2. PROJECT 2: VENTILATION EFFECTIVENESS ADVANCED SYSTEM RESEARCH

2.1 Executive Summary

Overview

ASHRAE Standard 62.2–2007 — Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings sets recommended ventilation rates for residential dwelling units. Many jurisdictions are considering adopting it into their building codes, yet it currently contains a critical flaw. The Standard in effect tells the designer or builder how much ventilation air to provide, yet does not give any guidance on where or how to provide that air. The amount of ventilation air is determined by the size of the dwelling and the number of occupants, typically determined from the number of bedrooms. No attempt is made to distinguish between the effectiveness of different ventilation systems, although the ventilation community widely agrees that different systems provide very different performance.

The purpose of this research is to provide quantitative information regarding the performance of broad classes of ventilation systems on the market. Currently, many homes are built without ventilation systems, and of those that do have ventilation systems, many are systems that are relatively ineffective at removing contaminants. This creates a situation where the homes may have poor indoor air quality and high contaminant concentrations. Evidence of such occurrences was found in a recent study commissioned by the California Air Resources Board. Due to incomplete knowledge regarding the failure of these ventilation systems, there may be political pressure to increase ventilation rates in building codes and standards such as ASHRAE Standard 62.2, which would unnecessarily penalize systems that are effective at the current rates. Increasing ventilation rates would increase energy consumption for space conditioning loads and may not improve indoor air quality. One of the outcomes of this work is expected to be a modification to the ASHRAE Standard 62.2 to account for the effectiveness of different types of ventilation systems. The modification would result in an equation of the form shown in the equation below:

$Q_{fan} = C_D * Q_{vent}$,

where

Q_{fan} = required ventilation system flow rate,

C_D = coefficient of distribution (assigned based on the type of ventilation system selected), and

Q_{vent} = the current ventilation flow rate recommended by Standard 62.2-2007.

In this manner, ineffective ventilation systems will have their required ventilation rates increased while higher-performing systems will not.

Key Results

In 2009 BSC has made major efforts to promote the acceptance of a proposed addendum to ASHRAE Standard 62.2 to account for the effect of system types and operation. A supermajority of the SSPC committee agrees with the approach. The public review process for the proposed addendum is proceeding and will continue into 2010. Further work may be needed in areas not yet identified.

Gate Status

1. *Source Energy Savings and Whole Building Benefits ("must meet")*

This project meets the Gate 1B "must meet" requirement for source energy savings. The modifications to ASHRAE Standard 62.2 will address the current need for effective ventilation and good indoor air quality, while encouraging high-performing ventilation systems including those that often incorporate heat or energy recovery. This will have the net effect of reducing the amount of energy needed to condition homes.

2. *Performance-Based Code Approval ("must meet")*

This project meets both the Gate1B "must meet" requirement for performance-based and "should meet" requirement for prescriptive-based safety, health and building code requirements for new homes. Commercially-available ventilation systems that comply with ASHRAE Standard 62.2 will be products that meet this requirement.

3. *Prescriptive-Based Code Approval ("should meet")*

This project meets both the Gate1B "must meet" requirement for performance-based and "should meet" requirement for prescriptive-based safety, health and building code requirements for new homes. Commercially-available ventilation systems that comply with ASHRAE Standard 62.2 will be products that meet this requirement.

4. *Cost Advantage ("should meet")*

This project meets the Gate 1B "should meet" requirement for strong potential to provide cost benefits relative to current systems. Because the net effect of this change to the standard would be to encourage high-performing ventilation systems including those that often incorporate heat and energy recovery, it will encourage greater market penetration of these systems and innovation with other ventilation systems, resulting in a price advantage to the builder and consumer.

5. *Reliability Advantage ("should meet")*

This project meets the Gate 1B "should meet" requirement to meet reliability, durability, ease of operation, and net added value requirements for use in new homes. The change to the standard will not affect the products' reliability, durability, or ease of operation, and should add net value to new homes through improved indoor air quality and lower energy consumption and bills.

6. *Manufacturer/Supplier/Builder Commitment ("should meet")*

This project meets the Gate 1B "should meet" requirement of manufacturer/supplier/builder commitment. Manufacturers are eager to sell more ventilation equipment, and builders are beginning to install more ventilation systems. The ASHRAE Standard 62.2 Committee has engaged with BSC in this issue, and progress is being made.

7. Gaps Analysis (“should meet”)

Previously identified gaps for this project have been overcome. A future research gap to overcome includes addressing the technical knowledge needed to accurately account for the source of outside air on occupant exposure. The impact on indoor air quality should be assessed for systems when the source of outside air is either unknown or expected to come from undesirable locations (such as garage, attic, crawl space, or below grade soil). There are no major market barriers to implementing this change to the standard.

Conclusions

In 2009 BSC has made major efforts to promote the acceptance of a proposed addendum to ASHRAE Standard 62.2 to account for the effect of system types and operation. A supermajority of the SSPC committee agrees with the approach. The public review process for the proposed addendum is proceeding and will continue into 2010. Further work may be needed in areas not yet identified.

2.2 Sacramento Tracer Gas Testing

In January 2006 BSC (in conjunction with the National Renewable Energy Laboratory (NREL)) performed tracer-gas testing of two new Building America homes near Sacramento, California. NREL performed testing on one house and BSC performed testing on the second. The field testing involved several multi-zone tracer gas tests in each house over the course of two weeks. The results of this testing were written up by Bob Hendron at NREL and were published in a draft NREL report (Hendron 2006) and an ASHRAE paper (Hendron 2007).

2.2.1. Description of House

This work looks only at the house tested by BSC. The house is two-story, approximately 2600 ft^2, with four bedrooms and three bathrooms. The first floor consists of one bedroom, one bathroom, a laundry room, the living room area, and a kitchen and dining room. The second floor consists of the master bedroom and bathroom, two additional bedrooms, an additional bathroom, and a small common area at the top of the stairway which overlooks the living room below. Figure 2.1 contains a drawing of the floor plan of the house, and Figure 2.2 contains a photograph of the front elevation.

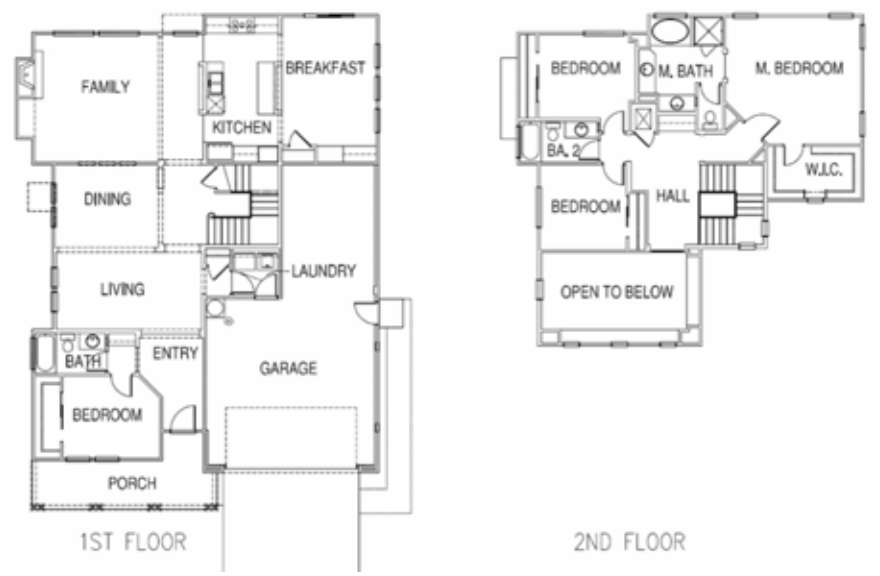

Figure 2.1: Floor plan of the house tested

Figure 2.2: Front elevation of the house tested

2.2.2. Description of Test Method

The two houses were tested using tracer gas decay techniques. In these tests, a tracer gas was injected into the house and the central air handler (AHU) was operated continuously in order to mix the house to a uniform tracer gas concentration. The test was initiated by deactivating the mixing systems and activating the ventilation system as appropriate for the test, and leaving the house in that state for a period of 2 to 14 hours. Three ventilation systems were tested. The first ventilation system tested was the central-fan-integrated supply (CFIS) ventilation system, which consists of an outside-air duct to the return side of the AHU and a controller that operates the AHU on a minimum duty cycle. The outside-air duct contains a damper that remains closed except when the CFIS system is activated. The duty cycle of the AHU and CFIS system varied from test to test. This ventilation system was operated at different ventilation rates using a variable-speed fan installed in line with the outside air duct, as described in Table 2.1. The second and third ventilation systems were upgraded exhaust fans located in the laundry room and master bedroom, respectively. The exhaust fans were tested only at 100% of the ASHRAE Standard 62.2-2003 ventilation rate, and were tested with and without simultaneous operation of the AHU for mixing. In addition to the ventilation tests, natural infiltration and air handler bump (natural infiltration with the AHU running) tests were also conducted. During the tracer gas tests, the bedroom doors were either open or closed. The house was built with transfer grills, which are passive openings above the doorways that allow a return air path when the bedroom doors are closed. The transfer grills were also either open or closed (taped over) during the tracer gas tests. The doors to the bathrooms and laundry room were always open. All exterior doors and windows were always closed.

2.2.3. Test Performed

In the tracer gas testing, two common ventilation systems were tested: an upgraded bathroom exhaust fan and a central-fan-integrated supply (CFIS) system. Tests were performed with the interior doors in the houses open and closed, with the transfer grills open and closed, and with and without mixing via the AHU. In total, seventeen ventilation tests were performed on the house using tracer gas decay methods. Table 2.1 lists the tracer gas tests performed.

Table 2.1: List of tracer gas tests

Test Number	Description
CFIS Tests With Mixing (All have AHU 20 min off/10 min on)	
1	Doors Closed, Transfer Grills Open, 95% of the 62.2 Ventilation Rate*
2	Doors Closed, Transfer Grills Open, 60% of the 62.2 Ventilation Rate
3	Doors Closed, Transfer Grills Open, 33% of the 62.2 Ventilation Rate
4	Doors Closed, Transfer Grills Closed, 60% of the 62.2 Ventilation Rate
Laundry Exhaust Tests With Mixing (All at 100% of the 62.2 ventilation rate)	
5	Doors Closed, Transfer Grills Open, AHU 20 min off/10 min on
6	Doors Closed, Transfer Grills Open, AHU 25 min off/5 min on
7	Doors Closed, Transfer Grills Closed, AHU 25 min off/5 min on
Laundry Exhaust Tests Without Mixing (All at 100% of the 62.2 ventilation rate)	
8	Doors Open, Transfer Grills Open
9	Doors Closed, Transfer Grills Open
10	Doors Closed, Transfer Grills Closed
Master Bathroom Exhaust Tests With Mixing (All at 100% of the 62.2 ventilation rate)	

11	Doors Closed, Transfer Grills Open, AHU 25 min off/5 min on
Master Bathroom Exhaust Tests Without Mixing (All at 100% of the 62.2 ventilation rate)	
12	Doors Closed, Transfer Grills Open
13	Doors Closed, Transfer Grills Closed
Natural Infiltration Tests (No ventilation or AHU operation)	
14	Doors Open, Transfer Grills Open
Air Handler Bump Tests (No ventilation, AHU on)	
15	Doors Open, Transfer Grills Open
16	Doors Closed, Transfer Grills Open
17	Doors Closed, Transfer Grills Closed

*Test 1 was 95% instead of 100% of the 62.2 ventilation rate due to hardware limitations.

2.2.4. Results

The results from these tests showed that the two ventilation systems had substantially different room-to-room difference in tracer gas concentration and therefore different efficacy at distributing ventilation air to each of the rooms in the houses. Figure 2.3 shows the decay in tracer gas concentration for one of the exhaust-only tests, and Figure 2.4 shows the decay in tracer gas concentration for one of the CFIS tests. The difference in uniformity is clear, and convinced BSC that an effort should be made to address the differences between different types of ventilation systems.

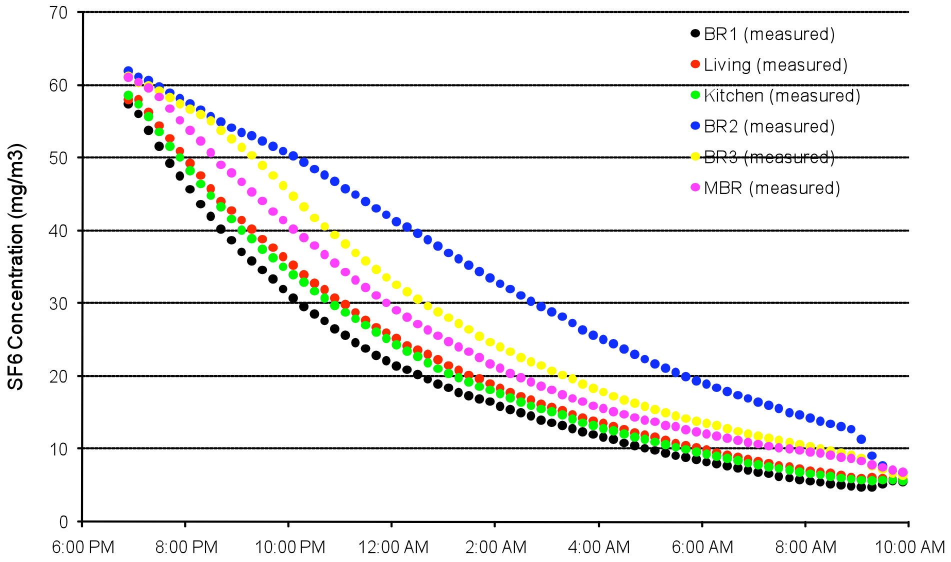

Figure 2.3: Tracer gas measurement results for Test 1 (exhaust from laundry room)

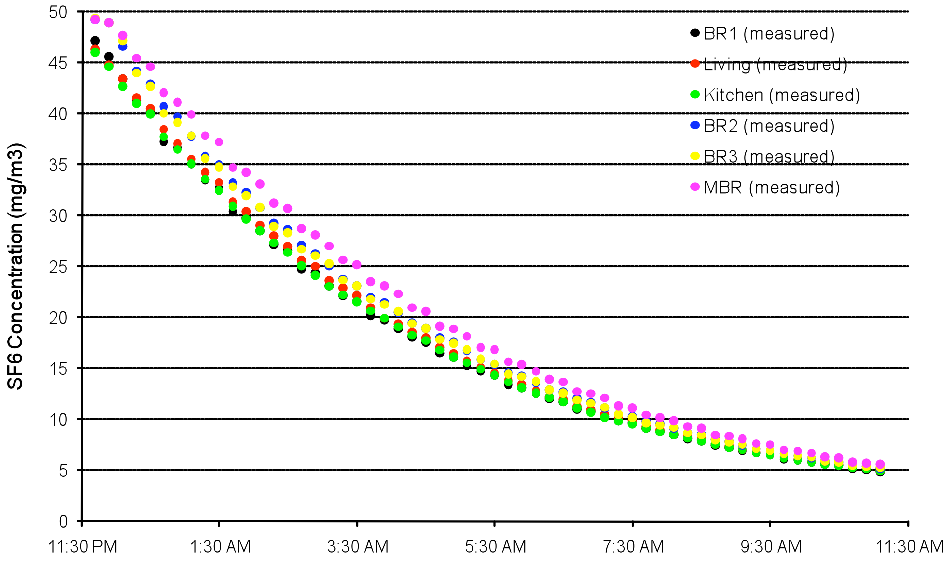

Figure 2.4: Tracer gas measurement results for Test 3 (CFIS)

2.2.5. Conclusions

The tracer gas tests showed clear differences in the efficacy of the two different ventilation systems tested at removing pollutants from all zones in the house. It was decided that a computer model should be constructed in order to determine the efficacy of ventilation systems not tested in the tracer gas testing.

2.3 Calibration of First Model

In order to extend the results obtained during the physical testing to ventilation systems not present in the two houses tested, a computer program was used to create a calibrated model which could accurately recreate the physical testing results and therefore could be expected to predict the performance of other types of ventilation systems.

2.3.1. Introduction to CONTAM

The computer program used for the model was CONTAM. CONTAM is a multi-zone air flow network modeling software developed by the National Institute of Standards and. It is commonly used in ventilation research to model buildings, ventilation systems, and contaminants in indoor and outdoor air. In CONTAM, the user specifies attributes of the building's zones, air flow pathways between zones (such as leaks or fans and ducts), contaminant sources and sinks, and other relevant inputs. The software performs the simulation and the results are available for visualization or export.

2.3.2. Testing of Substitute House

The results from CONTAM are very dependent on having realistic inputs for the attributes of the building in terms of air flow pathways; however at the time of the tracer gas testing described above the only diagnostic test that was performed on the house was an enclosure air leakage test. No further diagnostics were performed on the house enclosure or interior demising walls because further work was not planned at that time. Later, when the decision was made to create a calibrated computer model, much more detailed information about the enclosure and interior airflow paths was needed in order to provide a reasonable starting point for the calibration process. The original house was no longer available for testing, so another house of the same floor plan was tested instead. While two houses of the same floor plan can certainly have different leakage characteristics, these two houses were built within a few months of each other, by the same builder and likely the same subcontractors, and the overall enclosure leakage testing results were similar. The original house had a leakage rate of 1346 cfm50, and the substitute house had 1608 cfm50. The substitute house was slightly larger due to an option that added two additional bedrooms and an additional bathroom; after subtracting the leakage in the additional bedrooms, the substitute house was 1411 cfm50. As the substitute house was simply a starting point for calibrating the model, differences between the houses were of minor consequence and were remedied during the calibration process.

Air leakage characterization on the substitute house was performed to quantify both house-to-exterior and room-to-room leakage characteristics. The testing also included tests of zone pressures and central forced-air system airflow to each room. The testing procedure was able to quantify the leakage characteristics of each room to the exterior and to neighboring zones, but no attempt was made to identify the specific locations of leakage within each room. Further details of the testing at the substitute house are included in Appendix A.

2.3.3. Calibration Procedure

The goal of the calibration procedure was to produce a set of inputs for the house enclosure and zone-to-zone leakage pathways that, when simulated with CONTAM, would produce the same results as the tracer gas tests when the ventilation systems were operated in the same manner as each of the tracer gas tests.

As a starting condition, leakage values calculated from the leakage testing in the substitute house were used for the exterior enclosure and the interior partition walls. Because the actual leakage locations within each room were not determined by the testing, leakage within each room was initially distributed proportional to the wall and ceiling area. Wall leakage was broken into leakage for each wall orientation and into five vertical locations on each wall, with equal vertical separation between the locations. Each leakage location on a wall had the same leakage coefficient and exponent. Initial test runs with simplified models showed the vertical spacing chosen (5 leaks per wall, equally spaced on a 9 ft (2.7 m) wall) approximated diffuse wall leakage, while still maintaining a manageable number of leakage elements in the model. The temperature in each room and the outdoor temperature and wind speed had been recorded during the tracer gas testing, and were used as inputs to the model. Wind direction was not recorded during the tracer gas testing, so meteorological data from the nearest airport (Auburn, CA, approximately 10 miles away) was obtained and the wind direction data was used as an input to the model. Drawings and specifications for the AHU and duct system were obtained from the subcontractor, which were used to create a full duct and AHU model. The AHU and all ductwork in this house are located within conditioned space, greatly simplifying the need to characterize duct leakage. For each test simulated, a schedule was created that controlled the ventilation systems, AHU operation, and transfer grill and bedroom door status to replicate operation as performed in the tracer gas tests. Results from the model were compared to the tracer gas data and the leakage inputs were modified via trial-and-error to decrease the error between the model output and the tested data. No formal method was used to obtain a minimized error function, only visual comparison of the measured and simulated tracer gas decay curves, so there is no reason to assume that the final inputs represent a unique or optimized solution.

During the initial comparisons of measured and simulated data, it became clear that the most difficult tests to replicate were the tests with large differences in tracer gas decay rates between the different rooms. Stated differently, it is easier to replicate the decay rate in a well-mixed house (which might be approximated as a single well-mixed zone) than it is to replicate the decay rates of six interconnected zones. Consequently, a single test was used for the calibration, and the remaining tests were used after the calibration was complete in order to evaluate the results. The test used to calibrate the model was one which utilized the continuously-operating laundry room exhaust fan as the ventilation system, did not have mixing via the AHU, and had the bedroom doors closed and the transfer grills open.

2.3.4. Calibration Results

Overall, good agreement between the modeling and tracer gas results was obtained. The best agreement was obtained for cases with mixing and the least agreement was obtained for the natural infiltration case. Tracer gas concentration decay plots are presented below for several tests.

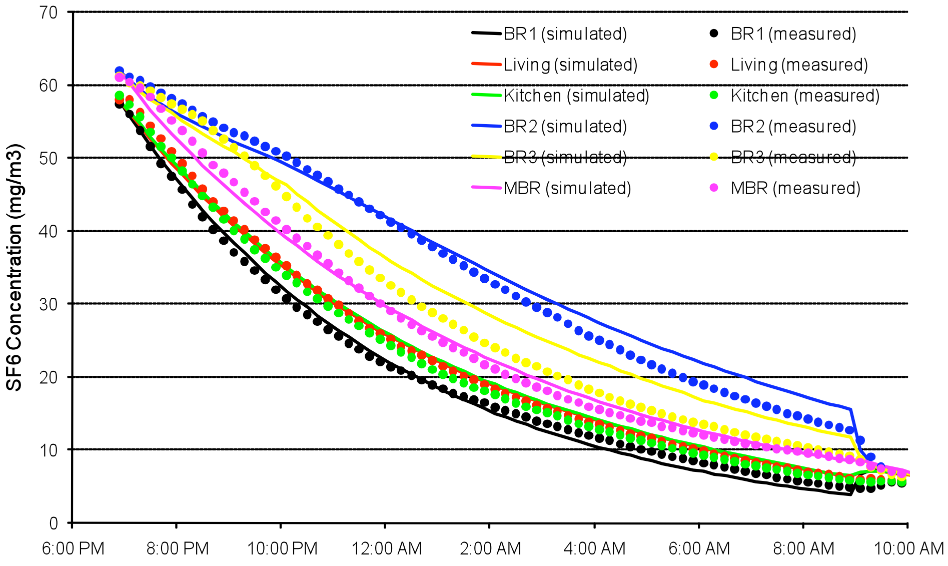

Figure 2.5: Comparison of results for the laundry exhaust test without mixing (test 1)

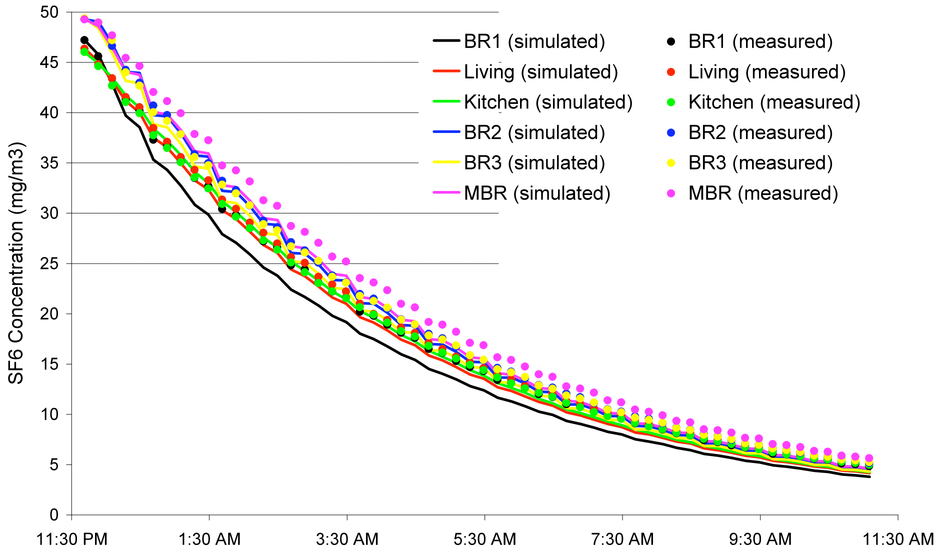

Figure 2.6: Comparison of measured results for the CFIS test (test 3)

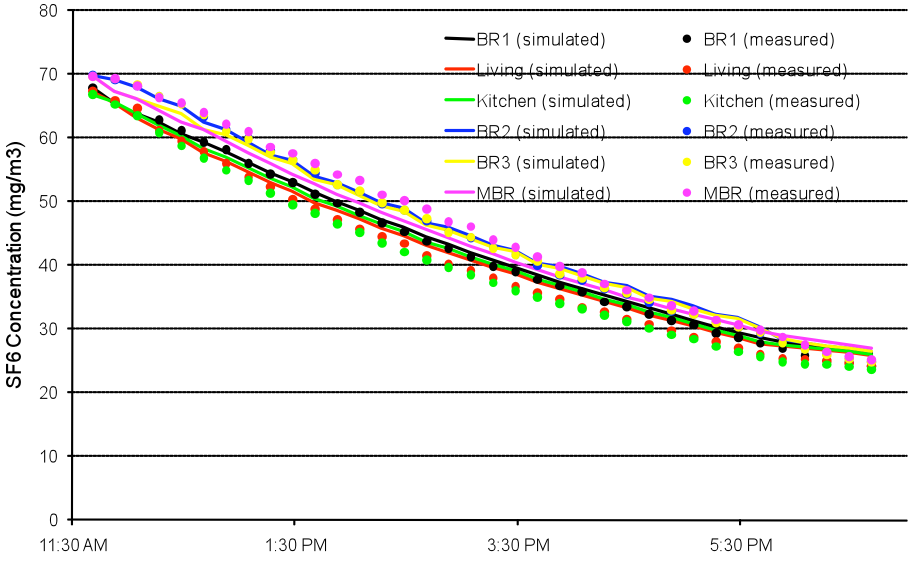

Figure 2.7: Comparison of results for the laundry exhaust test with mixing (test 6)

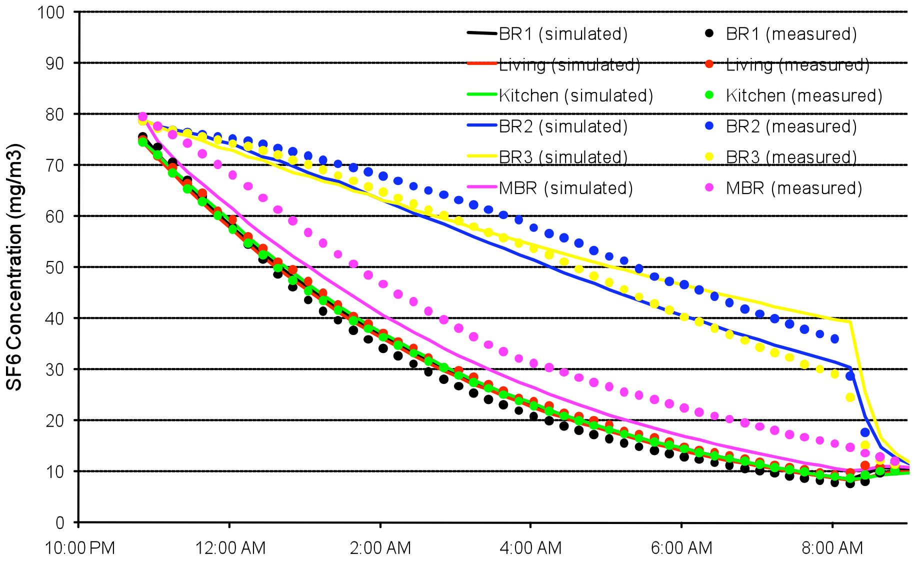

Figure 2.8: Comparison of results for the master bathroom exhaust test without mixing (test 15)

A technical paper describing the calibrated model and results was written and published in ASHRAE Transactions (Townsend 2009).

Because all of the simulations necessary for modeling ventilation systems necessarily have ventilation, the model was deemed sufficiently accurate to enable simulations of systems not tested in the tracer gas tests.

2.3.5. Use of Calibrated Model for Other Ventilation Systems

Six different ventilation systems were simulated using the calibrated model. The ventilation systems compared using the calibrated model were:

1. Exhaust ventilation, without central duct system
2. Supply ventilation, without central duct system
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer
6. Fully ducted balanced ventilation system, without central duct system

For the extension, a single day was examined. During this day, the outdoor temperature varied between 10 and 24 °C and the indoor temperature was constant at 22 °C as shown in Figure 2.10.

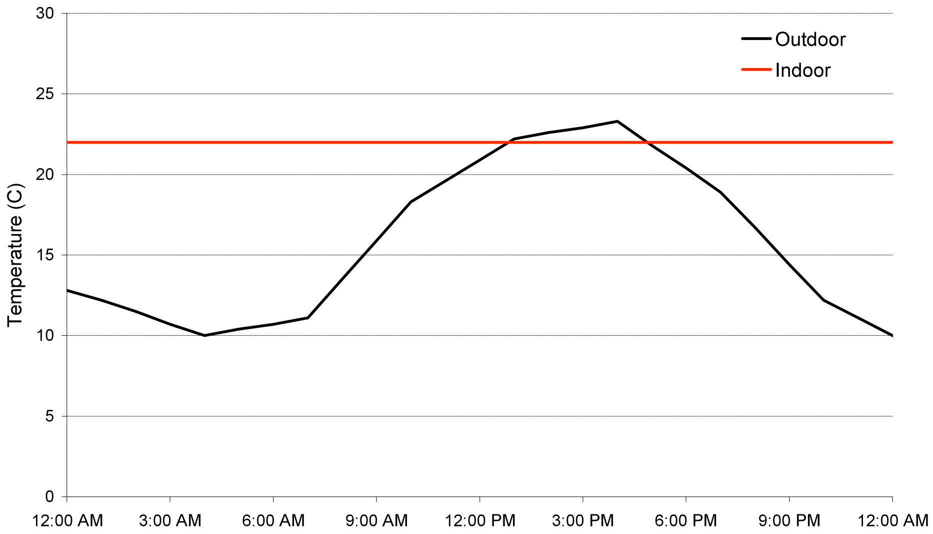

Figure 2.10: Indoor and outdoor temperatures used in extension cases

The tracer gas decay curves for each of these systems are shown in Figure 2.11 through Figure 2.16.

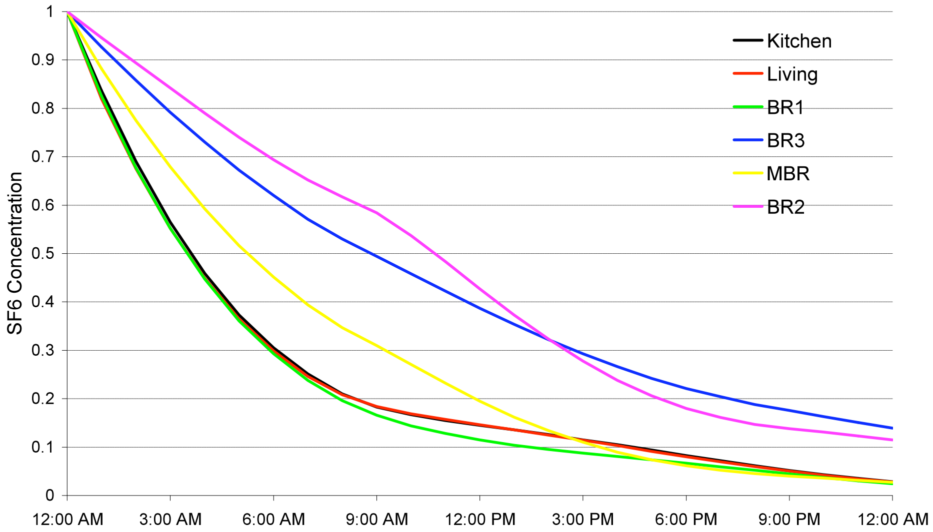

Figure 2.11: Extension case—exhaust ventilation without central AHU

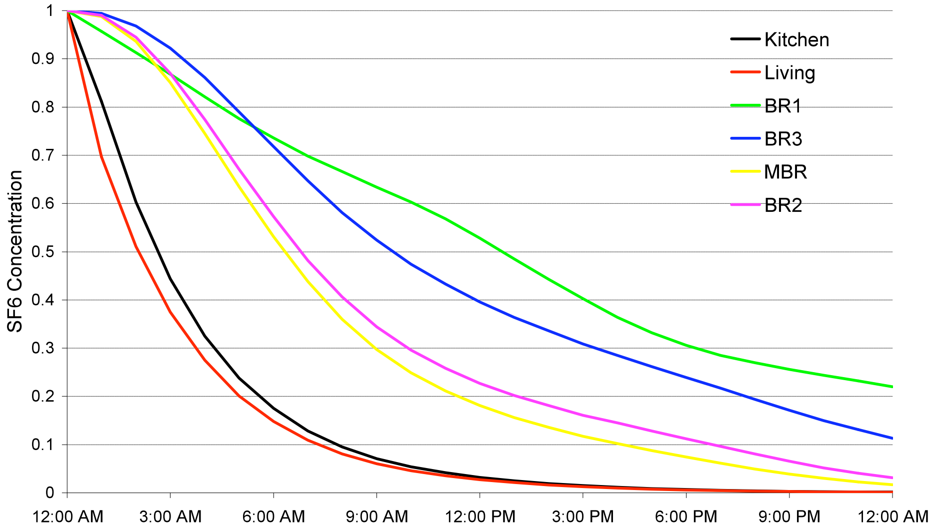

Figure 2.12: Extension case—supply ventilation without central AHU

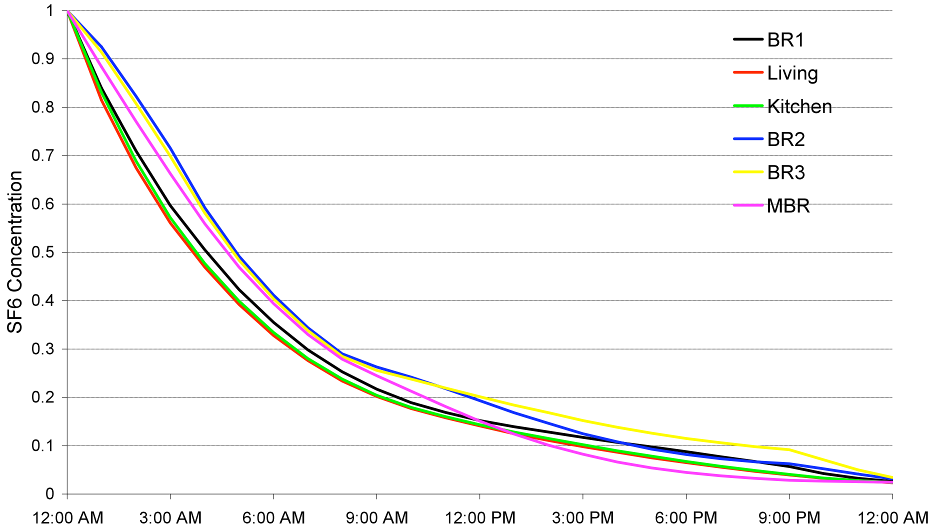

Figure 2.13: Extension case—exhaust ventilation with central AHU and standard thermostat

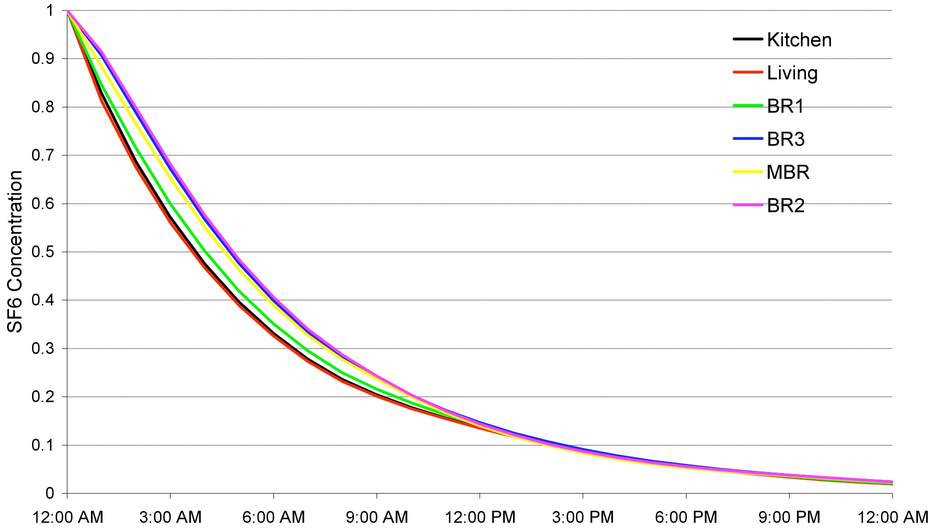

Figure 2.14: Extension case—exhaust ventilation with central AHU and minimum run timer

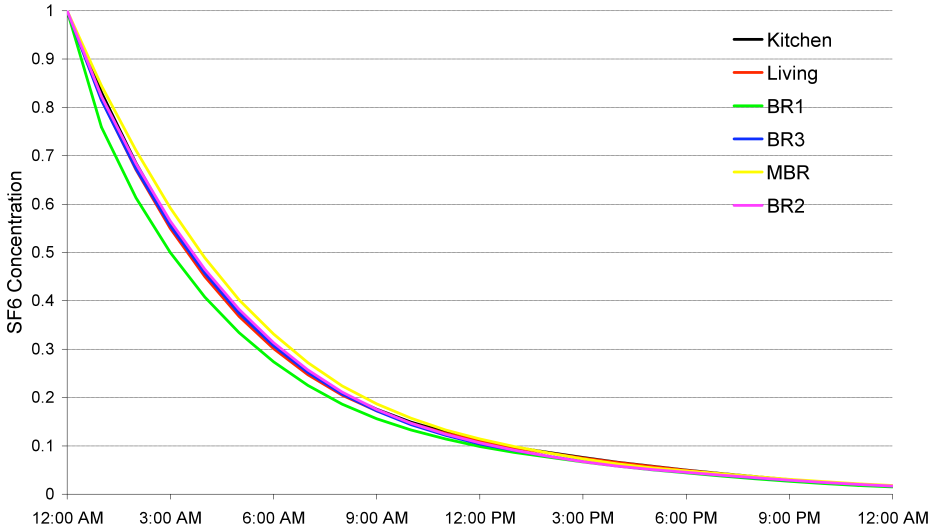

Figure 2.15: Extension case—CFIS ventilation with minimum run timer

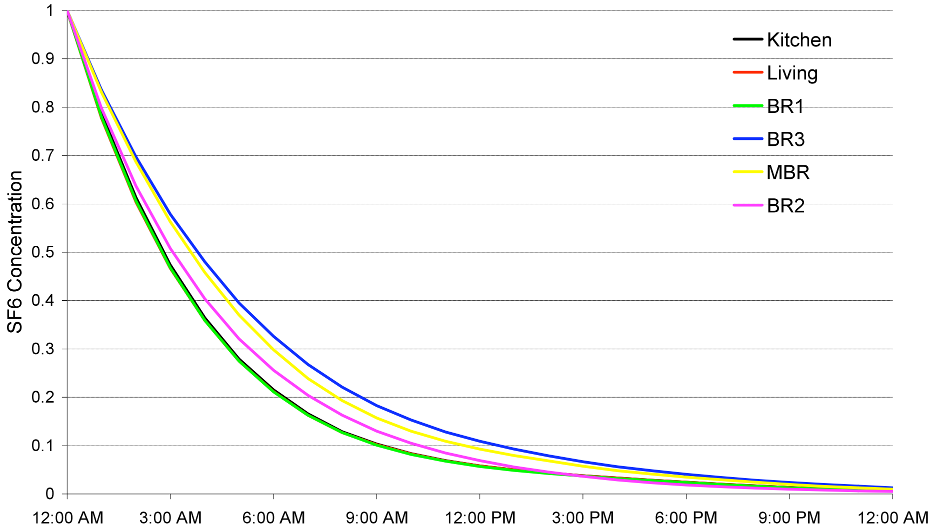

Figure 2.16: Extension case—balanced ventilation system without AHU

The results of these simulations indicated that the worst performance of any of the systems simulated was the exhaust system without an AHU. Therefore the average decay rate of this system was established as a minimum performance criterion, and the other systems were compared to this system to determine if the airflow rates could be modified while still meeting the minimum performance criterion. Figure 2.17 shows the established minimum performance criterion as an average of what the occupants of the house would experience as they moved from zone to zone over the course of a day.

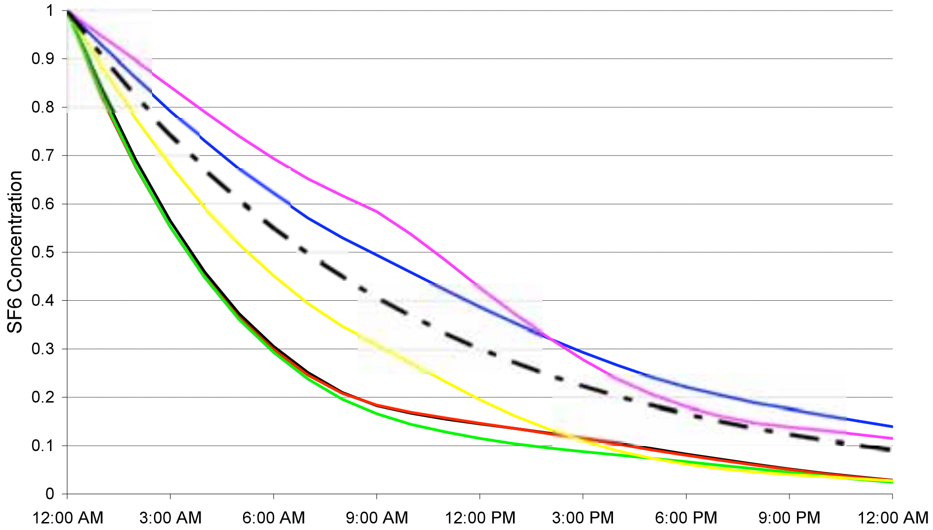

Figure 2.17: Establishing the reference decay rate using the exhaust ventilation system without and AHU

Figure 2.18 shows the same minimum performance criterion and the decay curves for the balanced ventilation system at 100% of the 62.2 ventilation rate. It is clear that the balanced ventilation system exceeds the minimum decay rate criterion, and therefore it may be possible to reduce the airflow somewhat and still meet the minimum decay rate criterion.

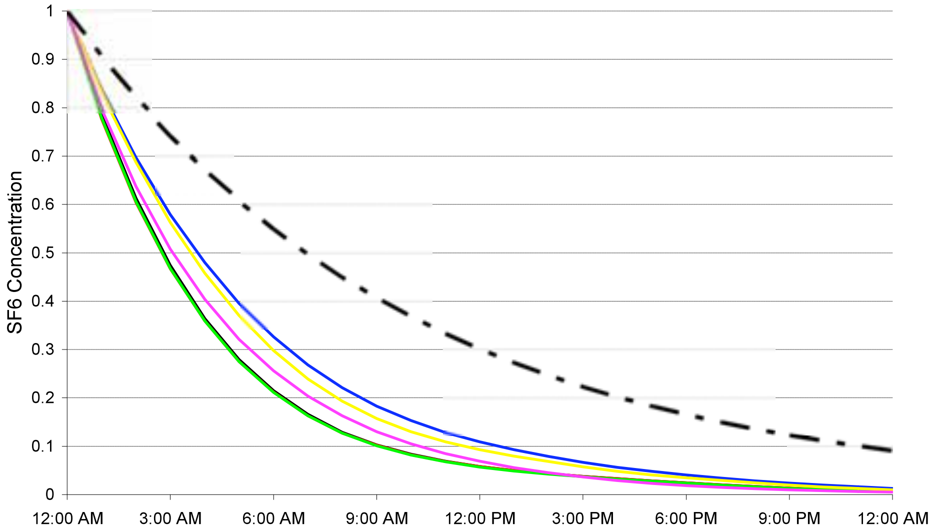

Figure 2.18: Comparison of reference decay rate with decay rates of house with balanced ventilation at 100% of the 62.2 rate

Figure 2.19 shows the same minimum performance criterion and the decay curves for the balanced ventilation system at 50% of the 62.2 ventilation rate. The figure shows that even at 50% of the airflow the tracer gas decay curves are below the established minimum performance criterion. This suggests that the balanced ventilation system could provide only half as much air as the exhaust system and still provide faster decay rates.

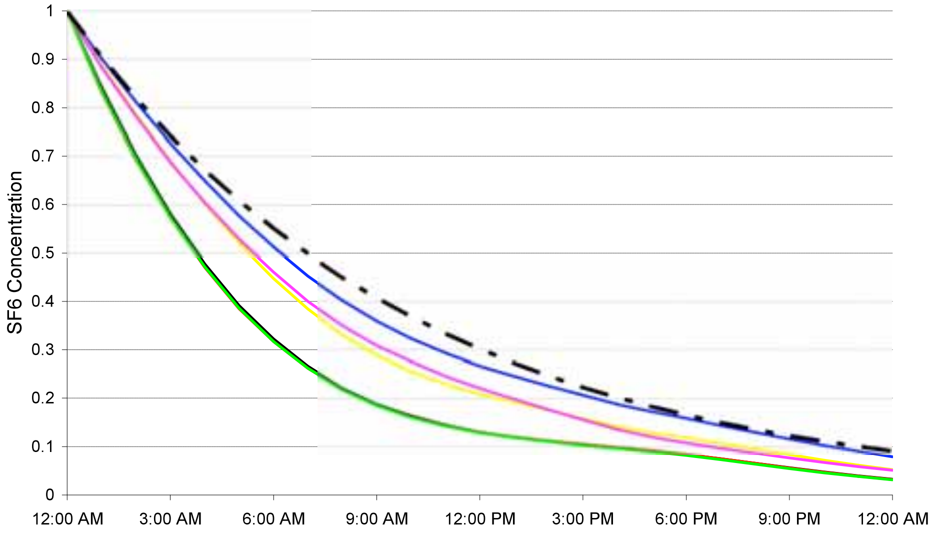

Figure 2.19: Comparison of reference decay rate with decay rates of house with balanced ventilation at 50% of the 62.2 rate

Based on this very limited set of simulations, distribution coefficients for these systems would be:

1. Exhaust ventilation, without central duct system C_D=1.25
2. Supply ventilation, without central duct system C_D =1.25
3. Exhaust ventilation, with central ducts, AHU controlled by standard thermostat C_D =1
4. Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer C_D =0.75
5. Supply ventilation, with central ducts, AHU controlled by thermostat with timer C_D =0.75
6. Fully ducted balanced ventilation system, without central duct system C_D =0.5

2.4 ASHRAE Meeting—January 2007, Dallas

2.4.1. Building America Expert Meeting

BSC presented the results from the tracer gas testing, model calibration, and extension cases at a Building America Expert Meeting in January 2007 in Dallas, just before the ASHRAE Standard 62.2 meeting. Speakers during this meeting were Ren Anderson of NREL, Bjarne Olesen of the Technical University of Denmark, Max Sherman of Lawrence Berkeley National Laboratory, and Aaron Townsend of Building Science Corporation. The expert meeting summary is included in Appendix B.

2.4.2. SSPC 62.2 Meeting

BSC also presented our work to the ASHRAE SSPC 62.2 committee during their normal meeting. In general, the committee engaged with BSC's presentation and was receptive to the idea of modifying airflow rates in order to achieve equivalent performance, but wanted to see the effect of different assumptions in the model before agreeing to any change to the standard. In particular, they wanted to see the effect of these assumptions:

1. Full-year calculation of exposure
2. Climate
3. Enclosure air tightness
4. AHU location
5. Duct leakage
6. Ventilation system duty cycle

In addition to identifying these areas of concern, several members of the committee offered advice and suggestions on how to approach the task of modeling this many combinations of parameters.

2.5 Preparation for First Round of Simulations

In order to determine the effects of the assumptions listed above, a larger batch of simulations was performed. In order to execute these simulations, a test plan was created; weather files were prepared; operational schedules were prepared for the AHU and other equipment; AHU sizes were determined; CONTAM automation tools were gathered; and the necessary post-processing tools were created.

2.5.1. Weather Files

CONTAM uses a custom text format for its climate input files, so TMY2 data files for each climate in the test plan were used to create CONTAM weather files.

2.5.2. Schedule Files

CONTAM also allows the user to specify the operation schedule for many components of the model using custom text files. These files specify a multiplier that is applied to the component, such that the component is between 0 and 100% of its input value.

For basic AHU operation in each climate, the operation schedule was derived from the TMY2 outdoor temperature data. Under either heating or cooling conditions, the AHU was assumed to operate 80% of the hour under design conditions and 0% of the hour at the balance point. Points between the balance point and design conditions were linearly interpolated between 0 and 80%. Points between the heating and cooling balance points had no operation.

Schedules were also created that layered an additional requirement on top of the above schedule. These schedules imposed a minimum runtime of 10 minutes out of every 30 minutes.

Schedules were also prepared for bedroom door operation. The doors were closed at night and open during the day.

2.5.3. AC Sizes

For each of the climates in the simulation plan, an ACCA Manual J calculation was performed to determine the proper size air conditioner for this house in the climate. The AHU airflow was set at 400 cfm per ton.

2.5.4. CONTAM Automation Tools

NIST personnel provided a parametric automation tool called CONTAM Factorial. This program requires the user to create a base CONTAM file, then open the file in a text editor and insert wildcard characters where the Factorial program will insert different values as specified in a separate text file. The Factorial program can change any number of variables with up to eight values per variable. The Factorial program creates a CONTAM file for every combination of value for each variable, and a .BAT file for executing the files in a batch process.

2.5.5. Post-Processing Tools

The output of CONTAM is a text file with contaminant concentrations in each zone for each time step. In order to convert these concentrations into an occupant exposure, the text file must be processed. An Excel macro program was written to perform this conversion.

2.6 First Round of Simulations

2.6.1. Model Description

In order to model a larger subset of the housing stock as requested by the 62.2 committee, the model necessarily became less specific and more general. In this case it means the model was detuned from its calibrated state (where it was calibrated to match one particular house) in order to predict general behavior over a larger population of houses.

The model was expanded from a single day to cover an entire year. The model was also enhanced to include the effects of wind, pollutant generation within the house, and occupants moving around within the house.

Wind speed and direction data were taken from the TMY2 data for each climate. The local wind shielding model and modifiers from ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings were used.

In previous simulations, the house was first loaded to a uniform concentration of pollutant, and the performance metric of interest was how fast the concentration decayed. For these year-long simulations, constant pollutant sources were inserted in each zone in the model and CONTAM calculated the pollutant concentration in each zone each time step. The net result is that the pollutant concentration does not decay, but varies up or down according to the amount of air exchange between the building and the outdoors.

The enclosure leakage was assumed to be distributed as reported in ASHRAE Fundamentals Chapter 27. Walls, windows, and doors made up 62% of the total leakage, ceilings and non-operating exhaust vents 23%, and ducts 15%.

The model layout in this round of simulations is shown in Figure 2.20 below.

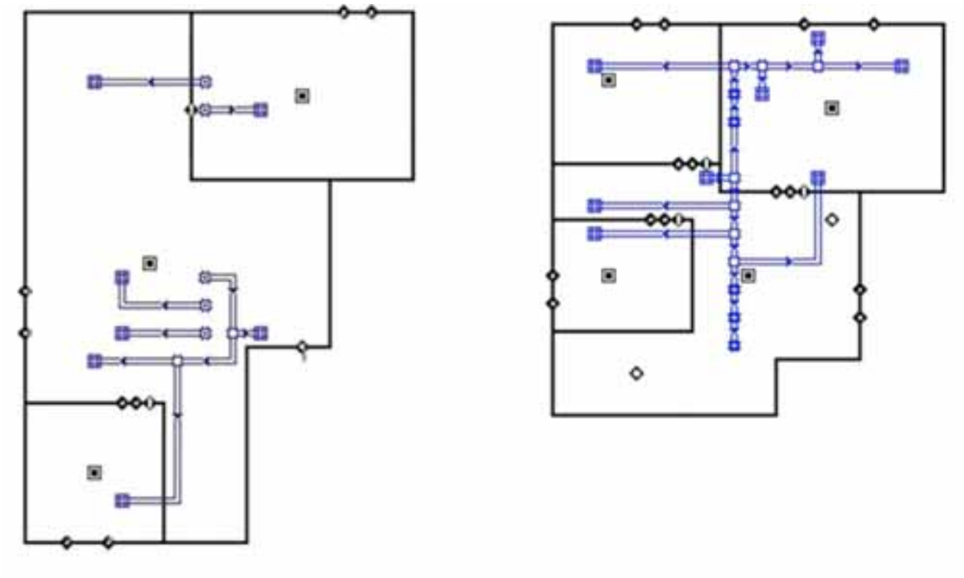

Figure 2.20: CONTAM layour during the first round of simulations

2.6.2. Parameters Varied

The parameters varied in this round of simulations were the presence and location of the central system, the amount of duct leakage, the AHU operation, the enclosure leakage rate, the ventilation system, the ventilation rate, and the climate.

2.6.2.1. Presence and location of central system

The AHU and central duct system is either absent, present but outside of the conditioned space, or present and inside the conditioned space.

2.6.2.2. Duct leakage

If a central system was present, duct leakage was either 6% or 12% of the nominal AHU flow.

2.6.2.3. AHU operation

The AHU, if present, operates either with a standard thermostat or with a thermostat with a minimum of 10 minutes runtime every 30 minutes.

2.6.2.4. Enclosure leakage

Total enclosure leakage rates included 1.5, 3.5, and 7.0 ACH50.

2.6.2.5. Ventilation system

Four ventilation systems were modeled, included a single-point exhaust system, a single-point supply system, a two-point balanced system, and a balanced system with a fully-ducted supply and a single-point exhaust.

2.6.2.6. Ventilation rate

The ventilation rate was 0%, 50%, 100%, or 150% of the ASHRAE Standard 62.2-2003 rate for this house (which was 63 cfm).

2.6.2.7. Climate

Three climates were modeled: Phoenix, Seattle, and Minneapolis (DOE climate zones 2B, 4C, and 6, respectively).

2.6.3. Occupant Exposure as Metric Comparison

The metric for the calibration round of simulations was tracer gas decay rate. This is useful for short time periods, however for longer time periods it is not useful. Instead, pollutant sources are located within the model and CONTAM calculates the pollutant concentration in each zone each time step. The metric for this round of simulations and all rounds after this is exposure to the occupants, which is expressed as an average concentration of pollutant in the air the occupant is breathing. The average can be taken over any time period of interest, for example an hour, a day, or a year. In this round of simulations, averages were taken over three-hour, eight-hour, and one-year time periods.

Exposures were calculated assuming a volume-weighted pollutant source. This type of source simulates pollutants from building materials and finishes such as paint, OSB, carpet, etc.

2.6.4. Post-Processing

An Excel macro program was created to reformat the output from CONTAM and provide the output in a human-readable format.

A different approach was used to determine the airflow ratios. In this round, the “best” system was assumed to be the balanced system with fully ducted supply. Other systems were compared to this system in order to determine how much air they need to supply or exhaust to achieve equivalent performance.

2.6.5. Results

This round of analysis showed that other ventilation systems had airflow ratios in the range of 0.9 to 2.6, with approximate medians in the range of 1.0 to 2.0 for each group.

System Type	**Range**	**Approximate Median**
Fully ducted balanced ventilation system, with or without central duct system	1.0	1.0
Non-fully ducted balanced ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	0.9 to 1.1	1.0
Supply ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.7	1.25

Exhaust ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.9	1.25
Exhaust ventilation, with central duct system, and central air handler unit not controlled to a minimum runtime of at least 10 minutes per hour	1.0 to 1.8	1.5
Supply ventilation, without central duct system	1.4 to 1.9	1.75
Exhaust ventilation, without central duct system	1.3 to 2.6	2.0

2.7 ASHRAE Meeting—June 2007, Long Beach

2.7.1. Building America Expert Meeting

BSC held a second expert meeting before the June 2007 ASHRAE meeting in Long Beach to discuss further developments in the ventilation field. The meeting was again held the same day as the ASHRAE 62.2 committee meeting, allowing greater participation by the committee members. Speakers during this meeting were Max Sherman and Iain Walker of Lawrence Berkeley National Laboratory, Bob Hendron of NREL, and Aaron Townsend of Building Science Corporation. The expert meeting summary is included as Appendix C.

2.7.2. SSPC 62.2 Meeting

BSC again presented our work to the ASHRAE SSPC 62.2 committee during their normal meeting. The committee remained engaged with BSC's work, but wanted further explanation of the effect of each parameter varied, and comparison with other work presented. Their questions are summarized as:

1. How do the cases BSC examined fit with the work LBL presented?
2. What happens if the air conditioner is not sized by ACCA Manual J?
3. What is the effect of each of the varied parameters?
4. Are these consistent with other climates?

2.8 Second Round of Simulations

In order to expand the number of climates and extend the results to 200% of the 62.2 rate, further simulations were performed. The climates added were Daytona Beach, FL, and Raleigh, NC (DOE climate zones 2A and 4A, respectively).

2.8.1. Changes from Previous Modeling

Minimal changes were made to the model. This round was primarily an expansion of the previous results in terms of number of climates and higher ventilation rates. The largest change to the model was to increase the number of leakage points on each wall from two to five, in order to better approximate diffuse leakage over the height of the wall. The other change was to a separate set of simulations that fully mixed the house in order to replicate some of the metrics that LBL presented in the previous expert meeting.

2.8.2. Model Description

The only change to the model for the main group of simulations was the change from two leakage points per wall, located at the top and bottom of the wall, to five leakage points per wall, spaced equally over the wall's height. For a small subset, the house was fully mixed in order to provide a baseline comparison similar to one metric presented by LBL.

2.8.3. Parameters Varied

The only change to the parameters varied from the first round of simulations was the number of climates and the ventilation rates.

2.8.3.1. Presence of central system

The AHU and central duct system is either absent, present but outside of the conditioned space, or present and inside the conditioned space.

2.8.3.2. Duct leakage

If a central system was present, duct leakage was either 6% or 12% of the nominal AHU flow.

2.8.3.3. AHU operation

The AHU, if present, operates either with a standard thermostat or with a thermostat with a minimum of 10 minutes runtime every 30 minutes.

2.8.3.4. Enclosure leakage

Total enclosure leakage rates included 1.5, 3.5, and 7.0 ACH50.

2.8.3.5. Ventilation system

Four ventilation systems were modeled, included a single-point exhaust system, a single-point supply system, a two-point balanced system, and a balanced system with a fully-ducted supply and a single-point exhaust.

2.8.3.6. Ventilation rate

The ventilation rate was 0%, 50%, 100%, 150%, or 200% of the ASHRAE Standard 62.2-2003 rate for this house (which was 63 cfm).

2.8.3.7. Climate

Five climates were modeled: Daytona Beach, Phoenix, Raleigh, Seattle, and Minneapolis (DOE climate zones 2A, 2B, 4A, 4C, and 6, respectively).

2.8.4. Exposure Calculation Method and Scenarios

Exposures were calculated in several different ways in order to compare BSC's results with LBL's results. These included different source locations and different assumptions about occupancy. The following methods were examined:

1. Everybody Everywhere
    a. Equal source in each zone (source strengths independent of zone sizes)

    b. Occupants spend equal time in each zone
    c. Exposure each hour is average of all zones
2. Volume Weighted Sources
    a. Source strengths proportional to volume of each zone (meets age of air assumptions)
    b. Occupants spend equal time in each zone
    c. Exposure each hour is average of all zones
3. Worst Case Age of Air
    a. Source strengths proportional to volume of each zone (meets age of air assumptions)
    b. Varying degrees of worst case:
        i. Case A: Occupant in worst zone each hour
        ii. Case B: Occupant always in zone with worst yearly average
        iii. Case C: Occupant has worst exposure of all occupants in the house, assuming a daily schedule
4. I Stink
    a. Single source in same zone as occupant
    b. Occupant stays in worst zone
5. You Stink
    a. Single source different zone than occupant
    b. Worst combination of source zone and occupied zone

2.8.5. Post-Processing

An Excel macro program was created to perform most of the calculations and post-processing for this round of simulations.

2.8.6. Results

This round of simulations and analysis focused on answering several specific questions posed by the 62.2 committee. These questions were:

1. How do the cases BSC examined fit with the work LBL presented?
2. What happens if the air conditioner is not sized by ACCA Manual J?
3. What is the effect of each of the varied parameters?
4. Are these consistent with other climates?

To answer the first question, BSC replicated the cases LBL had previously presented in order to determine if there were any inconsistencies between the two sets of data. Table 2.2 through Table 2.6 compare the results of the BSC and LBL analyses. The results are remarkably close given the different approaches taken by the two research teams, and there are no results that suggest that the two sets of data are inconsistent.

Table 2.2: Comparison of BSC and LBL results for Everybody Everywhere case

Simple Exhaust

	BSC	LBL
Leaky House	1.22 to 1.27	1.06 to 1.64
Tight House	1.22 to 1.44	1.37 to 2.43

CFI

	BSC	LBL
Leaky House	1.16 to 1.20	1.16 to 1.36
Tight House	0.96 to 1.06	1.01 to 1.10

Exhaust with Mixing

	BSC	LBL
Leaky House	1.12 to 1.16	1.13 to 1.18
Tight House	1.00 to 1.07	1.03 to 1.05

Table 2.3: Comparison of BSC and LBL results for Volume Weighted Sources case

Simple Exhaust

	BSC	LBL
Leaky House	0.91 to 1.01	0.95 to 1.14
Tight House	0.90 to 1.10	1.05 to 1.20

CFI

	BSC	LBL
Leaky House	0.98 to 1.00	1.01 to 1.04
Tight House	0.92 to 1.02	1.00 to 1.00

Exhaust with Mixing

	BSC	LBL
Leaky House	0.99 to 1.00	0.99 to 1.00
Tight House	0.99 to 1.06	0.99 to 1.00

Table 2.4: Comparison of BSC and LBL results for Worst-Case Age-of-Air case

Simple Exhaust

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.30 to 1.44	0.98 to 1.33	1.01 to 1.17	1.05 to 1.59
Tight House	1.22 to 1.50	1.00 to 1.42	0.98 to 1.23	1.09 to 1.83

CFI

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.14 to 1.22	1.02 to 1.18	1.07 to 1.09	1.06 to 1.18
Tight House	1.05 to 1.12	1.05 to 1.11	0.93 to 1.03	1.01 to 1.03

Exhaust with Mixing

	BSC			LBL
	Case A	Case B	Case C	
Leaky House	1.10 to 1.13	1.02 to 1.10	1.05 to 1.06	1.05 to 1.06
Tight House	1.05 to 1.11	1.05 to 1.09	1.00 to 1.07	1.01 to 1.02

Table 2.5: Comparison of BSC and LBL results for I Stink case

Simple Exhaust

	BSC	LBL
Leaky House	9.09 to 10.05	3.25 to 10.85
Tight House	8.47 to 10.44	4.25 to 24.80

CFI

	BSC	LBL
Leaky House	6.14 to 7.68	2.96 to 7.22
Tight House	3.21 to 3.70	1.94 to 2.83

Exhaust with Mixing

	BSC	LBL
Leaky House	4.62 to 5.94	3.14 to 5.19
Tight House	2.17 to 2.45	1.88 to 2.21

Figure 2.6: Comparison of BSC and LBL results for You Stink case

Simple Exhaust

	BSC	LBL
Leaky House	1.44 to 2.05	1.04 to 1.88
Tight House	1.72 to 2.43	2.53 to 2.95

CFI

	BSC	LBL
Leaky House	1.13 to 1.22	0.90 to 2.04
Tight House	1.02 to 1.13	1.16 to 1.20

Exhaust with Mixing

	BSC	LBL
Leaky House	1.1 to 1.19	0.94 to 1.28
Tight House	1.02 to 1.09	1.13 to 1.14

In order to answer the second question, BSC analyzed the effect of doubling the size of the air conditioner and AHU. For a system using a standard thermostat, this has minimal effect because the heating or cooling load will be met in half the time, resulting in the same amount of mixing in the house. Figure 2.21 below shows this effect.

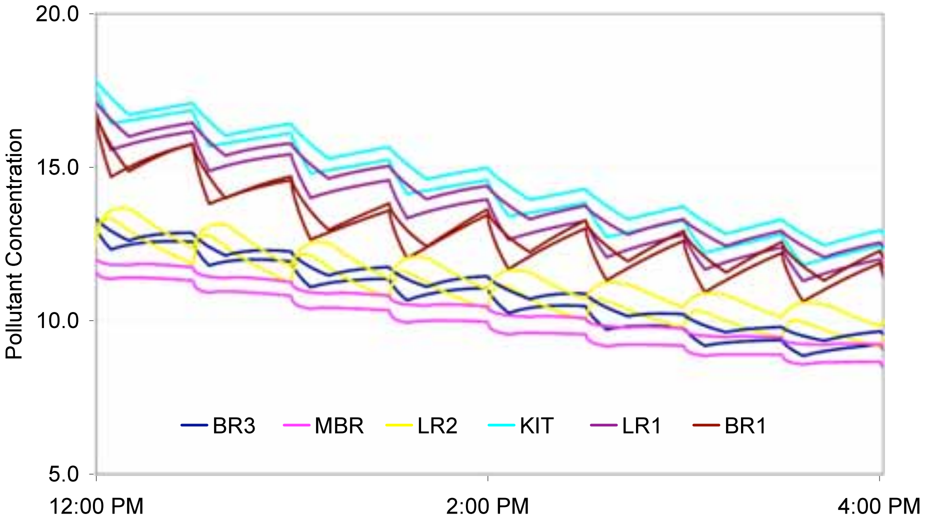

Figure 2.21: Difference between 1X and 2X Manual J sizing

In the cases where a minimum runtime is used, oversizing does result in more mixing; however at the level of a minimum of 10 minutes per 30 minute period the house is well mixed already and further mixing does little to increase the uniformity of pollutant concentrations in the house.

In order to answer the third question, the data set was analyzed one variable at a time, holding the other variables constant or averaging over all values of the other variables. The effects of climate, central system presence, duct leakage, central system minimum runtime, and envelope tightness were examined.

Figure 2.22 shows the effect of climate (as represented by infiltration degree days) on the calculated yearly average exposure. The results show that for no or low ventilation, mild climates have higher exposures than severe climates; however this effect is greatly reduced at the 62.2 ventilation rate and is nearly gone at twice the 62.2 rate. The effect of enclosure is similar: climate matters more with leakier houses than with tight houses.

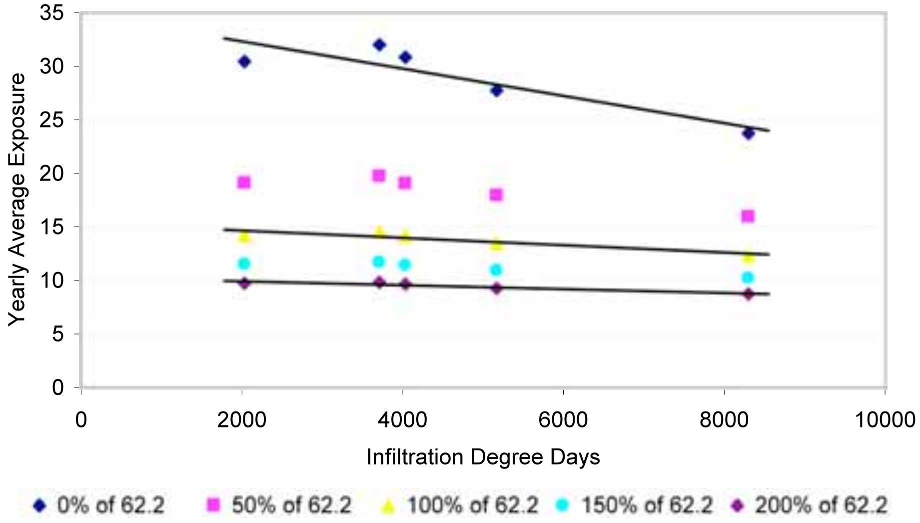

Figure 2.22: Effect of climate on yearly average exposure

Figure 2.23 shows the effect of central system presence and location on yearly average exposure. The results show that duct leakage in unconditioned space results in rejecting indoor pollutants to those locations and therefore lowers the exposure in this analysis. This may not be true in reality, particularly if the ducts are located in spaces with poor air quality such as unconditioned crawlspaces. Additionally, the graph shows that the difference is fairly consistent from 50% to 200% of the 62.2 rate.

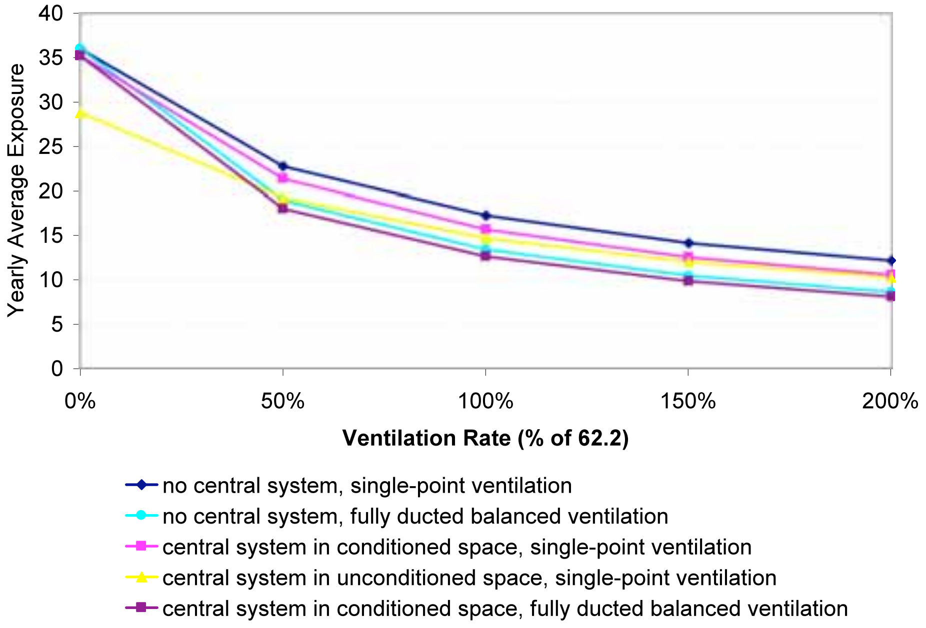

Figure 2.23: Effect of central system on yearly average exposure

Figure 2.24 shows the effect of duct location and leakage rate on the yearly average exposure. The graph shows that when ducts are located inside conditioned space, the leakage rate does not affect the pollutant concentration, as all the leakage is to the interior. However, when the ducts are located outside the conditioned space, more duct leakage leads to more air exchange with the exterior and therefore lower pollutant levels in the home, unless the leakage results in air being pulled in from a zone with poor air quality such as an unconditioned crawlspace.

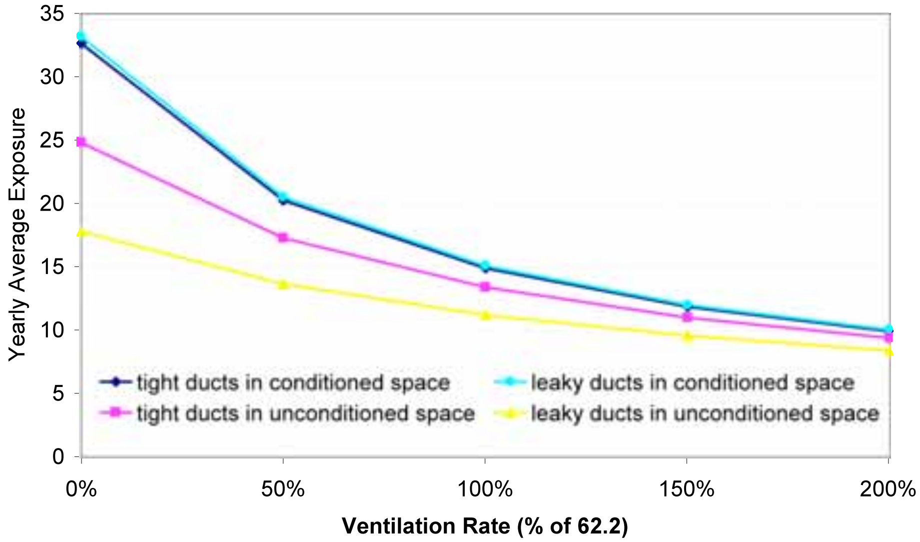

Figure 2.24: Effect of duct location and leakage level on yearly average exposure

Figure 2.25 shows the effect of minimum runtime on yearly average exposure. The graph shows that minimum runtime reduces the yearly average exposure both when ducts are in conditioned space and when they are in unconditioned space.

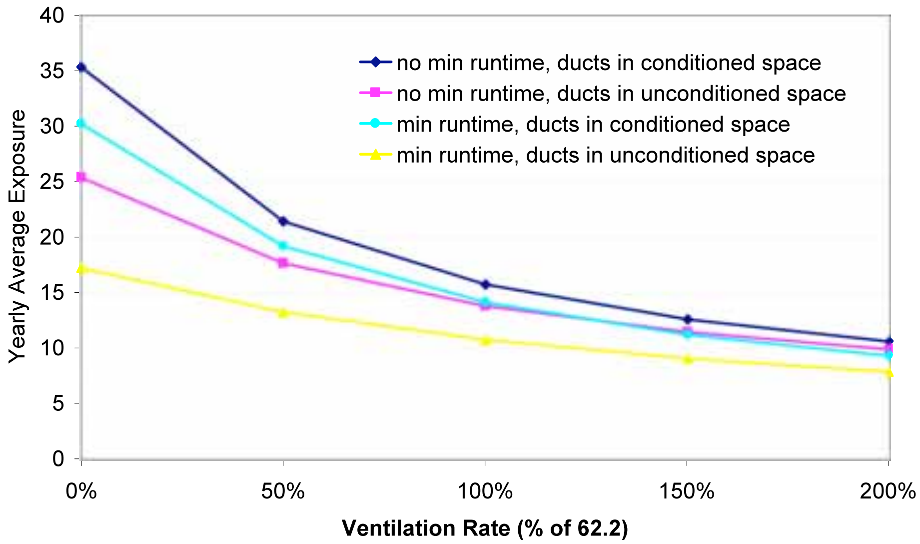

Figure 2.25: Effect of minimum runtime on yearly average exposure

Figure 2.26 shows the effect of envelope leakage rate on yearly average exposure. The graph shows that there is a large dependence on the envelop leakage rate at low ventilation levels, but that the difference becomes smaller at the 62.2 rate and much smaller at twice the 62.2 rate.

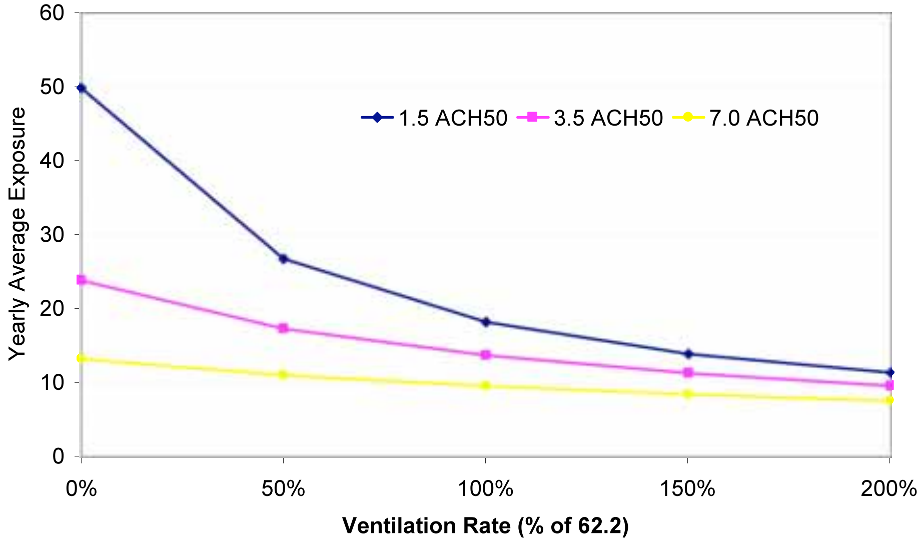

Figure 2.26: Effect of envelope leakage rate on yearly average exposure

Finally, the last question from the June 2007 meeting was whether the results were consistent if we examined additional climates. The two additional climates added (Daytona Beach and Raleigh) confirmed that the results were consistent.

2.9 ASHRAE Meeting – January 2008 – New York City

2.9.1. Building America Expert Meeting

BSC hosted a Building America Expert Meeting before the ASHRAE SSPC 62.2 meeting in January 2008. Speakers at this meeting were Bud Offerman of Indoor Environmental Engineering, Bill Rittleman of Ibacos, and Aaron Townsend of BSC. The summary report for the Expert Meeting is included in Appendix D.

2.9.2. SSPC 62.2 Meeting

BSC again presented to the SSPC 62.2 committee. The presentation covered the results of the simulations and analysis performed since the June 2007 meeting. The committee remained engaged and open to the change proposal but wanted to see results from more climates, a wider variety of ventilation systems, no duct leakage, slight changes to the leakage distribution over the enclosure, additional detail in the occupant schedules, and different source locations.

2.10 Third Round of Simulations

In order to provide the requested data, a third round of simulations was planned and executed.

2.10.1. Model Description

Several substantial changes were made to the model for this round of testing.

Duct leakage was eliminated. The committee felt that duct leakage in the model provided a benefit, whereas several members of the committee were concerned that duct leakage in unconditioned areas with poor air quality (such as crawlspaces) would lead to contaminants being introduced from those areas and therefore should not be rewarded.

Enclosure leakage previously assigned to the ducts was assigned to the ceiling. Enclosure distribution was distributed as follows: 55% walls, 45% ceilings.

An additional enclosure leakage rate was added to represent a typical existing leaky house (20 ach50).

The minimum runtime criterion for the AHU was changed to a minimum turnover requirement, in order to remove the effect of sizing and more truly represent the amount of mixing that occurs.

Four additional zones were added to the house. On the first floor a bathroom and the laundry room were added, and on the second floor the master bathroom and a secondary bathroom were added. In previous rounds of simulations these rooms were lumped within the room that contains them. Figure 2.27 shows the location of the new zones in the CONTAM model layout.

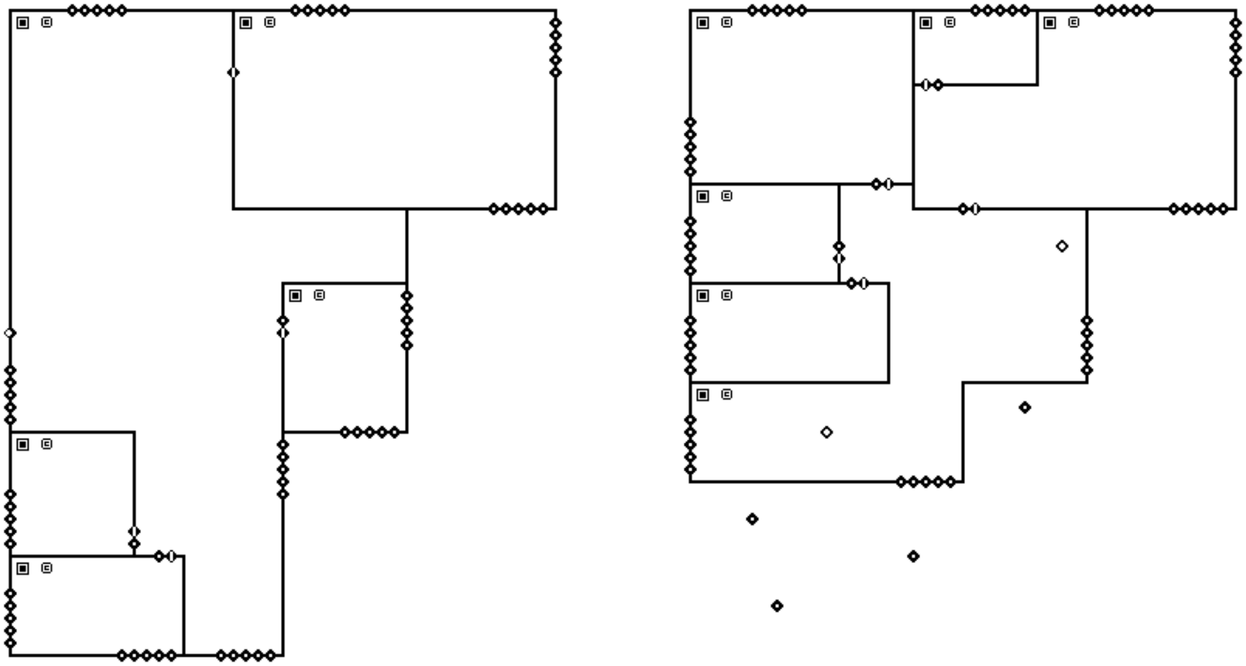

Figure 2.27: CONTAM model layout with added zones

2.10.2. Parameters Varied

The parameters varied for this round of simulations were the presence of the AHU, the AHU operation, the enclosure leakage rate, the ventilation system, and the ventilation rate.

2.10.2.1. Presence of central system

The AHU and central duct system is either absent or present and inside the conditioned space.

2.10.2.2. AHU operation

The AHU, if present, operates either with a standard thermostat or with a thermostat with a minimum runtime to achieve at least 0.7 turnovers of air per hour. (One turnover is the equivalent of passing the same amount of air through the AHU as the house volume.)

2.10.2.3. Enclosure leakage

Total enclosure leakage rates included 1.5, 3.5, 7, and 20 ACH50.

2.10.2.4. Ventilation system

Ten different ventilation systems were modeled:

1. Single-point exhaust from common area
2. Single-point exhaust from master bathroom
3. Single-point supply to common area
4. Central-fan-integrated supply
5. Three-point exhaust, 1/3 from each bathroom continuously
6. Four-point exhaust, 1/4 from kitchen and each bathroom continuously
7. Two-point balanced (supply into common area, exhaust from family bathroom)
8. Two-point balanced combined with central system (supply into supply ducts, exhaust from return plenum, interlock with central system operation)
9. Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, single exhaust from the common area)
10. Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, exhaust from each bathroom, utility room, and kitchen)

2.10.2.5. Ventilation rate

The ventilation rate was 0%, 50%, 100%, 150%, or 200% of the ASHRAE Standard 62.2-2003 rate for this house (which was 63 cfm).

2.10.2.6. Climate

Seven climates were simulated in this round. These were Houston (DOE climate zone 2A), Phoenix (2B), Sacramento (3B), San Diego (3B), Seattle (4C), Raleigh (4A), and Minneapolis (6).

2.10.3. Exposure Scenarios

For this round of simulations, a unique pollutant was generated in each zone. In post-processing, the pollutants were weighted in different combinations to create different source scenarios. In this way, four scenarios were examined:

1. Generation rate in each zone proportional to the zone volume, with new occupant schedule described below
2. Generation rate in each zone proportional to the zone volume, assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)
3. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), with new occupant schedule described below
4. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

The previous occupant schedule was modified to include time spent in the bathrooms. The schedule is the same for all occupants:

1. 10 PM to 7 AM: in bedroom with door closed
2. 7 AM to 7:30 AM: in the bathroom nearest to occupant's bedroom
3. 7:30 AM to 9 AM: in kitchen
4. 9 AM to 12 PM: in living room
5. 12 PM to 1 PM: in kitchen
6. 1 PM to 5 PM: in living room
7. 5 PM to 7 PM: in kitchen
8. 7 PM to 9:30 PM: in other bedrooms
9. 9:30 PM to 10:00 PM: in the bathroom nearest to occupant's bedroom

2.10.4. Post Processing

An Excel macro program was created to perform the calculations and post-processing for this round of simulations.

2.10.5. Results

The results of this set of simulations are a set of airflow ratios for each climate, enclosure leakage level, and exposure scenario. Figure 2.28 through Figure 2.31 show these results in graphical format for the four exposure scenarios described above, respectfully.

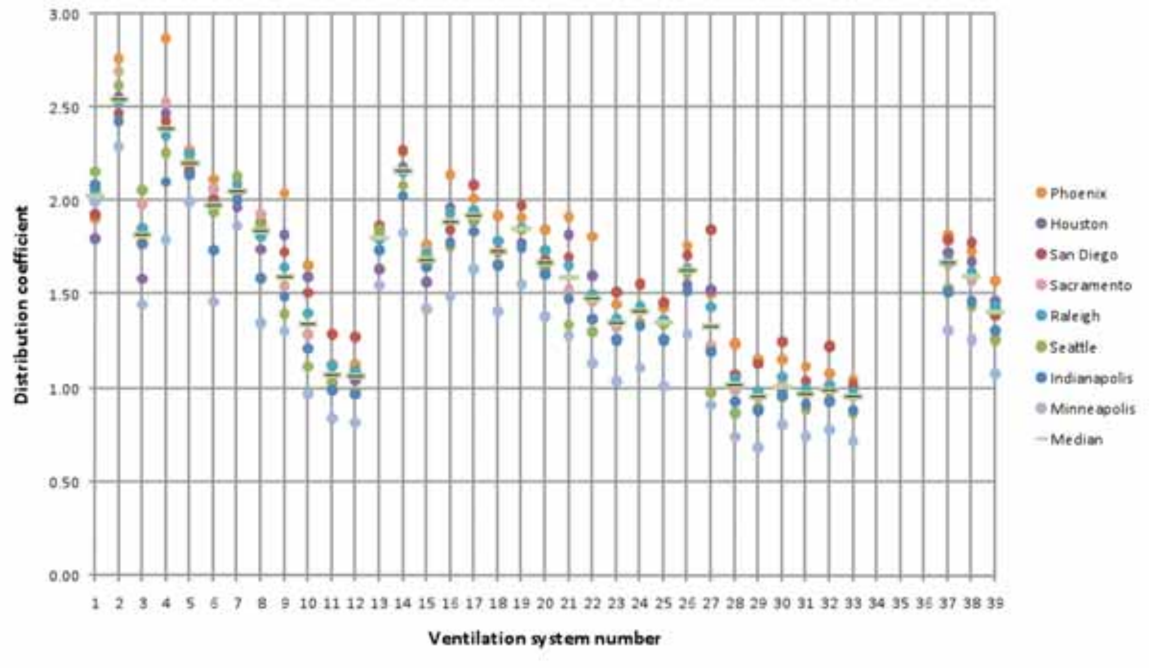

Figure 2.28: System coefficients for 3.5 ach50 enclosure, exposure scenario 1

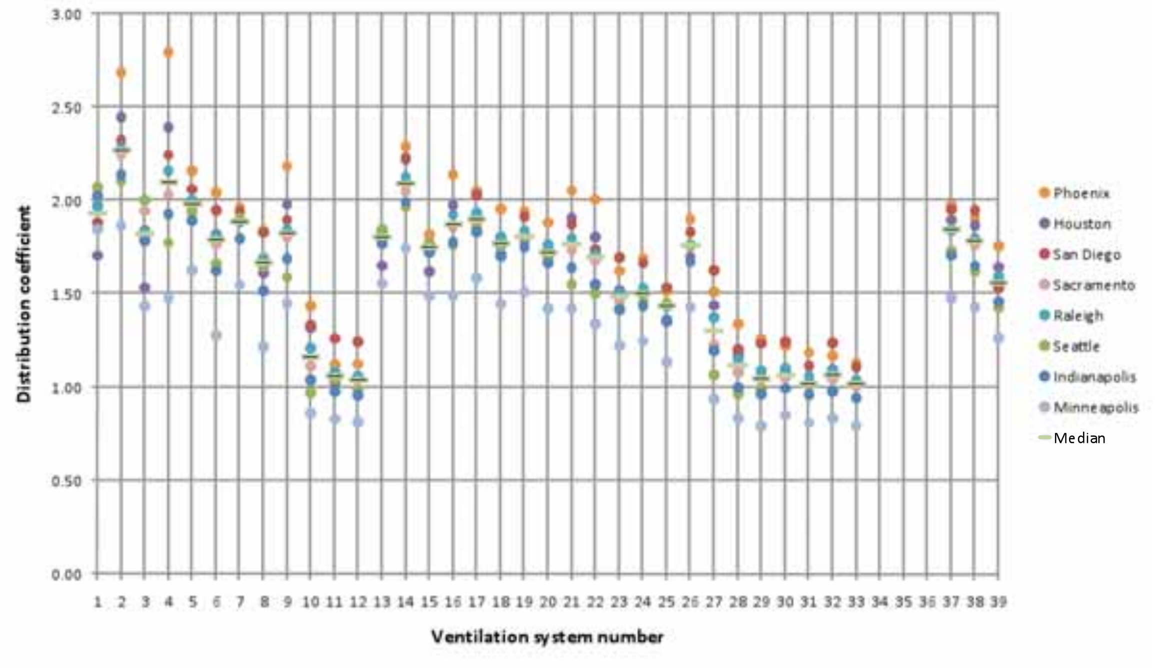

Figure 2.29: System coefficients for 3.5 ach50 enclosure, exposure scenario 2

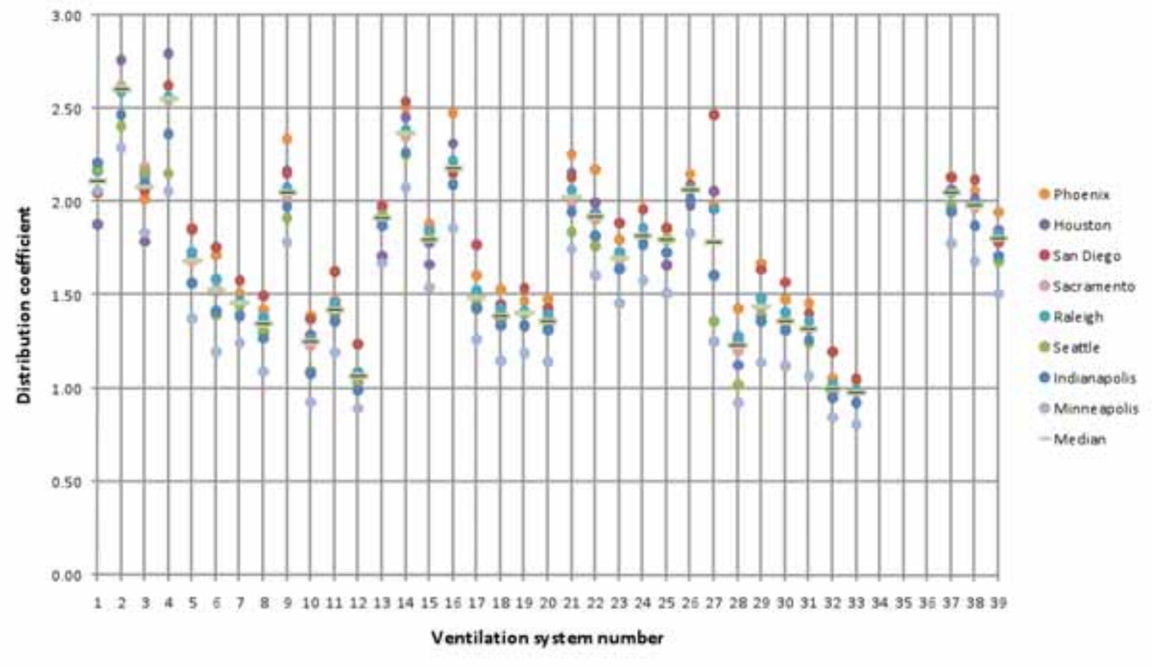

Figure 2.30: System coefficients for 3.5 ach50 enclosure, exposure scenario 3

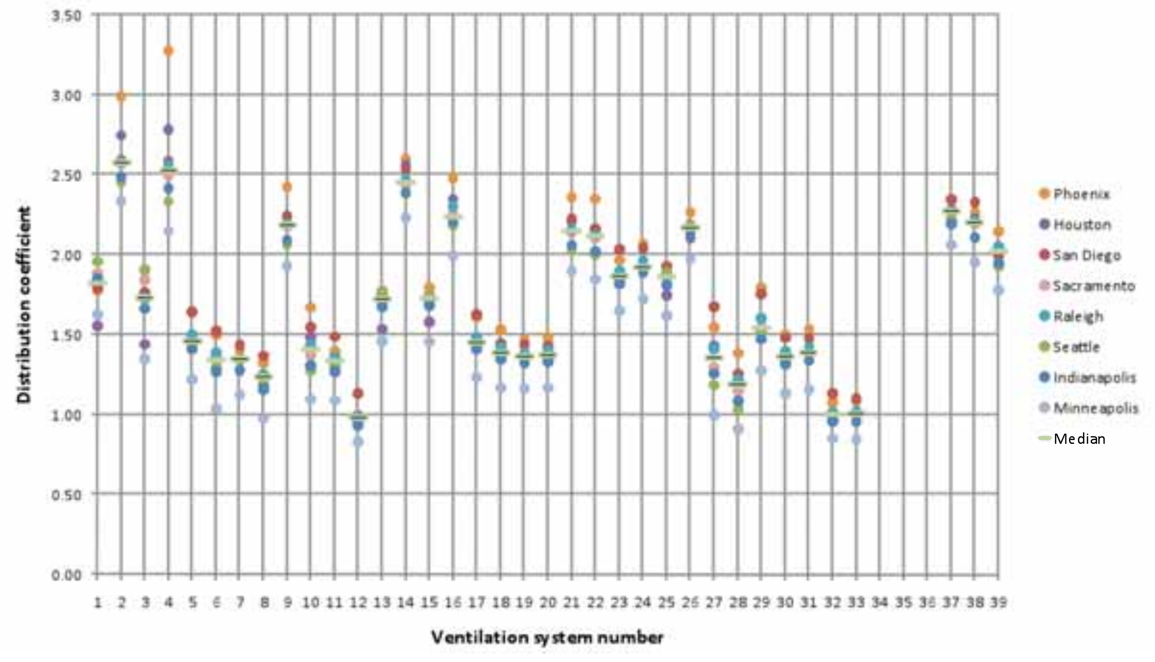

Figure 2.31: System coefficients for 3.5 ach50 enclosure, exposure scenario 3

When grouped into categories of systems and averaged across all the climates, these scenarios produce the system coefficient tables in Table 2.7 through Table 2.8.

Table 2.7: System coefficients for 3.5 ach50 enclosure, exposure scenario 1

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1.35	1.65	1.65
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.65	2	2
	not fully ducted	1.65	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.35	1.35

Table 2.8: System coefficients for 3.5 ach50 enclosure, exposure scenario 3

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1.65	2	2
	not fully ducted	2	2	2
Exhaust	fully ducted	1.35	1.65	1.65
	not fully ducted	2	2	2
Balanced	fully ducted	1.35	1.35	1.35
	fully ducted + exhaust in wet rooms	1	1	1
	not fully ducted	1.35	1.65	2

2.11 ASHRAE Meeting – June 2008 – Salt Lake City

2.11.1. SSPC 62.2 Committee Meeting

At the SSPC 62.2 committee meeting at the June 2008 ASHRAE meeting, BSC presented the results from the latest round of simulations in a working group format (no official presentation, simply working from Excel spreadsheets). The committee was in general agreement with several of BSC's proposals, such as using the 3.5 ach50 enclosure tightness as the reference case and using the annual average exposure. In other areas there was disagreement between committee members as to the proper approach to take, particularly regarding the exposure scenario to select, and whether or not to exempt very leaky houses from the system coefficient. In order to help address the issue, BSC agreed to perform additional simulations at an enclosure tightness level of 5 ach50. One additional important issue that was raised was the desire to see the effect of pollutants generated by the occupants themselves.

2.12 Fourth Round of Simulations

In order to see the effect of pollutants generated by the occupants themselves, another round of simulations had to be performed.

2.12.1. Model Description

The model was substantially the same as the previous round of simulations, except that in addition to the stationary pollutant sources in each zone, the occupants also emitted pollutants at a constant rate. As before, weighting factors were applied in post-processing to create the different exposure scenarios.

2.12.2. Parameters Varied

The parameters varied in the fourth round of simulations were the same as in the third round of simulations.

2.12.3. Exposure Scenarios

For this round of simulations, a unique pollutant was generated in each zone and by each occupant. In post-processing, the pollutants were weighted in different combinations to create different source scenarios. In this way, six scenarios were examined. The first four are identical to the previous round of simulations; the last two are the new scenarios:

1. Generation rate in each zone proportional to the zone volume, with the occupant schedule described below

2. Generation rate in each zone proportional to the zone volume, assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

3. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), with the occupant schedule described below

4. 1/3 of pollutants generated in master bathroom and 2/3 in kitchen (no pollutants generated anywhere else), assuming occupants spend equal time in each zone each hour ("Everybody Everywhere" scenario)

5. All pollutants generated by the occupants, with the occupant schedule as described below.

6. Half of the pollutants generated by the occupants and the other half generated proportional to zone volumes, with the occupant schedule as described below.

The occupant schedule is the same for all occupants:

1. 10 PM to 7 AM: in bedroom with door closed

2. 7 AM to 7:30 AM: in the bathroom nearest to occupant's bedroom

3. 7:30 AM to 9 AM: in kitchen

4. 9 AM to 12 PM: in living room

5. 12 PM to 1 PM: in kitchen

6. 1 PM to 5 PM: in living room

7. 5 PM to 7 PM: in kitchen

8. 7 PM to 9:30 PM: in other bedrooms

9. 9:30 PM to 10:00 PM: in the bathroom nearest to occupant's bedroom

2.12.4. Post Processing

Due to the additional exposure scenarios, another Excel macro program was created to perform post-processing of the data.

2.12.5. Results

In addition to the results produced in the third round of simulations, the fourth round of simulations produced airflow ratios for the added exposure scenarios. Graphs of these results are shown in Figure 2.32 and Figure 2.33.

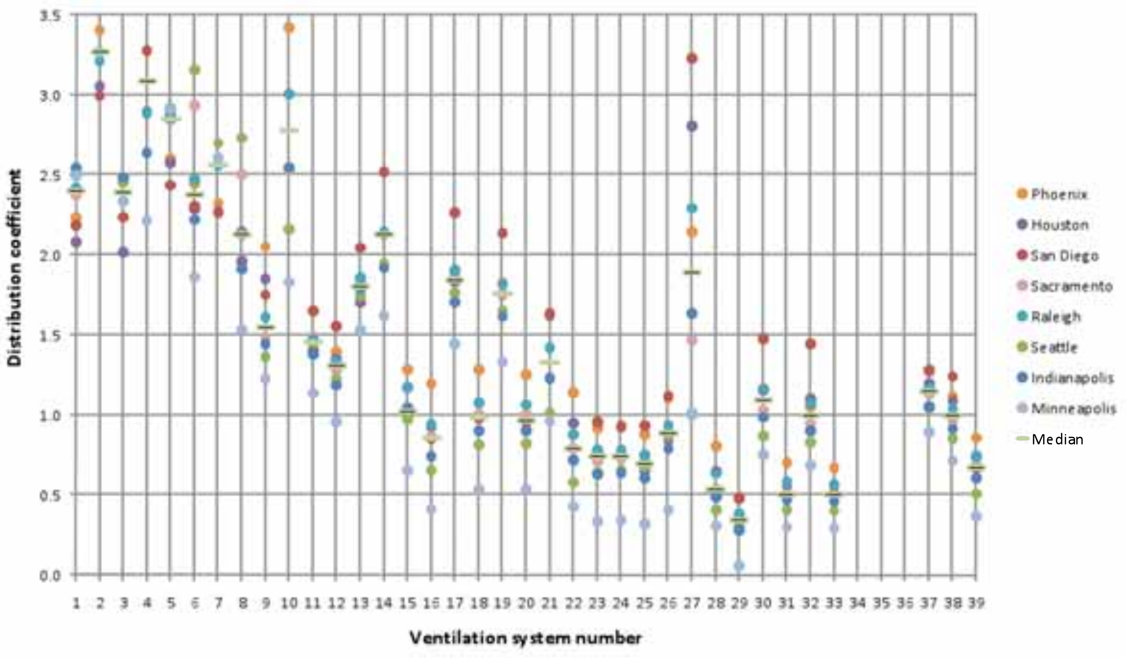

Figure 2.32: System coefficients for 3.5 ach50 enclosure, exposure scenario 5

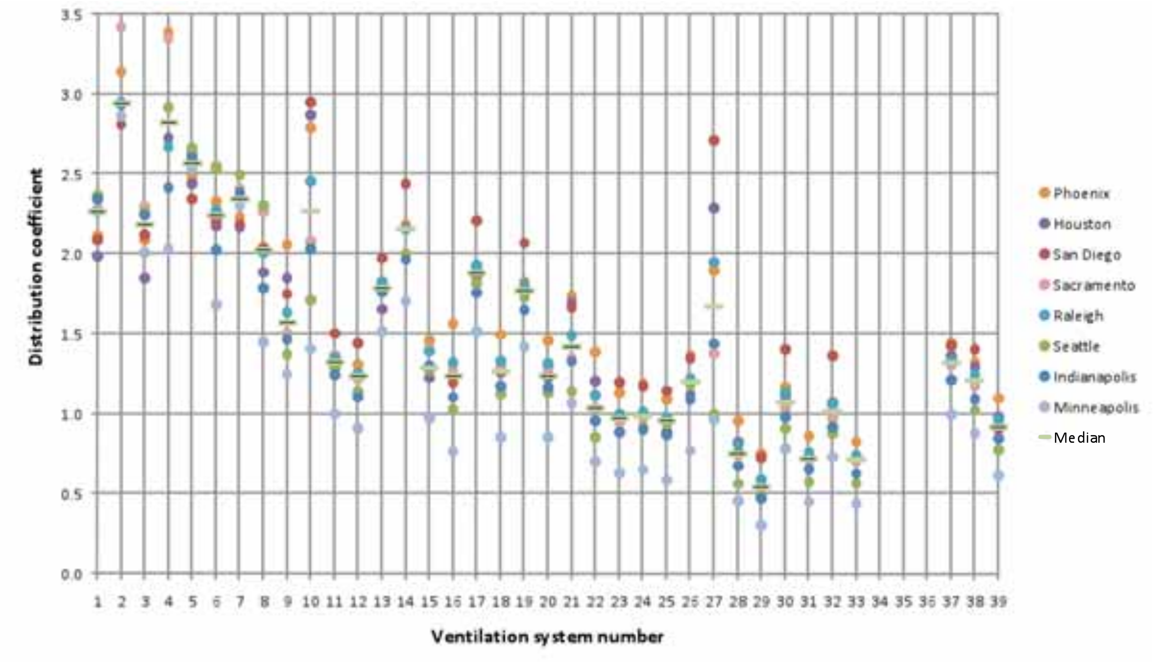

Figure 2.33: System coefficients for 3.5 ach50 enclosure, exposure scenario 6

When grouped into categories of systems and averaged across all the climates, these scenarios produce the system coefficient tables in Table 2.9 and Table 2.10.

Table 2.9: System coefficients for 3.5 ach50 enclosure, exposure scenario 5

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1	1
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	1.65	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

Table 2.10: System coefficients for 3.5 ach50 enclosure, exposure scenario 6

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	2	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

2.12.6. Sensitivity Analysis

In order to help move the committee nearer a decision on the exposure scenario, BSC performed a sensitivity study on the ratio of pollutant sources. The following cases were examined to determine where the tipping points occurred in the tables. Exposure scenarios 1, 3, 5, and 6 were previously done. Exposure cases 7-12 were added for the sensitivity analysis. All of these exposure cases use the occupant schedules.

Table 2.11: Pollutant source cases for sensitivity study

Scenario	1	3	5	6	7	8	9	10	11	12
Volume Weighted	100	0	0	50	40	30	50	50	33	20
Kitchens & Baths Only	0	100	0	0	10	20	10	20	33	20
Occupants Only	0	0	100	50	50	50	40	30	33	60

When grouped into categories of systems and averaged across all the climates, these scenarios produce the system coefficient tables in Table 2.12 through Table 2.17. The tables show minor differences, but predominantly indicate that the coefficients are heavily influenced by the presence of occupant-emitted pollutants.

Table 2.12: System coefficients for 3.5 ach50 enclosure, exposure scenario 7

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Table 2.13: System coefficients for 3.5 ach50 enclosure, exposure scenario 8

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Table 2.14: System coefficients for 3.5 ach50 enclosure, exposure scenario 9

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	1.65	2

Table 2.15: System coefficients for 3.5 ach50 enclosure, exposure scenario 10

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.65	2

Table 2.16: System coefficients for 3.5 ach50 enclosure, exposure scenario 11

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1.35	1.35
	not fully ducted	1.35	1.65	1.65
Exhaust	fully ducted	1.35	1.65	2
	not fully ducted	1.35	2	2
Balanced	fully ducted	1	1	1
	not fully ducted	1	1.65	2

Table 2.17: System coefficients for 3.5 ach50 enclosure, exposure scenario 12

Ventilation type	Ventilation ducting	With AHU		Without AHU
		With Min Turnover	Without Min Turnover	
Supply	fully ducted	1	1	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	2	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

2.13 ASHRAE Meeting – January 2009 – Chicago

2.13.1. Building America Expert Meeting

Before the ASHRAE meeting in January 2009, BSC held a Building America Expert Meeting. The focus of this meeting was gathering information about what exposure scenarios were most appropriate. Presenters were Jeff Siegel and Atila Novoselac from the University of Texas at Austin, and Aaron Townsend from BSC. The summary meeting report is included in Appendix E.

2.13.2. SSPC 62.2 Committee Meeting

At the SSPC 62.2 committee meeting, BSC presented an overview of the whole process of discovery and learning since the Sacramento tracer gas testing and capped it off with the results of the latest simulations and the sensitivity study. The committee was processing the information and seemed prepared to accept the change, but got bogged down in the mechanics of how to reduce the top end of the system coefficients into a politically viable range.

2.14 Post January 2009 meeting

2.14.1. Rescaling Coefficient Range

After the January 2009 meeting, BSC worked with the committee to rescale the coefficient range into an acceptable range. Figure 2.34 shows one example of this process. First, the actual average air flow ratios as calculated from the simulation post-processing are rescaled into the desired range. Then, thresholds are applied to assign each system into a coefficient bin. Bin sizes from 0.1 to 0.35 were examined, with a recommended value of 1/6 (0.1666).

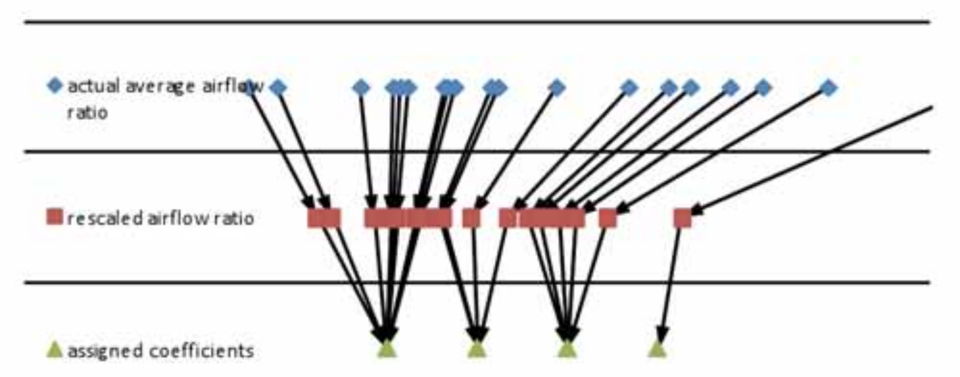

Figure 2.34: Example illustration of the process of rescaling the coefficients

2.14.2. Average Exposures Instead of Highest Occupant Exposures

One vocal member of the committee objected to choosing the highest occupant exposure in the house as the basis for the standard. His opinion was that this would lead to skewed results and might possibly results in increased average exposures. This issue mostly revolves around the question of if mixing via an AHU could actually increase exposures by bringing pollutants from a remote zone into the zone where the occupants are located. In order to answer this question, BSC performed an analysis of the average exposure as well as the maximum exposure with three systems: exhaust only, CFIS, and fully-ducted balanced. Figure 2.35 through Figure 2.37 illustrate the results of this analysis. The exhaust-only ventilation system consistently results in higher occupant exposures. This is true even in the kitchens and bathrooms source scenario, where all of the pollutants are generated in rooms other than the rooms where the occupants spend most of their time.

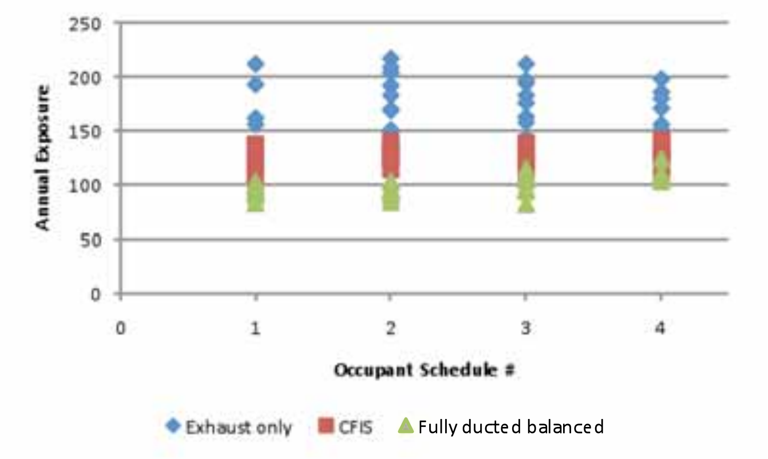

Figure 2.35: Results of average exposure analysis for volume-weighted source scenarios

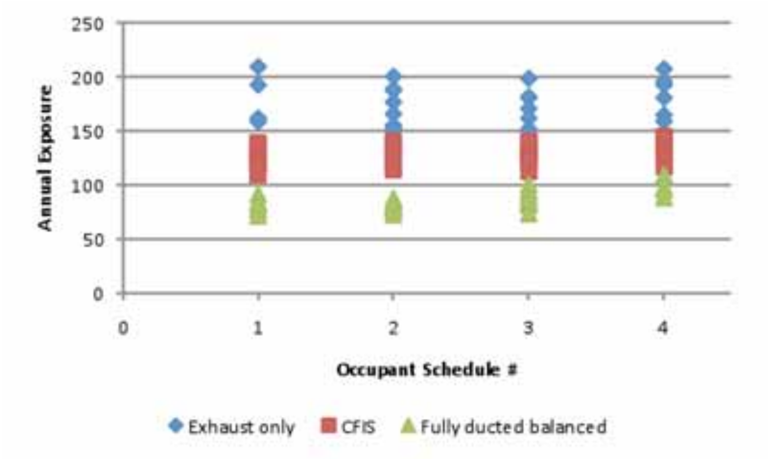

Figure 2.36: Results of average exposure analysis for kitchen & bathrooms source scenarios

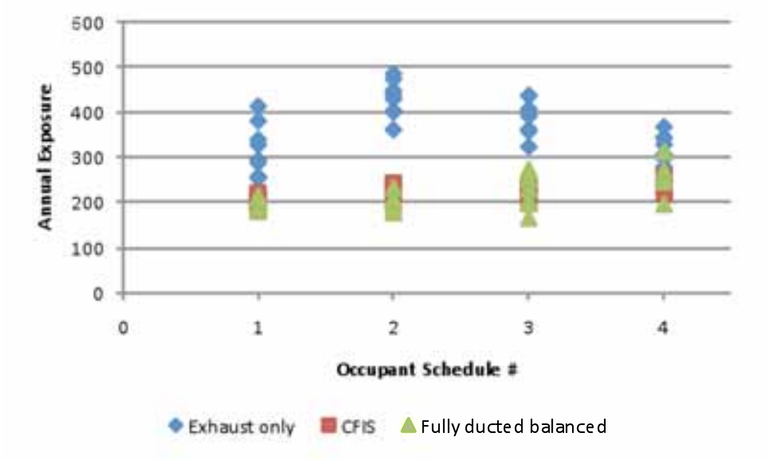

Figure 2.37: Results of average exposure analysis for occupant-generated source scenario

2.15 ASHRAE Meeting – June 2009 – Louisville

2.15.1. SSPC 62.2 Committee Meeting

At the SSPC 62.2 meeting in June 2009, BSC put forward a change proposal to the envelope subcommittee. The change proposes coefficients to account for the effect of system types and operation. The subcommittee voted to forward the change proposal to the full committee with a recommendation to publish the change proposal for public review. The full committee considered the change proposal and voted to do so.

The change proposes coefficients to account for the effect of system types and operation. The proposed system coefficients are based on three factors: the difference between balanced and unbalanced systems; the difference between fully ducted and not fully ducted systems; and the effect of mixing.

The change increases mechanical ventilation system flow rates for systems that are unbalanced and not fully ducted. The motion does not increase mechanical ventilation system flow rates for systems that are balanced and fully ducted or systems that are balanced and not fully ducted that have a provision for mixing and systems that are unbalanced and fully ducted that have a provision for mixing.

The change assigns a system coefficient of 1.0 for a balanced and fully ducted system. Systems that are balanced but not fully ducted and systems that are not balanced but fully ducted have a system coefficient of 1.25. An unbalanced not fully ducted system has a system coefficient of 1.5. These system coefficient values assume no provision for mixing. If mixing is provided then the systems that had coefficients of 1.25 without mixing have coefficients reduced to 1.0 and the systems that had coefficients of 1.5 without mixing have coefficients reduced to 1.25.

The analysis supporting the coefficients values is based on annual average exposure and assumes that contaminants are distributed in houses roughly 1/3 for occupants, 1/3 for furnishings and materials uniformly distributed throughout the house and 1/3 split between the kitchen and the bathrooms.

The change contains definitions for "fully-ducted ventilation system"; for "balanced ventilation system"; and for "minimum turnover" or mixing. Minimum turnover is defined as whole-building air mixing such that at least 50 percent of the house air volume is moved through a forced air distribution system each hour.

The change excludes buildings that have leakage rates of 7 ach @ 50 Pa or greater; the change excludes systems in building enclosures other than single family detached; and the change excludes systems installed according to the Existing Building Appendix.

2.15.2. Presentation of Technical Papers

Aaron Townsend of BSC presented two technical papers arising from this work during the June 2009 ASHRAE meeting (Townsend 2009a, Townsend 2009b). The presentation slides are given in Appendices F and G, respectively.

2.16 Post June 2009 Meeting

2.16.1. Progress and current status of change proposal

Because not all of the voting members of the committee were able to attend the meeting, the change proposal was sent out on a letter ballot to all voting members of the full committee. In the letter ballot vote, the committee voted to publish the change proposal for public review. The ASHRAE Standards Committee then also voted to publish the change proposal as a proposed addendum for public review. After public review, the SSPC 62.2 committee will have to address all public comments received. If all comments are acceptably addressed, the change could be incorporated into the 2010 version of the ASHRAE 62.2 Standard.

2.17 References

Hendron, B., Anderson, R., Barley, D., Hancock, E. 2006. Building America Field Test and Analysis Report. Draft NREL report.

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

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

Townsend, A., A. Rudd, and J. Lstiburek. 2009b. A Method for Modifying Ventilation Airflow Rates to Achieve Equivalent Occupant Exposure. ASHRAE Transactions 115(2).

2.18 APPENDICES

2.18.1. Substitute House Testing Trip Report

2.18.2. January 2007 Expert Meeting Summary Report

2.18.3. June 2007 Expert Meeting Summary Report

2.18.4. January 2008 Expert Meeting Summary Report

2.18.5. January 2009 Expert Meeting Summary Report

2.18.6. 2009 ASHRAE Transactions 11, Paper #1 Presentation

2.18.7. 2009 ASHRAE Transactions 12, Paper #2 Presentation