A Method for Modifying Ventilation Airflow Rates to Achieve Equivalent Occupant Exposure

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ABSTRACT

A method for quantitatively comparing dissimilar ventilation systems has been developed. A calibrated ventilation model was exercised over a range of parameters seen in new and existing housing in the United States. Varied parameters included climate, building enclosure air leakage, presence or absence of a central forced-air space conditioning system, ventilation system type, ventilation airflow rate, and contaminant generation locations. A baseline exposure was established based on the ASHRAE Standard 62.2-2007 ventilation rate using a fully-ducted balanced ventilation system as the reference system and a moderately airtight building enclosure (3.5 ach50). A ventilation airflow coefficient was then determined for each ventilation system such that the occupant exposure using the subject ventilation system was equal to the occupant exposure using the reference system at the baseline ventilation rate. These coefficients can be used to compare the effectiveness of different ventilation systems.

INTRODUCTION

ASHRAE Standard 62.2–2007 — Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings (ASHRAE 2008) (furthermore referred to in this paper simply as "Standard 62.2") sets minimum required ventilation rates for residential dwelling units. The amount of air prescribed by the standard is determined by the size of the dwelling and the number of occupants, typically determined from the number of bedrooms. No further instruction is given as to what type of ventilation system is acceptable. This omission may lead some users of the standard to believe that all ventilation systems that provide the same amount of air provide the same benefit. This is in fact not the case.

Past work has shown that different residential ventilation systems do not provide equivalent performance even when providing the same nominal outside air flow rate. For example, Hendron (2007) found that when interior doors were closed, an exhaust-only ventilation system provides less uniform distribution of ventilation air than a ventilation system that incorporates the central air handler to periodically mix the spaces. Sherman (2008) found that exposure levels calculated from tracer gas testing within a house depended strongly on the ventilation system and assumptions about the pollutant source and occupant location.

The purpose of the work described in this paper is to address this particular weakness in Standard 62.2. It is an attempt to quantitatively compare many existing ventilation systems and provide a method for adjusting the Standard 62.2 ventilation rate for a house based on the type of ventilation system installed. This method results in a coefficient assigned to each ventilation system (C_S) that modifies the current Standard 62.2 mechanical ventilation rate. This would result in an equation of the form shown in Equation 1:

$$Q_{fan} = C_S \cdot Q_{vent} \tag{1}$$

Where

Q_{fan} = required ventilation system flow rate

C_S = system coefficient (assigned based on the ventilation system selected)

Q_{vent} = the minimum mechanical ventilation flow rate required by Standard 62.2.

Townsend (2009) demonstrated that it was possible to replicate field measurements in a calibrated computer model to predict the performance of different ventilation systems

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under similar conditions; however this work was limited to a single, two-story house in one climate and was not directly applicable to the entire stock of existing and new residential homes in the United States. The range of climates and house characteristics, especially the building enclosure air leakage rate, across the U.S. heavily influence the performance of ventilation systems.

The work described in this paper addresses some of the limitations of the work in Townsend (2009) by exercising a similar computer model over a wide range of climates and building enclosure air leakage rates. By doing so, this work covers a much larger subset of typical single-family houses found in the United States. Next, by choosing a reference ventilation system for baseline performance, the ventilation systems considered in this work are evaluated in the manner described above and their equivalency determined. The end goal is to show how this method works and assign example system coefficient to each of the several ventilation systems considered.

DESCRIPTION OF COMPUTER MODEL

This work follows previous work (Townsend 2009) in which CONTAM, a multi-zone airflow modeling program (Walton 2005, Dols 2001) was used in a calibrated model of one house to reproduce the results of field tests and then to predict the performance of ventilation systems that were not tested in the field. In the current work, the CONTAM model was used in a similar fashion, except that instead of duplicating the results from one specific house, it was exercised over a range of parameters in order to cover a reasonable subset of the new and existing houses in the United States. This range of parameters and the input assumptions used came about through consensus agreement working directly with ASHRAE Standing Standards Project Committee 62.2 members over the course of several meetings from 2006 to 2009.

House Characteristics

A single house plan was used in this study. The house modeled is a two-story, approximately 2600 sf (240 m^2) house with four bedrooms and three bathrooms. The first floor consists of one bedroom, one bathroom, a laundry/utility room, a living room, and a kitchen/dining room. The second floor consists of the master bedroom and master bathroom, two additional bedrooms, one additional bathroom, and a small area at the top of the stairway overlooking living room below. In the model, each room with a closeable door was modeled as a separate zone with the exception of closets, which were modeled as part of the room they were connected to. The kitchen was modeled as a separate zone from the living room even though there was no closeable door between the two. The arrangement of the zones in the house is shown in Figure 1 and the relevant zone attributes are listed in Table 1. The house has a garage and vented attic that were both neglected in the computer model; these spaces were modeled as outdoors.

Occupancy

Two occupants were assigned to the master bedroom and a single occupant was assigned to each of the remaining

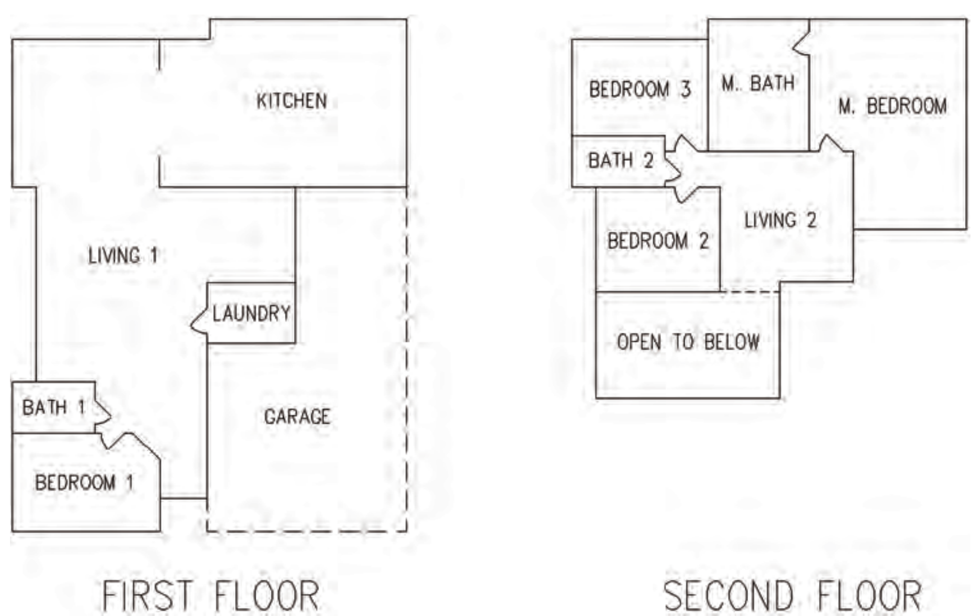

Figure 1 *Zones in the modeled house.*

Table 1. Zone Attributes

Zone	Room Volume (cf)	Floor Area (sf)	Wall 1 Area (sf)	Wall 2 Area (sf)	Wall 3 Area (sf)	Wall 4 Area (sf)	Roof Area (sf)	Total Wall Area (sf)
Kitchen	4590	459	280	180	120	0	0	580
Living room 1	8290	820	260	50	400	160	84	870
Bedroom 1	1590	159	160	110	0	0	159	270
Bath 1	480	48	80	0	0	0	37	80
Laundry	590	59	60	90	0	0	50	150
Bedroom 2	1260	140	99	0	0	0	140	99
Bedroom 3	1404	156	90	135	0	0	156	225
Bath 2	486	54	72	0	0	0	54	72
M. bathroom	1341	149	126	0	0	0	149	126
M. bedroom	2997	333	153	207	108	0	333	468
Living room 2	4104	205	153	243	99	0	456	495
Total	27132	2582	1533	1015	727	160	1618	3435

bedrooms, for a total of five occupants in the four-bedroom house. Each occupant was assumed to follow the same schedule each day, as described in Table 2. As the occupants moved around the house on their daily schedule, they were exposed to the pollutants in that location.

ASHRAE Standard 62.2 Mechanical Ventilation Rate

The ASHRAE 62.2 minimum required mechanical ventilation rate for this house and occupancy is 63 cfm (30 L/s).

Bedroom Doors

All doorways were modeled with appropriate sized openings that allowed two-way flow due to temperature differences between the rooms. Bedroom doors were assumed to be open except during the sleeping period of 10:00 PM to 7:00 AM.

Interior Temperature

Each zone temperature was held constant at either 71.6 or 71.63 °F (22 or 22.015 °C). The small temperature difference was used to cause thermally-driven two-way flow through open doorways as occurs naturally in buildings. In reality temperature differences between zones are likely to be larger than these; however when larger temperature differences were used in the model unrealistically high two-way flows resulted through the doorways (about 225 cfm (113 L/s) with a 2 °F (1 °C) temperature difference). As modeled the temperature difference resulted in flow of about 30 cfm (15 L/s) in each direction through the bedroom doorways and about 140 cfm (70 L/s) through the opening between the kitchen and the living area. Small changes in interior temperatures will make little difference in the natural infiltration rate except during very mild outdoor conditions.

Table 2. Occupancy Schedules

Time of Day	Occupant Location
12:00 AM to 7:00 AM	In their assigned bedroom
7:00 AM to 7:30 AM	In the bathroom nearest their bedroom
7:30 AM to 9:00 AM	In the kitchen
9:00 AM to 12:00 PM	In the living room
12:00 PM to 1:00 PM	In the kitchen
1:00 PM to 5:00 PM	In the living room
5:00 PM to 7:00 PM	In the kitchen
7:00 PM to 9:30 PM	Circulating through all the bedrooms
9:30 PM to 10:00 PM	In the bathroom nearest their bedroom
10:00 PM to 12:00 AM	In their assigned bedroom

Contaminant Generation

Unique contaminants were generated in each zone of the house and by each of the occupants. The contaminants are generic (i.e. they are not a specific chemical) and are assumed to be non-reacting. This simplifying assumption results in the ability to consider different contaminant-generation scenarios in post-processing, while only running one CONTAM simulation per combination of inputs. Reacting contaminants and removal mechanisms other than dilution by outside air are beyond the scope of this work. It is also important to note that the generation rate is arbitrary; therefore it is the relative values of the contaminant concentrations with respect to other ventilation systems that are meaningful, rather than the absolute values.

Enclosure Leakage

Enclosure leakage was varied from very tight to very leaky. Total enclosure leakage was divided between walls, ceilings, and ducts. The first floor was assumed to be a slab-on-grade with no air leakage. The proportion of enclosure leakage assigned to each enclosure component (walls, ceiling, or ducts) changed during the different rounds of analysis, but was always based on Dickerhoff (1982) and Harrje (1982) as summarized in ASHRAE (2005) and was modified based on the engineering judgment of the research team. The specific proportion assigned to each of the enclosure components is listed in the description of each round of analysis later in this report. Enclosure leakage pathways were assumed to follow the power law model as described in Equation 2:

$$Q = C \cdot (\Delta P)^n \tag{2}$$

Where

Q = volumetric leakage rate through leakage pathway
C = leakage coefficient
ΔP = pressure difference across leakage pathway
n = leakage exponent = 0.65 (ASHRAE 2005, page 27.12)

Enclosure Leakage Locations

While the total enclosure leakage was varied (and is described later), the locations of the leakage pathways were held constant. The house was assumed to have a slab-on-grade foundation, so there were no leakage paths through the first floor. Diffuse leakage over the entire wall area was approximated by assigning five discrete leakage pathways along each vertical section of the wall, at 2.25 ft (0.686 m) intervals starting at 0 ft (0 m) above the surface of the first floor and extending all the way up to the surface of the ceiling on the second floor. Uniform ceiling leakage was approximated by assigning a single discrete leakage pathway for each ceiling, as there is no spatial dependency in the horizontal plane within each zone. Each wall or ceiling leakage pathway was assigned leakage characteristics as follows:

$$C_i / C_t = A_i / A_t \tag{3}$$

Where

C_i = total leakage coefficient for wall or ceiling i
C_t = total leakage coefficient for all walls or ceilings in the house
A_i = exterior area of wall or ceiling i
A_t = total exterior area of all walls or ceilings in the house

Climate

Various climates were simulated. Cities were chosen as representative of their respective climates (based on the Department of Energy/2006 IECC climate zone map (Briggs 2003)), and TMY2 weather data (Marion 1995) from that city was used for the outdoor temperature, wind speed, and wind direction. The cities considered in each round of analysis are discussed later.

Wind Pressure

Leakage due to wind pressure was modeled for all of the wall leakage pathways. The wind speed and direction was obtained from TMY2 data (Marion 1995) for each site. The surroundings were assumed to be suburban and a wind pressure modifier was used to account for the difference in wind speed between the weather measurement site and the site of the modeled house. The components of the wind speed pressure modifier were Ao = 0.6 and a = 0.28, as described in Walton (2005) and ASHRAE (1993). Average wind pressure coefficients were assumed to be 0.6 with the wind blowing directly towards the wall, -0.3 with the wind blowing directly away from the wall, and -0.65 with the wind blowing parallel to the wall. Intermediate angles were interpolated based on the equation developed by Walker (1994) as described in ASHRAE (2005). Wind was neglected for the ceiling leakage pathways due to the large dependence on the shape and pitch of the roof assembly, and the authors' success in replicating experimental data in previous work while similarly neglecting wind effects on ceiling leakage (Townsend 2009).

Air Handler Size and Operation

The air handler unit (AHU) size for each climate was determined by the cooling requirement for that climate as determined using a common commercial software that performs ACCA Manual J (ACCA 2003) calculations. Table 3 contains the results of these calculations. The heating airflow was assumed to be 85% of the cooling airflow. An AHU was not present in all of the cases simulated; if it was present, its operation each hour of the year was scheduled based on the TMY2 data for each climate and the following assumptions:

1. At the climate's heating or cooling design temperature, the AHU runs 80% of the time.
2. Between the heating and cooling balance points, the AHU does not run for space conditioning, but may run according to a minimum runtime or minimum turnover criteria.
3. Between the balance and design points, the AHU runs as described in Equation 4 below:

$$RTF = (T - T_b)/(T_d - T_b) \cdot 0.8 \tag{4}$$

Where

RTF = runtime fraction of AHU (fraction of the hour)
T = hourly average outdoor temperature from TMY2 data
T_b = heating or cooling balance point
T_d = design heating or cooling temperature for the climate

The heating and cooling balance point temperatures varied depending on the round of analysis and are described later. As the simulation time step was five minutes, the runtime was rounded to the nearest five-minute increment. The runtime each hour was assumed to occur in two cycles: one beginning at the top of the hour and one beginning at thirty minutes past the hour. While heating and cooling cycle times in actual buildings may vary from this assumption, the important parameter in the analysis of ventilation air distribution is the amount of air turnover that occurs in any given hour, which gives the same result whether that occurs in more frequent short cycles or less frequent long cycles within the hour.

It is important to note that the hourly runtime fraction above is not the same as the cycle time from Table 4.2 in Section 4.4 of Standard 62.2. The runtime fraction above is for the AHU. The cycle time from Section 4.4 of Standard 62.2 is for the ventilation system. Furthermore, the cycle time from Section 4.4 of Standard 62.2 is used for ventilation systems that have cycle times (off-time plus on-time) of over six hours. All the ventilation systems considered in this paper have off periods of less than 30 minutes and therefore do not use the cycle time from Section 4.4 of Standard 62.2.

Minimum Runtime and Turnover Criteria

For cases with a forced-air space conditioning system, the AHU was operated to meet the assumed space conditioning requirements. In some cases, additional AHU operation was added to provide mixing between the different zones in the house. Two different mixing strategies were examined. The first mixing strategy was a minimum runtime, which is simply a minimum number of minutes per half-hour that the AHU must run. The second mixing strategy was a minimum turnover, which is the fraction of the total air volume in the house that passes through the AHU in an hour. For example, for this house with volume of 27,000 ft^3 (765 m^3) to have a turnover of 0.5/hr, the AHU must move 13,500 ft^3 (382.5 m^3) of air each hour. For cases with a minimum turnover requirement in this work, the AHU runtime was increased so that it would run long enough to provide 0.7 turnovers per hour. This criterion for air volume turnovers per hour is based not on modeling but on our experience of the minimum AHU operation needed to maintain a reasonably well-mixed condition within real-world houses. The 0.7 turnovers per hour resulted in a minimum runtime criteria that varied based on the size of the AHU, which was determined by the climate.

Ducts

In cases where a central AHU was present, ducts were located either in the vented attic (considered to be outdoors in this analysis) or in conditioned space. In cases where a central AHU was not present, there were no ducts except as required for the ventilation system being modeled.

Ventilation Rate

The ventilation rate was modeled as 0%, 50%, 100%, 150%, and 200% of the Standard 62.2 minimum required mechanical ventilation rate. The Standard 62.2 minimum required mechanical ventilation rate for this house is 63 cfm (30 L/s).

Table 3. Air Conditioner Sizes and AHU Flow Rates

City	Air Conditioner Size, tons (kW)	AHU Air Flow, cfm (L/s)
Daytona Beach	3 (10.5)	1200 (9.4)
Houston	3.5 (12.3)	1400 (11)
Indianapolis	3 (10.5)	1200 (9.4)
Minneapolis	3 (10.5)	1200 (9.4)
Phoenix	3 (10.5)	1200 (9.4)
Raleigh	3 (10.5)	1200 (9.4)
Sacramento	3 (10.5)	1200 (9.4)
San Diego	2 (7)	800 (6.3)
Seattle	2 (7)	800 (6.3)

Parametrics and Computer Model

Once a model was completed for each of the ventilation systems, a specialized program was used to create additional models with the appropriate variations in the input parameters (climate, enclosure leakage, duct leakage, ventilation rate, etc). These input files were then simulated as a batch and the results available for post-processing.

Exposure Scenarios and Time Period

For some contaminants, it may be appropriate to assume that the contaminant sources are evenly distributed throughout the house: i.e., the rate of contaminant generation in each zone is proportional to the zone's volume. Other contaminants may be generated preferentially in certain rooms of the house, or the occupants themselves may cause contaminants to be generated in their vicinity. In this work, four scenarios were considered to bracket a range of possibilities: contaminants generated proportional to zone volume; contaminants generated in bathrooms and kitchens only; contaminants generated by occupants only; and contaminants generated half by zone volume and half by occupants.

The contaminant source generation discussed here is only relative to that addressed by whole-house ventilation by dilution. Spot ventilation for high polluting events in kitchens and bathrooms is required separately by the Standard 62.2, and ventilation needed for unusual polluting events, such as hobbies, remodeling/construction, etc. are not covered by the Standard.

The source scenario where contaminants are generated proportional to zone volume (used for exposure scenarios A & B) represents the limiting case where all emissions are uniformly distributed throughout the house. This scenario was meant to address the emissions from building materials, finishes, adhesives, furnishings, electronics, and other materials or objects that are uniformly distributed and do not change location.

The source scenario where contaminants are generated in only bathrooms and kitchens (used for exposure scenarios C & D) represents the limiting case where all emissions are from specific zones in the house. This scenario was meant to address a concern that kitchens and bathrooms may have a disproportionately high amount of emission from cabinets and stored cleaning supplies.

The source scenario where all the contaminants are generated by the occupants and their activities (used for exposure scenario E) represents the limiting case where all emissions are from the occupants and their activities as they move throughout the house during the course of the day. This scenario was meant to address occupant-generated contaminants such as bioeffluent, personal care products and fragrances, use of cleaning products, vacuuming, particles re-suspension due to movement, etcetera.

A combined source scenario (exposure scenario F) where half the contaminants are generated by sources that are evenly distributed throughout the house (scenario A) and half the contaminants are generated by occupants and their activities (scenario E) is likely the most realistic scenario considered in this paper. It represents the static building elements as well as the dynamic occupants and their activities. The occupant schedules include time spent in the bathrooms and kitchen, resulting in contaminants from these zones due to both occupant behavior and their zone volumes. This results in 20% of the contaminant generation occurring in the kitchen and bath zones and 80% in the other zones.

Additionally, different occupant schedules can be considered. The previously-described schedule is a rigid one that repeats every day; while this schedule was chosen to be realistic, it obviously does not precisely represent the real world. An alternative to assigning a rigid schedule is to not assign a schedule at all, but to instead assume that all occupants are exposed to all zones equally throughout the day and night.

Table 4 describes exposure scenarios based on logical combinations of the above contaminant source and occupant schedule assumptions.

In addition to establishing the exposure scenario, an exposure time period must be established. Standard 62.2 does not specify a time period; however as it is intended to provide acceptable indoor air quality for both odors and occupant health, and as short-duration events should be provided for by spot ventilation, an appropriate exposure time period for background dilution ventilation might be one day, one week, one month or one year. For the analysis presented here, an exposure period of one year was used.

Post-Processing: Translating Concentrations to Exposure

Post-processing included applying pollutant weights to each zone and applying occupant schedules to determine exposure. Under the assumption of non-reacting contaminants, contaminant concentration is linear with respect to emission strength. This allows consideration of different pollutant generation scenarios by scaling the contaminant concentration results by an appropriate factor. The following method is used to calculate occupant exposure and the resulting figures of merit. This analysis assumes that exposure is linearly related to the total concentration of contaminants in the zone.

The output from the model is a 3-dimensional matrix consisting of the contaminant concentration level of each contaminant in each zone for each output time step. Let R(c,z,t) be the c by z by t matrix of contaminant concentrations which is the result of each simulation, where c, z, and t are the number of contaminants, zones, and time steps, respectively. Let W(c) be the weighting vector for one of the contaminant source scenarios. W(c) will then contain c values representing the relative source strengths of the

Table 4. Exposure Scenarios

Exposure Scenario	Exposure Scenario Description
A	Contaminant sources weighted by zone volume; occupants do not emit contaminants; occupants are exposed according to their daily schedule; consider the occupant with the highest yearly exposure
B	Contaminant sources weighted by zone volume; occupants do not emit contaminants; occupants are exposed to all zones equally (all occupants have same exposure)
C	1/6 of total contaminant source is in each bathroom, 1/2 is in kitchen; occupants do not emit contaminants; occupants are exposed according to their daily schedule; consider the occupant with the highest yearly exposure
D	1/6 of total contaminant source is in each bathroom, 1/2 is in kitchen; occupants do not emit contaminants; occupants are exposed to all zones equally (all occupants have same exposure)
E	The occupants are the only sources; occupants are exposed according to their daily schedule; consider the occupant with the highest yearly exposure
F	Zones emit 1/2 of total contaminants weighted by zone volume, occupants emit 1/2 of total contaminants in the zone that they occupy according to their daily schedule; occupants are exposed according to their daily schedule; consider the occupant with the highest yearly exposure

contaminants. The scenario-specific concentration in each zone for each time step is then

$$R_{ss}(z,t) = R(c,z,t) \cdot W(c) \quad (5)$$

Where $R_{ss}(z,t)$ is a z by t matrix containing the scenario-specific concentration of contaminants in each zone for each time step. Assuming the occupants' exposures are linearly related to the total concentration of contaminants in the zone, the exposure each hour is

$$E(t) = R_{ss}(t) \cdot Z(t) \quad (6)$$

Where Z(t) is a z by t matrix containing the weighting factors that the occupant is exposed to each hour. From the exposure vector E(t) and the exposure time period, the exposure for each occupant can be calculated. For this work the exposure time period is the full year, so the full-year average exposure for each occupant i was calculated.

$$E_{FY,i} = (\Sigma E_i(t))/t \quad (7)$$

The final figure of merit for each simulation is the occupant with the highest exposure.

$$FM = \text{maximum of } (E_{FY,1}, E_{FY,2}, E_{FY,3}, E_{FY,4}) \quad (8)$$

These figures of merit can then be compared to figures of merit from other cases within the same exposure scenario. Figures of merit cannot be compared across exposure scenarios.

RESULTS FROM INITIAL SIMULATIONS

Several rounds of parametric simulations were performed. In the initial rounds, several parameters were varied to determine their effect on the resulting yearly average exposure. These results helped guide decisions regarding the appropriate parameters for the final simulations (reported below).

In the first round, the climates simulated were Phoenix (climate zone 2), Daytona Beach (climate zone 2), Raleigh (climate zone 4), Minneapolis (climate zone 6), and Seattle (climate zone 4). In this round the heating and cooling balance points were assumed to be 65 and 75°F (18.3 and 23.9°C), respectively, and did not change with the enclosure leakage rate. The enclosure leakage was distributed in the following manner: wall leakage 62% of total enclosure leakage, ceilings 23% of total enclosure leakage, and ducts 12% of total enclosure leakage. The total enclosure leakage rate was 1.5, 3.5, and 7 ACH50. The central AHU and duct system were either in unconditioned space, in conditioned space, or not present. In cases with a central AHU, it was controlled either with a standard thermostat or with a thermostat and a minimum runtime of 10 minutes every 30 minutes. Duct leakage was either 6% or 12% of total AHU flow. Four ventilation systems were modeled: a single-point exhaust from the first floor living area, a single-point supply to the first floor living area, a balanced system supplying to and exhausting from the first floor living area, and a balanced system with a supply in each bedroom and the central living area and a single exhaust from the central living area. All reasonable combinations of the above variables were created and the simulations performed; only exposure scenario A (as described in Table 4) was considered in post-processing of this round. The results are discussed below.

Effect of Climate

Figure 2 shows the effect of climate, as represented by DOE/IECC 2006 climate zone (Briggs 2003), and enclosure leakage, at ventilation rates ranging from 0% to 200% of the Standard 62.2 rate, and for exposure scenario A (contaminants generated by zone volume, occupants exposed according to daily schedule). As the climate zone number increases, the climate gets colder and the driving force for infiltration

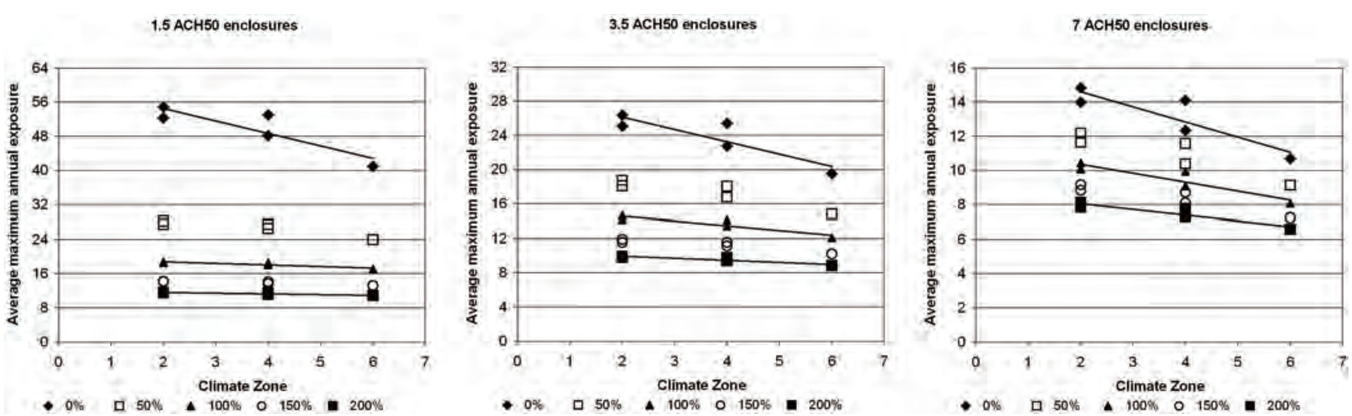

Figure 2 *Effect of climate and ventilation rate on yearly average exposure.*

(temperature difference) generally increases, increasing infiltration and therefore decreasing the yearly average exposure. The effect of climate decreases at high ventilation rates and in houses with tighter enclosures. Note that the scale of the y-axis changes between these three graphs.

Effect of Central System Presence and Location

Figure 3 shows the effect of the central system presence and location. A central system located outside of conditioned space leaks to and from (exchanges air with) that unconditioned space. In the modeling, this unconditioned space was modeled as outdoors, which results in lower contaminant concentrations (since the outdoors was not modeled as a source of contaminants) and lower yearly average exposure. In the final simulations (described later), central system ducts were modeled as inside conditioned space in order to eliminate any possible benefit from duct leakage when operating the central system fan. Air exchange with unconditioned spaces, whether by central system return air duct leakage or by an exhaust ventilation system, is problematic from an air quality perspective. Garages, crawlspaces, attics, and basements often have poor air quality and should not be a source of ventilation air for the conditioned space. The air quality of these spaces was not accounted for in this modeling effort; future research efforts are anticipated to examine the effects of the source of ventilation air.

With uniformly distributed contaminant sources, at any ventilation rate, a central system with no leakage to outside results in lower yearly average exposure than a house without a central system. This is due in part to slight pressure differentials that can cause increased air exchange between indoors and outside when bedroom doors are closed and the AHU is running, but the greater effect is that the central system provides mixing to the house and therefore a more uniform distribution of pollutants within the house, which the ventilation system can remove/dilute. In other words, the zones that are not directly connected to the ventilation system are indirectly connected when the central system moves air around the house.

Effect of Duct Leakage and Location

Figure 4 shows the effect of duct leakage and location. With ducts located inside conditioned space, all leakage is to and from conditioned space, so duct leakage has negligible effect on the contaminant concentrations in the house and therefore negligible effect on the yearly average exposure of the occupants. On the other hand, if ducts are located in unconditioned space, duct leakage plays a large role in air exchange between the house and the spaces where the ducts are located. The unconditioned spaces where ducts typically are located are often problematic from an air quality, energy, or durability perspective, which is not captured by the information shown in Figure 4.

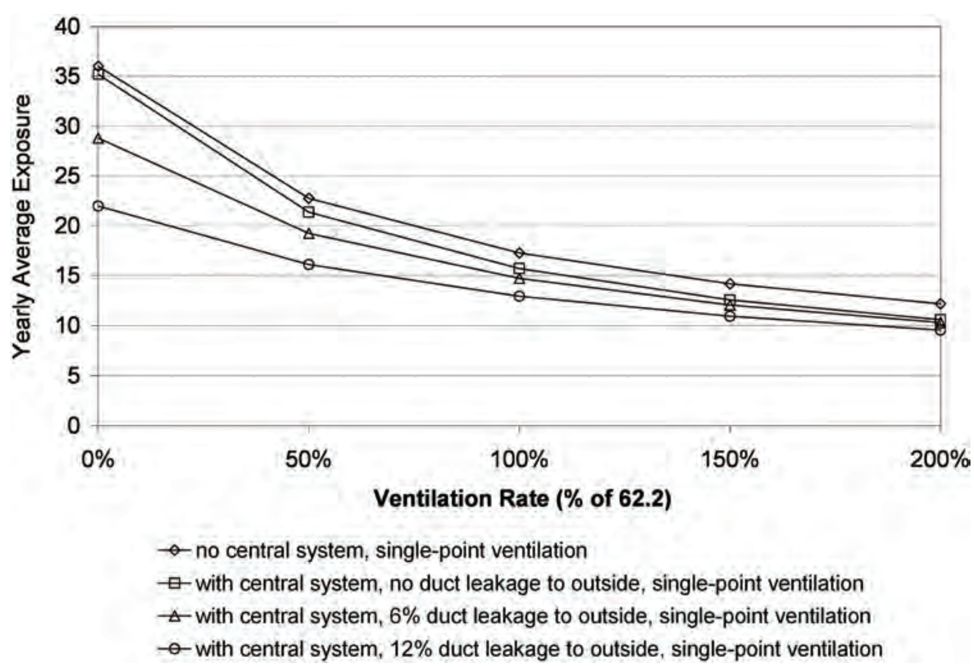

Figure 3 *Effect of central forced-air space conditioning system presence and location.*

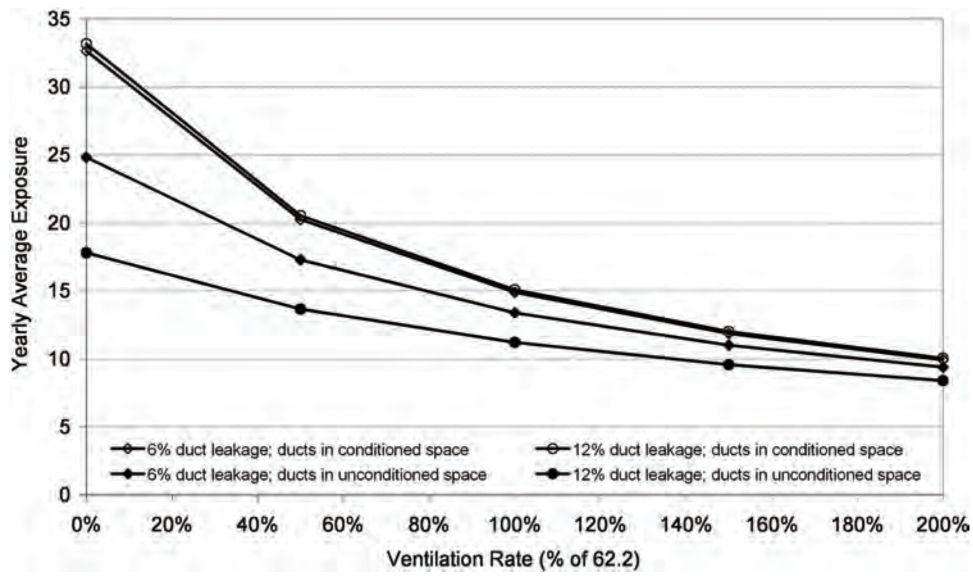

Figure 4 *Effect of duct location and leakage rate.*

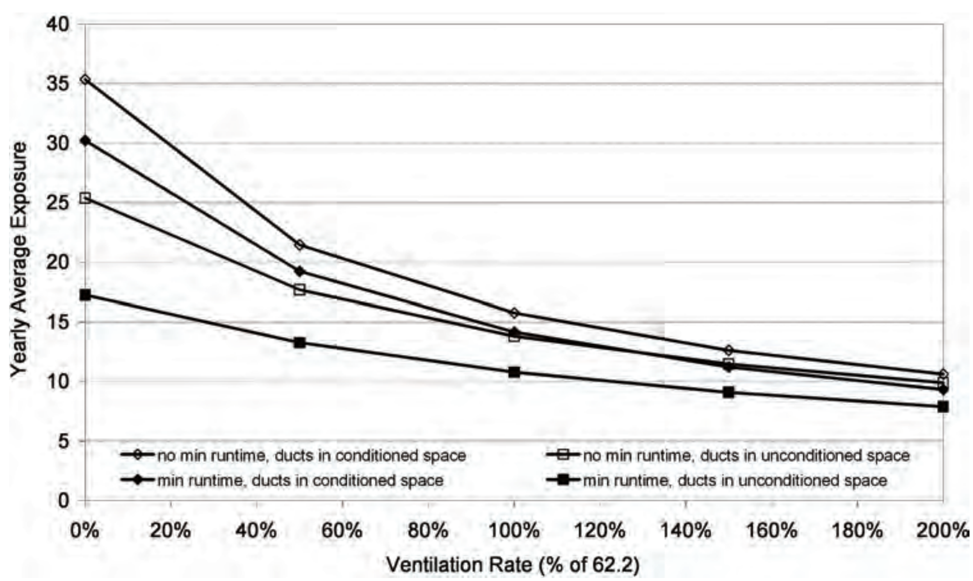

Figure 5 *Effect of duct location and minimum runtime.*

Effect of Duct Location and Minimum Runtime

Figure 5 shows the effect of duct location and minimum runtime. A minimum runtime requirement increases the overall amount of duct leakage, since the central system is running more often. If this duct leakage occurs in unconditioned space, there is again the potential for air quality, energy, and durability problems. On the other hand, if the duct leakage occurs in conditioned space, the indoor contaminant concentrations are lower with a minimum runtime than without a minimum runtime (due to better mixing of air within the house and connection of all the zones to the ventilation air), and there is no connection of the house to the undesirable spaces adjacent to it.

Effect of Enclosure Leakage

Figure 6 shows the yearly average exposure for the three different enclosure leakage. Holding everything else constant

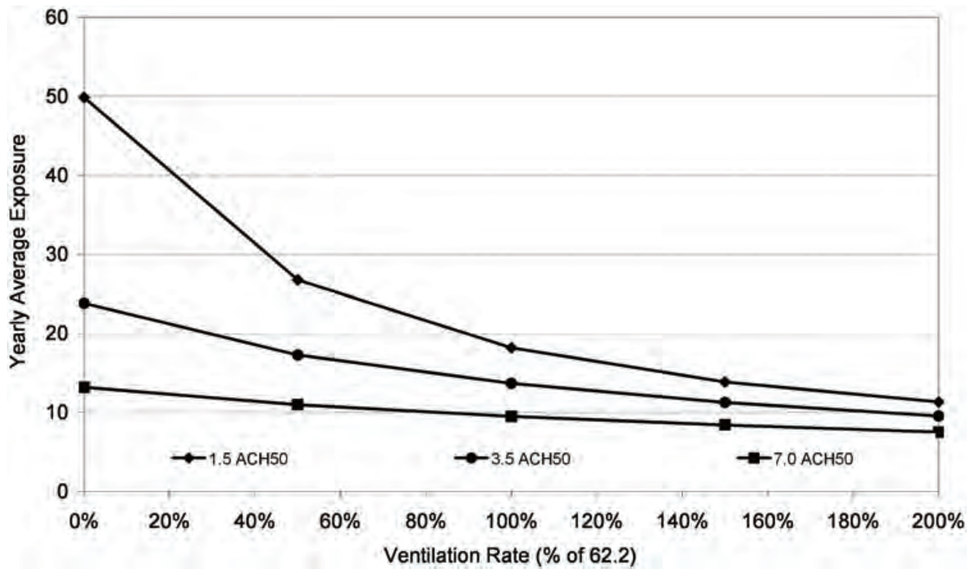

Figure 6 *Effect of enclosure leakage rate.*

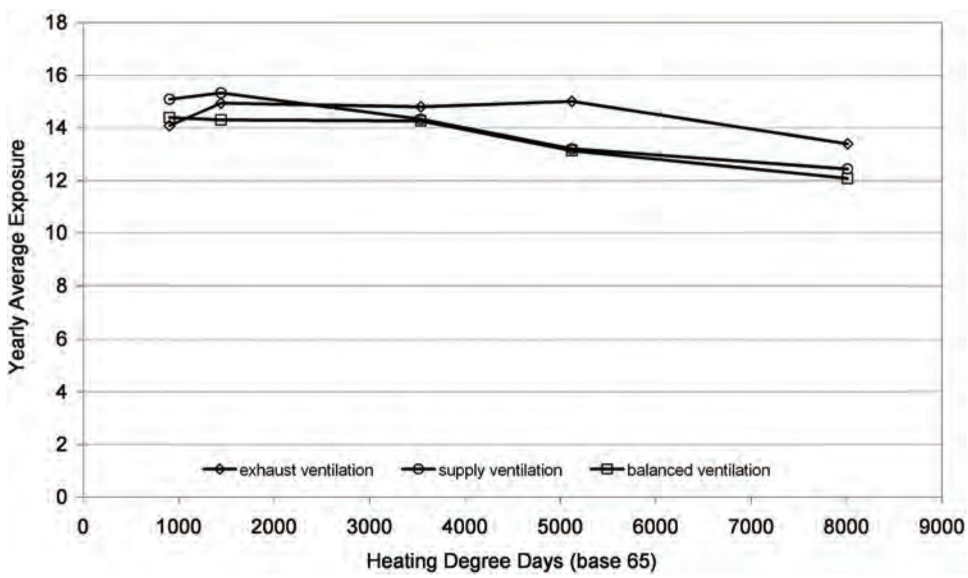

Figure 7 *Effect of ventilation direction and climate.*

(contaminant source strengths, ventilation system and rate, climate, etc.), a leakier house will have lower annual average exposure than a tight house. A leakier house will also have a penalty in terms of energy and in some cases occupant comfort and exposure to particulates (dust, dirt, pollen) which this modeling does not account for. In addition, without source control or appropriate spot ventilation, short-term exposures can be quite high even in very leaky houses.

Effect of Climate and Ventilation Type

Figure 7 shows the effect of climate and ventilation type (exhaust, supply, or balanced) versus heating degree days. In cold climates, a supply system works to balance the natural driving force (the stack effect) and therefore provides more air exchange than an exhaust system. The reverse is also true: in warm climates, an exhaust system works to balance the natural driving force (the reverse-stack effect) and provides more air

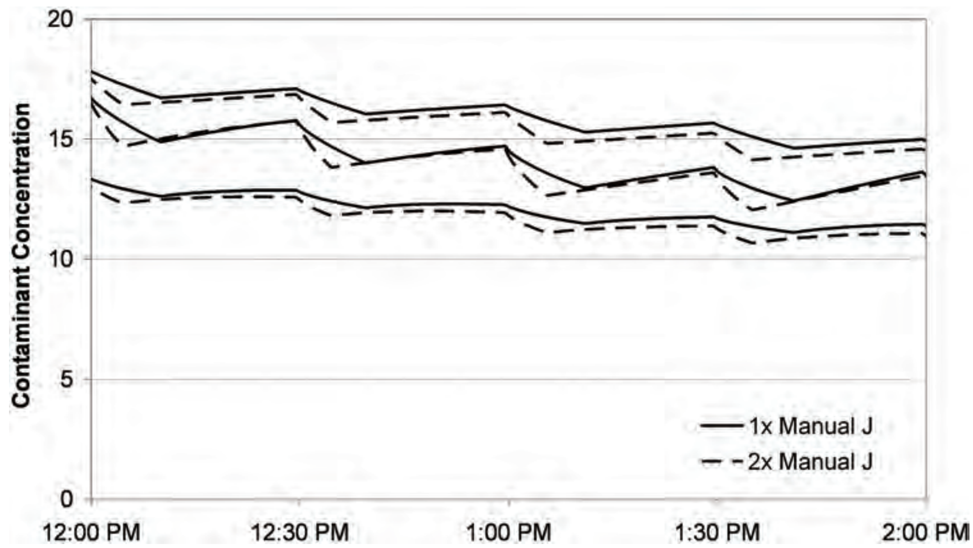

Figure 8 *Manual J sizing vs. 2x Manual J sizing.*

exchange than a supply system (ARTI 2007). For more information regarding the applicability and performance differences of supply, exhaust, and balanced ventilation systems, refer to Rudd (2006).

Effect of AHU Size

In a separate round of simulations, the effect of AHU size was explored. At first glance the AHU size might be expected to have a large impact on the amount of mixing that occurred as a result of AHU operation. This turns out to be false, as the amount of mixing is dependent on the amount of air supplied to each room, which (in the absence of a minimum runtime controller) is governed by the space conditioning load, not the size of the AHU. A larger AHU will deliver the same amount of air in less time, and then turn off. Even with a minimum runtime controller, sizing of the AHU, within reasonable limits, was not influential, as the minimum runtime controller was able to maintain reasonably well-mixed conditions even with a small AHU. Figure 8 shows the small effect of doubling the AHU size. The figure compares the contaminant concentration in three zones in the house over a two-hour period with moderate space conditioning load. Comparing each pair of lines shows the small difference in contaminant concentration between the airflow for a central air distribution system sized according to ACCA Manual J and one two times larger.

RESULTS FROM FINAL SIMULATIONS

Based on the initial findings that duct leakage resulted in apparently lower contaminant concentrations, and not wanting to reward duct leakage as mechanically induced air exchange, the final round of simulations were performed with the AHU and duct system (if present) inside conditioned space. Duct leakage was eliminated; walls were assumed to have 55% of the total leakage and ceilings were assumed to have 45%. Eight cities were chosen to simulate: Houston (climate zone 2), Phoenix (climate zone 2), Sacramento (climate zone 3), San Diego (climate zone 3), Raleigh (climate zone 4), Seattle (climate zone 4), Indianapolis (climate zone 5), and Minneapolis (climate zone 6). Five enclosure leakage levels were simulated: 1.5 ACH50, 3.5 ACH50, 5 ACH50, 7 ACH50, and 20 ACH50. In this set of simulations, the enclosure leakage rate determined the balance point temperature. Heating and cooling balance point temperatures corresponding to the enclosure leakage levels are listed in Table 5.

Table 5. Heating and Cooling Balance Point Temperatures

Enclosure Leakage Level, ACH50	Heating Balance Point Temperature, °F (°C)	Cooling Balance Point Temperature, °F (°C)
1.5 and 3.5	55 (12.8)	75 (23.9)
5 and 7	60 (15.6)	75 (23.9)
20	65 (18.3)	75 (23.9)

Thirty-six ventilation systems that provide the ASHRAE 62.2 standard minimum mechanical ventilation rate were simulated. These systems were selected based on the systems commonly seen in practice as well as systems specifically requested by the participating Standard 62.2 committee members. The systems were a collection of individual systems that were then grouped by the major categories of supply, exhaust, and balanced. Additional distinctions were made for the presence of a central AHU and a subgroup that included a minimum turnover via the AHU. These systems are described in Table 6.

Table 6. Ventilation Systems

System #	System Description
1	Single-point continuous exhaust from first floor common area, no central system
2	Single-point continuous exhaust from second floor master bathroom, no central system
3	Single-point continuous exhaust from first floor common area, no central system, inlets at top of window in bedrooms and living room
4	Single-point continuous exhaust from second floor master bathroom, no central system, inlets at top of window in bedrooms and living room
5	Three-point continuous exhaust, 1/3 from each bathroom, no central system
6	Three-point continuous exhaust, 1/3 from each bathroom, no central system inlets at top of window in bedrooms and living room
7	Four-point continuous exhaust, 1/4 from kitchen and each bathroom, no central system
8	Four-point continuous exhaust, 1/4 from kitchen and each bathroom, no central system inlets at top of window in bedrooms and living room
9	Single-point continuous supply to first floor common area, no central system
10	Two-point continuous balanced, supply into first floor common area, exhaust from second floor family bathroom, no central system
11	Fully-ducted continuous balanced, supply into the 1st floor common area and each bedroom, single exhaust from the 1st floor common area, no central system
12	Fully-ducted continuous balanced, supply into the 1st floor common area and each bedroom, exhaust from each bathroom, utility room, and kitchen, no central system
13	Single-point continuous exhaust from first floor common area, with central system
14	Single-point continuous exhaust from second floor master bathroom, with central system
15	Single-point continuous exhaust from first floor common area, with central system, with minimum AHU turnover
16	Single-point continuous exhaust from second floor master bathroom, with central system, with minimum AHU turnover
17	Three-point continuous exhaust, 1/3 from each bathroom, with central system
18	Three-point continuous exhaust, 1/3 from each bathroom, with central system, with minimum AHU turnover
19	Four-point continuous exhaust, 1/4 from kitchen and each bathroom, with central system
20	Four-point continuous exhaust, 1/4 from kitchen and each bathrooms, with central system, with minimum AHU turnover
21	Single-point continuous supply to first floor common area, with central system
22	Single-point continuous supply to first floor common area, with central system, with minimum AHU turnover
23	Central-fan-integrated supply (flow=3x 62.2 continuous rate) with 33% minimum runtime, no maximum damper open time (ventilation may exceed desired rate)
24	Central-fan-integrated supply (flow=3x 62.2 continuous rate) with 33% minimum runtime, with 33% maximum damper open time (ventilation will not exceed desired rate)
25	Central-fan-integrated supply (flow=62.2 continuous rate) with 33% minimum runtime, no maximum damper open time, plus single-point continuous exhaust from 1st floor common area
26	Central-fan-integrated supply (flow=62.2 continuous rate) with 33% minimum runtime, no maximum damper open time, plus single-point exhaust when central fan not active
27	Two-point continuous balanced, supply into first floor common area, exhaust from second floor family bathroom, with central system
28	Two-point continuous balanced, supply into first floor common area, exhaust from second floor family bathroom, with central system, with minimum AHU turnover
29	Two-point balanced (flow=2x 62.2 continuous rate), 50% runtime interlocked with AHU, supply to central system supply, exhaust from central system return
30	Fully-ducted continuous balanced, supply into the 1st floor common area and each bedroom, single exhaust from the 1st floor common area, with central system
31	Fully-ducted continuous balanced, supply into the 1st floor common area and each bedroom, single exhaust from the 1st floor common area, with central system, with minimum AHU turnover
32	Fully-ducted continuous balanced, supply into the 1st floor common area and each bedroom, exhaust from each bathroom, utility room, and kitchen, with central system
33	Fully-ducted continuous balanced, supply into the 1st floor common area and each bedroom, exhaust from each bathroom, utility room, and kitchen, with central system with minimum AHU turnover
34	Ducted supply with 3:1 dilution ratio, supply into the 1st floor common area and each bedroom, dilution air from 1st floor common area, no central system
35	Ducted supply with 3:1 dilution ratio, supply into the 1st floor common area and each bedroom, dilution air from 1st floor common area, with central system
36	Ducted supply with 3:1 dilution ratio, supply into the 1st floor common area and each bedroom, dilution air from 1st floor common area, with central system, with minimum AHU turnover

In the final analysis, all of the exposure scenarios described in Table 4 were examined.

Reference System

A reference system was chosen to provide the baseline performance to which the remaining systems could be compared. System 32, a fully-ducted balanced ventilation system, which continuously supplies into each bedroom and the downstairs living area; exhausts from each bathroom, utility room, and kitchen; with a central AHU for space conditioning, was chosen as the reference system due to the system's reputation as being one of the best commonly used systems. Also, a reasonably tight house (3.5 ACH50) was chosen as the reference house. Table 7 shows the resulting contaminant concentrations for the eight climates and five contaminant generation scenarios, at 100% of the current Standard 62.2 rate. As discussed previously, the contaminant generation rates in each scenario are arbitrary and the reference exposure values should not be compared across scenarios.

Taking the average of the eight climates gives a single reference exposure value for each of the exposure scenarios, which can then be compared with the remaining ventilation systems to determine their relative effectiveness. Averaging the reference exposure across the climates is not the only approach that can be accommodated by the method described here. It is also possible to select a reference exposure for each climate, or to select an exposure limit based on a specific contaminant. For the purposes of the example system coefficients presented in this paper, the participating 62.2 committee members chose the climate averaged reference exposure approach. Interpolation between the simulated ventilation rates (or, in some cases, extrapolation beyond) gives the ventilation flow rate that would be required to achieve the same annual average exposure as the reference case. Figure 9 gives a graphical illustration of this concept for one ventilation system, climate, enclosure leakage, and exposure scenario combination. In this case, the airflow required to achieve the same annual exposure as the reference case is 175% of the Standard 62.2 rate; the system coefficient for this specific case would be C_S = 175%/100% = 1.75.

Each of the cases was analyzed in this manner. It would be convenient if the system coefficient for a particular ventilation system did not vary with climate or enclosure leakage. This is not the case, yet the systems do tend to cluster. Figure 10 shows the system coefficients for all ventilation

Table 7. Reference Exposure Values

	Exposure Scenario					
Climate	**A**	**B**	**C**	**D**	**E**	**F**
Houston	109	105	93	95	271	190
Indianapolis	104	98	90	91	248	176
Minneapolis	96	90	83	84	229	162
Phoenix	115	109	98	100	265	190
Raleigh	111	104	96	96	267	189
Sacramento	110	102	95	95	254	182
San Diego	124	114	108	103	309	216
Seattle	105	99	93	93	242	174
Average	109	103	95	94	261	185

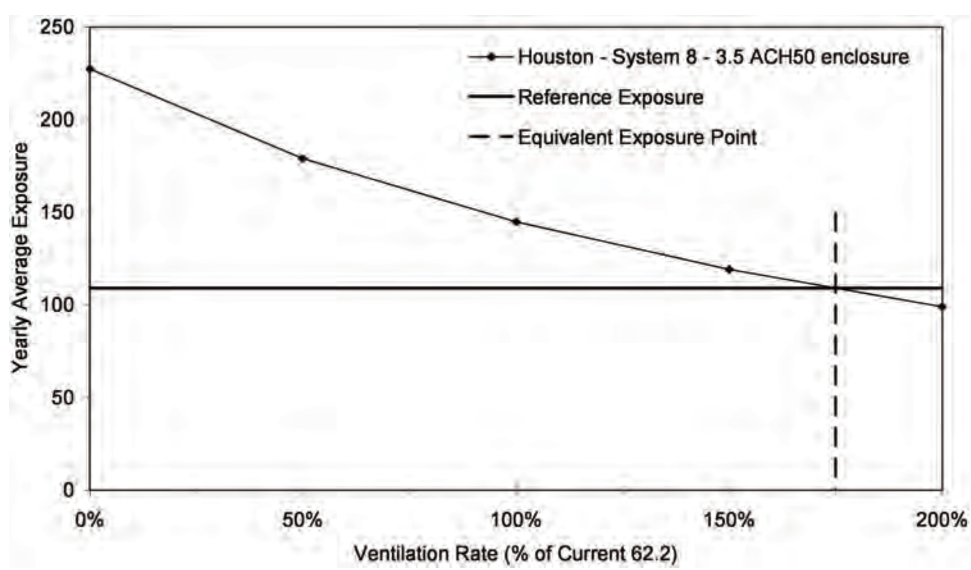

Figure 9 *Illustration of linear interpolation used to determine airflow required to achieve equivalent exposure to reference system, for ventilation system 8, Houston, 3.5 ACH50, and exposure scenario A.*

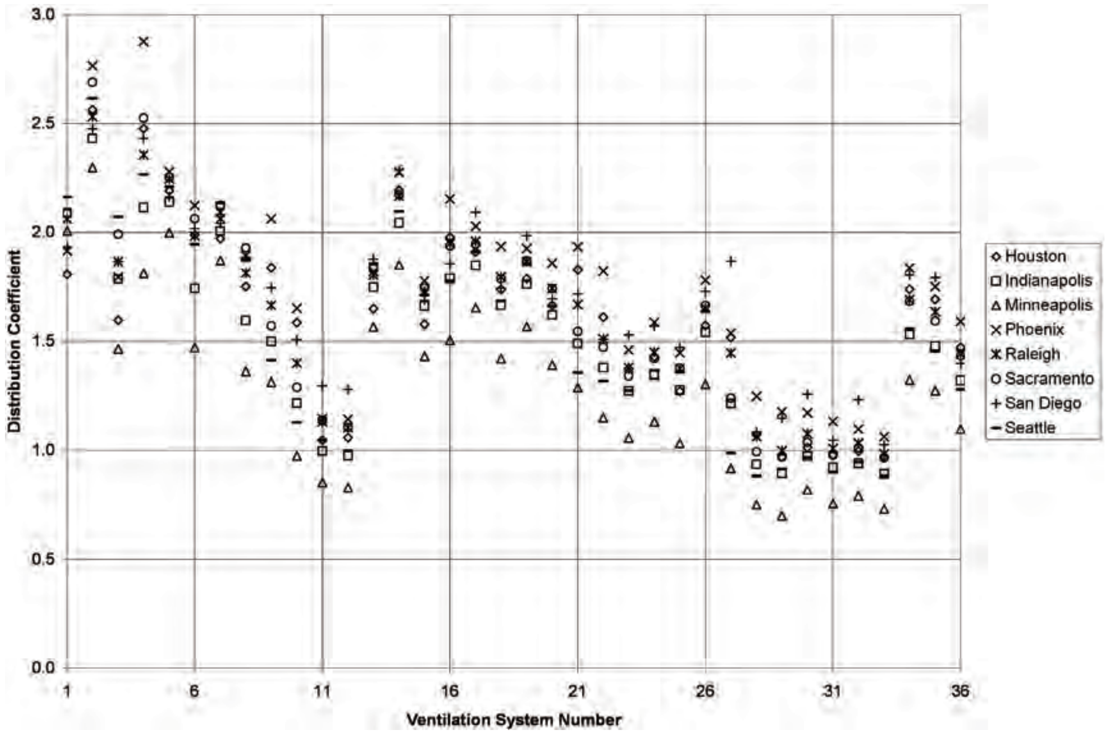

Figure 10 *System coefficients for exposure scenario A, 3.5 ACH50 houses.*

systems and climates for the 3.5 ACH50 houses and for exposure scenario A. Ventilation systems without a central AHU are systems 1 through 12 and system 34. Within systems 1 through 12, there is a general improvement in performance (as quantified by the system coefficient) as the system changes from single-point ventilation to multi-point and finally to fully-ducted. This trend is repeated in the ventilation systems with a central AHU (systems 13-33 and 35-36).

The full set of results is too long for this paper and is contained in a research report (Townsend 2008). Table 8 presents the system coefficients for each of the different ventilation systems, exposure scenarios, and air tightness levels, averaged over all eight climates that were simulated. The 20 ACH50 enclosure leakage results are not included in Table 8 because all calculated coefficients are zero.

The results detailed in Table 9 show that the effect of mixing due to AHU operation or minimum runtime is almost always beneficial. That effect is most pronounced when the occupants themselves are the source of the contaminant, as mixing will tend to dilute the contaminants in the occupied zones (for an example of this, compare systems 1 (single-point exhaust ventilation without AHU), 13 (single-point exhaust ventilation with AHU), and 15 (single-point exhaust ventilation with AHU and minimum turnover), under exposure scenario E). Even when the contaminant sources are located in zones that are infrequently visited by the occupants, mixing is either neutral or reduces exposure slightly (compare systems 1, 13, and 15 under exposure scenario C).

Coefficient Generation

Final selection of a system coefficient requires selection of: an exposure scenario; reference case (including enclosure leakage, ventilation system, and climate); and exposure time period. For example, if one chooses exposure scenario F, which has both volume-weighted contaminants and occupant-generated contaminants; a 3.5 ACH50 house with ventilation system 32 and an average of all climates; and an annual average exposure time period, the system coefficients are as described in Table 10. These are sorted in order of ascending system coefficient. Note that several of the systems have performance better than the reference system (i.e. coefficients less than one).

DISCUSSION

This process for developing ventilation system coefficients is one that requires a series of decisions to be made about an appropriate reference case made up of house characteristics, contaminant source scenario, and occupant schedules. The simulation and analysis mechanics lead to ventilation system coefficients that provide occupant exposure equivalent to the reference case. This analysis neglected reactions of contaminants and other contaminant removal

Table 8. System Coefficients

Enclosure Leakage Level	1.5 ACH50						3.5 ACH50						5 ACH50						7 ACH50					
Exposure Scenario	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
Ventilation System #																								
1	1.9	1.8	2.0	1.8	2.1	2.0	2.0	1.9	2.1	1.8	2.4	2.2	1.8	1.5	1.9	1.4	2.4	2.2	1.0	0.6	1.1	0.7	1.6	1.1
2	2.3	2.2	2.5	2.5	2.5	2.4	2.5	2.2	2.6	2.6	3.4	3.1	2.6	1.8	2.6	2.6	4.3	3.4	1.7	0.8	1.9	1.7	3.2	2.3
3	1.9	1.8	2.0	1.8	2.1	2.0	1.8	1.7	2.0	1.7	2.3	2.1	1.4	1.2	1.7	1.2	2.2	1.8	0.6	0.4	0.8	0.6	1.0	0.7
4	2.2	2.2	2.6	2.5	2.3	2.2	2.4	2.0	2.6	2.6	3.2	2.8	2.1	1.5	2.5	2.4	2.9	2.5	1.1	0.5	1.6	1.4	1.4	1.2
5	2.2	2.1	2.0	1.8	2.4	2.3	2.2	1.9	1.7	1.5	2.8	2.5	1.9	1.4	1.3	1.1	3.1	2.5	1.1	0.6	0.7	0.6	4.7	1.3
6	2.0	2.0	1.9	1.7	2.2	2.2	1.9	1.7	1.5	1.3	2.5	2.2	1.5	1.1	1.1	1.0	2.3	1.7	0.6	0.4	0.6	0.5	0.7	0.6
7	2.1	2.0	1.7	1.5	2.3	2.2	2.0	1.8	1.4	1.3	2.5	2.3	1.8	1.3	1.2	1.0	2.6	2.2	1.0	0.6	0.7	0.6	1.2	1.1
8	1.9	1.9	1.6	1.5	2.2	2.1	1.8	1.6	1.3	1.2	2.1	2.0	1.3	1.1	1.0	0.9	1.7	1.5	0.6	0.3	0.6	0.5	0.6	0.5
9	1.9	2.0	2.2	2.3	1.9	1.9	1.6	1.7	2.1	2.2	1.6	1.6	1.3	1.4	1.8	2.0	1.3	1.3	0.8	0.7	1.3	1.4	0.7	0.7
10	2.5	2.1	3.1	2.2	4.2	3.6	1.3	1.1	1.3	1.4	1.6	1.5	1.0	0.8	0.9	1.1	1.1	1.0	0.5	0.3	0.5	0.6	0.5	0.5
11	1.5	1.4	1.9	1.8	1.8	1.7	1.1	1.0	1.4	1.3	1.4	1.3	0.8	0.7	1.1	1.0	1.0	0.9	0.4	0.3	0.7	0.6	0.5	0.4
12	1.4	1.4	1.4	1.3	1.8	1.7	1.1	1.0	1.1	1.0	1.3	1.2	0.8	0.7	0.8	0.8	0.9	0.8	0.4	0.3	0.5	0.5	0.4	0.4
13	1.9	1.9	2.0	1.9	1.9	1.9	1.8	1.7	1.9	1.7	1.8	1.8	1.4	1.3	1.5	1.3	1.2	1.3	0.7	0.6	0.8	0.7	0.5	0.5
14	2.2	2.2	2.4	2.5	2.1	2.1	2.1	2.0	2.4	2.5	2.1	2.1	1.8	1.5	2.0	2.1	1.3	1.5	0.9	0.7	1.1	1.3	0.5	0.6
15	1.9	2.0	2.0	2.0	1.6	1.7	1.7	1.6	1.8	1.7	1.0	1.3	1.2	1.1	1.3	1.2	0.3	0.6	0.4	0.3	0.6	0.6	0.0	0.0
16	2.1	2.1	2.3	2.4	1.5	1.7	1.9	1.8	2.2	2.3	0.8	1.2	1.3	1.2	1.8	1.8	0.2	0.5	0.4	0.3	0.8	0.9	0.0	0.0
17	2.1	2.1	1.8	1.8	2.0	2.0	1.9	1.8	1.5	1.5	1.8	1.9	1.5	1.3	1.1	1.1	1.1	1.3	0.7	0.6	0.7	0.6	0.4	0.5
18	2.0	2.0	1.7	1.8	1.6	1.8	1.7	1.7	1.4	1.4	0.9	1.2	1.2	1.1	1.0	1.0	0.3	0.6	0.4	0.3	0.5	0.5	0.0	0.0
19	2.0	2.0	1.6	1.6	2.0	2.0	1.8	1.7	1.4	1.4	1.7	1.8	1.4	1.3	1.1	1.1	1.1	1.2	0.7	0.6	0.6	0.6	0.4	0.5
20	2.0	2.0	1.7	1.7	1.6	1.7	1.7	1.6	1.4	1.4	0.9	1.2	1.1	1.1	1.0	1.0	0.2	0.5	0.4	0.3	0.5	0.5	0.0	0.0
21	1.9	2.0	2.2	2.3	1.7	1.8	1.6	1.7	2.0	2.1	1.3	1.4	1.2	1.3	1.7	1.9	0.9	1.0	0.6	0.6	1.1	1.3	0.3	0.4
22	1.9	2.0	2.2	2.3	1.4	1.6	1.5	1.6	1.9	2.1	0.8	1.0	1.0	1.1	1.5	1.8	0.2	0.5	0.3	0.3	0.8	1.0	0.0	0.0
23	1.7	1.8	2.0	2.1	1.3	1.4	1.3	1.4	1.7	1.9	0.7	1.0	0.9	1.0	1.4	1.6	0.2	0.4	0.3	0.3	0.8	0.9	0.0	0.0
24	1.9	1.9	2.2	2.3	1.3	1.5	1.4	1.4	1.8	1.9	0.7	1.0	1.0	1.0	1.5	1.6	0.2	0.4	0.3	0.3	0.8	0.9	0.0	0.0
25	1.7	1.8	2.0	2.1	1.3	1.4	1.3	1.3	1.8	1.8	0.7	0.9	0.9	0.8	1.3	1.4	0.1	0.4	0.2	0.2	0.7	0.7	0.0	0.0
26	1.9	2.0	2.2	2.3	1.5	1.6	1.6	1.7	2.0	2.2	0.9	1.2	1.1	1.1	1.7	1.8	0.2	0.5	0.3	0.3	0.9	1.0	0.0	0.0
27	2.2	2.0	2.6	2.1	3.0	2.7	1.3	1.2	1.8	1.4	1.9	1.7	0.8	0.8	1.1	0.9	1.0	0.9	0.4	0.3	0.6	0.5	0.3	0.3
28	1.6	1.7	1.8	1.8	1.2	1.4	1.0	1.0	1.2	1.2	0.5	0.7	0.6	0.6	0.8	0.8	0.1	0.3	0.2	0.2	0.4	0.4	0.0	0.0
29	1.7	1.7	2.1	2.2	1.0	1.3	1.0	1.0	1.5	1.6	0.3	0.5	0.5	0.5	1.0	1.1	0.0	0.1	0.1	0.1	0.4	0.5	0.0	0.0
30	1.5	1.4	1.8	1.8	1.5	1.5	1.0	1.0	1.4	1.4	1.1	1.1	0.7	0.7	1.0	1.0	0.6	0.6	0.3	0.3	0.6	0.6	0.2	0.2
31	1.5	1.5	1.8	1.9	1.1	1.2	1.0	1.0	1.3	1.4	0.5	0.7	0.6	0.6	0.9	1.0	0.1	0.3	0.2	0.2	0.5	0.5	0.0	0.0
32	1.4	1.4	1.3	1.3	1.5	1.4	1.0	1.0	1.0	1.0	1.0	1.0	0.7	0.7	0.8	0.8	0.6	0.6	0.3	0.3	0.5	0.5	0.2	0.2
33	1.4	1.4	1.3	1.4	1.0	1.2	0.9	1.0	1.0	1.0	0.5	0.7	0.6	0.6	0.7	0.8	0.1	0.3	0.2	0.2	0.4	0.4	0.0	0.0
34	2.0	2.1	2.2	2.4	1.5	1.7	1.6	1.7	2.0	2.3	1.1	1.3	1.2	1.3	1.7	2.0	0.8	0.9	0.6	0.6	1.1	1.4	0.4	0.4
35	1.9	2.0	2.2	2.3	1.4	1.6	1.6	1.7	2.0	2.2	1.0	1.2	1.1	1.2	1.6	1.8	0.6	0.7	0.5	0.5	1.0	1.2	0.2	0.3
36	1.9	2.0	2.1	2.3	1.2	1.4	1.4	1.5	1.8	2.0	0.6	0.9	0.9	1.0	1.3	1.6	0.2	0.4	0.3	0.3	0.7	0.9	0.0	0.0

* 20 ACH50 enclosure leakage level is not presented because all coefficients are equal to zero, i.e. the exposure without ventilation was equal to or less than the reference exposure.

Table 9. Effect of Mixing

Enclosure Leakage Level	1.5 ACH50						3.5 ACH50						5 ACH50						7 ACH50					
Exposure Scenario	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
Ventilation System #																								
1	1.9	1.8	2.0	1.8	2.1	2.0	2.0	1.9	2.1	1.8	2.4	2.2	1.8	1.5	1.9	1.4	2.4	2.2	1.0	0.6	1.1	0.7	1.6	1.1
13	1.9	1.9	2.0	1.9	1.9	1.9	1.8	1.7	1.9	1.7	1.8	1.8	1.4	1.3	1.5	1.3	1.2	1.3	0.7	0.6	0.8	0.7	0.5	0.5
15	1.9	2.0	2.0	2.0	1.6	1.7	1.7	1.6	1.8	1.7	1.0	1.3	1.2	1.1	1.3	1.2	0.3	0.6	0.4	0.3	0.6	0.6	0.0	0.0

Table 10. Coefficients from 3.5 ACH50 Houses, Exposure Scenario F, Average of All Climates

Ventilation System #	System Coefficient
29	0.5
33	0.7
31	0.7
28	0.7
36	0.9
25	0.9
23	1.0
24	1.0
32	1.0
22	1.0
30	1.1
26	1.2
35	1.2
16	1.2
12	1.2
20	1.2
18	1.2
34	1.3
15	1.3
11	1.3
21	1.4
10	1.5
9	1.6
27	1.7
19	1.8
13	1.8
17	1.9
8	2.0
14	2.1
3	2.1
1	2.2
6	2.2
7	2.3
5	2.5
4	2.8
2	3.1

mechanisms, such as particle filtration or deposition on surfaces. This method also relied on a computer model that, while well-characterized for one house, did not attempt to quantify the effect of floor plan. Of particular interest would be the effect of different number of stories (1-story or 3-story), substantially larger or smaller houses, or enclosure leakage distributions that are significantly different than the uniform-leakage assumption made in this work. Development of these topics should be the focus of continuing work in this area.

CONCLUSION

A method for quantitatively comparing dissimilar ventilation systems is possible using a detailed network airflow model. The results from applying this method to one house plan in eight different climates show that system coefficients to the current ASHRAE Standard 62.2rates would be in the range of 0.5 to 3, if a reasonably airtight house and one of the better-performing ventilation systems such as a fully-ducted balanced ventilation system is selected as the reference case. Further research would expand the robustness of the example system coefficient results to cover the effect of different floor plans, including size and number of stories. Finally, contaminant source location and assumptions about occupant behavior have strong influence on the occupants' exposures and resulting system coefficients.

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REFERENCES

ACCA 2003. Manual J Residential Load Calculations, 8th Edition. Air Conditioning Contractors of America, Arlington, VA.

ARTI 2007. Whole House Ventilation System Options – Phase 1 Simulation Study. ARTI Report No. 30090-01. Arlington, VA: Air-conditioning and Refrigeration Technology Institute. p 24.

ASHRAE. Handbook of Fundamentals. (1993) American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. Handbook of Fundamentals. (2005) American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2008. ANSI/ASHRAE Standard 62.2-2007 with 2008 Supplement Incorporated. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Briggs, R.S., Lucas, R.G., and T. Taylor. 2003. Climate Classification for Building Energy Codes and Standards: Part 2 - Zone Definitions, Maps and Comparisons, Technical and Symposium Papers, ASHRAE Winter Meeting, 2003.

Dickerhoff, D.J., D.T. Grimsrud, and R.D. Lipshutz. 1982. Component leakage testing in residential buildings. Proceedings of the American Council for an Energy-Efficient Economy, 1982 Summer Study, Santa Cruz, CA. Report LBL 14735. Lawrence Berkeley National Laboratory, Berkeley, CA.

Dols, W.S. 2001. “A Tool for Modeling Airflow & Contaminant Transport.” In The ASHRAE Journal. March 2001, p. 35-41. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Harrje, D.T., and G.J. Born. 1982. Cataloguing air leakage components in houses. Proceedings of the ACEEE 1982 Summer Study. Santa Cruz, CA. American Council for an Energy-Efficient Economy, Washington, D.C.

Hendron, R., A. Rudd, R. Anderson, D. Barley, A. Townsend. 2007. Field Test of Room-to-Room Distribution of Outside Air with Two Residential Ventilation Systems. IAQ 2007: Healthy & Sustainable Buildings Conference Proceedings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Anderson, R., Barley, D., Rudd, A., Townsend, A., Hancock, E. 2008. Field Test of Room-to-Room Distribution of Outside Air with Two Residential Ventilation Systems. NREL/CP-550-41210. August 2008. Golden, Colorado: National Renewable Energy Laboratory.

Marion, W. and K. Urban. 1995. User's Manual for TMY2s Typical Meteorological Years Derived from the 1961-1990 National Solar Radiation Data Base. June 1995. Golden, Colorado: National Renewable Energy Laboratory.

Rudd, A. 2006. Ventilation Guide. Building Science Press, Inc. Somerville, MA.

Sherman, M.H., and I.S. Walker. 2007. Air Distribution Effectiveness for Different Mechanical Ventilation Systems. LBNL-62700. Berkeley, California: Lawrence Berkeley National Laboratory.

Sherman, M.H. and Walker, I.S. 2008. Measured Air Distribution Effectiveness for Residential Mechanical Ventilation Systems. LBNL-E303. Berkeley, California: Lawrence Berkeley National Laboratory.

Townsend, A., A. Rudd, and J. Lstiburek. 2008. 2008 Ventilation Research Report. Report to the Department of Energy Building America Program, December 2008. Building Science Corporation, Somerville, MA.

Townsend, A., A. Rudd, and J. Lstiburek. 2009. Extension of Ventilation System Tracer Gas Testing Using a Calibrated Multi-Zone Airflow Model. ASHRAE Transactions 115(2).

Walker, I.S. and D.J. Wilson. 1994. Simple Methods for Improving Estimates of Natural Ventilation Rates. Proceedings of the 15th AIVC Conference, Buxton, U.K. September.

Walton, G.N. and W.S. Dols. 2005. "CONTAM 2.4b User Guide and Program Documentation," NISTIR 7251, National Institute of Standards and Technology.

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