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Conference Paper - 0802

2007 October

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Conference Paper
NREL/CP-550-41210
August 2008

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Presented at ASHRAE IAQ 2007
Baltimore, Maryland
October 15–17, 2007

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337

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KEY WORDS
air distribution equipment, indoor air quality equipment & products, residential buildings, ventilation, age of air

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ABSTRACT

Uniform distribution of outside air is one way to ensure that residential dilution ventilation systems will provide a known amount of fresh air to all rooms regardless of house geometry and occupant behavior. To characterize outside air distribution in residential buildings, the authors developed a practical methodology adapted from ASHRAE Standard 129. Our methodology includes the examination of multi-zone single tracer gas decay curves, and the calculation of reciprocal local mean age-of-air to allow direct, quantitative comparisons of various ventilation approaches that might be factored into ventilation rate trade-offs in future updates to ASHRAE Standard 62.2. Two types of ventilation systems were tested using this method: single-point exhaust ventilation and central fan integrated supply ventilation. Analysis of the measured data showed that age-of-air analysis worked well to characterize outside air distribution as long as weather conditions were sufficiently steady-state. Test results indicated that ventilation supplied through a central air distribution system was distributed much more uniformly than by a single-point exhaust system. Operation of the air handler at a 33% duty cycle maintained relatively well-mixed conditions regardless of ventilation rate and type of system. For single-point exhaust ventilation, opening bedroom doors appeared to significantly increase the mixing of outside air among rooms, but passive air transfer grilles increased mixing only slightly.

INTRODUCTION

In addition to the whole house ventilation rate, the minimum amount of outside air that should be provided to individual rooms in a house has been an important area of debate among ventilation experts for many years. Residential ventilation standards in numerous European countries, including Belgium, Denmark, Finland, Germany, Italy, The Netherlands, Norway, Sweden, and the United Kingdom, specify minimum ventilation requirements in bedrooms, living rooms, or both (McWilliams and Sherman 2005). In the United States, ASHRAE Standard 62.2 (ASHRAE 2004), Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, specifies an acceptable minimum whole-house ventilation rate that depends on the timing of ventilation air delivery; however, it is silent about distribution of ventilation air. The Washington State Ventilation and Indoor Air Quality Code (WAC 2004) is also silent about ventilation air distribution. Both the Minnesota Building Code (MN Chapter 7672) and the National Building Code of Canada (NBC 2005), which refer to Canadian Standard F326-M91 (CSA 2005), require whole-house ventilation air distribution via a fully ducted ventilation system or by mixing via a central air-handling system. A large, U.S. private-sector, high-performance home program also requires periodic air handler operation to ensure whole-house mixing for ventilation air distribution and thermal comfort. Work by Rudd and Lstiburek (2000) showed that ventilation systems that used whole-house distribution and mixing via the central air-handling system had much less room-to-room variation in outside air delivery than other tested systems that did not.

One way for dilution ventilation systems to provide a predictable minimum amount of fresh air to all rooms, regardless of house geometry and the behavior of occupants, is to uniformly distribute outside air throughout the house. The primary purpose of this research project was to develop a practical field test methodology to characterize such distribution of outside air in a house under various operating conditions, irrespective of the overall desirability of uniform outside air distribution, which remains an unresolved issue even among experts in the field. We endeavored to be fully consistent with ASHRAE Standard 129 (ASHRAE 1997), although it was necessary to adapt this standard to residential buildings because it was developed with commercial buildings in mind. The standard includes what we believe are overly strict criteria for acceptable test spaces in a residential context where infiltration is an important component of the outside air reaching a zone, and it requires measurements in exhaust and supply flows that are inapplicable and impractical in most residential situations. A multi-point single tracer gas decay procedure was chosen for this project because of its relative simplicity compared to a multi-gas system, recognizing that even a single tracer gas system is too costly for most home energy efficiency practitioners. For this study, we assumed that dangerous pollutant sources such as radon are controlled with appropriate source mitigation strategies, and that remaining low-level pollutants are uniformly generated in proportion to volume throughout the house. The tests were designed to allow direct, quantitative comparisons of various ventilation approaches, which might be factored into ventilation rate trade-offs in future updates to ASHRAE Standard 62.2. We did not attempt to develop a specific figure of merit, such as the air-change effectiveness defined in ASHRAE Standard 129, which is more suitable for commercial buildings.

To evaluate the usefulness and practicality of this methodology, the distribution of outside air in two new houses in Sacramento, California, were evaluated using several different ventilation system configurations and air-mixing scenarios. The test program was conducted in late December 2005 and early January 2006, during relatively mild winter weather conditions. The first test house was a one-story model with four bedrooms. The second was a two-story model, also with four bedrooms. Both houses were part of the U.S. Department of Energy's Building America program, and were designed to be much more energy efficient than typical new California houses. Each house had a slab-on-grade foundation with ducts located in conditioned spaces, and had a very tight envelope as measured with a blower door (less than 1.25 in^2 equivalent leakage area per 100 ft^2 envelope area). Because the building envelopes were tight for these houses, we expected less interaction between ventilation and infiltration than we would observe in leakier houses, and conclusions must be interpreted in that context. The minimum acceptable ventilation rates specified in ASHRAE 62.2 were 58 cfm for the one-story house and 63 cfm for the two-story house. Other key specifications for both houses are summarized in Table 1. Floor plans are shown in Figures 1 and 2. The results of this research have been documented in a more complete, unpublished field test report that is available upon request from the authors.

TABLE 1
Specifications for the One-Story and Two-Story Test Houses

	One-Story	Two-Story
Geometry	4 bedrooms, 2 baths 2075 ft^2 10-ft ceilings	4 bedrooms, 2 baths 2582 ft^2 10-ft ceilings
Building envelope		
Walls	2 × 4, blown fiberglass, 1-in. insulating sheathing (R-15 total)	2 × 4, blown fiberglass, 1-in. insulating sheathing (R-15 total)
Ceiling	R-30 blown fiberglass, vented attic	R-30 blown fiberglass, vented attic
Foundation	Slab-on-grade	Slab-on-grade
Mechanical systems		
Heat	Sealed-combustion gas furnace	Sealed-combustion gas furnace
Cooling	14 SEER air conditioner	14 SEER air conditioner
Air distribution	Ducts inside conditioned space, transfer grilles between bedrooms and main living space	Ducts inside conditioned space, transfer grilles between bedrooms and main living space
Ventilation	Central fan integrated supply (CFIS) ventilation with fan cycling control @ 33% duty cycle, motorized damper	CFIS ventilation with fan cycling control @ 33% duty cycle, motorized damper

TEST METHODOLOGY

Test and Analysis Procedure

Because outside air distribution is a multi-zone problem, a single-tracer gas decay test with multi-zone sampling was used to evaluate the performance of each ventilation system based on how uniformly outside air was distributed to each of six well-mixed zones within the house. The decay curves demonstrate the rate at which the tracer gas (representing a pollutant), which is initially distributed uniformly throughout the house, is diluted within each zone, as a result of outside air that enters the zone directly as well as air that is exchanged among zones. Air entering one zone from another may contain either a higher or a lower concentration of the tracer than the air already in the zone. The initial decay rate represents the rate of dilution only from direct outside air supply to the zone, because other zones begin at the same concentration. The decay rate over a longer period is a result of dilution from outside air entering either directly or via air exchange with other zones, including the effects of outside air provided by both mechanical ventilation and natural infiltration.

We used a version of local mean age-of-air analysis that we modified for this application to evaluate the results more quantitatively. Age-of-air analysis is a well-established approach for characterizing ventilation at various points within an initially well-mixed test space, which in our case is the whole house (Grieve 1991). Although the Grieve publication was written in the context of multi-zone tracer gas testing within a single room in a commercial building, we believe the same methodology applies to a house or other multiple room test space, as long as the initial conditions can be established with the test space beginning at a uniform concentration and outside spaces at zero concentration. Age-of-air is defined as the average length of time air molecules have resided within the test space. Age of air calculations are a characteristic of the house and ventilation system under specific weather and operating conditions, and are valid regardless of the eventual distribution of source pollutants in the house. However, because age-of-air is independent of the pollutant sources, it cannot be used to predict exposure except in the limiting case of uniform pollutant generation. The formula for calculating local mean age-of-air in a tracer gas decay test is given in both Grieve and ASHRAE Standard 129-1997 (ASHRAE 1997) as follows:

$$A_i = \frac{1}{C_0}\int_0^\infty C_i(t)dt \qquad (1)$$

where:

i = Index for measurement point
A_i = Local mean age-of-air at point i (h)
C = Concentration of tracer gas (lb_m/ft^3)
C_0 = Initial value of C in a well-mixed building (lb_m/ft^3)
C_i = Time-varying concentration of tracer gas at point i (lb_m/ft^3)
t = Time (h).

To compare individual zones in this test, the primary metric used by NREL was the reciprocal of the local mean age-of-air (from this point forward referred to simply as reciprocal age-of-air) at a central point in each well-mixed zone:

$$\text{Reciprocal age-of-air} = 1/A_i \qquad (2)$$

Reciprocal age-of-air has units of 1/h and would be equivalent to the air change rate in units of air changes per hour (ACH) for the limiting case when the house behaves as a single, well-mixed zone. Its precise physical meaning is difficult to put into words, but we believe it is a good indicator of the rate at which outside air is provided to a zone. The definition of A_i in Equation 1 involves an integral of infinite duration. This was handled in the test procedure through a two-step process:

Step 1. The tracer gas decay test was continued until (a) the initial transient effects of interzonal airflow have subsided and all the decay curves resembled simple exponential functions, and (b) the tracer concentrations were rather small compared to their initial values, so that any extrapolation errors would have a minimal effect on the result. These portions of the decay curves were integrated numerically with the trapezoid rule applied to actual measured data.

Step 2. The remaining portions (the tails) of the decay curves were extrapolated to infinity with a simple exponential decay function, which was matched to the decay rate of the final portion of each measured decay curve. These portions of the curves were integrated analytically. This extrapolation can be prone to significant errors if there are unsteady operating conditions, such as occasional cycling of the air handler. A larger data set is required in such cases

The test equipment consisted of a tracer gas monitor and a multi-point sampler. Sample tubes were placed in six locations in each house and attached to the multi-point sampler. The six sampled locations are designated with red stars on the floor plans in Figures 1 and 2, and each represents a well-mixed "zone" as defined in this paper. The air sample in each zone was taken near the center of the zone at a height of 4 feet above the floor. The zone air temperature was measured at the same location. The sampler was programmed to draw a sample from each sequential location at an interval of about 2 minutes; thus all six locations were sampled at an interval of about 12 minutes. The local zone air temperature measurement was used to control an electric heater in each zone to achieve a uniform and constant air temperature throughout the house. Small mixing fans were used to maintain uniform temperatures and tracer gas concentrations within each zone, so that the sampled point would represent the room average concentration that would occur under normal operating conditions. Natural infiltration rates varied during the tests depending on weather conditions, which were monitored with a portable weather station. The tests were planned for rather mild weather to minimize infiltration effects, allowing us to more easily isolate and test the performance of the mechanical ventilation systems.

The air flow rates for supply and exhaust ventilation were carefully controlled during the test with a ducted, calibrated, variable-speed fan and measurement system of the type often used to measure duct leakage. For exhaust ventilation, the variable-speed fan was placed near the ceiling exhaust fan and a length of flexible duct was used to connect the normal register for the exhaust fan to the duct for the variable-speed fan. The exhaust fan was operated in conjunction with the variable-speed fan to reduce resistance to air flow. A similar application of the calibrated variable-speed fan was used to control and measure the supply air flow rate during the tests of the central fan integrated supply (CFIS) system. The normal configuration of flexible duct connecting the air handler return to the outside was changed so that all outside air would flow through the variable-speed fan.

The tracer gas used was sulfur hexafluoride (SF_6), a stable, nontoxic gas that was injected into each house from a small compressed gas cylinder carried by hand around the house. During the dosing period, the air handler was used to achieve an initially well-mixed condition with a concentration of about 15 parts per million (ppm). During this period, the doors were kept open and a portable destratification fan was used in the two-story house to improve mixing between floors. Once well-mixed conditions were achieved, the air handler and destratification fans were stopped and the ventilation conditions of interest were established. The divergence in concentration from zone to zone was then observed as the tracer gas decayed. At the conclusion of the test, the whole house was again mixed to the extent possible by opening the doors (if they were closed during the test) and turning on the air handler, allowing the effective whole-house air change rate to be calculated.

The results of the multi-zone tracer gas decay tests were plotted graphically as families of decay curves. If a test met the necessary criteria, we calculated reciprocal age-of-air based on the decay curves and examined the results. These criteria included uniform initial concentration, steady weather conditions (and therefore steady natural infiltration), steady operating conditions (except for the small effect of fan cycling), and all decay curves in the exponential regime at the end of the test period.

Test Matrix

The test conditions for each of the relevant test cases in the one- and two-story houses are summarized in Tables 2 and 3. The test period was December 28, 2005, through January 9, 2006.

TABLE 2
Test Sequence for One-Story Test House

Test #	Date	Time	Duration (h)	Vent. Config.	Vent. flow rate (cfm)	Air handler cycling (min off, min on)	Doors	Notes
A3	Dec 28	overnight	12	Exhaust	58	none	closed	
A6	Dec 29	overnight	12	Supply	174, 33% duty cycle	20,10	closed	
A7	Dec 30	a.m.-p.m.	8	None	0	none	open	Natural infiltration
A9		overnight	12	Exhaust	58	none	open	
A10	Dec 31	a.m.-p.m.	6	Exhaust	58	none	closed	Transfer grilles taped
A12	Jan 1	overnight	12	Exhaust	58	20,10	closed	
A15	Jan 2	a.m.-p.m.	6	None	0	none	closed	Natural infiltration
A16		overnight	12	Exhaust	58	none	closed	Master bath exhaust

TABLE 3
Test Sequence for Two-Story Test House

Test #	Date	Time	Duration (hrs)	Vent. Config.	Vent. flow rate (cfm)	Air handler cycling (min off, min on)	Doors	Notes
B1	Jan 3	overnight	14	Exhaust	63	none	closed	
B3	Jan 4	overnight	11	Supply	180, 33% duty cycle	20, 10	closed	95% ASHRAE 62.2

B6	Jan 6	p.m.	6	Exhaust	63	20,10	closed	
B7		overnight	12	Exhaust	63	none	closed	Transfer grilles taped
B10	Jan 7	p.m.	2	Exhaust	63	none	open	
B18	Jan 9	overnight	12	Exhaust	63	none	closed	Master bath exhaust

TEST RESULTS FROM ONE-STORY HOUSE

Natural Infiltration

A test of natural infiltration was conducted for an 8-hour period on December 30 to examine the magnitude and distribution of outside air entering the house through leaks in the building envelope (Test A7). The test was conducted with doors open and the thermostat turned down to make sure the furnace would not turn on during the test, which would have mixed the air in the house and obscured the effects of the natural movement of air. Interior temperatures were controlled to about 20ºC throughout the test using small electric heaters in each zone.

The tracer gas decay curves are shown in Figure 3. The house was evidently very well mixed during this test, which allowed a running, instantaneous calculation of whole-house ACH over the same period (see Figure 4). Although the air change rate indicated that the house was relatively tight (about 0.085 ACH on average), the effect of natural infiltration was far from negligible, especially when the wind was blowing. This variability of natural infiltration must be kept in mind when interpreting the decay curves and reciprocal age-of-air calculations that follow.

An air handler bump test was performed between 1300 and 1500 hours to examine the effect of air handler operation on whole house air change rate, including the effects of duct leakage to the outside and changes in room-to-room pressurization caused by the movement of air from the supply registers in each room to the central return in the main living area. Figure 4 shows both the hourly average ACH and the wind speed during this period. At first glance the air change rate appears to have increased by about 0.03 ACH when the air handler was turned on, but there was a coincident jump in wind speed that complicates this interpretation. There was no corresponding decrease in ACH when the air handler was turned off at 1500 hours. Thus, we cannot conclusively quantify the change in air change rate associated with operation of the air handler, but it appears to have been no more than 0.03 ACH.

The natural ventilation test was repeated on January 2 with the doors closed instead of open (Test A15), yielding the decay curves shown in Figure 5. The average air change rate for this case was 0.086 ACH, calculated based on the two well-mixed cases at the beginning and end of the test. Comparing this number with the doors-open case is difficult because the wind speed was relatively high (4 to 5 mph) for the first few hours of this test. However, clearly the room-to-room uniformity of outside air distribution was significantly less when the doors were closed, even with transfer grilles present. We did not calculate age-of-air for this test, because the test conditions were not sufficiently steady state. This fact is very evident at about 1500 hours, when the curves for bedroom 2 and bedroom 3 suddenly begin to diverge from the master bedroom curve.

Distributed Supply versus Point Exhaust Ventilation

Two of the most common ventilation schemes in Building America homes are continuous single-point exhaust ventilation and intermittent CFIS ventilation. Exhaust ventilation is most commonly installed in a bathroom, laundry room, or utility room. Make-up air enters through the cracks and holes in the building envelope when the house is depressurized. Because of pressure interactions with the natural infiltration process, the increase in outside air change rate provided by an exhaust-only system is not the same as the exhaust flow rate specified by ASHRAE 62.2. The distribution of outside air to a specific room is also fairly unpredictable because it depends on the amount of depressurization in the room, the number and size of openings in exterior walls, and the influence of adjacent rooms. We hypothesize that supply ventilation provided by a central-fan integrated system would be distributed more uniformly throughout the house by the supply ducts, and that the indoor air would be mixed more thoroughly by the air handler, providing a more predictable amount of fresh air to every room that has supply registers. However, most fan-cycling controls used for a CFIS system operate the fan on a duty cycle of about 33% to economize on fan energy use. One goal of this study was to evaluate the effect of that duty cycle on the consistency of outside air distribution and mixing. In this study, we did not attempt to disaggregate the separate effects of supply versus exhaust ventilation, and multi-point versus single-point ventilation.

The decay curves for a 12-hour overnight test with exhaust ventilation (Test A3) are shown in Figure 6. The exhaust fan register in the laundry room was used as the exhaust point, and the calibrated, variable-speed fan was used to exhaust 58 cfm continuously, corresponding to the minimum ventilation rate specified by ASHRAE for a

2075 ft^2, four-bedroom house. The decay curves show clearly that significantly more outside air reached the master bedroom, and less reached bedroom 2, compared to the other rooms in the house.

The corresponding decay curves for the CFIS system (Test A6) are shown in Figure 7. The air handler operated at a 33% duty cycle (20 minutes off, 10 minutes on) with a ventilation rate of 174 cfm, resulting in an average ventilation rate of 58 cfm, again meeting the minimum ASHRAE 62.2 ventilation rate. The outside air appeared to be well distributed in this case, because the decay curves were clustered together throughout the test. Even during the 20-minute periods when the air handler was off, there was very little divergence. A comparison of Figure 6 to Figure 7 indicates that outside air was distributed much more uniformly when the CFIS system was used.

Reciprocal age-of-air calculations were performed to provide a quantitative comparison of the two ventilation systems. These values of reciprocal age-of-air for each room are shown in Figure 8 and Table 4, along with the values for all the other one-story house tests that will be discussed later in this paper. Values were in the range of 0.080 h^{-1} for the exhaust ventilation system, compared to 0.005 h^{-1} for the CFIS ventilation system. With the exhaust ventilation in the laundry room, the master bedroom had the highest reciprocal age-of-air. We suspect this was caused by the presence of the exhaust fans in the master bathroom, which may have provided greater leakage area in the master bedroom than in other areas of the house. The supply system distributed the outside air more uniformly, but this test alone did not show whether this was primarily caused by ventilation air being introduced through the supply ducts, or by the air handler mixing air throughout the house.

TABLE 4
Reciprocal age-of-air for one-story house under various operating conditions.

	Reciprocal Age-of-Air, 1/hr					
Zone	**A3: Exhaust in laundry room, no mixing, 100% ASHRAE, doors closed, transfer grilles untaped**	**A3 with central supply, mixing @ 33% duty cycle (A6)**	**A3 with doors open (A9)**	**A3 with 33% air handler operation (A12)**	**A3 with exhaust in master bathroom (A16)**	**A3 with transfer grilles taped (A10)**
Living	0.169	0.175	0.191	0.230	0.150	0.190
Entry	0.169	0.175	0.192	0.226	0.151	0.197
BR1	0.154	0.174	0.202	0.207	0.126	0.145
BR2	0.131	0.171	0.211	0.203	0.122	0.145
BR3	0.176	0.170	0.214	0.200	0.136	0.195
MBR	0.211	0.173	0.217	0.203	0.167	0.211
ACH_{avg}	0.176	0.181	0.202	0.216	0.146	0.185
Range	0.080	0.005	0.026	0.030	0.045	0.066

It is also noteworthy that the average net air change rates provided by both the supply and exhaust ventilation systems were only about 0.18 ACH, compared to the 0.25 ACH that would be expected if the mechanical ventilation rate (0.17 ACH) and the natural infiltration rate (0.08 ACH) were additive, as they might be with a balanced ventilation system. Adding mechanical ventilation to natural infiltration in quadrature in accordance with ASHRAE Standard 136 (ASHRAE 1993) results in an estimated average net air change rate of 0.19 ACH, which is fairly consistent with the measured values.

Simulations by Walker (BSC 2007) have shown that not all systems will provide the same service in terms of annual average air change rate. For the same air flow rate and duty cycle, balanced ventilation will yield a higher average air exchange than supply ventilation, and supply ventilation will yield a higher average air exchange than exhaust ventilation. That can be explained in general terms by understanding that wind and stack effects act to depressurize a building most of the time. Exhaust fans increase the building depressurization further but supply fans decrease the depressurization. Balanced fans generally don't change the enclosure differential pressure and infiltration rate at all. Because of the nonlinear relationship between differential pressure and air flows across the building enclosure, a supply fan changes the pressures across the enclosure less than an exhaust fan, acting more like a balanced fan. Thus, the effect on ventilation air change rate from a supply fan is somewhere between that of an exhaust fan and a true balanced system.

Air Handler Operation

To determine how much mixing was caused by the air handler, the exhaust-only test was rerun with the air handler operating at 33% duty cycle (20 minutes off, 10 minutes on) (Test A12). Compared to Test A3, there was a noticeable increase in uniformity when the air handler was operating, even though the entry points for the ventilation air were uncontrolled. As shown in Figure 8, the reciprocal age-of-air range was reduced from 0.080 h^{-1} to 0.030 h^{-1}. The air handler operation appeared to explain most of the difference between the supply and exhaust ventilation systems discussed earlier. Although the overall average air change rate seemed to be higher when the air handler was operating (0.216 ACH versus 0.176 ACH), the average wind speed was also significantly higher. The wind speed, rather than a difference in the mechanical ventilation rate, was likely the primary cause of the difference in average air change rate with the air handler operating.

Exhaust Location

The preceding analysis of exhaust ventilation was based on an exhaust point in the laundry room, which was relatively centrally located in the one-story house. To examine the effect of moving the exhaust point, the calibrated variable-speed fan was moved to the master bathroom in a far corner of the house (Test A16). A continuous exhaust ventilation rate of 58 cfm was again applied to the house. It was difficult to identify a significant difference between the resulting series of curves and those shown in Figure 6 for the laundry room exhaust location, but because the curves were steady, we were again able to compare the results based on reciprocal age-of-air (see Figure 8). There appeared to be very little change in the distribution of outside air to most rooms. However, the reciprocal age-of-air in the master bedroom dropped noticeably when the exhaust location was moved to the master bathroom, probably because a greater fraction of the outside air now passed through other rooms before reaching the master bedroom. With the exhaust point centrally located, most of the ventilation air passing through the master bedroom probably entered from the outside. In both cases, however, the master bedroom had the highest reciprocal age-of-air of all the rooms in the house, and bedroom 2 had the lowest.

Ventilation Rate

The supply ventilation test was repeated using flow rates corresponding to 60% and 33% of the minimum ASHRAE specifications. The intent of this series of tests was to evaluate the uniformity of outside air distribution for ventilation rates consistent with ASHRAE 62.2 compared to the uniformity for reduced mechanical ventilation rates. Each test was conducted for only 4 hours because of time limitations. Because the rooms were well mixed during the CFIS tests, the average whole-house ACH could be compared directly to the reciprocal age-of-air for the exhaust ventilation tests. Figure 9 shows the supply ventilation air change rate for each of the three ventilation levels (33%, 60%, 100%), compared to room-by-room reciprocal age-of-air for the exhaust ventilation system with doors closed and no air handler operation. In the supply ventilation case, all rooms seemed to receive more outside air than the least ventilated room in the exhaust case (bedroom 2), even at 60% of ASHRAE 62.2. These results illustrate the tradeoff between whole-house ventilation rate and room-to-room ventilation uniformity, in terms of their impact on the room(s) that receive the least amount of outside air.

Because the 62.2 committee has not specified a minimum level of mixing as part of the standard, the intended ventilation rate for individual rooms is unclear. Some might interpret the results of this test to suggest that a house without mixing can have certain rooms that do not receive sufficient outside air even though the ventilation system is operating at 62.2 specified rates, while other rooms receive more outside air than the acceptable minimum. For example, if the exhaust system performance shown in Figure 9 is acceptable, does this mean that a ventilation system that provides uniform distribution of outside air may be sufficiently well ventilated at 60% of the 62.2 level, or perhaps even less? Alternatively, it might be concluded that exhaust ventilation rates should be increased over current 62.2 recommendations because certain rooms may receive very little fresh air. It can also be argued that mixing is undesirable because pollutants will be distributed throughout the house instead of being confined to one location where a local exhaust fan can remove them. Unfortunately, because the current standard does not include air mixing requirements and the committee's assumptions about ventilation air distribution are not well documented, we cannot make any firm recommendations in this area.

Bedroom Doors

Except for the first natural ventilation test, the preceding tests were all conducted with the bedroom doors closed to represent a worst-case situation for air mixing. The exhaust ventilation test was repeated with the bedroom doors open (Test A9), resulting in decay curves that were much more tightly bundled. A comparison based on reciprocal age-of-air is shown in Figure 8. A significant increase in room-to-room mixing was evident during the open-door test. Also, the average air change rate was clearly higher during the test with open doors compared to closed doors (0.202 versus 0.176 ACH), even though we know the ventilation rate was controlled to the same value using a variable-speed fan. Because the average wind speed was higher during the open-door test period compared to the closed-door test period (2.0 mph compared to 0.6 mph), this test does not necessarily indicate that closing doors reduces the average air change rate associated with an exhaust system. In future tests, continuous measurement of the depressurization of the house with respect to outside, along with single-point differential pressure measurements across interior doors, would provide more information about the effect of closing doors when exhaust ventilation systems are used. It would also be valuable to conduct this test during steady weather conditions using the exhaust fan (uncontrolled flow rate) instead of the calibrated, variable-speed fan (controlled flow rate) to observe the net effect of closed doors on whole-house air change rate. We would expect a reduction in net air change rate for an uncontrolled exhaust flow rate with bedroom doors closed because of the greater resistance to air flow between the bedrooms and the exhaust fan.

Transfer Grilles

Because the test houses used central returns rather than hard ducted returns in the bedrooms, transfer grilles were installed over the bedroom doors to provide a flow path for return air without excessive room pressurization when the doors were closed. These transfer grilles also allowed ventilation and infiltration air to pass more freely from the bedrooms to the main living space. The effect of transfer grilles on outside air distribution was evaluated by taping over the grilles and rerunning the exhaust ventilation test (Test A10). The results of the reciprocal age-of-air analysis are shown in Figure 8. Taping the transfer grilles did not appear to significantly affect the room-to-room variability in outside air distribution, although there appeared to be some slight reranking of rooms from highest to lowest reciprocal age-of-air. There was an increase in average wind speed from 2.6 mph to 4.1 mph starting at 1300 hours, including a half-hour period when the average wind speed was 7 mph. This weather effect produced noticeable kinks in the decay curves, introducing errors into the reciprocal age-of-air calculations and causing them to be meaningful only on a qualitative basis.

The transfer grilles may have played a much smaller role than the supply ducts in providing a path for ventilation air. Because the air handler was not operating, the ducts were not pressurized and were thus available as passive airflow conduits. The resistance to air flow was probably weaker for the air ducts than for the transfer grilles, depending on their size and the number of supply registers in each bedroom. The door undercuts are also thought to have played a role. The effects of ducts and door undercuts can be tested in the future by running separate tests with ducts and door undercuts taped over.

Minimum Test Duration

To evaluate the length of time needed to estimate the reciprocal age-of-air with reasonable accuracy, we examined the results that we would have obtained for one of the exhaust ventilation tests had we halted the test period after less than 12 hours. The reciprocal age-of-air calculations for the exhaust ventilation decay curves (Test A3, see Figure 6) based on test durations of 3, 6, 9, and 12 hours are shown in Figure 10. These test durations ranged from 0.53 to 2.1 air changes based on the average air change rate of 0.18 ACH (5.6 hours per air change) calculated for this test. The ratio of highest to lowest reciprocal age-of-air is shown above the data points for each case. These results suggest that shorter tests tend to overestimate the range and that perhaps 1½ to 2 air changes (roughly 9 to 12 hours in this case) may be necessary to obtain accurate reciprocal age-of-air calculations when there is significant divergence among rooms. From a qualitative standpoint, one air change may be sufficient to determine the basic trend. Without knowing in advance which mixing pattern will occur, recommending a minimum test duration is difficult. But assuming this test is fairly representative of a worst-case scenario, at least 1.5 air changes would be necessary to have a high degree of confidence in the quantitative difference in reciprocal age-of-air among rooms.

TEST RESULTS FROM THE TWO-STORY HOUSE

The two-story house was tested from January 3 to 10, 2006. Three zones were selected on the first floor, and three more were selected on the second floor, as indicated by the red stars in Figure 2. The initial mixing of air among the rooms at the start of each test in this house was less thorough than in the one-story house. Evidently, the combined effects of the air handler and the portable destratification fan were not sufficient to overcome upward transport of tracer gas, driven by stack and wind effects, from the first to the second floor. The resulting differences in initial tracer gas concentration among the rooms was about 5% to 10%. This outcome emphasizes the significant effect of stack and wind-driven infiltration on outside air distribution in multi-story homes. Because our test method and equipment did not achieve a well-mixed condition at the start of each test, some errors were introduced into the reciprocal age-of-air analysis. For future tests, we recommend larger destratification fans to obtain more well-mixed conditions in multi-story houses.

Typical errors introduced by incomplete mixing of the tracer gas at the start of a test were analyzed by examining two hypothetical cases where either all the air entering a room comes from the outside or all the air comes from an adjacent room with a different starting concentration. If all the air entering a space comes from the outside, a change in the initial concentration would have no effect on the reciprocal age-of-air because the decay curve would be exponential from the start and the area under the curve would be normalized based on the starting concentration in that zone. However, if the air entering a room passes through another room with a lower initial concentration, the room receiving the air would have a lower concentration of tracer gas throughout the test compared to what the concentration would have been if the starting points were the same in both rooms. An error in reciprocal age-of-air of about 7.5% could be expected for a room downstream of another room with a 10% lower starting concentration, assuming 0.1 ACH for both rooms. The error would be about 5% smaller if the air change rate were higher for both rooms (0.2 ACH). Although the degree of error in the reciprocal age-of-air calculations can be affected by additional variables not examined here, we feel that these percentages are reasonable estimates of the errors in our results for the two-story house because the initial mixing of air was incomplete. In each case, an engineering judgment must be made about the significance of the error introduced by incomplete initial mixing. As a general rule for the results to be considered valid, the differences in concentration at the start of the test should be small compared to the differences that are being analyzed.

Natural Infiltration and Duct Leakage

A natural infiltration test was performed over a 2-hour period on the evening of January 8 (Test B14). The tracer gas decay curves showed a slight divergence between the first and second floors once the air handler was turned off, but the rooms on each floor appeared to remain fairly well mixed. The average air change rate during the test period was about 0.11 ACH, which was somewhat higher than it was in the one-story house, as might be expected with an increased stack height and greater wind exposure.

An air handler/bedroom door bump test was also conducted for the two-story house to allow the combined effect of duct leakage to the outside and increased infiltration caused by room pressurization to be observed. The average air change rate during that bump test was 0.13 ACH, suggesting that closing doors and operating the fan added approximately 0.02 ACH to the whole-house average air change rate. The average wind speed was a bit higher while the air handler was running (1.7 mph compared to 0.5 mph), so the effect of air handler operation may actually be somewhat less than the average ACH numbers indicate.

Distributed Supply versus Point Exhaust Ventilation

A 14-hour test (Test B1) was performed with an exhaust ventilation rate of 63 cfm in the laundry room near the stairwell in the middle of the first floor. The ventilation rate was again consistent with the minimum acceptable rate specified in ASHRAE 62.2. The tracer gas decay curves are shown in Figure 11. All three second-floor rooms showed a delay before entering an exponential decay, suggesting that some air was moving from the first to the second floor, even though the mechanical exhaust point was on the first floor. The further depressurization of the first floor was apparently insufficient to overcome the stack and wind effects, and draw a significant amount of outside air in through the rooms on the second floor.

A supply ventilation test was performed on the two-story house for about 11 hours starting late on January 4 (Test B3). The calibrated variable-speed fan was unable to provide the ventilation rate necessary to meet the minimum specified in ASHRAE 62.2, supplying 180 cfm instead of 189 cfm (95%). The decay curves were much more tightly packed than they were with the exhaust system, but there was more divergence than we saw with the CFIS system in the one-story house, most notably in the master bedroom.

The reciprocal age-of-air calculations for both the single-point exhaust and CFIS ventilation systems are shown in Figure 12 and Table 5, along with the reciprocal age-of-air results for other operating modes that will be discussed later in this paper. Once again, it must be noted that multiple variables are included in comparisons of these systems, including exhaust vs. supply, single-point vs. distributed, and mixing vs. no mixing. As we saw in the one-story house, the two-story results indicate that outside air was distributed much more uniformly by the CFIS system than by the single-point exhaust system with the bedroom doors closed and no air handler operation. However, for the CFIS test, the differences in the initial tracer gas concentration were of the same magnitude as the differences in decay rates among the rooms. As a result, no conclusions should be drawn about the relative ranking among rooms for the supply ventilation case based on Figure 12. However, because the initial concentration differences for the CFIS test are small compared to the differences among rooms for the exhaust ventilation test, a direct qualitative comparison of the two systems remains valid.

TABLE 5

Reciprocal age-of-air for two-story house under various operating conditions. (*Note: Uncertainties introduced by nonuniform starting concentration are of the same order of magnitude as the differences in reciprocal age-of-air among rooms for the supply ventilation case (B3) and the open doors case (B10). The range is not sufficiently accurate for either case.)

	Reciprocal Age-of-Air, 1/hr					
Zone	**B1: Exhaust in laundry room, no mixing, 100% ASHRAE, doors closed, transfer grilles untaped**	**B1 with central supply, mixing @ 33% duty cycle (B3)**	**B1 with doors open (B10)**	**B1 with 33% air handler operation (B6)**	**B1 with exhaust in master bathroom (B18)**	**B1 with transfer grilles taped (B7)**
BR1	0.181	0.204	0.138	0.160	0.243	0.186
Living	0.158	0.195	0.145	0.165	0.231	0.155
Kitchen	0.166	0.197	0.151	0.172	0.233	0.155
BR2	0.107	0.198	0.145	0.162	0.093	0.082
BR3	0.127	0.198	0.145	0.164	0.104	0.068
MBR	0.136	0.186	0.153	0.155	0.191	0.100
ACH_{avg}	0.147	0.196	0.128	0.144	0.187	0.128
Range	0.074	*	*	0.017	0.150	0.118

Air Handler Operation

The effect of occasional air handler operation on the distribution of outside air using the exhaust ventilation system was evaluated on the afternoon of January 6 (Test B6). The reciprocal age-of-air calculations are shown in Figure 12. During the test, the doors were closed and the air handler operated at a 33% duty cycle (20 minutes off, 10 minutes on). As was the case in the one-story house, this occasional operation of the air handler substantially increased the uniformity of outside air distribution among rooms, even in conjunction with the point exhaust ventilation system. However, because the initial differences in tracer gas concentration among rooms were as large as the differences in reciprocal age-of-air, no conclusions should be drawn about the relative ranking of ventilation rates among the rooms for this case.

Exhaust Location

The variable-speed fan was moved to the master bathroom exhaust register to see if there was a resulting change in outside air distribution (Test B18). The master bathroom was in the back of the house, on the second floor, between the master bedroom and bedroom 3. The reciprocal age-of-air results are shown in Figure 12. The rooms on each floor were well mixed before the test began, although the mixing between the two floors was not as good. Very wide divergence among rooms occurred during the test, especially between the upstairs bedrooms and the rest of the house. Once again, all three upstairs rooms appeared to receive some air from the first floor because their decay rates began very flat before dropping more quickly once the first floor had been significantly diluted. A similar effect can be seen in Figure 11 for the laundry room exhaust ventilation case. However, the master bedroom received a much higher volume of outside air than the other two second-floor bedrooms, which appeared to be relatively stagnant.

Ventilation Rate

The supply ventilation tests were repeated using flow rates of 60% and 33% of the minimum acceptable ventilation rate according to ASHRAE 62.2, corresponding to 114 cfm and 63 cfm, respectively (Tests B2 and B4). In all cases, the zones remained fairly well mixed, especially those on the same floor. As we observed in the one-story house, the ventilation rate in the two-story house appeared to have very little effect on the uniformity of outside air provided to each zone as long the air handler was used to mix it. In addition, all rooms received more outside air than the worst-ventilated room in the exhaust ventilation case (about 0.11 h^{-1}), even at 33% of the ASHRAE 62.2 minimum rate. Again, for all three cases, the initial differences in tracer gas concentration among zones were as large as the divergence in the decay curves, preventing any conclusions about the relative ranking of zones. The relative errors caused by imperfect initial concentration uniformity were larger for the cases with air handler mixing because the relative divergence in the decay curves were so small compared to cases with no air handler mixing. In other words, the errors in relative ranking of ventilation rates for the cases with air handler mixing were relatively large, but less important because the differences between rooms were small.

Bedroom Doors

The laundry room exhaust ventilation test with no air handler operation was repeated with the doors open to evaluate the change in outside air distribution (Test B10). The reciprocal age-of-air calculations are shown in Figure 12. However, the test began before the rooms were completely mixed, resulting in decay curves that might be somewhat misleading. Because the tracer gas concentration in the master bedroom was about 10% higher than in the other rooms at the start of the test, any room that received air from the master bedroom would appear to have a slower decay rate than if the rooms had started out at the same concentration. Therefore, relative reciprocal age-of-air among rooms was not meaningful for the open-doors test. But despite the difference in starting concentration, it is clear on a qualitative basis that outside air was fairly well distributed when the doors were open, even without operation of the air handler.

Transfer Grilles

A final exhaust ventilation test was run on the two-story house with the doors closed and the transfer grilles taped over (Test B7). The reciprocal age-of-air calculations are shown in Figure 12. By examining the reciprocal age-of-air results, it is apparent that the transfer grilles in the two-story house noticeably improved the outside air distribution, but the improvement was smaller than when the doors were opened.

CONCLUSIONS

- The modified reciprocal age-of-air technique developed by the authors using a multi-zone single tracer gas system is a practical approach that provides meaningful insights into the uniformity of outside air distribution using various ventilation systems and operating conditions. The approach does not quantify pollutant exposure, which is heavily dependent on actual source generation rates and locations.
- The reciprocal age-of-air methodology provides valid results only when weather conditions are sufficiently steady, an initially well-mixed state is obtained, and the test is run for a long enough duration that the decay curves are in the exponential regime.
- With closed doors, supply ventilation distributed by the air handler through the central duct system provided much more uniform distribution of outside air than the single-point exhaust system with no air handler operation.
- Operation of the central fan at a 33% duty cycle maintained relatively well-mixed conditions regardless of ventilation rate, type of ventilation system (supply or exhaust), or house configuration (one- or two-story).
- For exhaust-only ventilation without central fan operation, opening bedroom doors significantly increased the uniformity of outside air distribution among rooms. The uniformity was already high for the CFIS system, so an open door test was not performed. Transfer grilles improved the distribution of ventilation air slightly, but much less than opening the bedroom doors.
- In the two-story house, the stack and wind effects appeared to cause air movement from the first floor to the second floor even when exhaust ventilation was applied to the first floor, resulting in consistently lower values of reciprocal age-of-air on the second floor. As a consequence, we would expect pollutants generated on the first floor to pass through the rooms on the second floor before exiting the house.
- Interactions between natural infiltration and unbalanced exhaust and supply mechanical ventilation were very significant. When the ventilation systems were activated, the combined average air change rate did not increase commensurate with the mechanical ventilation rate, but instead by only half that amount. This result was consistent with combining ventilation and infiltration in quadrature to estimate whole-house air change rate in accordance with ASHRAE Standard 136 (ASHRAE 1993).

ACKNOWLEDGMENTS

The authors express their appreciation to Rich Coyle of D.R. Horton for providing the test houses, and to Joseph Lstiburek of BSC, Subrato Chandra and Neil Moyer of FSEC, and Greg Barker of Mountain Energy Partnership for their assistance in the planning and execution of this ventilation study. We also express our thanks to Ed Pollock and George James of the U.S. Department of Energy's Building America program for funding this research.

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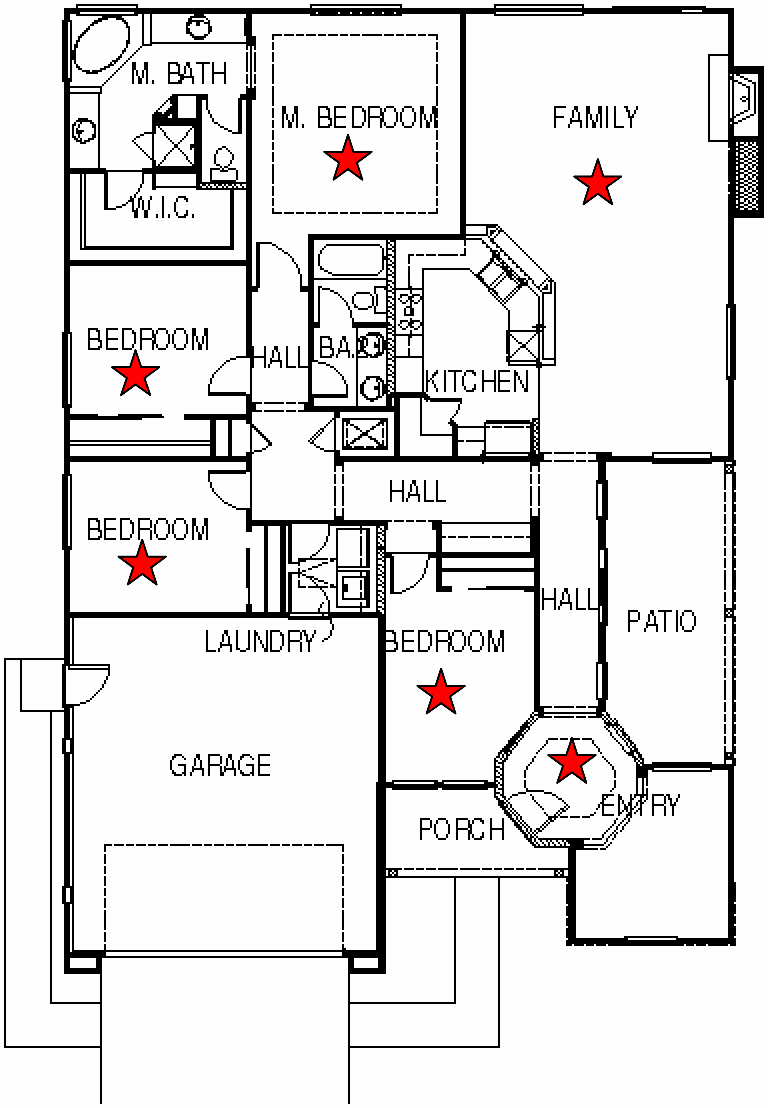

Figure 1. One-story test house floor plan. Stars indicate tracer gas sampling points.

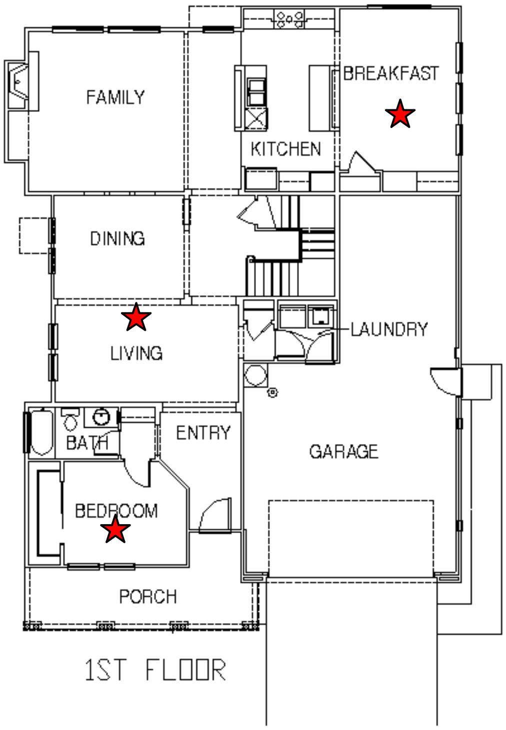

Figure 2. Two-story test house floor plan. Stars indicate tracer gas sampling points.

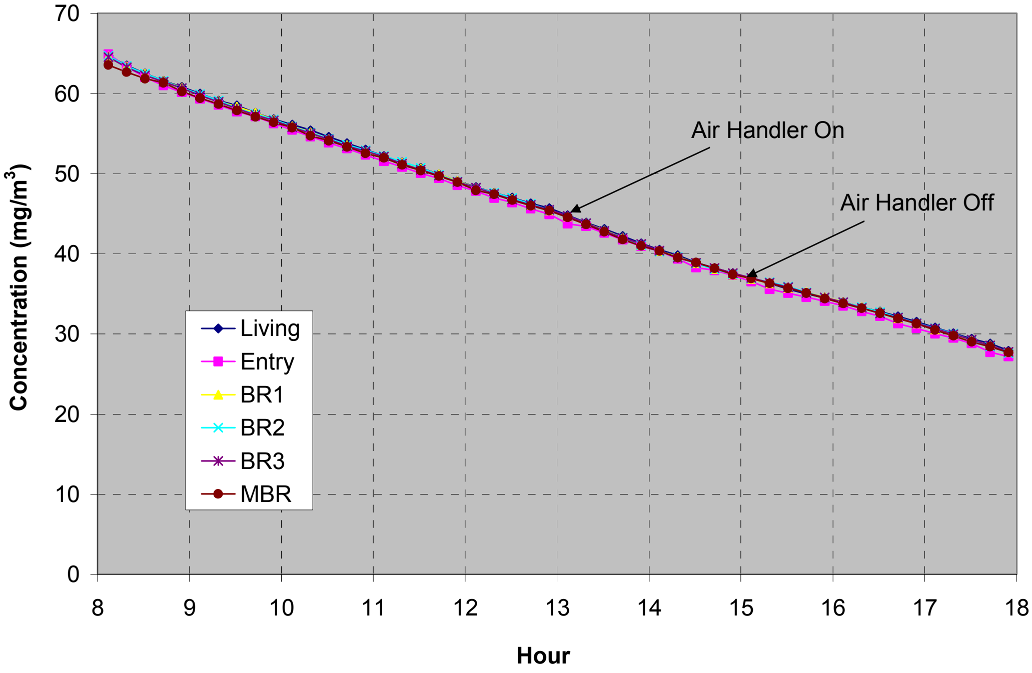

Figure 3. Tracer gas decay for one-story house with no ventilation and bedroom doors open, with and without air handler operation (Test A7). This is an example of a well-mixed case where air change rate in terms of ACH can be calculated throughout the test.

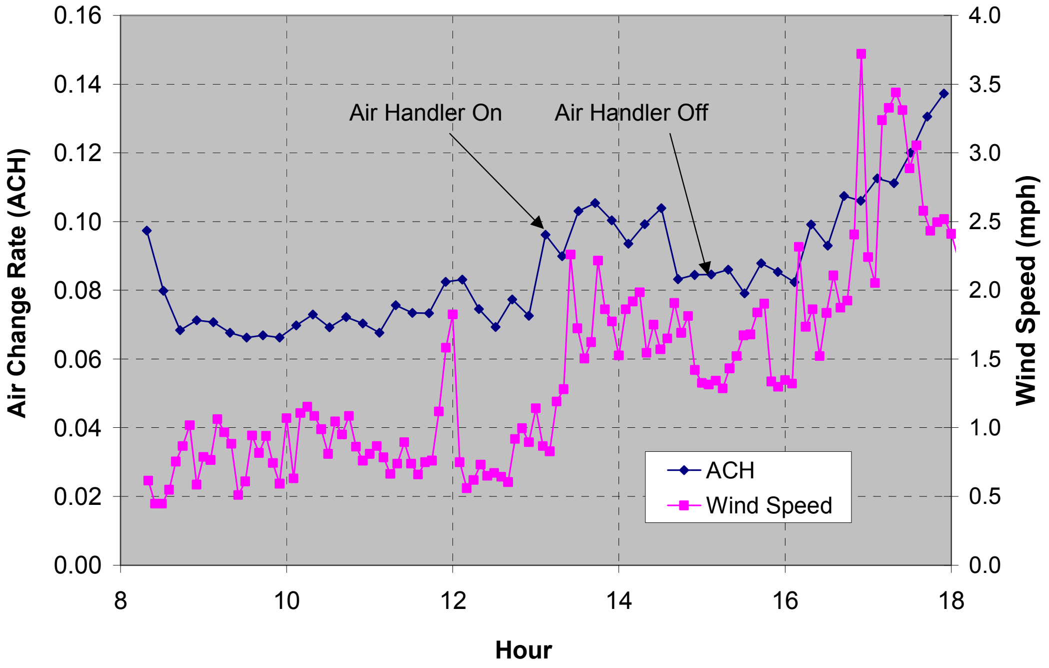

Figure 4. Average air change rate for one-story house with no ventilation, no air handler operation, and bedroom doors open (Test A7).

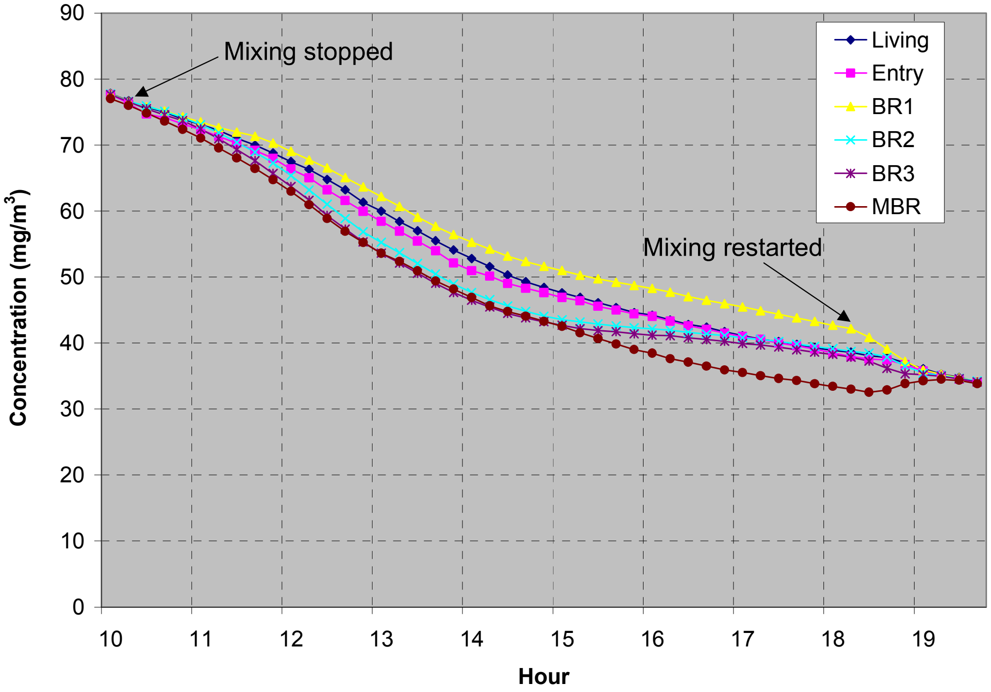

Figure 5. Tracer gas decay for one-story house with no ventilation, no air handler operation, and bedroom doors closed (Test A15). This is an example of a non-uniform case where steady-state conditions, needed for age-of-air analysis, are not met.

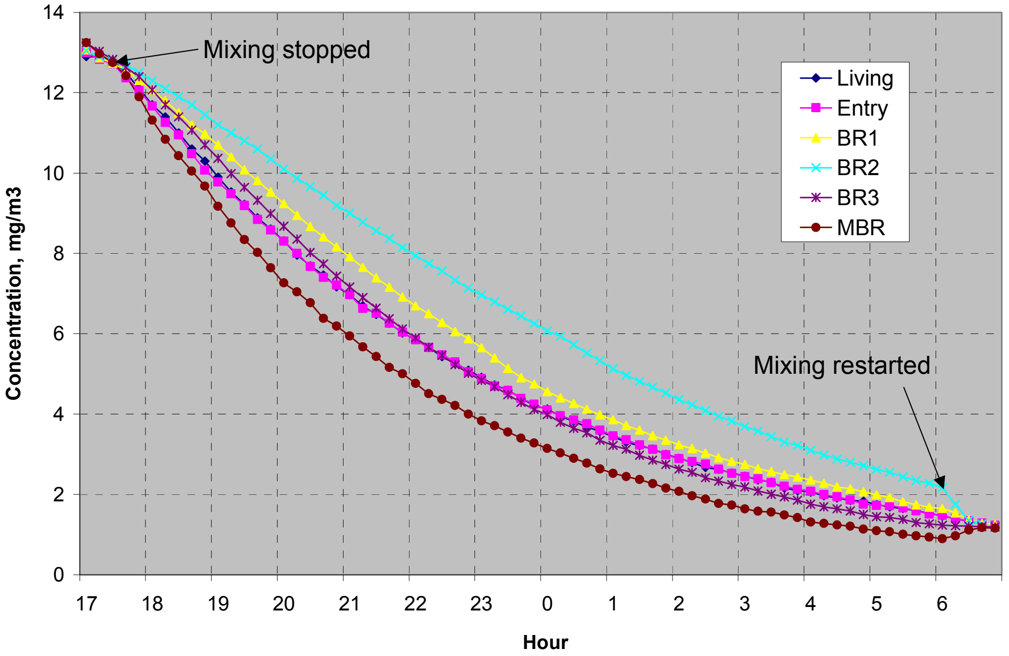

Figure 6. Tracer gas decay for one-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no air handler operation, and bedroom doors closed (Test A3). This is an example of a non-uniform case that is deemed sufficiently steady state for age-of-air analysis.

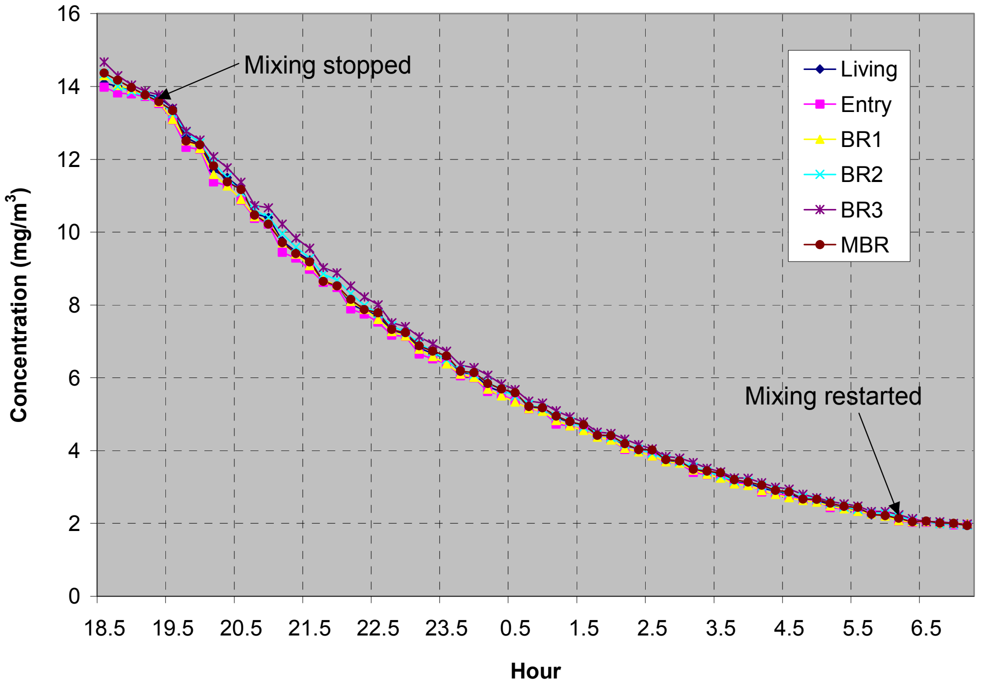

Figure 7. Tracer gas decay for one-story house with supply ventilation at ASHRAE 62.2 level, 33% air handler operation (20 minutes off, 10 minutes on), and bedroom doors closed (Test A6). This graph illustrates the minimal effects of air handler intermittence on the regularity of the tracer decay curves and the mixing among rooms.

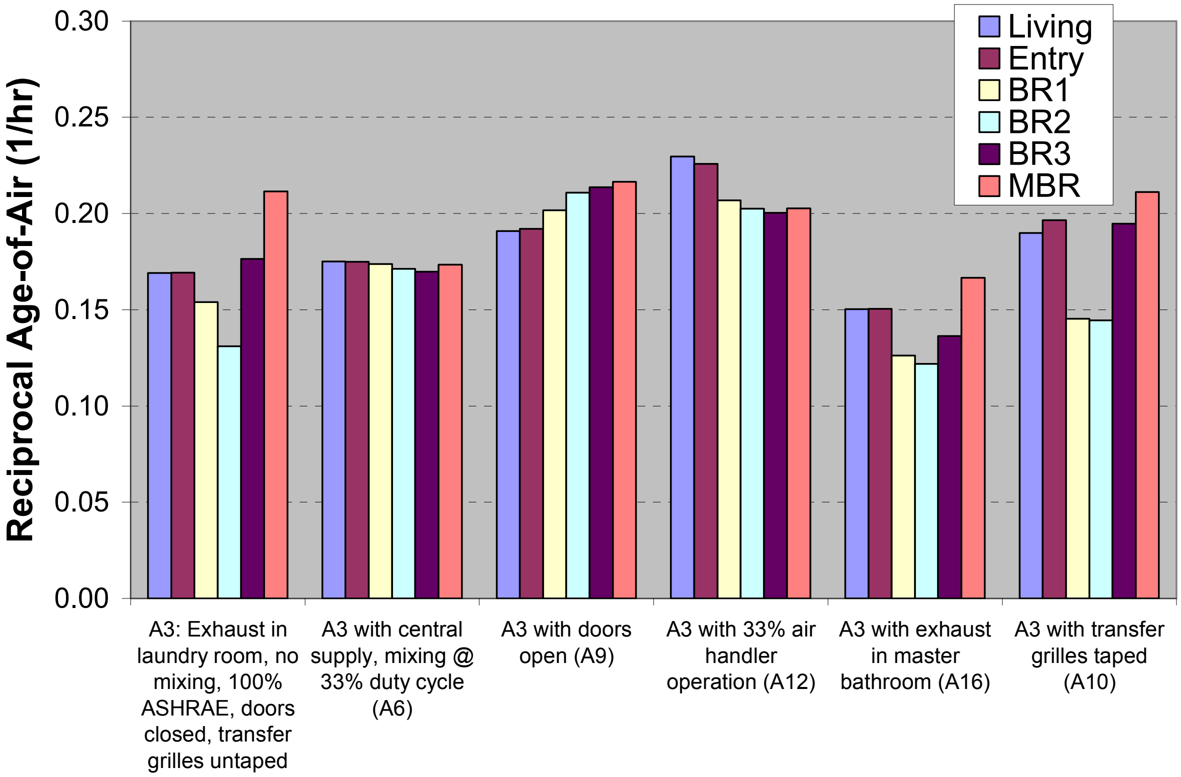

Figure 8. Reciprocal age-of-air for one-story house under various operating conditions.

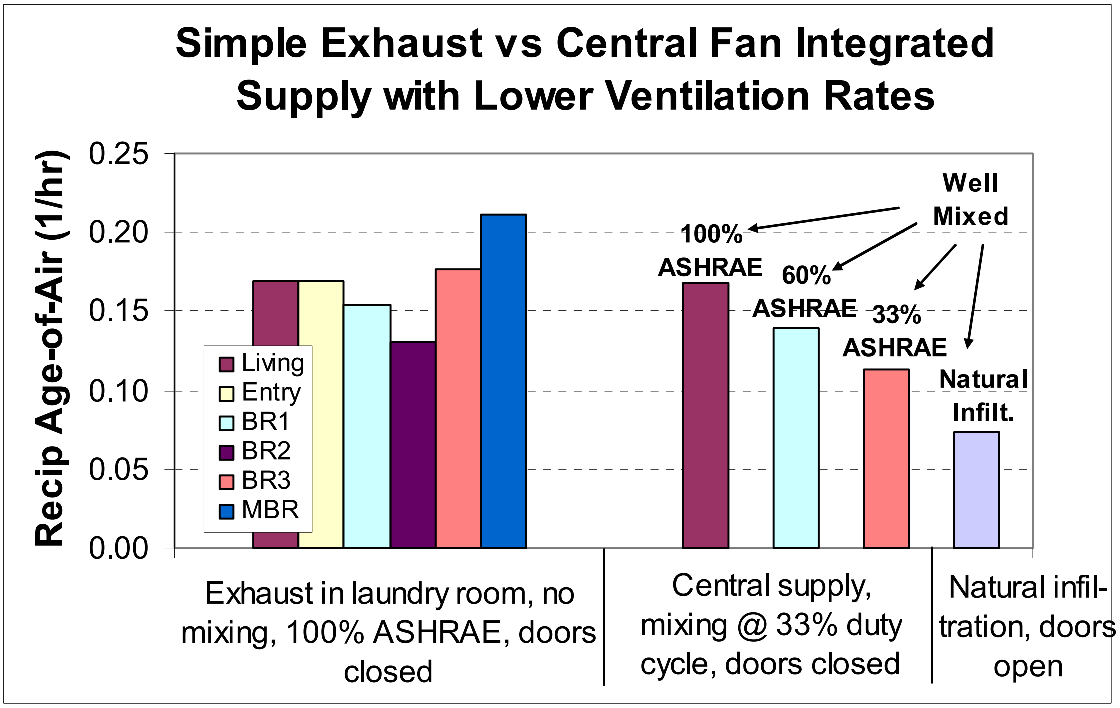

Figure 9. Reciprocal age-of-air for one-story house with supply ventilation at 33%, 60%, and 100% of ASHRAE 62.2 level (Tests A5, A4, A6) compared to exhaust ventilation with no air handler operation (Test A3). Bedroom doors were closed.

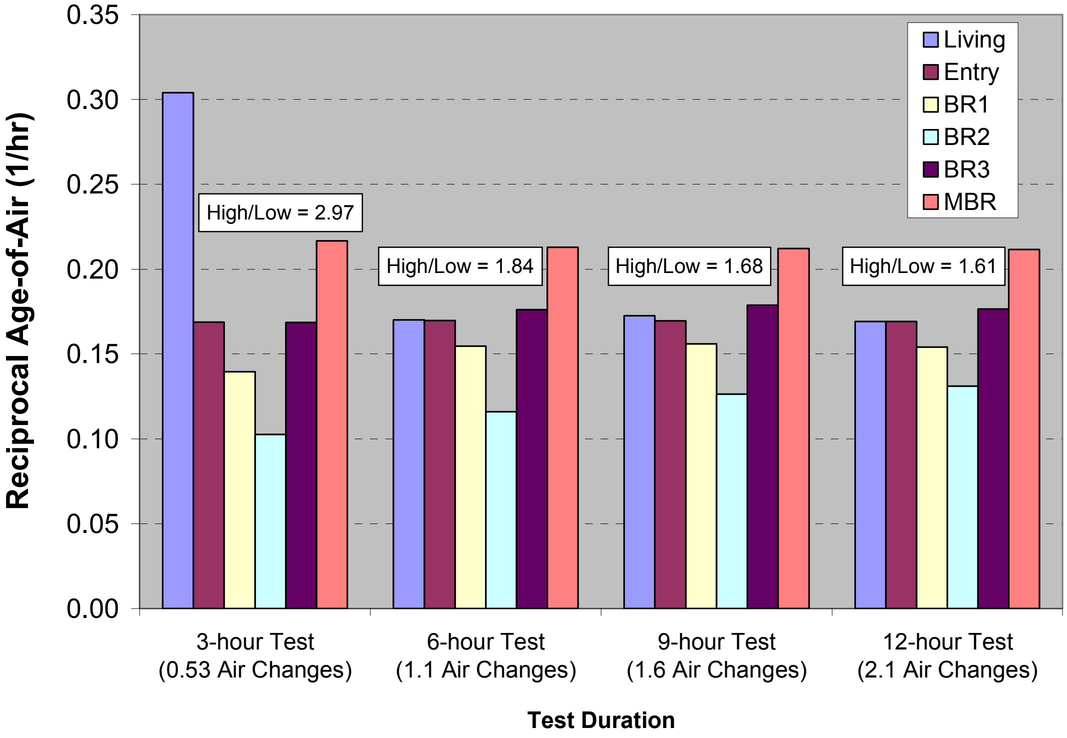

Figure 10. reciprocal age-of-air based on alternate test durations for one-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no air handler operation, and doors closed (Test A3). Average air change rate was 0.18 ACH.

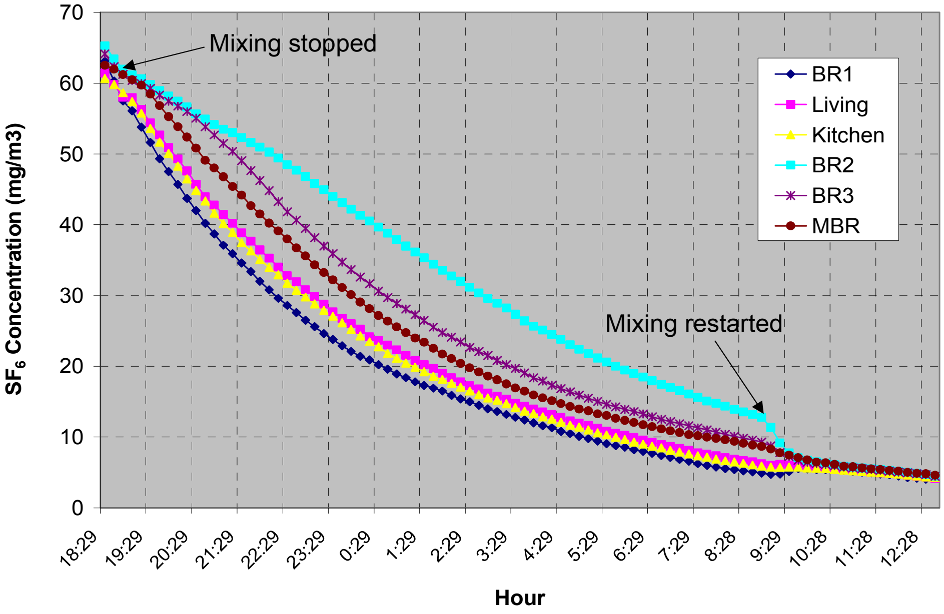

Figure 11. Tracer gas decay for two-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no air handler operation, and bedroom doors closed (Test B1). This graph illustrates a distinctive decay pattern observed in the two-story house.

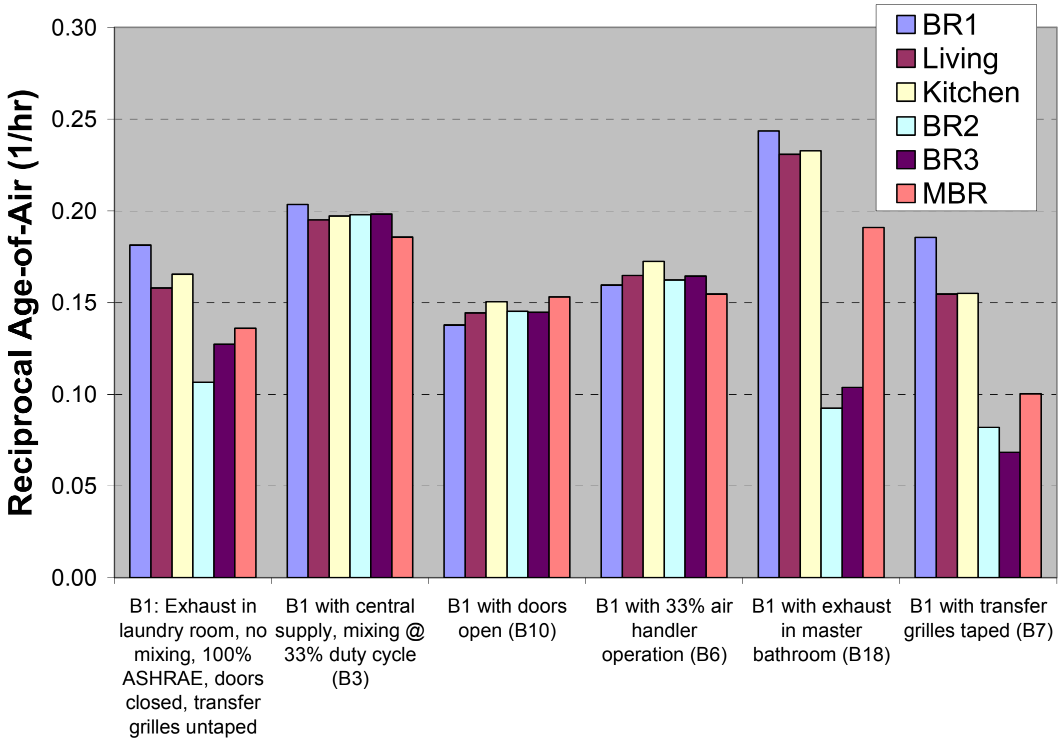

Figure 12. Reciprocal age-of-air for two-story house under various operating conditions. (Note: Uncertainties introduced by nonuniform starting concentration are of the same order of magnitude as the differences in reciprocal age-of-air among rooms for the supply ventilation case (B3) and the open doors case (B10). The relative ranking of rooms is not meaningful for either case.)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
August 2008

2. REPORT TYPE
Conference Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Field Test of Room-to-Room Distribution of Outside Air with Two Residential Ventilation Systems

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
R. Hendron, R. Anderson, D. Barley, A. Rudd, A. Townsend, and E. Hancock

5d. PROJECT NUMBER
NREL/CP-550-41210

5e. TASK NUMBER
BET88004

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-550-41210

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

Uniform distribution of outside air is one way to ensure that residential dilution ventilation systems will provide a known amount of fresh air to all rooms regardless of house geometry and occupant behavior. To characterize outside air distribution in residential buildings, the authors developed a practical methodology adapted from ASHRAE Standard 129.

15. SUBJECT TERMS
outside air; ventilation; building america

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(09/2007)

About this Paper

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