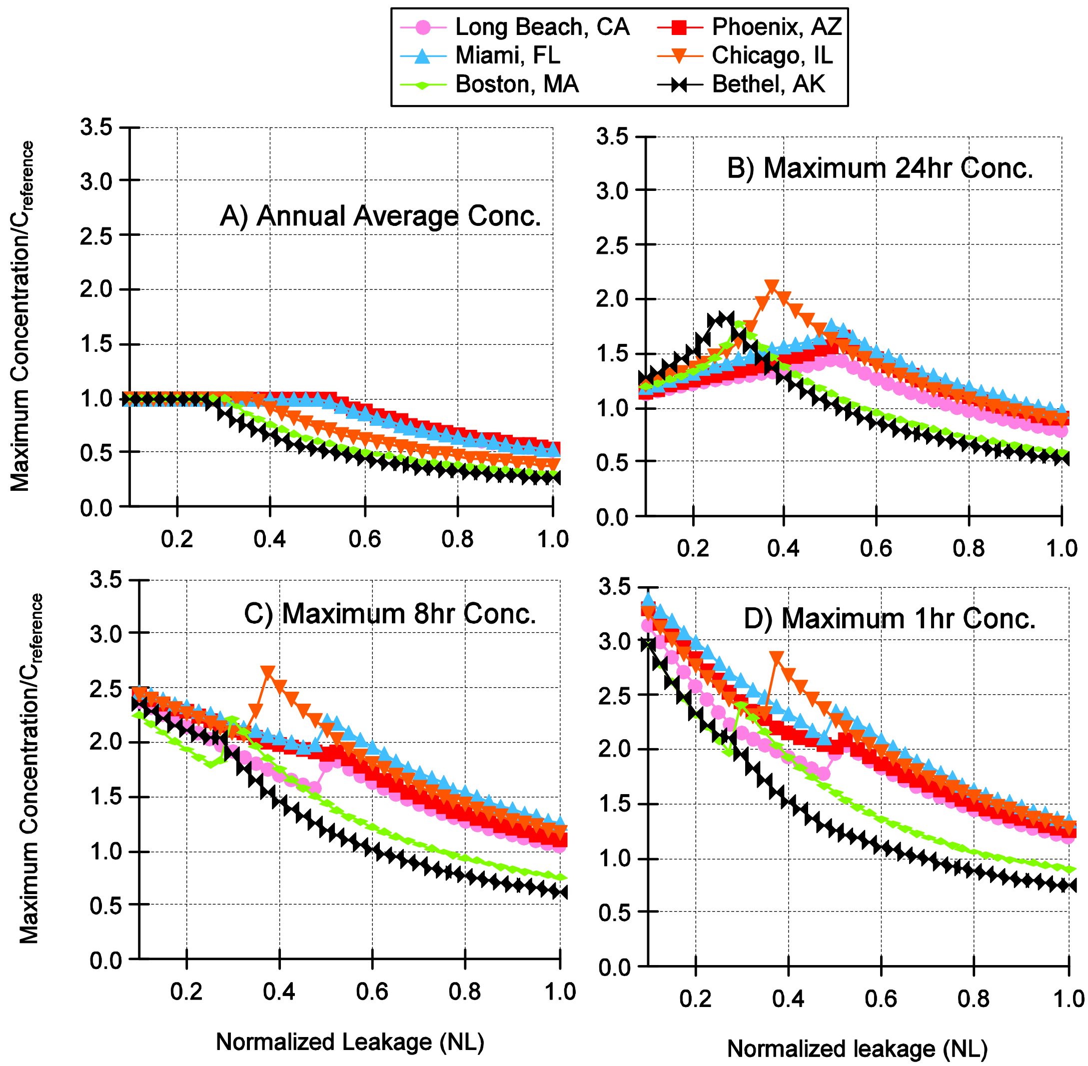

Figure 5. Results for Intermittent Optimized scenario; mechanical ventilation operated on cycle of 12 h off, 12 h on with rate set to the lowest level possible while still achieving an annual average concentration that is at least as low as that of the reference case set by ASHRAE 62.2-2010. Displayed in each panel are the highest concentrations for the stated averaging time and normalized leakage, divided by the non-varying concentrations that would result if infiltration airflow were constant and at the rate assumed in 62.2. See text for additional details