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Field test of room-to-room uniformity of ventilation air distribution in two new houses

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Abstract:

In order for dilution ventilation systems to provide predictable results independent of the geometry of individual homes, outside air must be uniformly distributed throughout the house. The primary purpose of this field test was to characterize the uniformity of room-to-room ventilation air distribution under various operating conditions by examining multi-zone tracer gas decay curves and calculating local age-of-air. The tests were conducted in two Sacramento houses, and were designed to allow direct, quantitative comparisons of various ventilation approaches, which could potentially be factored into ventilation rate trade-offs in future updates to ASHRAE Standard 62.2. We observed the effects of providing single-point exhaust ventilation versus central-fan-integrated supply ventilation, and the *impacts of operating the central fan at a minimum duty cycle for mixing, closing the bedroom doors, and covering passive return air transfer grilles above the doors. Analysis of the measured data showed that reciprocal age-of-air analysis worked well to characterize room-to-room uniformity of ventilation air distribution as long as the house was well mixed at the beginning of the test, and weather conditions were sufficiently steady-state. A test period of at least 1.5 air changes was necessary to obtain valid age-of-air results when there was significant divergence in tracer gas concentration among the rooms. Both houses had relatively low natural infiltration and duct leakage to outdoors. Ventilation supplied through the central air distribution system provided much more uniform distribution of ventilation air than the single-point exhaust system. 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 (1-story or 2-story). For single-point exhaust ventilation, opening bedroom doors appeared to significantly improve the mixing of ventilation air among rooms. Passive air transfer grilles improved the distribution of ventilation air only slightly.*

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KEY WORDS
ventilation, air distribution, age-of-air, multi-zone tracer gas decay

ABSTRACT
In order for dilution ventilation systems to provide predictable results independent of the geometry of individual homes, outside air must be uniformly distributed throughout the house. The primary purpose of this field test was to characterize the uniformity of room-to-room ventilation air distribution under various operating conditions by examining multi-zone tracer gas decay curves and calculating local age-of-air. The tests were conducted in two Sacramento houses, and were designed to allow direct, quantitative comparisons of various ventilation approaches, which could potentially be factored into ventilation rate trade-offs in future updates to ASHRAE Standard 62.2. We observed the effects of providing single-point exhaust ventilation versus central-fan-integrated supply ventilation, and the impacts of operating the central fan at a minimum duty cycle for mixing, closing the bedroom doors, and covering passive return air transfer grilles above the doors. Analysis of the measured data showed that reciprocal age-of-air analysis worked well to characterize room-to-room uniformity of ventilation air distribution as long as the house was well mixed at the beginning of the test, and weather conditions were sufficiently steady-state. A test period of at least 1.5 air changes was necessary to obtain valid age-of-air results when there was significant divergence in tracer gas concentration among the rooms. Both houses had relatively low natural infiltration and duct leakage to outdoors. Ventilation supplied through the central air distribution system provided much more uniform distribution of ventilation air than the single-point exhaust system. 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 (1-story or 2-story). For single-point exhaust ventilation, opening bedroom doors appeared to significantly improve the mixing of ventilation air among rooms. Passive air transfer grilles improved the distribution of ventilation air only slightly.

INTRODUCTION

ASHRAE Standard 62.2 (ASHRAE 2004), "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings," specifies a minimum ventilation flow rate that depends on the timing of ventilation air delivery but it is silent on whole-house distribution of ventilation air. The Washington State Ventilation and Indoor Air Quality Code (WAC 2004) is also silent regarding ventilation air distribution. Both the Minnesota Building Code (MN Chapter 7672) and the National Building Code of Canada (NBC 2005) referring to Canadian Standard F326-M91 (CSA 2005) require whole-house ventilation air distribution by means of fully ducted ventilation systems or by mixing via a central air handling system. A large, U.S. private-sector, high-performance home program also requires periodic central air handler operation to assure whole-house mixing for ventilation air distribution and thermal comfort. Prior work by Rudd (2000) showed that ventilation systems that utilized whole-house distribution and mixing via the central air handling system had much less room-to-room variation in ventilation air exchange than systems that did not.

This research program evaluated the distribution of ventilation air in two new test houses 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 in Sacramento. 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 designed to be energy efficient, had slab-on-grade foundations, ducts in conditioned space, and met the builder's airtightness target measured with a blower door (<1.25 in^2 effective leakage area per 100 ft^2 envelope area). Other key specifications for both houses are summarized in Table 1, and photos are shown in Figures 1 and 2. Floor plans are shown in Figures 3 and 4.

The primary purpose of this test program was to characterize the uniformity of room-to-room distribution of outside air under various conditions by examining multi-zone tracer gas decay curves. In order for dilution ventilation systems to provide predictable results independent of the geometry of individual homes, outside air must be uniformly distributed throughout the house. The tests in the Sacramento houses were designed to allow direct, quantitative comparisons of various ventilation approaches, which could potentially be factored into ventilation rate trade-offs in future updates to ASHRAE Standard 62.2 (ASHRAE 2004).

Table 1. Specifications for DR Horton test houses.

	1-Story (1111 Montague)	2-Story (1117 Montague)
Geometry	4-bedrooms, 2-bath 2075 ft^2 10 ft ceilings	4-bedrooms, 2-bath 2582 ft^2 10 ft ceilings
Building envelope		
Ceiling & walls	Optima advanced insulation system	Optima advanced insulation system
Foundation	Slab-on-grade	Slab-on-grade
Infiltration	1583 CFM50 as tested using a blower-door	1383 CFM50 as tested using a blower-door
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, 49 CFM25 duct leakage to the inside, transfer grilles between bedrooms and main living space	Ducts inside conditioned space, 44 CFM25 duct leakage to the inside, transfer grilles between bedrooms and main living space
Ventilation	Central fan integrated supply (CFIS) ventilation w/ Aprilaire VCS model 8126, motorized damper, 33% duty cycle	Central fan integrated supply ventilation (CFIS) w/ Aprilaire VCS model 8126, motorized damper, 33% duty cycle

Figure 1. DR Horton 1-story test house (1111 Montague).

Figure 2. DR Horton 2-story test house (1117 Montague).

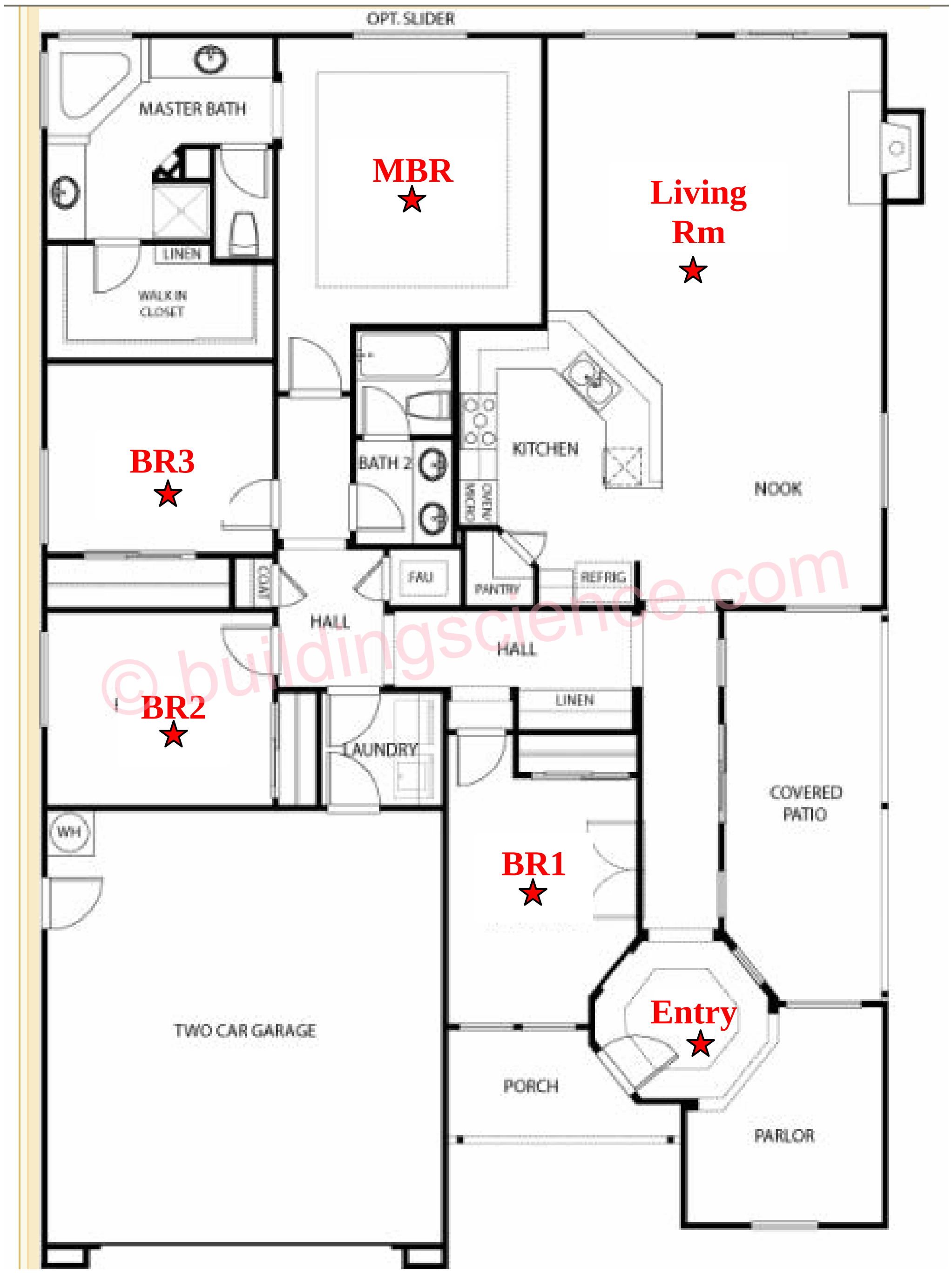

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Figure 3. 1-story test house floor plan (1111 Montague).

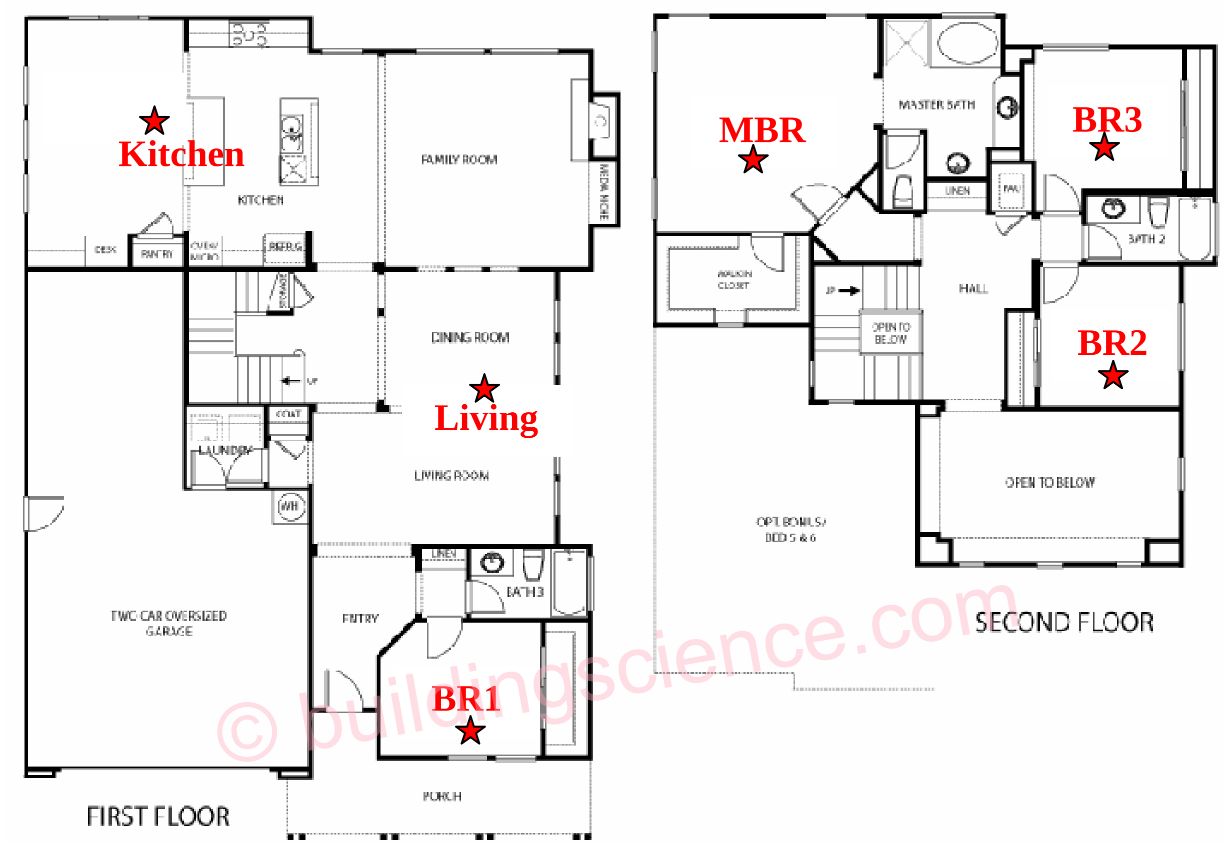

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Figure 4. 2-story test house floor plan (mirror image of 1117 Montague).

TEST PLAN

Research Questions

The following series of research questions were identified by the researchers to quantify the ventilation distribution characteristics of the test houses under various operating conditions:

1. What is the natural air change rate (ACH) for each house with bedroom doors open, no air handler operation, and no mechanical ventilation? What is the room-to-room uniformity in outside air distribution?
2. What is the change in whole-house ACH caused by air handler operation? What is the change in room-to-room uniformity of outside air distribution?
3. What is the change in whole-house ACH caused by closing the bedroom doors? What is the change in room-to-room uniformity of outside air distribution?
4. What is the change in whole-house ACH caused by taping over the transfer grilles? What is the change in room-to-room uniformity of outside air distribution?
5. What is the difference in whole-house ACH for a central-fan integrated supply ventilation system (CFIS) operating at 33% duty cycle compared to a continuous exhaust ventilation

system, with both systems meeting the ASHRAE 62.2 recommended minimum ventilation rate on average? How does the resulting room-to-room uniformity of outside air distribution compare?

6. How does the whole-house ACH and uniformity of outside air distribution change for a CFIS ventilation system when the ventilation rate is lowered from 100% of the ASHRAE 62.2 recommendation to 60% and to 33%?
7. How does the whole-house ACH and uniformity of outside air distribution change for the continuous exhaust ventilation system when the location of the exhaust port is changed from the utility room to the master bathroom?
8. How uniform is the outside air distribution for the two-story house compared to the one-story house?

Test Set-Up

Single-tracer gas decay with multi-zone sampling was used to evaluate the performance of each ventilation system based on how uniformly outside air was distributed to each room or zone 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 lower concentration of the tracer than the air already in the zone. This test method is designed as a practical method to evaluate the uniformity of ventilation air distribution within a home, assuming that dangerous pollutants such as radon are controlled using appropriate source mitigation strategies. Uniform distribution of outside air is required for dilution ventilation systems to provide predictable results independent of the geometry of individual homes.

A multi-zone tracer gas sampling system was installed in each house for the test. This equipment consisted of a Bruel and Kjaer model 1302 multi-gas monitor and a model 1303 multi-point sampler, as shown in Figure 5. 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 3 and 4. 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 air sample in each zone was taken near the center of the room at a height of four feet above the floor. The zone air temperature was measured at the same location. The local zone air temperature measurement was used to control the electric heater in each zone (see Test Procedure section below) to achieve a uniform and constant air temperature throughout the house. Mixing fans were used to maintain uniform temperatures and concentrations within each room. A photo of this set up is shown in Figure 6.

Figure 5. Multi-zone tracer gas sampling and monitoring equipment.

Figure 6. Tracer gas sampling point, temperature sensor, room air mixing and co-heating set-up.

The air flow rates for both supply and exhaust ventilation were carefully controlled during the test using a Duct Blaster fan and measurement system. For exhaust ventilation, the Duct Blaster fan was placed near the location of the ceiling exhaust fan and a length of flexible duct was used to connect the normal entrance for the exhaust fan to the Duct Blaster. All of the air flowing through the exhaust fan during the test was first routed through the Duct Blaster. The Duct Blaster speed control was adjusted to achieve the desired flow rate and the Duct Blaster flow ring and pressure tap were used to measure the air flow rate. The exhaust fan itself was operated in conjunction with the duct blaster to reduce the resistance to air flow. Figure 7 shows the Duct Blaster installed at the laundry room exhaust register.

Figure 7. Duct Blaster installed at the laundry room exhaust register.

A similar application of the Duct Blaster was used to control and measure the supply air flow rate during the tests of the 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 Duct Blaster. The flexible duct was disconnected from the air handler return and attached to the inlet to the Duct Blaster. The Duct Blaster outlet duct was attached to the air handler return. The Duct Blaster speed control was used to achieve the desired air flow rate and the Duct Blaster flow ring and pressure tap were used to measure the flow rate. This installation is shown in Figure 8.

Natural infiltration rates varied during the tests depending on weather conditions, which were monitored using a portable weather station.

It should be noted that the supply ventilation ducts in the test houses were not sized for the flow rates desired in the tests. The ventilation flow rate measured during normal operation of the air handler in the 1-story house was about 10 cfm compared to 174 cfm required to meet the ASHRAE 62.2 recommendations. This flow rate was also significantly less than the design flow rate of about 40-60 cfm. It was necessary to operate the Duct Blaster fan at maximum power to achieve the required air flow rate during some tests. It was unclear if the outside air duct was too long, too small, or too tortuous, or if insufficient negative pressure was present at the return of the air handler because the central return grille was just a few inches away (see Figure 8).

Figure 8. Duct Blaster installed between the outside air duct and the return of the air handler to provide supply ventilation.

Test Procedure

The tracer gas used was sulfur hexafluoride (SF_6), a stable, non-toxic gas that was injected into each house volume from a small compressed gas cylinder carried by hand around the house. During the dosing period, the furnace fan 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 de-stratification fan was used in the 2-story house to improve mixing between floors. Then the mixing fans were stopped, and the divergence in concentration from zone to zone was observed (with doors either open or closed depending on the test objective). Small portable fans in each zone continued running to maintain a well-mixed condition within each zone. The interior air temperature in each zone was controlled during the test period using portable electric heaters instead of the furnace, so that operation of the air handler could be controlled independently from the demand for heating. At the conclusion of the test, the whole house was again mixed by opening the doors and turning on the air handler. This allowed the calculation of an average whole-house air change rate for each set of test conditions.

The tests were planned for rather mild weather to minimize infiltration effects, so as to isolate and test the performance of the mechanical ventilation systems. The general design goal was to provide the minimum amount of mechanical ventilation recommended by ASHRAE Standard 62.2-2004 (ASHRAE 2004) (58 cfm for the 1-story house, 63 cfm for the 2-story house), and observe the effects of providing central fan integrated supply versus single-point exhaust ventilation, operating the central fan, closing the bedroom doors, and taping the transfer grilles above the doors.

The results of the multi-zone tracer gas decay tests are presented graphically as families of decay curves. These graphs illustrate the uniformity or non-uniformity of the ventilation effect among the various rooms, and allow ranking of the rooms from the least to the most ventilation effect.

In addition, if the ventilation rates were sufficiently steady for the duration of the test period, we used local mean age-of-air analysis to evaluate the results more quantitatively. Age-of-air analysis is a well-established approach to testing ventilation rates at various points or in various zones within a building (Grieve 1991). Age-of-air is defined as the average length of time that air molecules have resided within the building. The formula for calculating local mean age-of-air in a tracer gas decay test is given in 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 representing a well-mixed zone
A_i = Local mean age-of-air at point i (hr)
C = Concentration of tracer gas (lb_m/ft^3)
C_0 = Initial value of C in well-mixed building (lb_m/ft^3)
C_i = Time-varying concentration of tracer gas at point i (lb_m/ft^3)
t = Time (hr).

In order to compare the ventilation rates among the rooms or zones in the home, we use the metric Reciprocal Age-of-Air:

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

Reciprocal Age-of-Air has units of 1/hr and is equivalent to the air change rate (ACH) in a single, well-mixed zone (Persily 2000).

The definition of A_i in Equation (1) involves an integral of infinite duration. This is handled in the test procedure through a two-step process:

Step 1. The tracer gas decay test is continued until (a) the initial transient effects of interzonal airflow have subsided and all of the decay curves resemble simple exponential functions, and (b) the tracer concentrations are rather small compared to their initial values, so that any extrapolation errors will have a small effect on the result. In this field test, most of the multi-zone tests were continued for 12 hours. These portions of the decay curves were integrated numerically using the trapezoid rule.

Step 2. The remaining portions (the tails) of the decay curves were extrapolated to infinity using 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.

Once the conditions of Step 1 were satisfied, the rooms were re-mixed by opening the bedroom doors and operating the air handler. This allowed the calculation of an effective whole-house air change rate using the relationship in Equation 3.

$$\text{Average whole-house air change rate (ACH)} = \ln(C_0/C_f)/\Delta t \qquad (3)$$

where:

C_f = Concentration of tracer gas after rooms are re-mixed (lbm/ft^3)
Δt = Elapsed time between initial and final well-mixed cases (hr)

Test Matrix

The series of test conditions for the 1-story and 2-story houses are described in Tables 2 and 3. Most of the important tests were conducted for a 12-hour period overnight to ensure sufficient accuracy when calculating reciprocal age-of-air.

Table 2. Test sequence for 1-story test house

Test #	Date	Time	Duration (hrs)	Vent. Config.	Vent. flow rate (cfm)	Central fan cycling (min off, min on)	Doors	Notes
A1	Dec 28	AM	3	Exhaust	58	none	closed	
A2		PM	3	Exhaust	58	20,10	closed	
A3		overnight	12	Exhaust	58	none	closed	
A4	Dec 29	AM	4	Supply	104, 33% duty cycle	20,10	closed	
A5		PM	4	Supply	58, 33% duty cycle	20,10	closed	
A6		overnight	12	Supply	174, 33% duty cycle	20,10	closed	
A7	Dec 30	AM-PM	8	None	0	none	open	Natural infiltration
A8		PM	2	None	0	none	open	AH bump
A9		overnight	12	Exhaust	58	none	open	
A10	Dec 31	AM-PM	6	Exhaust	58	none	closed	Transfer grills taped
A11		PM	6	Exhaust	58	20,10	closed	Transfer grills taped
A12	Jan 1	overnight	12	Exhaust	58	20,10	closed	
A13		PM	6	Exhaust	58	20,10	open	
A14		overnight	12	Exhaust	58, 54	none	closed	
A15	Jan 2	AM-PM	6	None	0	none	closed	Natural infiltration
A16		overnight	12	Exhaust	58	none	closed	Master bath exhaust

Table 3. Test sequence for 2-story test house

Test #	Date	Time	Duration (hrs)	Vent. Config.	Vent. flow rate (cfm)	Central fan cycling (min off, min on)	Doors	Notes
B1	Jan 3	overnight	14	Exhaust	63	none	closed	
B2	Jan 4	PM	5	Supply	114, 33% duty cycle	20, 10	closed	60% ASHRAE 62.2
B3		overnight	11	Supply	180, 33% duty cycle	20, 10	closed	95% ASHRAE 62.2
B4	Jan 5	PM	4	Supply	63, 33% duty cycle	20, 10	closed	33% ASHRAE 62.2
B5		overnight	13	Exhaust	63	50,10	closed	
B6	Jan 6	PM	6	Exhaust	63	20,10	closed	
B7		overnight	12	Exhaust	63	none	closed	Transfer grilles taped
B8	Jan 7	AM	4	Exhaust	63	50, 10	closed	Transfer grilles taped
B9		PM	4	Exhaust	63	none	closed	Transfer grilles taped, extra injection in MBR
B10		PM	2	Exhaust	63	none	open	
B11		overnight	9	Supply	114, 33% duty cycle	20, 10	closed	Transfer grilles taped
B12	Jan 8	PM	3	None	0	100%	closed	Transfer grilles taped, air handler bump test
B13		PM	2	None	0	100%	closed	Transfer grilles untaped
B14		PM	2	None	0	none	open	Natural infiltration
B15		overnight	9	Exhaust	63	none	closed	Master bath exhaust, transfer grilles taped
B16	Jan 9	AM	4	Exhaust	63	50, 10	closed	Master bath exhaust
B17		PM	4	Supply	178, 33% duty cycle	20, 10	closed	
B18		overnight	12	Exhaust	63	none	closed	Master bath exhaust

TEST RESULTS FROM 1-STORY HOUSE (1111 MONTAGUE)

Natural Infiltration

A test of natural infiltration was conducted for an 8-hour period on December 30 to examine the magnitude and variability of outside air entering the house through leaks in the building envelope (Test A7). The tracer gas decay curves are shown in Figure 9. It is evident that the house was very well mixed during this test, which allows a running, instantaneous calculation of whole-house ACH over the same time period (see Figure 10). Although the air change rate indicated that the house is 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 exchange rate, including duct leakage to the outside and changes in room-to-room pressurization caused by moving air from the supply registers in each room to the central return in the main living area. Figure 10 shows both the hourly average ACH and the wind speed during this period. At first glance it appears that the air change rate increased by about 0.03 ACH when the fan 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. Ultimately, we cannot conclusively quantify the change in ACH associated with operation of the air handler, but it appears to have been no more than 0.03 ACH.

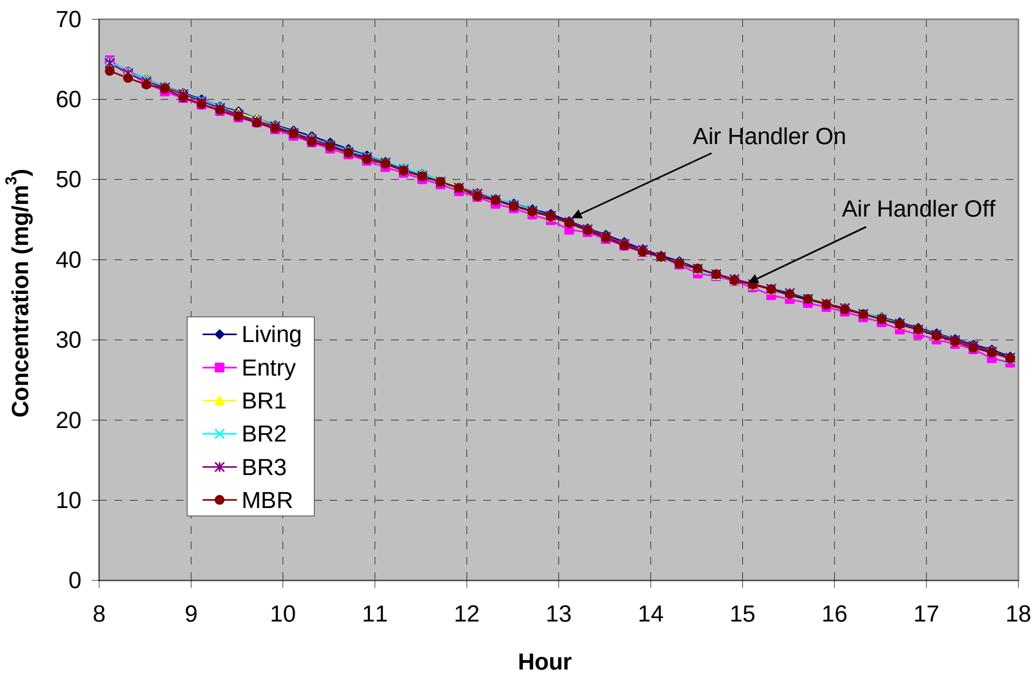

Figure 9. Tracer gas decay for 1-story house with no ventilation and bedroom doors open, with and without central fan operation (Test A7).

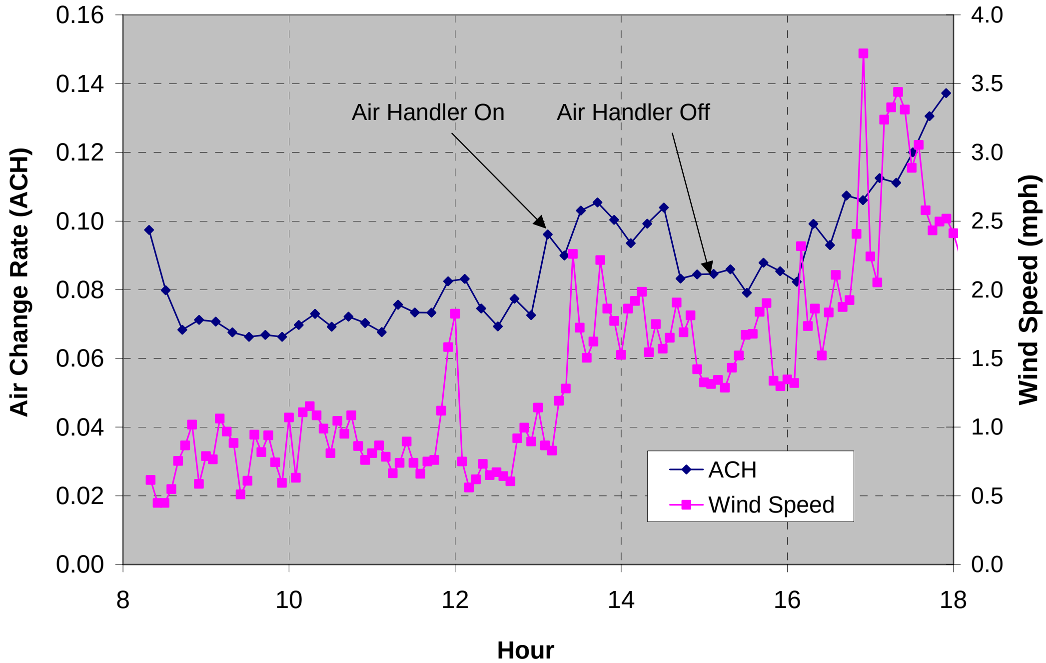

Figure 10. Average air change rate for 1-story house with no ventilation, no central fan operation, and bedroom doors open (Test A7).

The natural ventilation test was repeated on January 2 with the doors closed instead of open (Test A15), providing the decay curves shown in Figure 11. 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. It is difficult to compare this number with the doors-open case because it was windy (4-5 mph) for the first few hours of this test. However, it is very clear that the uniformity of room-to-room distribution of outside air was significantly less when the doors were closed, even with transfer grilles. 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 hour 15, where the BR2 and BR3 curves suddenly begin to diverge from the MBR curve.

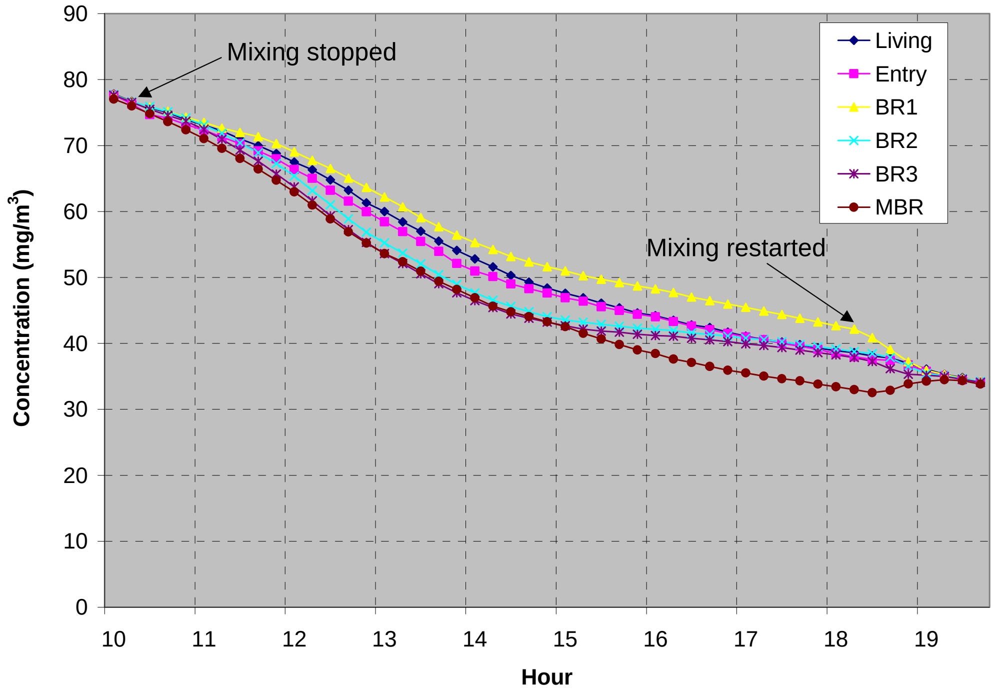

Figure 11. Tracer gas decay for 1-story house with no ventilation, no central fan operation, and bedroom doors closed (Test A15).

Distributed Supply vs Point Exhaust Ventilation

Two of the most common ventilation schemes in Building America homes are continuous single-point exhaust ventilation and intermittent central-fan integrated supply (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 upon depressurization of the house. The distribution of outside air in a given room is 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. Supply ventilation provided by a central-fan integrated system tends to be distributed more uniformly throughout the house. However, the fan is usually operated on a duty cycle of about 33% to limit the electricity used by the central fan, and one of the goals of this testing is to evaluate the effect of that duty cycle on the consistency of the air mixing.

The decay curves for a 12-hour overnight test with exhaust ventilation (Test A3) are shown in Figure 12. The exhaust fan register in the laundry room was used as the exhaust point, and the Duct Blaster was used to exhaust 58 cfm continuously, corresponding to the minimum ventilation rate recommended by ASHRAE for a 2075 ft^2, 4-bedroom house. It is evident from the decay curves that significantly more outside air reached the master bedroom, and less reached Bedroom 2, compared to the other rooms in the house.

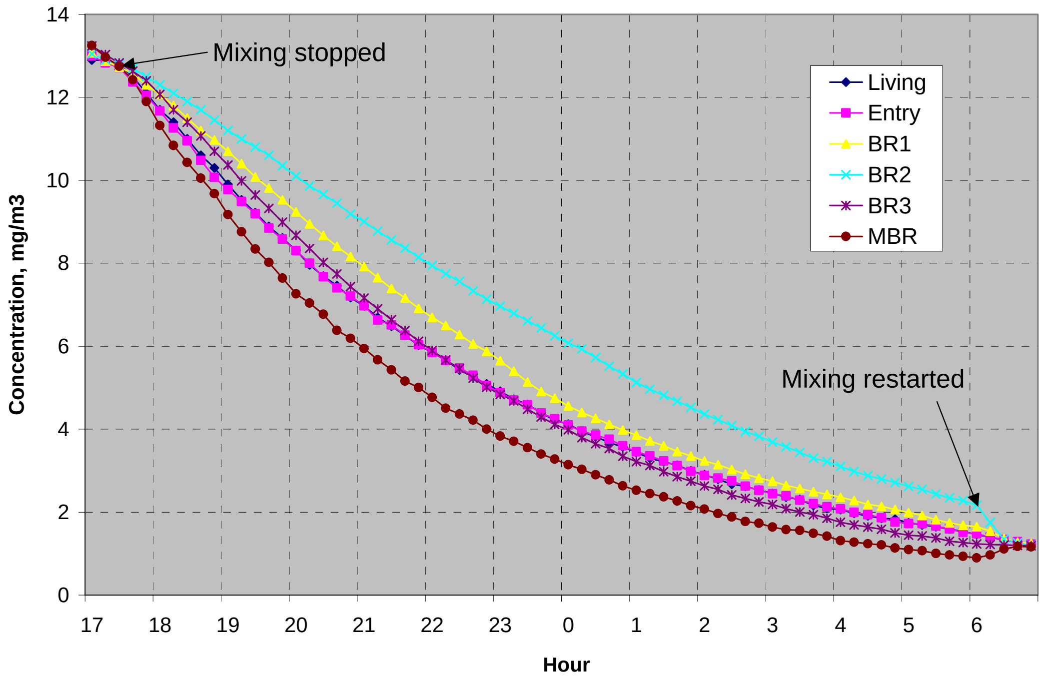

Figure 12. Tracer gas decay for 1-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and bedroom doors closed (Test A3).

The corresponding decay curves for the central fan integrated supply system (Test A6) are shown in Figure 13. The air handler operated at a 33% duty cycle (20 min. off, 10 min. on) with a ventilation rate of 174 cfm, resulting in an average ventilation rate of 58 cfm, again meeting the minimum ASHRAE 62.2 recommendations. The whole house appeared to be well-mixed 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 12 to Figure 13 indicates that much more uniform distribution of ventilation air was achieved by using the CFIS system.

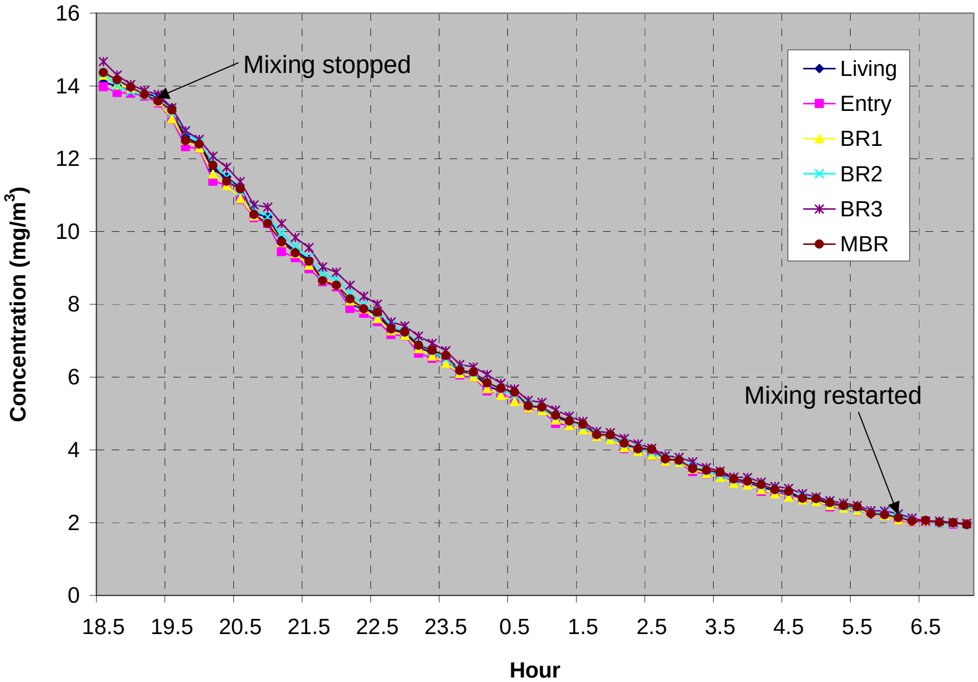

Figure 13. Tracer gas decay for 1-story house with supply ventilation at ASHRAE 62.2 level, 33% central fan operation (20 min. off, 10 min. on), and bedroom doors closed (Test A6).

Reciprocal age-of-air calculations were performed to provide a quantitative comparison of the two ventilation systems, as shown in Figure 14. Values were in the range of 0.169 hr^{-1} +0.042/-0.038 hr^{-1} for the exhaust ventilation system, compared to 0.173 hr^{-1} +0.002/-0.003 hr^{-1} for the supply ventilation system, expressed in terms of the range of differences between the reciprocal age-of-air in each room and the whole-house air change rate. With the exhaust ventilation at the laundry room, the master bedroom received the greatest amount of fresh air. We suspect this may have been caused by the presence of the exhaust ducts used for spot ventilation of the master bathroom, possibly providing greater leakage area near the master bathroom than is present in other areas of the house. The supply system distributed the ventilation air more uniformly, but it is not entirely clear whether this result was primarily caused by the introduction of ventilation air through the supply ducts, or by the air handler mixing air throughout the house. Since it is clear that the exhaust ventilation showed better uniformity of ventilation with central system mixing, it follows that mixing is likely to be the primary factor in the room-to-room uniformity shown by CFIS ventilation.

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 results in an estimated average air change rate of 0.19 ACH, which is fairly consistent with the measured values.

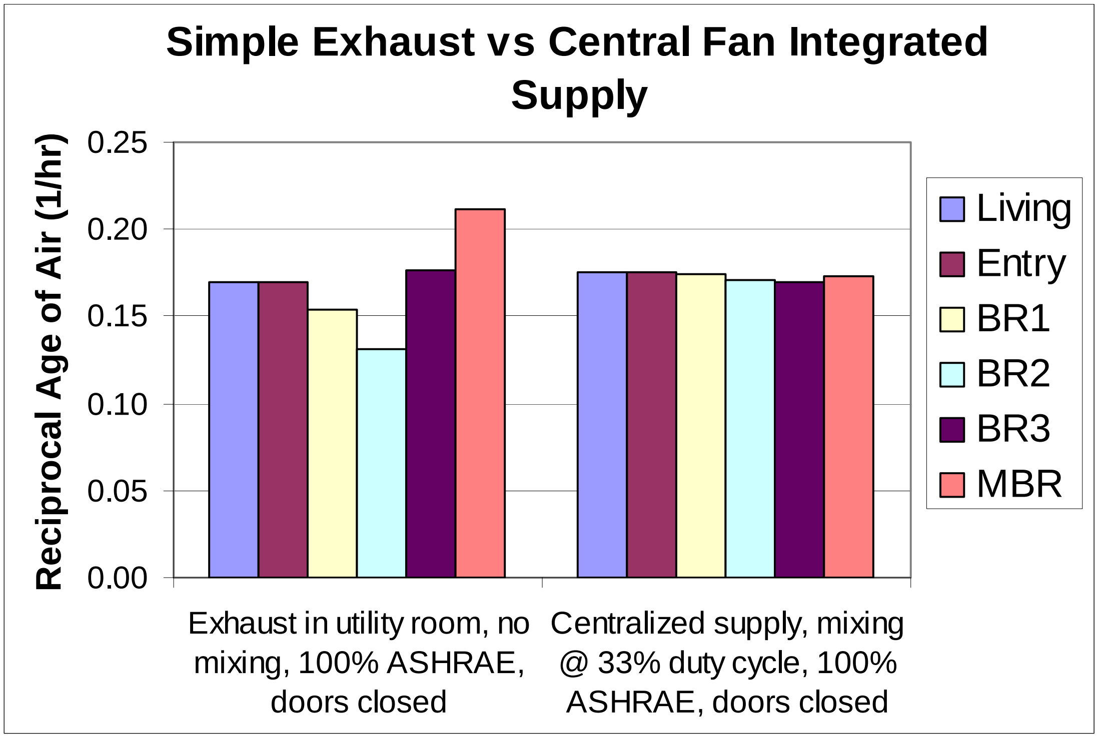

Figure 14. Reciprocal age-of-air for 1-story house with continuous exhaust ventilation (Test A3) compared to central fan integrated supply ventilation (Test A6).

Air Handler Operation

To determine how much room-to-room mixing was caused by the air handler, the exhaust only test was re-run with the air handler operating at 33% duty cycle (20 min. off, 10 min. on) (Test A12). The decay curves are shown in Figure 15. Compared to Test A3 (Figure 12), 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 16, the range of reciprocal age of air was reduced from +0.042/-0.038 hr^{-1} to +0.019/-0.011 hr^{-1}). It appears that operation of the air handler explains most of the difference between the supply and exhaust ventilation systems discussed earlier. Although it also appears that the overall average air change rate was higher in the case where the air handler was operating (0.216 ACH vs 0.176), it should be noted that the average wind speed was also significantly higher. It is likely that the wind speed was the primary cause of the difference in average ACH, not a difference in the mechanical ventilation rate.

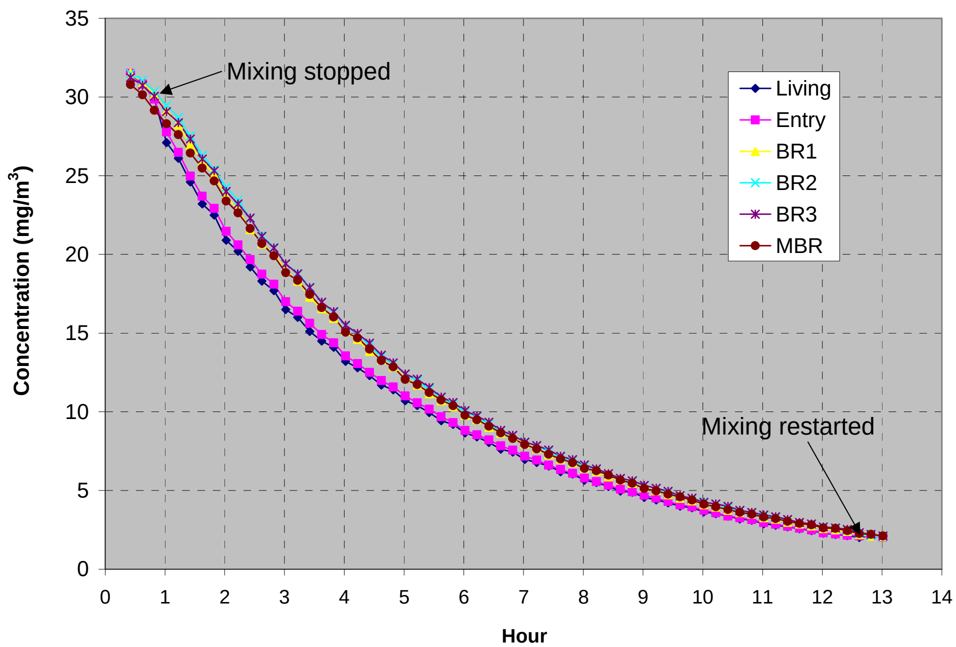

Figure 15. Tracer gas decay for 1-story house with continuous exhaust ventilation at ASHRAE 62.2 level, 33% central fan operation (20 min. off, 10 min. on), and bedroom doors closed (Test A12).

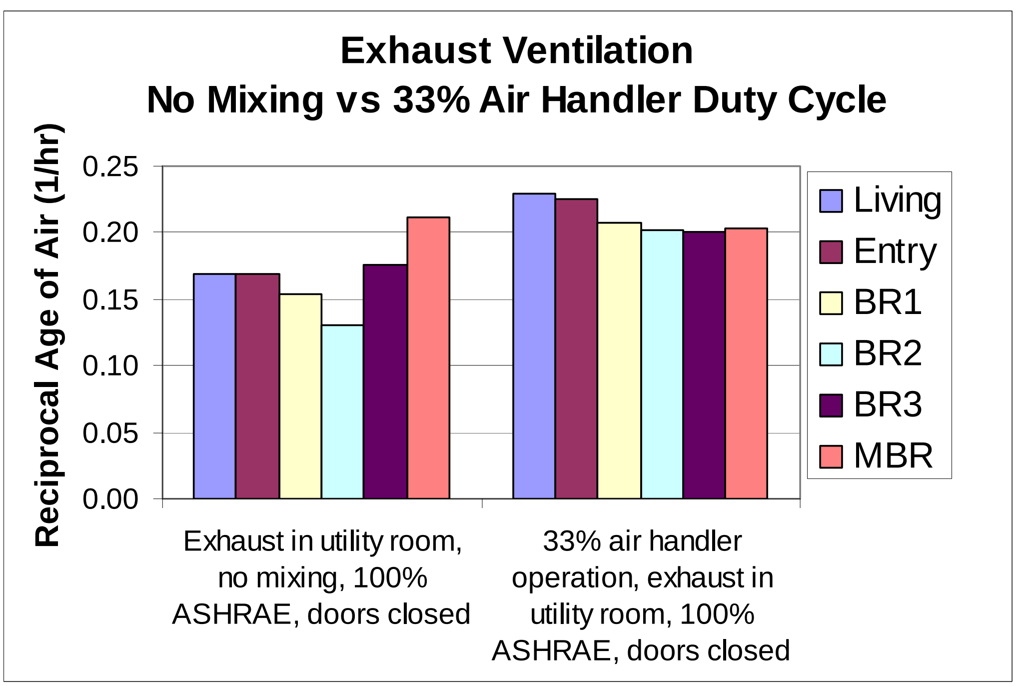

Figure 16. Reciprocal age-of-air for 1-story house with continuous exhaust ventilation with and without air handler operation (Tests A3 and A12).

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 1-story house. To examine the effect of moving the exhaust point, the duct blaster was moved to the master bathroom, which was located in a far corner of the house (Test A16). A continuous exhaust ventilation rate of 58 cfm was again applied to the house, resulting in the tracer gas decay curve shown in Figure 17. It is difficult to visually identify a significant difference between this series of curves and those shown in Figure 12 for the laundry room exhaust location.

Because the curves were steady, it is again possible to compare the results based on reciprocal age-of-air, as shown in Figure 18. 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 of the rooms in the house, and the BR2 location had the lowest.

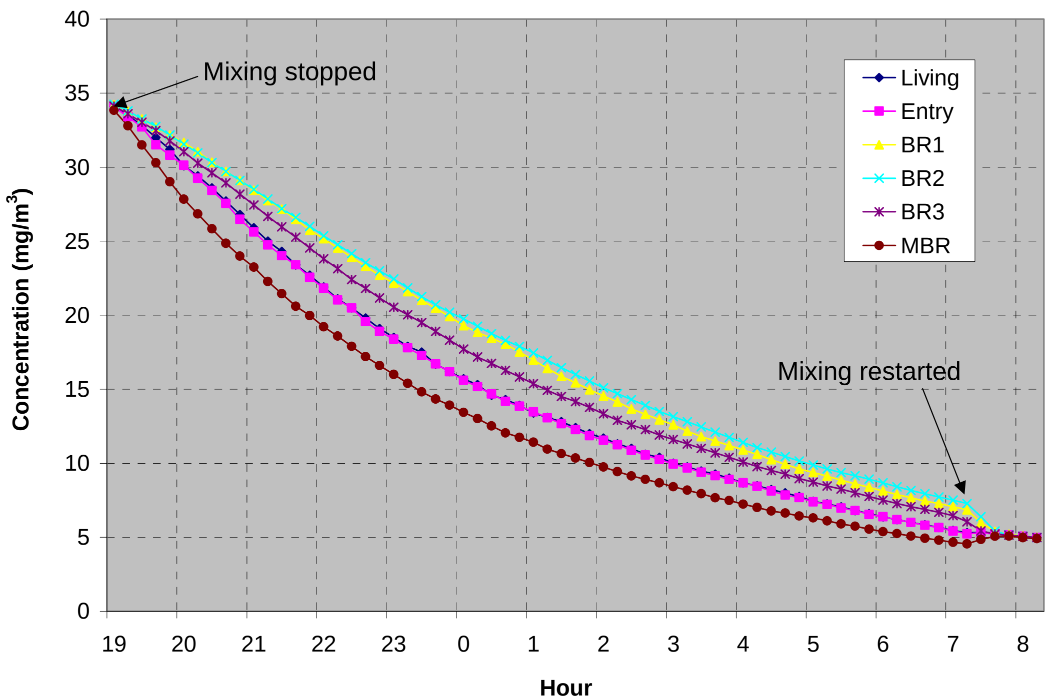

Figure 17. Tracer gas decay for 1-story house with exhaust ventilation from the master bathroom at ASHRAE 62.2 level, no central fan operation, and bedroom doors closed (Test A16).

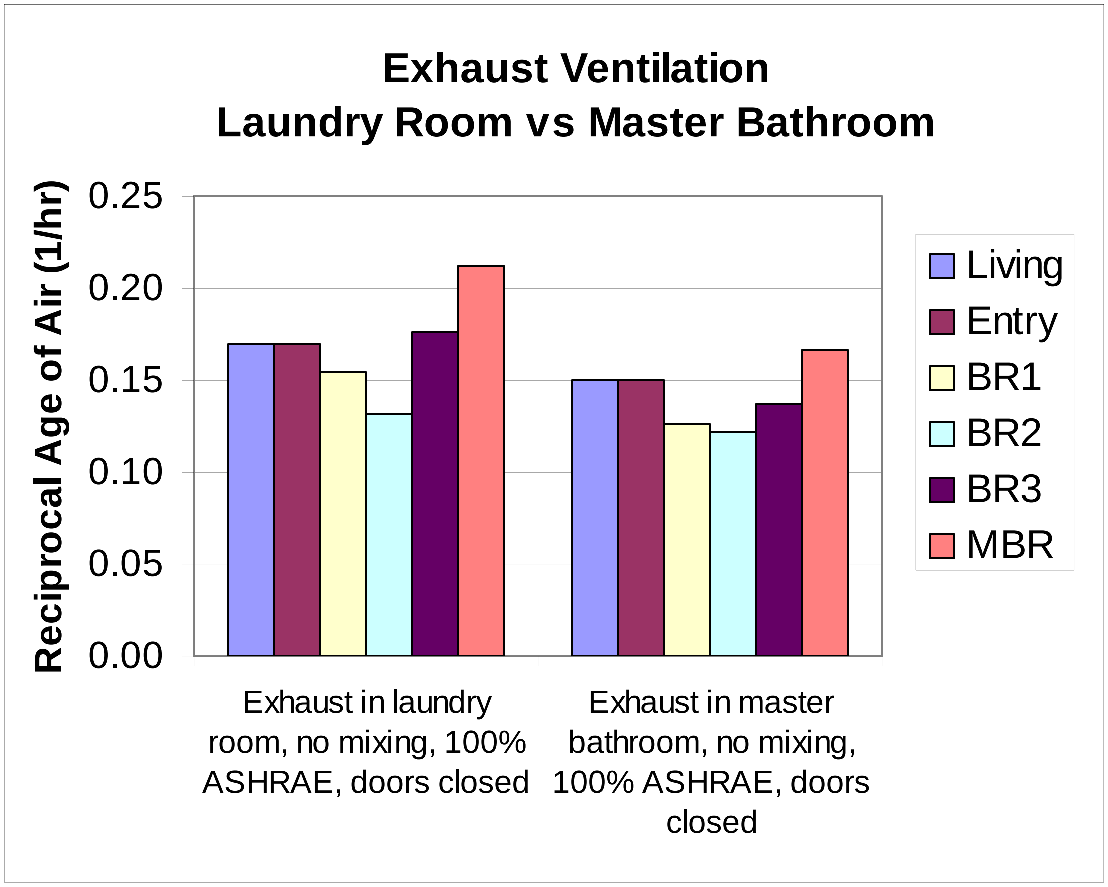

Figure 18. Reciprocal age-of-air for 1-story house with exhaust ventilation from the master bathroom compared to the laundry room at ASHRAE 62.2 level, no central fan operation, and bedroom doors closed (Tests A3 and A16).

Ventilation Rate

The supply ventilation test was repeated using flow rates corresponding to 60% and 33% of the ASHRAE recommendations. The intent of this series of tests was to evaluate the room-to-room ventilation uniformity 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. The decay curves are shown in Figures 19 and 20. Because the rooms were well-mixed during the supply ventilation tests, the average whole-house ACH can be compared directly to the reciprocal age-of-air for the exhaust ventilation tests. Figure 21 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 based on the boundary conditions present during the tests. It appears that in the supply ventilation case, all rooms receive more outside air than the least-ventilated room in the exhaust case (BR2), even at 60% of ASHRAE 62.2. These results serve to illustrate the trade-off between whole-house ventilation rate and room-to-room ventilation uniformity, in terms of their impact on the worst room(s).

The ASHRAE 62.2 committee has not currently defined the level of mixing that is required when choosing the minimum ventilation rate. Some might interpret the results of this test to suggest that a house without mixing can have individual rooms that do not receive sufficient outside air even though the ventilation system is operating at 62.2 specified rates. Because the 62.2 committee has not specified the level of mixing that is required when choosing the minimum ventilation rate, the ventilation rate required by different ventilation systems is open to interpretation. For example, if the exhaust system performance shown in Figure 21 is acceptable, does this mean that a ventilation system that provides good distribution of outside air may be sufficiently well-ventilated at 60% of the ASHRAE 62.2 level, or perhaps even less? Alternatively, it might be concluded that exhaust ventilation rates should be increased over current ASHRAE 62.2 recommendations because of the possibility that certain rooms may receive very little fresh air. Unfortunately, because the current 62.2 standard does not specify air mixing requirements and the committee's assumptions about ventilation air distribution are not well documented, it is difficult to make any firm recommendations in this area. However, we can conclude that air mixing is required for dilution ventilation systems to provide predictable results independent of the geometry of individual homes.

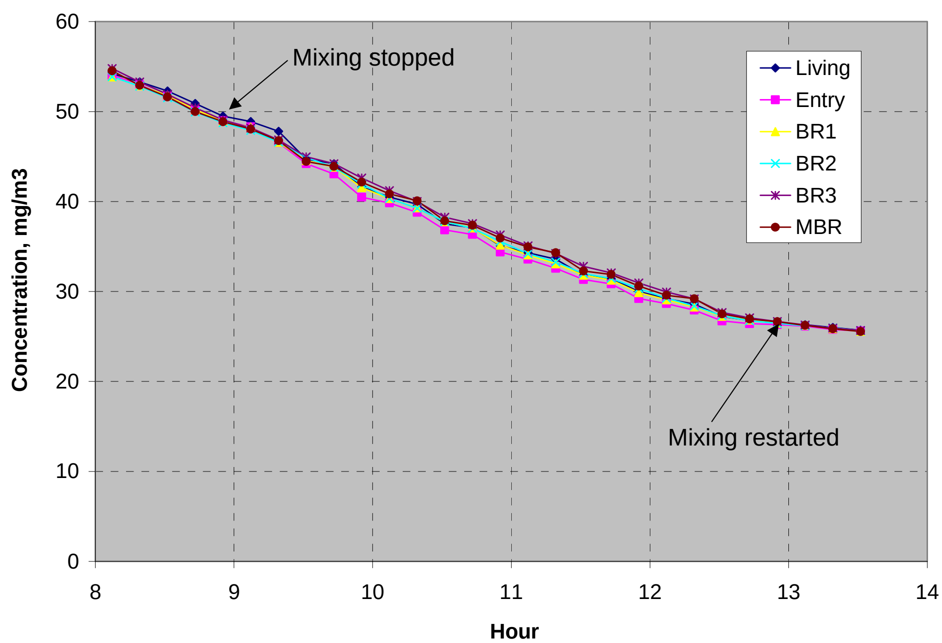

Figure 19. Tracer gas decay for 1-story house with supply ventilation at 60% of ASHRAE 62.2 level, 33% central fan operation (20 min. off, 10 min. on), and bedroom doors closed (Test A4).

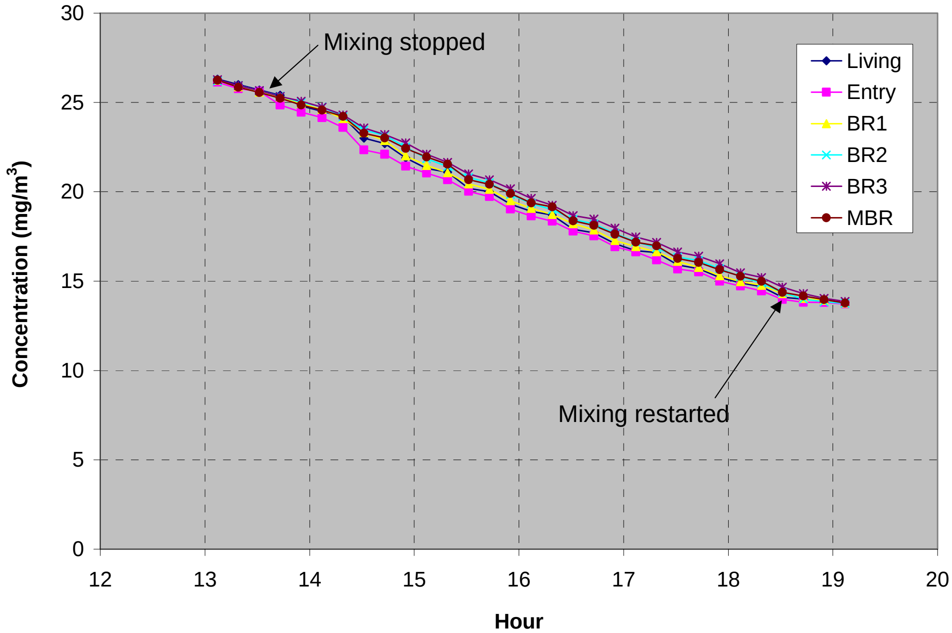

Figure 20. Tracer gas decay for 1-story house with supply ventilation at 33% of ASHRAE 62.2 level, 33% central fan operation (20 min. off, 10 min. on), and bedroom doors closed (Test A5).

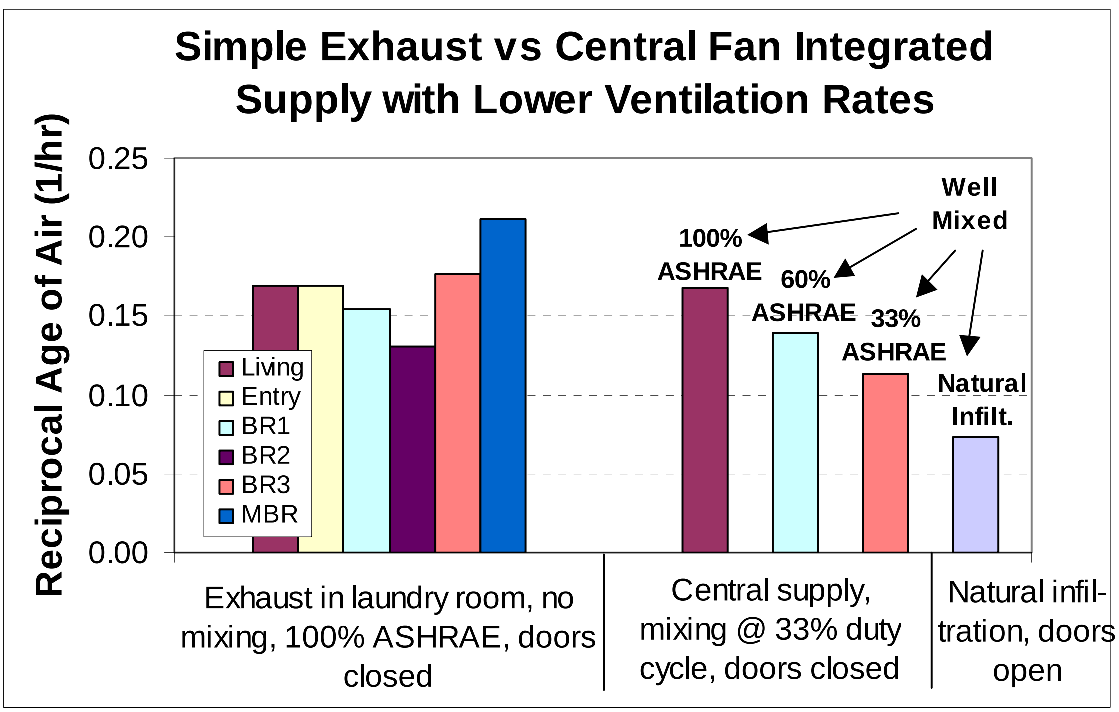

Figure 21. Reciprocal age-of-air for 1-story house with supply ventilation at 33%, 60%, and 100% of ASHRAE 62.2 level (Tests A5, A4, A6) compared to exhaust ventilation with no central fan operation (Test A3). Bedroom doors were closed.

Simulations by Walker (2006) have shown that all systems will not 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 don't change the enclosure differential pressure and air flow at all. Because of the non-linear 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. The result is that the effect on ventilation air change rate from a supply fan is somewhere between that of an exhaust fan and a true balanced system.

Bedroom Doors

Except for the natural ventilation test, the preceding tests were all conducted with the bedroom doors closed to simulate a worst-case situation for air circulation within the house. The exhaust ventilation test was repeated with the bedroom doors open (Test A9), producing the tracer gas decay curve shown in Figure 22. It is evident that the decay curves were much more tightly bundled with the doors open than they were with the doors closed (compare Figure 12). A comparison based on reciprocal age-of-air is shown in Figure 23. A significant improvement in room-to-room mixing is evident during the open-door test.

It is also evident that the average air change rate was higher when the doors were open (0.202 vs 0.176 ACH), but it must be remembered that the ventilation rate was controlled using a duct blaster, and 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). Therefore, this test alone 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 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 (with uncontrolled ventilation rate) instead of the duct blaster to observe the net effect of closed doors on whole-house air change rate.

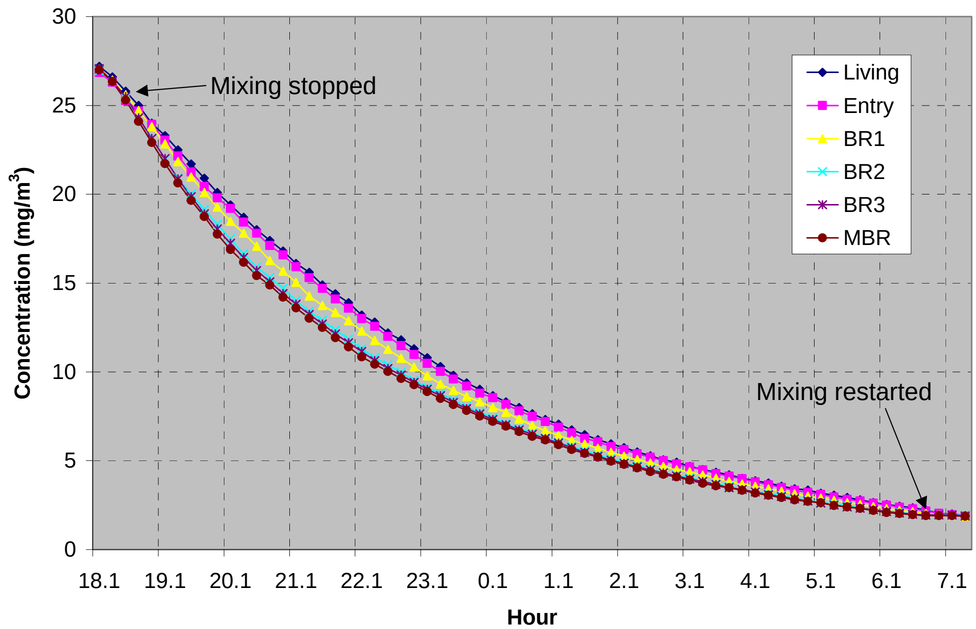

Figure 22. Tracer gas decay for 1-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and bedroom doors open (Test A9).

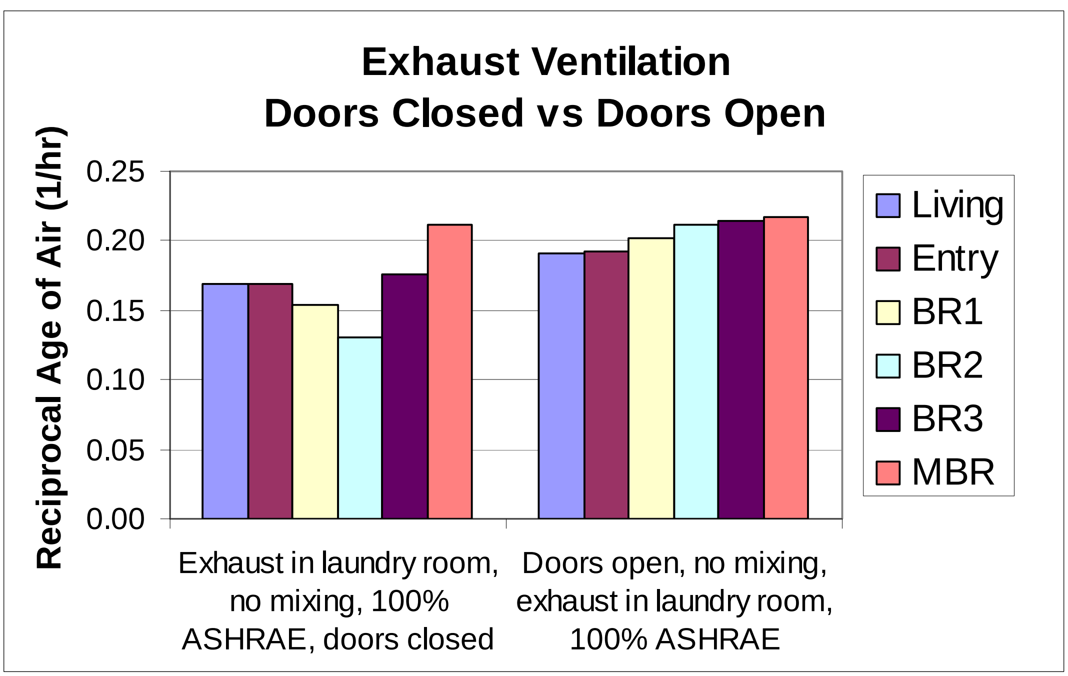

Figure 23. Reciprocal age-of-air for 1-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation. In the first case the bedroom doors were closed (Test A3), in the second the doors were open (Test A9).

Transfer Grilles

Because the test houses used central returns instead of 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 air to pass more freely from the bedrooms to the main living space. The effect of transfer grilles on ventilation air distribution was evaluated by taping over the grilles (see Figure 24) and re-running the exhaust ventilation test (Test A10). The corresponding tracer gas decay curve is shown in Figure 25, and the reciprocal age-of-air analysis is shown in Figure 26. Taping the transfer grilles did not appear to significantly affect the room-to-room variability in ventilation rate, although there appeared to be some slight re-ranking of rooms from highest to lowest reciprocal age-of-air. It should be noted that there was an increase in average wind speed from 2.6 mph to 4.1 mph starting at 1 pm, including a half hour period where the average wind speed was 7 mph. This weather effect produced noticeable kinks in the decay curves, and therefore would be expected to introduce significant errors into the reciprocal age-of-air results.

It's possible that the transfer grilles played a much smaller role in providing a path for ventilation air than the supply ducts. 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 smaller for the air ducts than for the transfer grilles, depending on their size and the number of supply registers in each bedroom. The existing door undercuts are also thought to have played a role. The effect of ducts and door undercuts can be tested in the future by running separate tests with ducts and door undercuts taped over.


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Figure 24. Transfer grilles over bedroom doors taped closed.

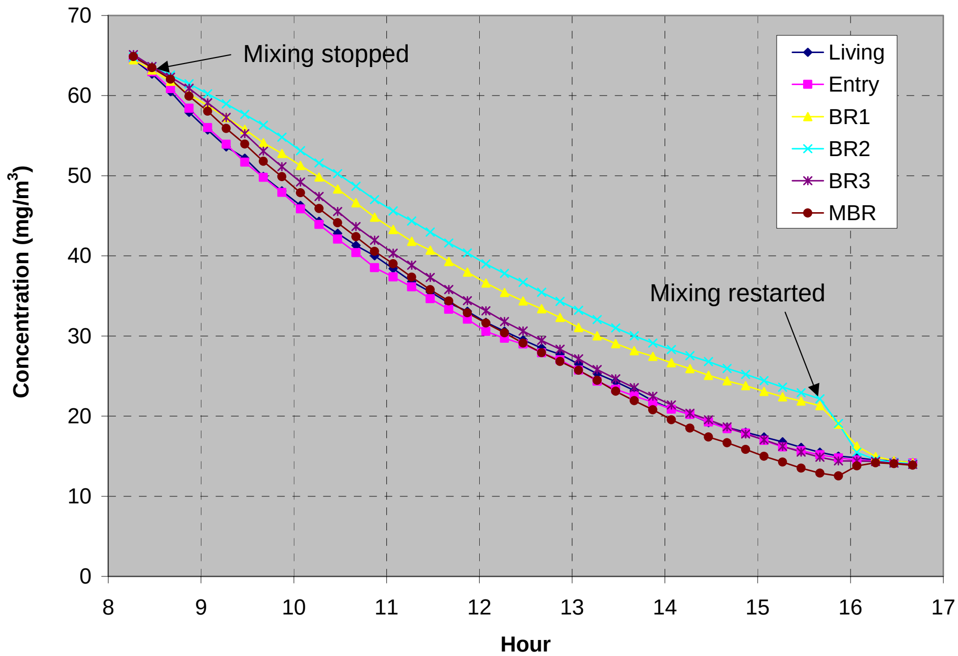

Figure 25. Tracer gas decay for 1-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, bedroom doors closed, and transfer grilles taped (Test A10).

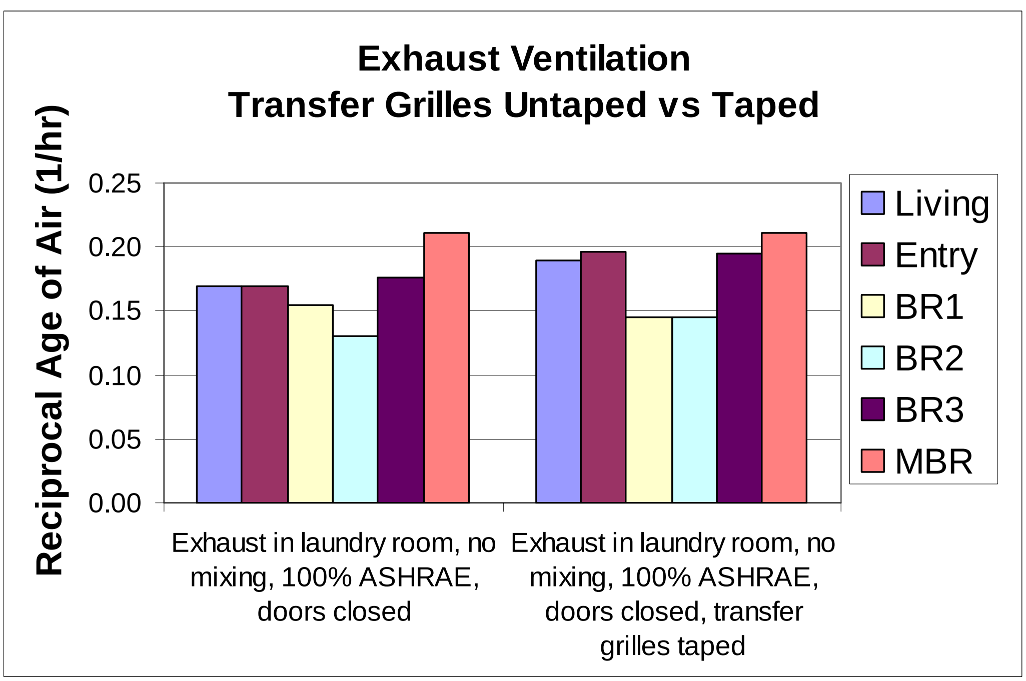

Figure 26. Reciprocal age-of-air for 1-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and doors closed. In the

first case the transfer grilles are untaped (Test A3), in the second they are taped closed (Test A10).

Minimum Test Duration

We were fortunate that DR Horton provided two full weeks of access to these homes to conduct this series of tests, which allowed us to run some of the more important tracer gas decay tests as long as 12 hours to help ensure that we could accurately calculate reciprocal age-of-air. In most cases, test houses would not be available for such a long time period. 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. For the supply ventilation tests, the rooms were sufficiently well-mixed that the test could have been stopped after 3 or 4 hours, assuming weather effects were steady.

The reciprocal age-of-air calculations for the exhaust ventilation decay curves (Test A3, see Figure 12) based on test durations of 3, 6, 9, and 12 hours are shown in Figure 27. These test durations range 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 1½-2 air changes (roughly 9 to 12 hours in this case) may be necessary to obtain accurate calculations of reciprocal age-of-air 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 what mixing pattern will occur, it is difficult to recommend a minimum test duration. But assuming this test is fairly representative of a worst-case scenario, a minimum of 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.

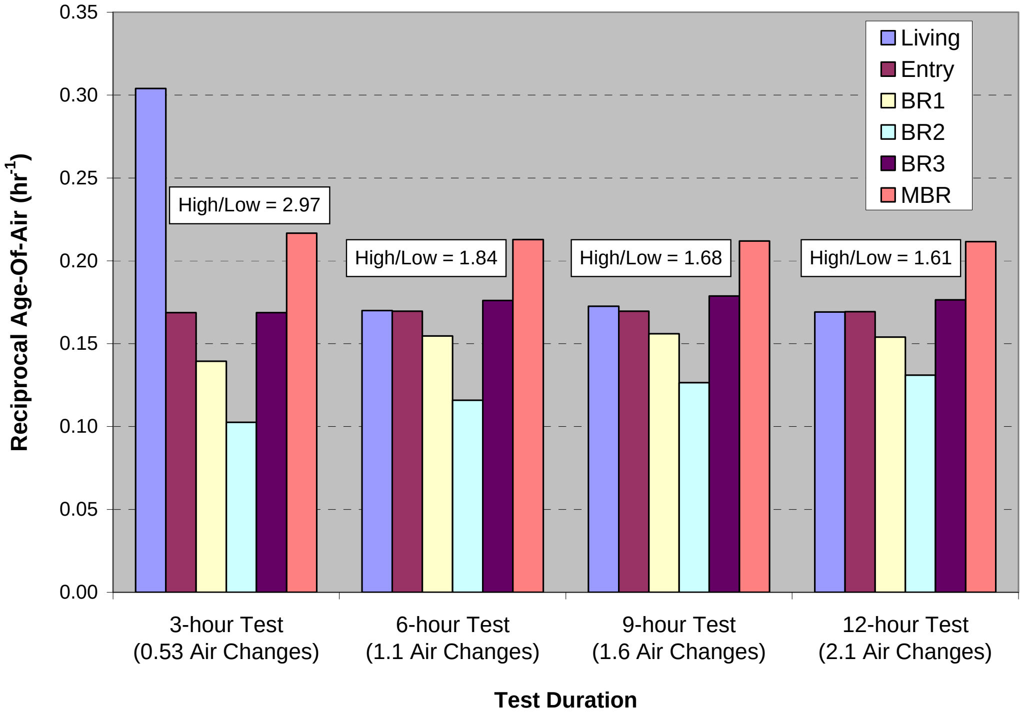

Figure 27. Reciprocal age-of-air based on alternate test durations for 1-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and doors closed (Test A3). Average air change rate was 0.18 ACH.

TEST RESULTS FROM 2-STORY HOUSE (1117 MONTAGUE)

The 2-story house was tested from January 3-10, 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 4. The initial mixing of air among the rooms at the start of each test in this 2-story house was not as thorough as it was in the 1-story house. Evidently, the combined effects of the air handler and the portable de-stratification fan were not sufficient to overcome upward transport of tracer gas, driven by the stack effect, from the first to the second floor. The resulting difference in initial tracer gas concentration among the rooms was about 5-10%. This outcome emphasizes the significant effect of stack-driven infiltration on ventilation non-uniformity in multi-story homes. Because our test method and equipment did not achieve a well-mixed condition at the start of each test, there were some errors introduced into the reciprocal age-of-air analysis. For future tests, we would recommend larger de-stratification 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 such a test were analyzed by examining two hypothetical cases where either all of the air entering a room comes from the outside or all of the air comes from an adjacent room with a different starting concentration. If all of the air entering a space comes from the outside, then 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 will 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. This case is illustrated in Figure 28, where assumptions are made that the rooms are the same size, the air exchange rate is 0.1 ACH for both rooms, and the initial tracer gas concentration is 10% lower in the first room (upstream) than it is in the second room.

The effect on reciprocal age-of-air is shown in Figure 29. A 10% difference in starting concentration results in an error of about 7.5% in reciprocal age-of-air for a room downstream of a room with a lower starting concentration assuming 0.1 ACH for both rooms. The error would be somewhat smaller (about 5%) if the air change rate was higher for both rooms (0.2 ACH). There would be no error introduced for rooms where all of the air infiltration comes from the outside. Although the amount 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 2-story house due to incomplete initial mixing of air.

In each case, an engineering judgment must be made regarding the significance of the error introduced by incomplete initial mixing. As a general rule, the differences in concentration at the start of the test should be small compared to the differences that are being measured, in order for the results to be considered valid.

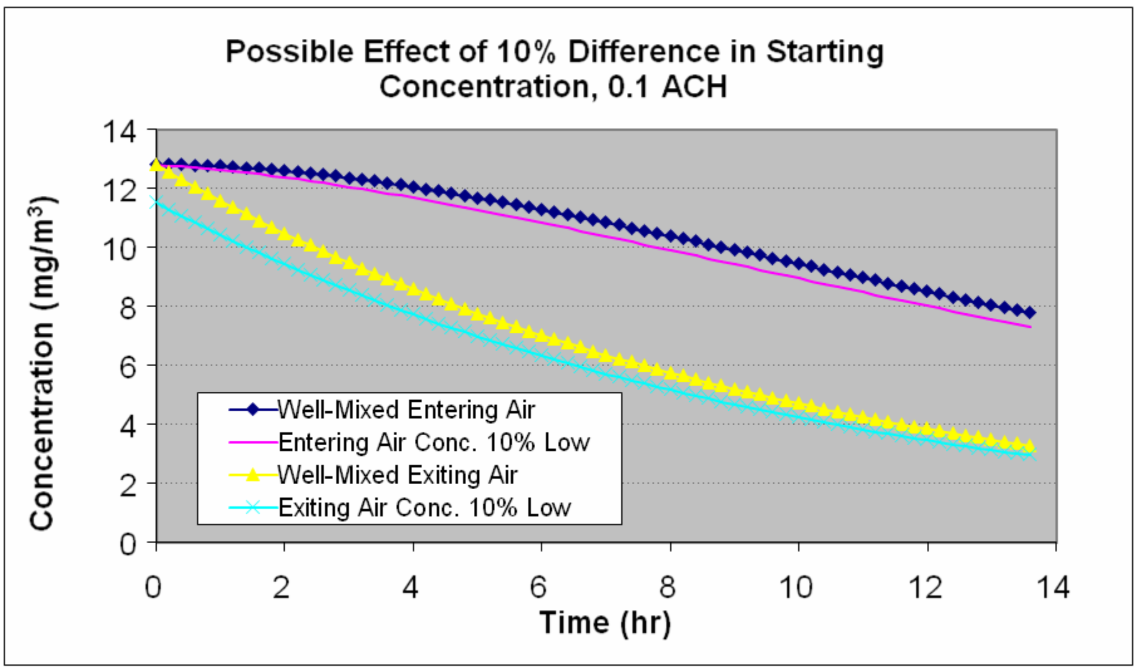

Figure 28. Theoretical decay curves for a well-mixed case with uniform tracer gas concentration compared to a case where the upstream room starts with a concentration 10% lower than the downstream room.

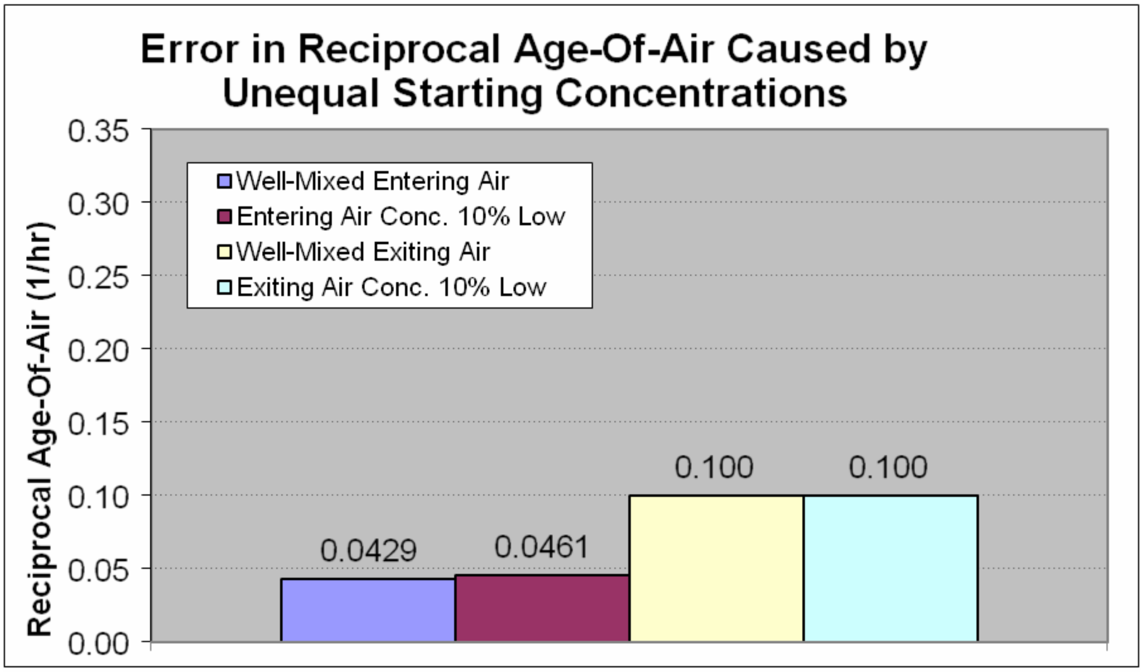

Figure 29. Theoretical reciprocal age-of-air for a well-mixed case with uniform tracer gas concentration compared to a case where the upstream room starts with a concentration 10% lower than the downstream room.

Natural Infiltration and Duct Leakage

A natural infiltration test was performed over a two hour period on the evening of January 8 (Test B14). The tracer gas decay curves are shown in Figure 30. There was a slight divergence between the first floor and second floor 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 the 1-story house, as might be expected with an increased stack height.

An air handler / bedroom door bump test was conducted just prior to the test period shown in Figure 30, allowing observation of the combined effect of duct leakage to the outside and increased infiltration caused by room pressurization. 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.

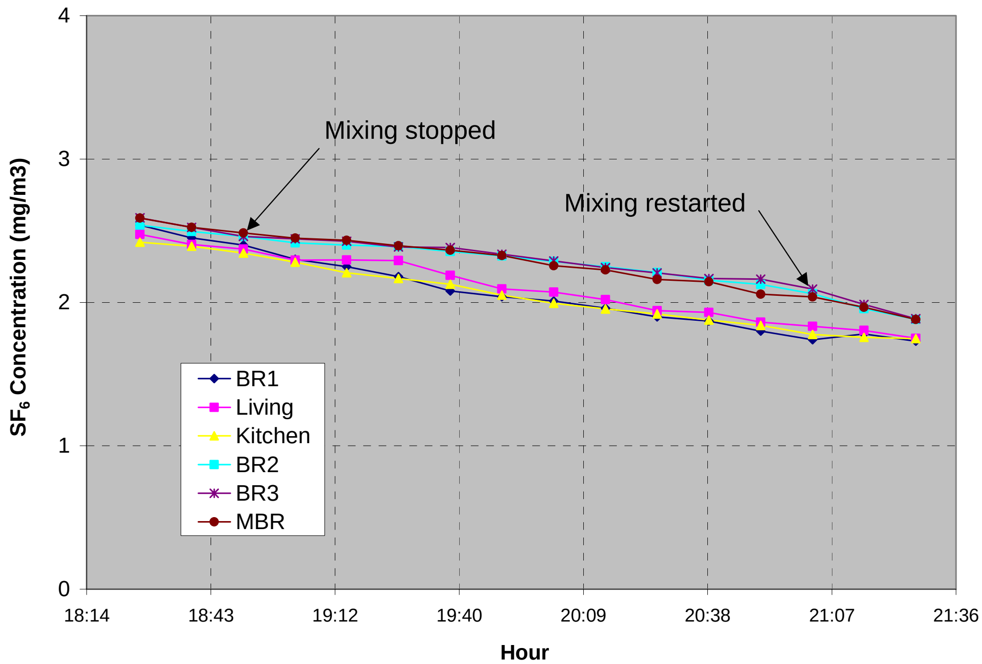

Figure 30. Tracer gas decay for 2-story house with no ventilation, no central fan operation, and bedroom doors open (Test B14).

Distributed Supply vs Point Exhaust Ventilation

A 14-hour test (Test B1) was performed with an exhaust ventilation rate of 63 cfm in the laundry room, which was located near the stairwell in the middle of the first floor. The ventilation rate was again consistent with the ASHRAE 62.2 recommendations. The tracer gas decay curves are shown in Figure 31. It is interesting that all three second floor rooms showed a delay before entering an exponential decay, suggesting that some amount of air was moving from the first floor to the second floor even though the mechanical exhaust point was on the first floor. It appears that the further depressurization of the first floor was insufficient to overcome the stack effect and draw a significant amount of outside air in through the rooms on the second floor.

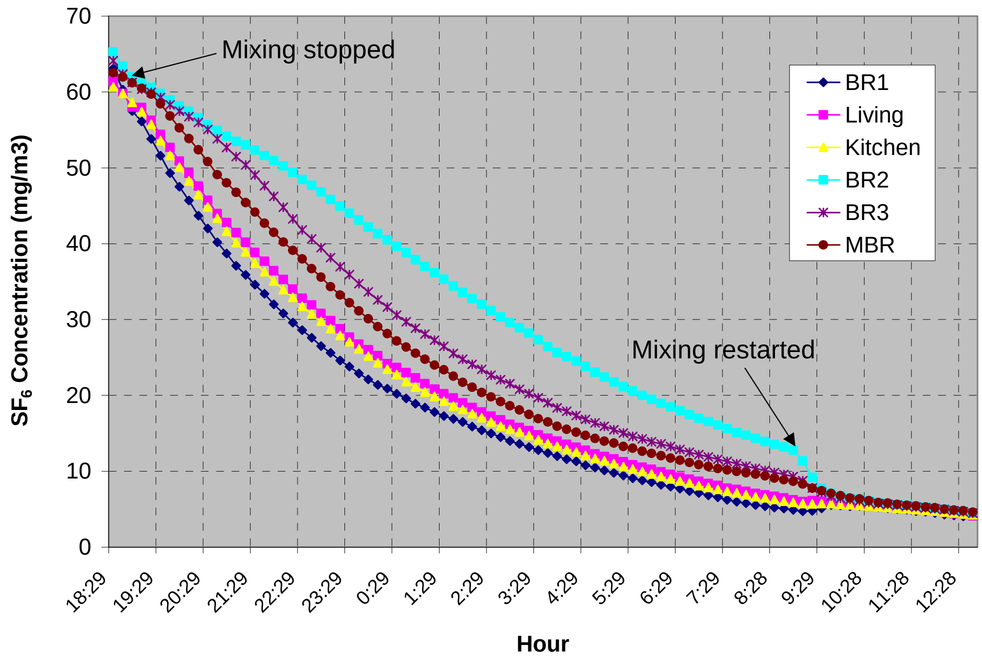

Figure 31. Tracer gas decay for 2-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and bedroom doors closed (Test B1).

A supply ventilation test was performed on the 2-story house for about 11 hours starting late on January 4 (Test B3). The duct blaster 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 are shown in Figure 32. Although the curves are much more tightly packed than they were with the exhaust system, there is more divergence than we saw with the supply system in the 1-story house, most notably in the master bedroom.

The reciprocal age-of-air calculations for both the exhaust and supply ventilation systems are shown in Figure 33. Again, the results indicate that much better room-to-room distribution of ventilation air was achieved by the central-fan integrated supply system compared to the single-point exhaust system. However, for the supply ventilation 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 of the supply ventilation rate among rooms based on Figure 33.

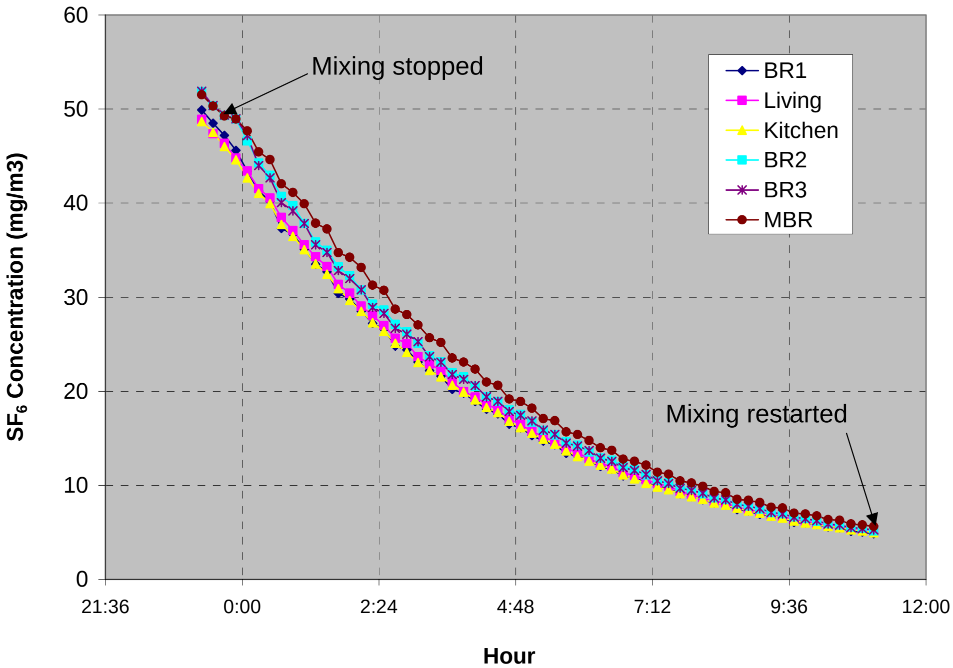

Figure 32. Tracer gas decay for 2-story house with supply ventilation just under ASHRAE 62.2 level, central fan operation at 33% duty cycle (20 min. off, 10 min. on), and bedroom doors closed (Test B3).

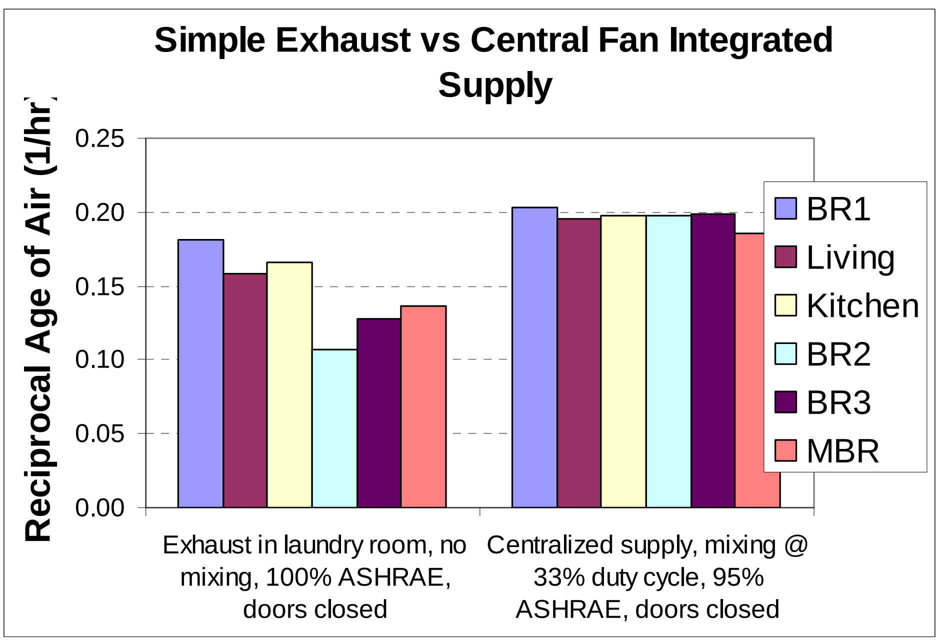

Figure 33. Reciprocal age-of-air for 2-story house with continuous exhaust ventilation (Test B1) compared to central fan integrated supply ventilation (Test B3). (Note: Uncertainties introduced by non-uniform starting concentration are of the same order of magnitude as the differences in reciprocal age-of-air among rooms for the supply ventilation case. The relative ranking of rooms is not meaningful for that case.)

Air Handler Operation

The effect of occasional air handler operation on the distribution of exhaust ventilation air was evaluated on the afternoon of January 6 (Test B6). The tracer gas decay curves are shown in Figure 34, and reciprocal age-of-air calculations are shown in Figure 35. It should again be noted that before the test started, the house was mixed using both the air handler and a de-stratification fan with the doors open. During the test, the doors were closed, the de-stratification fan was turned off, and the air handler operated at a 33% duty cycle (20 minutes off, 10 minutes on). As was the case in the 1-story house, this occasional operation of the air handler substantially improved the distribution of ventilation air among rooms, even in conjunction with the point exhaust ventilation system. There was very little divergence noticeable even with the air handler cycling on and off every half hour. However, because the initial differences in tracer gas concentration among rooms were as large as the differences in reciprocal age-of-air for the case with air handler operation, no conclusions should be drawn about the relative ranking of ventilation rates among the rooms for that case.

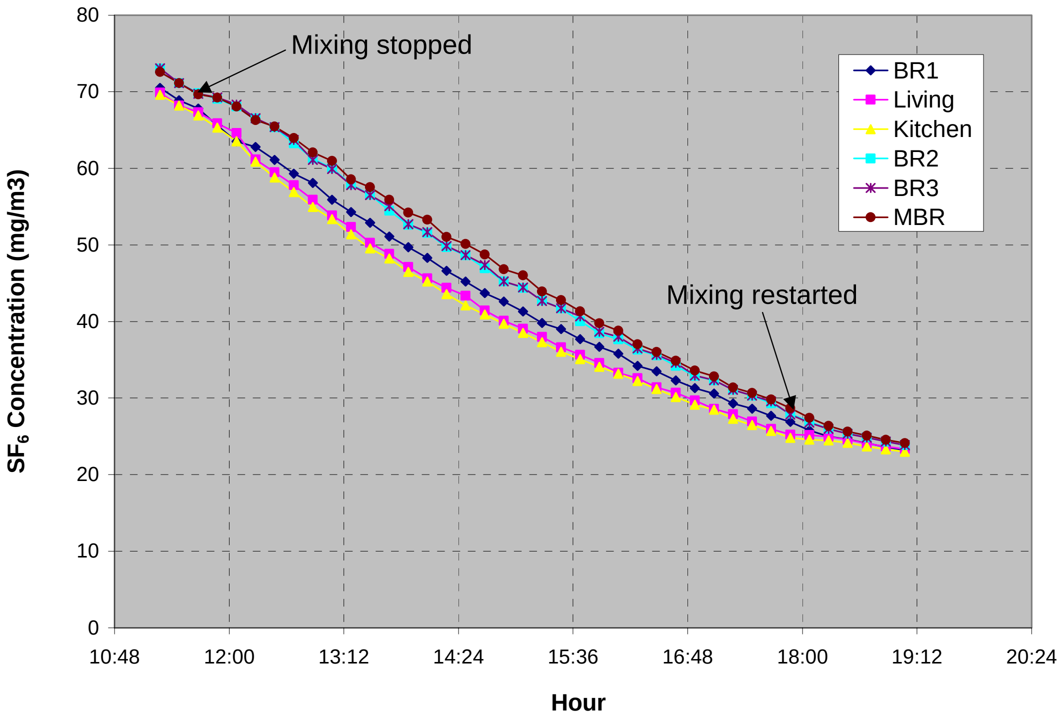

Figure 34. Tracer gas decay for 2-story house with continuous exhaust ventilation at ASHRAE 62.2 level, central fan operation at 33% duty cycle (20 min. off, 10 min. on), and bedroom doors closed (Test B6).

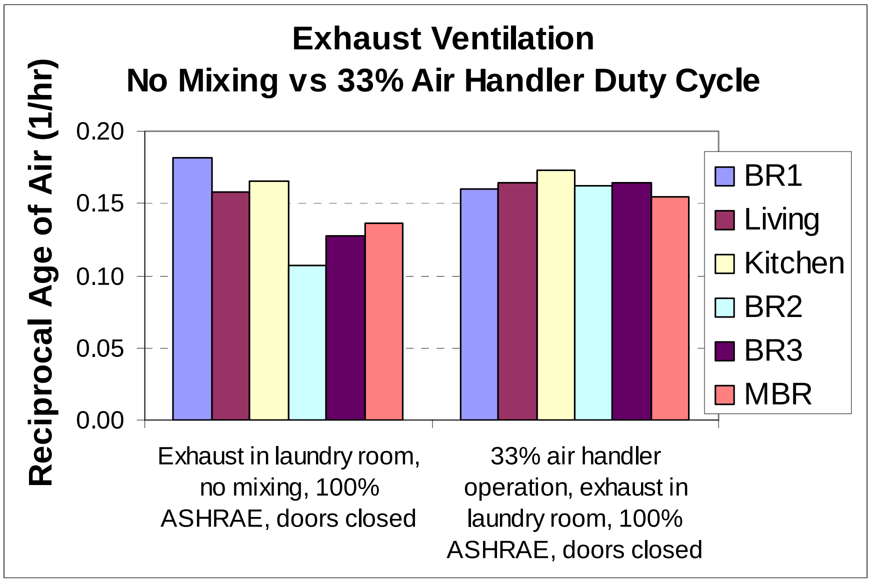

Figure 35. Reciprocal age-of-air for 2-story house with continuous exhaust ventilation with and without air handler operation (Tests B1 and B6). (Note: Uncertainties introduced by non-uniform starting concentration are of the same order of magnitude as the differences in reciprocal age-of-air among rooms for the case with air handler operation. The relative ranking of rooms is not meaningful for that case.)

Exhaust Location

The duct blaster was moved to the master bathroom exhaust register to see if there was a resulting change in ventilation 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 decay curves are shown in Figure 36, and the reciprocal age-of-air results are shown in Figure 37. 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 can be seen during the test, especially between the upstairs bedrooms and the rest of the house. Once again all three upstairs rooms appear to receive some air from the first floor, but the master bedroom experiences a much higher volume of circulated air than the other two second-floor bedrooms, which appear to be relatively stagnant.

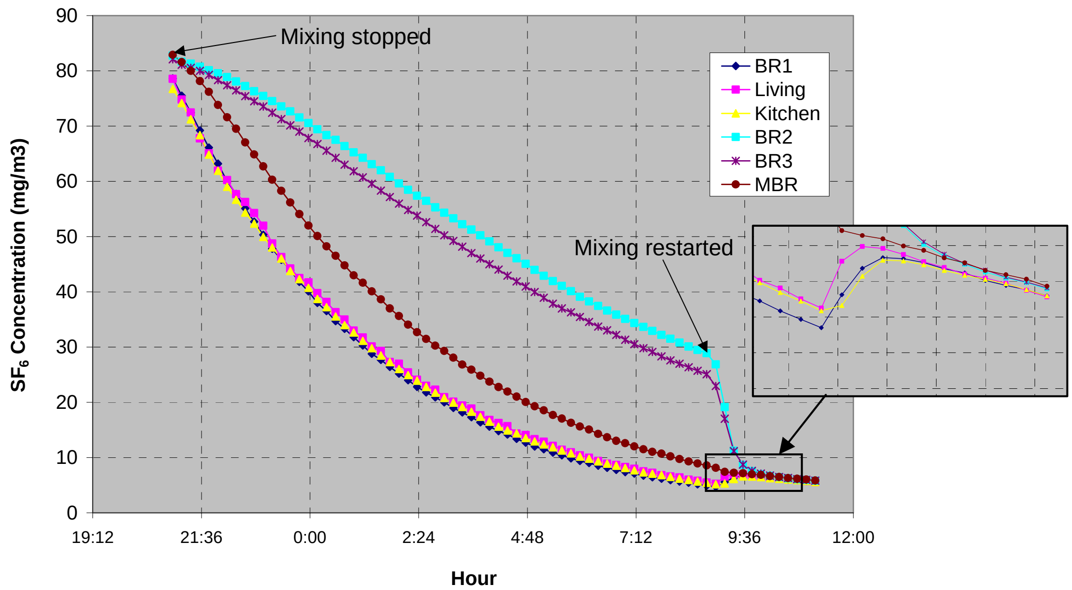

Figure 36. Tracer gas decay for 2-story house with exhaust ventilation from the master bathroom at ASHRAE 62.2 level, no central fan operation, and bedroom doors closed (Test B18).

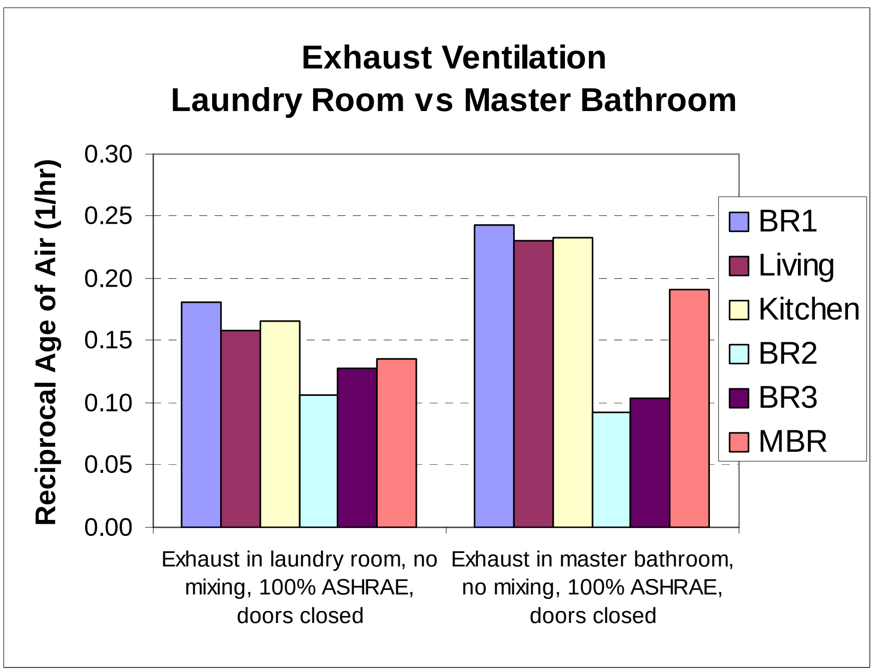

Figure 37. Reciprocal age-of-air for 2-story house with exhaust ventilation from the master bathroom compared to the laundry room at ASHRAE 62.2 level, no central fan operation, and bedroom doors closed (Tests B1 and B18).

Ventilation Rate

The supply ventilation tests were repeated using flow rates of 60% and 33% of ASHRAE 62.2 recommendations, corresponding to 114 cfm and 63 cfm respectively (Tests B2 and B4). The decay curves are shown in Figures 38 and 39. Reciprocal age-of-air for all three supply ventilation rates are shown in Figure 40. In all cases, the rooms remained fairly well mixed, especially rooms on the same floor. As we observed in the 1-story house, the ventilation rate in the 2-story house appeared to have very little effect on the uniformity of outside air provided to each room as long as it was mixed using the air handler. One again, the initial differences in tracer gas concentration among rooms were as large as the divergence in the decay curves, preventing any conclusions about the relative ranking of ventilation rates among rooms for all three cases. The error in initial concentration uniformity was bigger for the cases with air handler mixing because the relative divergence in the decay curves was so small compared to that of no air handler mixing. In other words, the error in relative ranking of ventilation rates for the cases with air handler mixing were not very important anyway because the relative differences between rooms were so small.

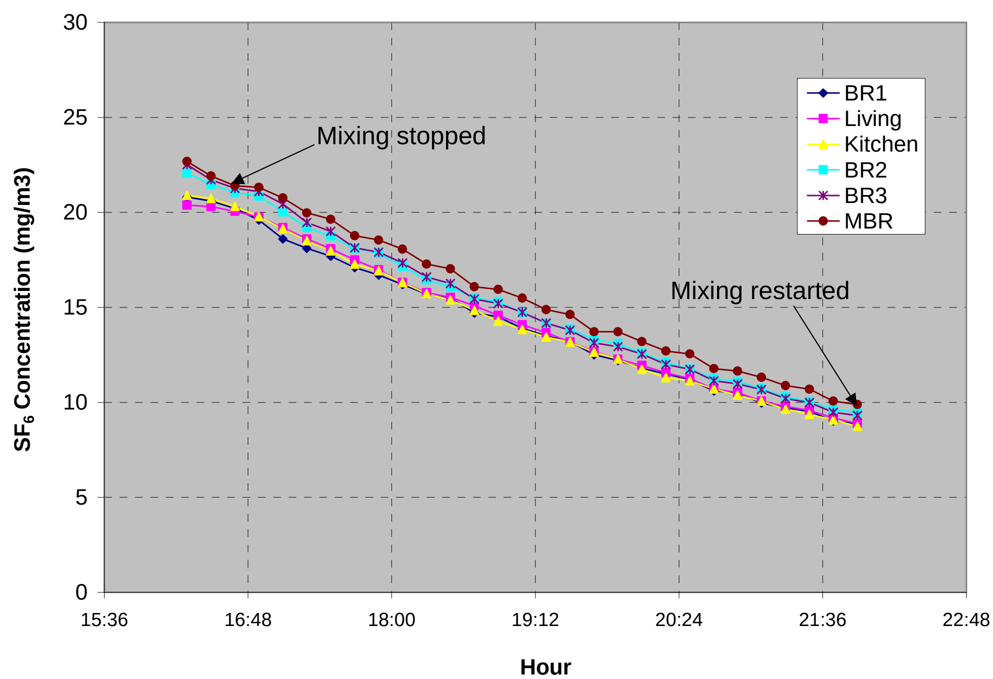

Figure 38. Tracer gas decay for 2-story house with supply ventilation at 60% of ASHRAE 62.2 level, 33% central fan operation (20 min. off, 10 min. on), and bedroom doors closed (Test B2).

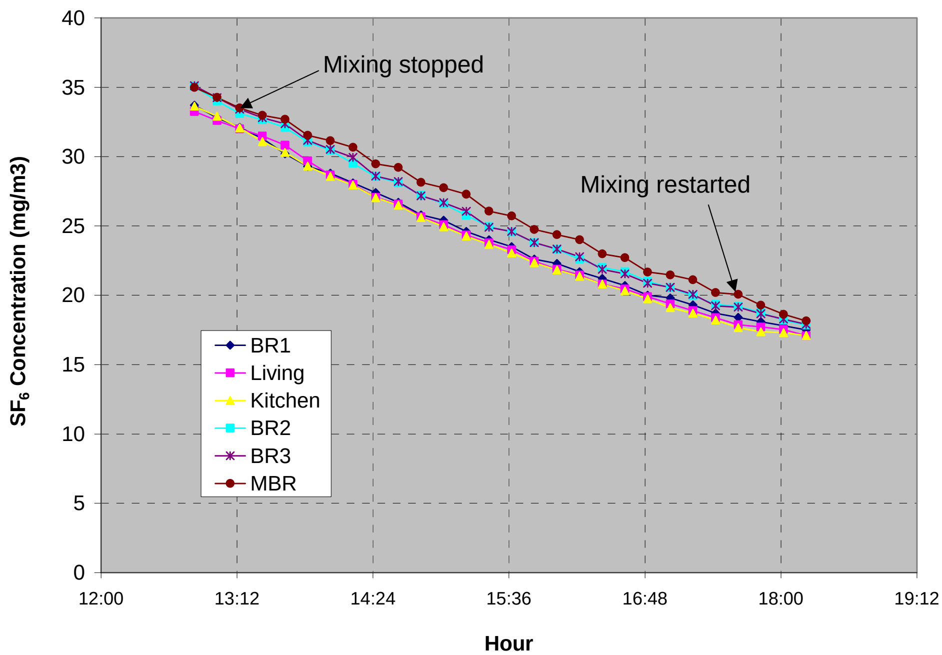

Figure 39. Tracer gas decay for 2-story house with supply ventilation at 33% of ASHRAE 62.2 level, 33% central fan operation (20 min. off, 10 min. on), and bedroom doors closed (Test B4).

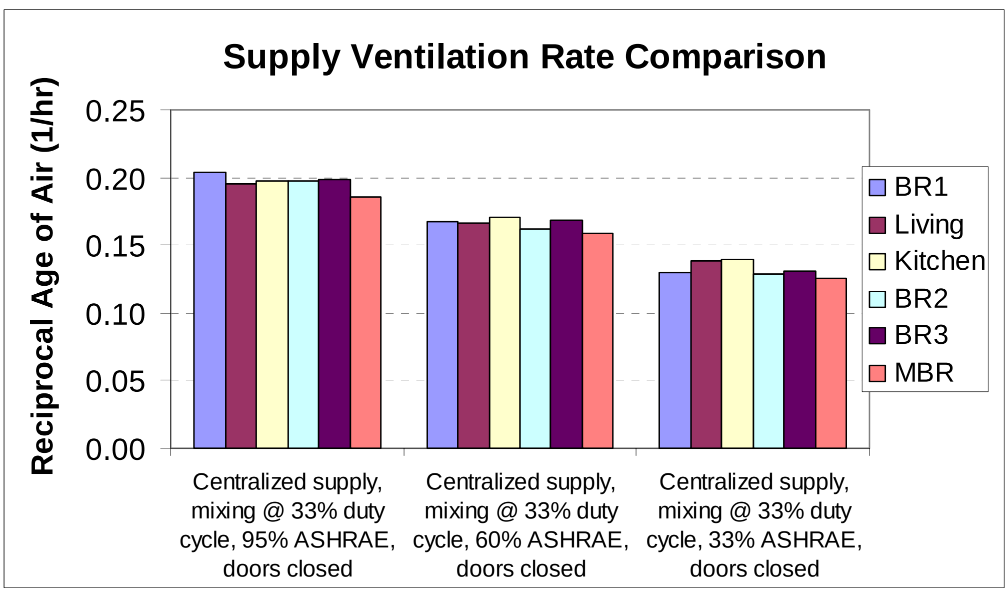

Figure 40. Reciprocal age-of-air for 2-story house with three levels of supply ventilation, central fan operation at 33% duty cycle (20 min. off, 10 min. on), and bedroom doors closed (Tests B3, B2, B4). (Note: Uncertainties introduced by non-uniform starting concentration are of the same order of magnitude as the differences in reciprocal age-of-air among rooms for all three cases. The relative ranking of rooms is not meaningful for these cases.)

The average air change rates for the three supply ventilation rates compared to the two exhaust ventilation schemes are shown in Figure 41. The CFIS system at 33% of the 62.2 ventilation flow rate provided a uniformly higher air change rate (0.13 ach) than the least ventilated rooms using exhaust ventilation from either the laundry or the master bathroom (0.10 ach, Figure 37). It is noteworthy that the combined net air change rate with exhaust ventilation from the laundry room was significantly less than the air change rates for both exhaust ventilation from the master bathroom and supply ventilation at the air handler. This illustrates the unpredictability of interactions between mechanical ventilation and natural infiltration, which depend strongly on the distribution and size of cracks through which the outside air must pass to enter the house. There may have been a relatively large building enclosure leakage opening near the laundry room (perhaps the utility penetrations or the door to the garage) that allowed a significant amount of outside air to quickly enter and leave the house through the exhaust flow without circulating around the house.

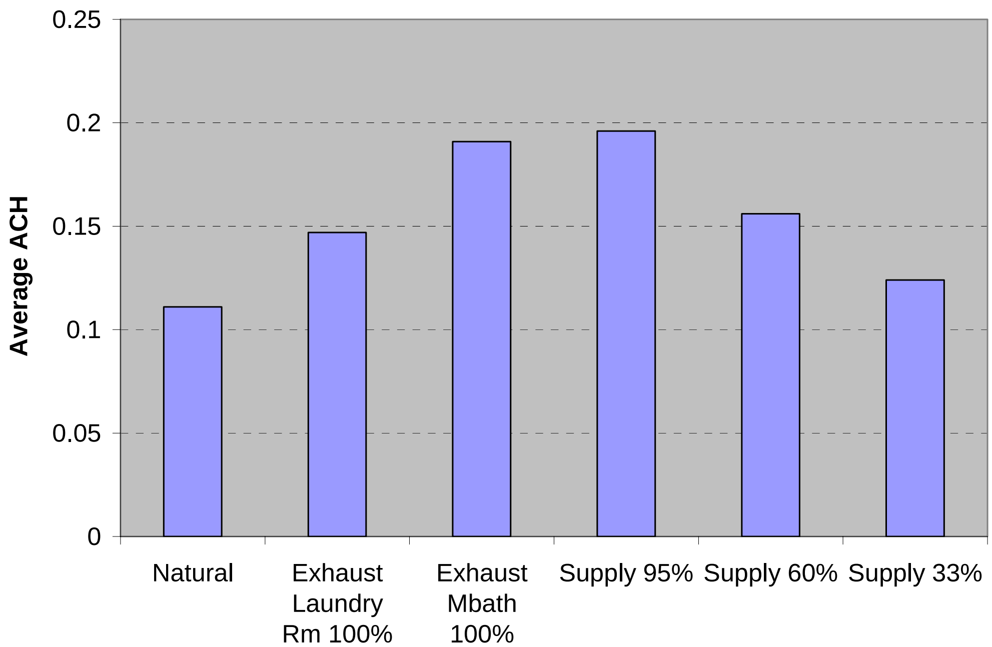

Figure 41. Average air change rates for 2-story house with supply ventilation at 33%, 60%, and 95% of ASHRAE 62.2 recommendations (Tests B4, B2, B3) compared to natural infiltration (Test B14) and exhaust ventilation with no central fan operation (Test B1). Bedroom doors were closed except for the natural infiltration test.

Bedroom Doors

The laundry room exhaust ventilation test with no air handler operation (see Figure 31) was repeated with the doors open to evaluate the change in room-to-room ventilation air distribution (Test B10). The decay curves are shown in Figure 42, and the reciprocal age-of air calculations are shown in Figure 43. It is evident from Figure 42 that the test began before the rooms were completely well mixed, resulting in decay curves that could be somewhat misleading. Because the master bedroom was at a higher concentration than 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 it would have if the rooms started out at the same concentration. Despite the difference in starting concentration, it is clear that outside air was well distributed when the doors were open, even without operation of the air handler.

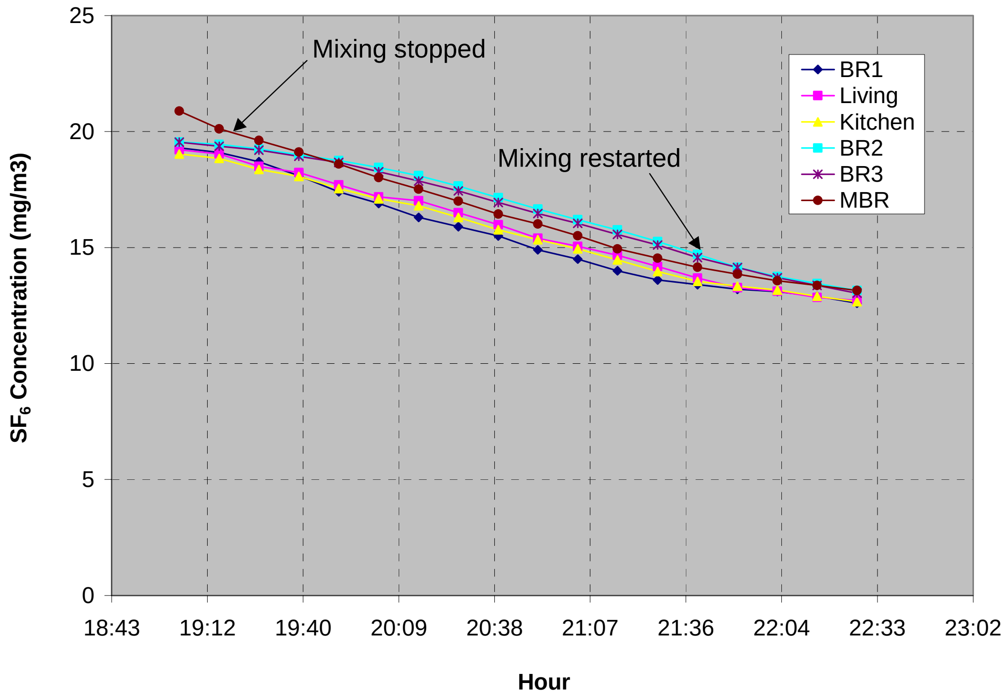

Figure 42. Tracer gas decay for the 2-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and bedroom doors open (Test B10).

Reciprocal age-of-air analysis was not performed for this case because of the combined effect of a short test duration (~2 hours) and unequal starting tracer gas concentrations, even though the house was relatively well-mixed. The important conclusion (that opening doors greatly improves mixing) can be drawn by inspecting the decay curves alone.

Transfer Grilles

A final exhaust ventilation test was run on the 2-story house with the doors closed and the transfer grilles taped over. The decay curves are shown in Figure 43, and the reciprocal age-of-air calculations are shown in Figure 44. The curves were clearly very divergent even after 12 hours. By examining the reciprocal age-of-air results, it is apparent that the transfer grilles in the 2-story house caused a noticeable improvement in ventilation air distribution, but the improvement was smaller than when the doors were opened (Figure 42).

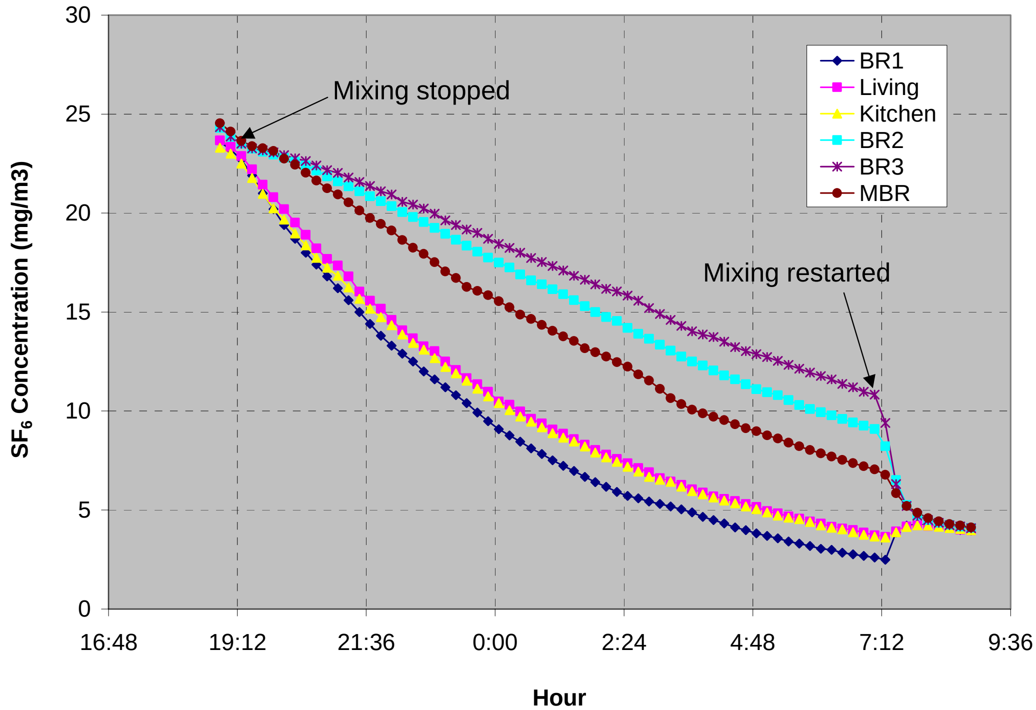

Figure 43. Tracer gas decay for 2-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, bedroom doors closed, transfer grilles taped closed (Test B7).

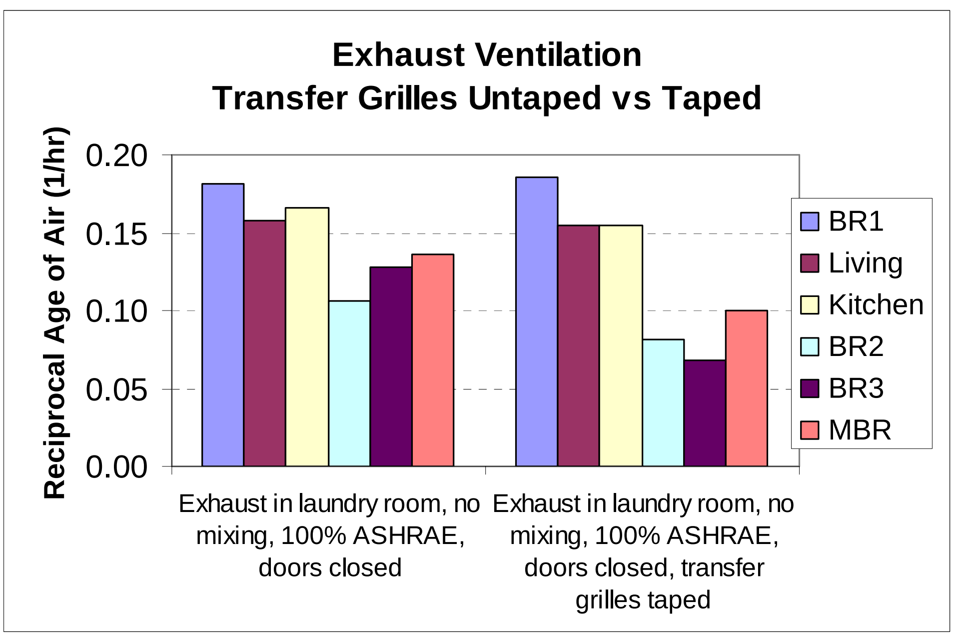

Figure 44. Reciprocal age-of-air for 2-story house with exhaust ventilation from the laundry room at ASHRAE 62.2 level, no central fan operation, and doors closed. In the first case the transfer grilles are untaped (Test B3), in the second they are taped closed (Test B7).

CONCLUSIONS

- Reciprocal age-of-air analysis was chosen as a quantitative method for characterizing distribution of ventilation air among rooms. This method worked well in cases where rooms were well mixed to begin the test, and weather conditions were sufficiently steady-state.
- A test period of at least 1½ air changes was necessary to obtain reasonably accurate age-of-air results when there was significant divergence in tracer gas concentration among the rooms.
- Although we did not achieve uniform initial concentration of tracer gas in the 2-story house using our test methodology and the equipment at hand, we believe the reciprocal age-of-air calculations were meaningful in many of the cases, as indicated in the discussion.
- Both houses were relatively tight, with natural infiltration averaging 0.08 ACH for the 1-story house and 0.11 ACH for the 2-story house.
- Both houses had relatively small (but not negligible) duct losses to the outside, producing an increase in infiltration of less than 0.03 ACH for the 1-story house and 0.02 ACH for the 2-story house when the air handler runs.
- Age-of-air analysis indicated that ventilation supplied through the central air distribution system provided much more uniform distribution of ventilation air than the single-point exhaust system when the doors were closed and the air handler was not running. For the 1-story house, the central-fan-integrated supply ventilation case at 60% of ASHRAE 62.2 provided more outside air to all rooms than the least-ventilated room in the exhaust case at 100% of 62.2. For the 2-story house, the central-fan-integrated supply system at 33% of the 62.2 flow rate provided more outside air to all rooms than the least ventilated rooms using exhaust ventilation at 100% of 62.2 from either the laundry or the master bathroom.
- 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 (1-story or 2-story).
- Exhaust location affected both the relative amount of outside air received by different rooms and the overall uniformity among rooms, but the effect was not predictable.
- For exhaust-only ventilation without central fan operation, opening bedroom doors appeared to significantly improve the mixing of ventilation air among rooms.
- Transfer grilles improved the distribution of ventilation air slightly, but much less than opening the bedroom doors.
- In the 2-story house, the stack effect caused air movement from the first floor to the second floor even when exhaust ventilation was applied to the first floor, resulting in consistently higher tracer gas concentrations on the second floor and more non-uniform ventilation air distribution in general.
- Interactions between natural infiltration and both exhaust and supply mechanical ventilation were very significant. When the ventilation system was activated, the combined air change rate did not increase commensurate with the measured ventilation rate, but instead increased 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).

FUTURE WORK

In future tests, continuous monitoring of pressure differentials would enhance our understanding of the multi-zone, combined infiltration and ventilation systems and our ability to model them. That would help to explain differences between tests in more detail, including the effects of multiple stories, location of ventilation supply outlets and exhaust inlets, interior door closure, and use of passive return air transfer grilles. Pressure differential measurement points should include:

- dP with respect to outside for each closed room and open space;
- dP across closed interior doors;
- dP between the floor cavity and outdoors; and
- dP between the house and the attic.

Measurement of wind direction along with wind speed could also be helpful for modeling these buildings and systems. However, because of micro-climate wind shielding, it may be very difficult to relate a single-point wind direction measurement to actual wind vectors on the building surfaces.

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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.

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This report was prepared for the US Department of Energy's Building America Program. The report is freely available to the public at www.buildingamerica.gov.

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