Final Report on the Expert Meeting for Ventilation Effectiveness in Residential Systems

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Executive Summary

1. Title: Final Report on the Expert Meeting for Ventilation Effectiveness in Residential Systems (Gate 1B)

2. Overview: The Building Science Consortium held an Expert Meeting on Ventilation Air Distribution Effectiveness in Residential Systems on 18 January 2008 at the Hilton Hotel in New York City, New York. The expert meeting was held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program. Invited speakers gave presentations in their particular area of expertise. Speakers included Armin Rudd of Building Science Corporation, who presented for Bud Offerman of Indoor Environmental Engineering as he was not able to attend, Bill Rittelmann of IBACOS, Keith Gawlik of NREL, and Aaron Townsend of Building Science Corporation.

3. Key Results: Key results from this meeting were a greater buy-in from the ASHRAE 62.2 community that BSC's approach to ventilation effectiveness is producing meaningful results and with appropriate modifications can reach results that can be adopted by the 62.2 committee.

4. Gate Status: This project meets the "must meet" and "should meet" criteria for Gate 1B. The project provides source energy and whole building performance benefits by incentivizing efficient ventilation systems and tight enclosures, thereby reducing the source energy needed to condition the house. The project also meets the performance-based safety, health, and building code requirements for use in new homes, as it directly attempts to improve the ventilation code, which will likely be adopted by building codes at some point in the future. For the same reason, this project meets the prescriptive-based code requirements. The project will be cost-neutral for new homes, as builders will still be free to choose from a variety of ventilation systems. The project will increase reliability by increasing the likelihood of uniform indoor air quality. Finally, the project does not require any new products to be manufactured, and suppliers, manufactures, and builders will continue responding to market forces as they do.

5. Conclusions: The key gaps that remain are objections by the weatherization industry as to how the proposed revisions would affect their industry, and drafting, approval, and execution of a final simulation plan. Next steps involve continuing a dialogue with the weatherization community to further identify and address their concerns, and drafting, submitting for approval, and executing a final set of simulations. After these steps are complete, the ASHRAE 62.2 committee will be given the opportunity to adopt the suggested revisions into the next version of the 62.2 standard. Expected benefits include energy savings (due to credit given to ducted ventilation systems), reliability (due to improved indoor air quality), durability (due to guaranteed ventilation and therefore lower chances of moisture damage), and expected value to builders, contractors, and homeowners (due to improved homeowner satisfaction with their homes, which also benefits builders and contractors).

INTRODUCTION

The Building Science Consortium held an Expert Meetings on Ventilation Air Distribution Effectiveness in Residential Systems on 18 January 2008 at the Hilton Hotel in New York City, New York. The expert meeting was held immediately before the ASHRAE SSPC 62.2 meetings in advance of the ASHRAE technical program in order to make it easier for experts who had already traveled there to participate. There were 37 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

A summary of the individual presentations and major discussion points is provided in the sections below.

The final agenda for the meeting is listed in Appendix A. A list of attendees for the first meeting is given in Appendix B. The presentations are included in Appendices C through G. A plan for further work in ventilation simulations is included in Appendix H.

PRESENTATIONS

Speaker 1: Armin Rudd, Building Science Corporation, for Francis (Bud) Offerman, PE, CIH, Indoor Environmental Engineering, San Francisco

<u>Presenter bio:</u> Armin Rudd is a Principal of Building Science Corporation. He presented for Francis (Bud) Offerman, PE, CIH. Mr. Offerman has 28 years experience as an IAQ researcher, sick building investigator, mitigation planner, healthy building design consultant, and expert witness. He is president of Indoor Environmental Engineering, a San Francisco based IAQ consulting firm.

<u>Presentation Title:</u> *Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions*

<u>Presentation Summary:</u>

Note that Armin Rudd of Building Science Corporation presented in place of Bud Offerman of Indoor Environmental Engineering, as Bud was not able to attend the meeting for personal reasons.

In 2006-2007, Indoor Environmental Engineering performed a study of ventilation and indoor air contaminants in 108 occupied new California homes. Key findings presented were the following:

- The majority of the houses in the study had similar envelope leakage characteristics, as measured by a blower door, at 4-5 ACH50.
- The data set included 42 houses without mechanical ventilation, 8 houses with supply ventilation, and 3 houses with HRV ventilation.
- Those houses with a central-fan-integrated (CFI) supply system did not have a minimum runtimer on the air handler and the median continuous outside air flow rate was 7 cfm.
- Perhaps because of this, the houses with CFI systems had about the same natural air change rate as the houses without any mechanical ventilation system.

- The houses in this study with HRV ventilation systems had a median outside air flow rate of 153 cfm, about 20 times that of the CFI systems and 3 times the recommended ASHRAE 62.2 rate for this size home.
- Occupants in houses with CFI supply systems opened their windows about the same amount as occupants in houses without any mechanical ventilation system.
- Occupants in houses with HRV ventilation systems opened their windows about twice as often as occupants in houses with supply or no mechanical ventilation.
- PFT tests were performed on a subset of the homes in the study. The median natural air change rate of homes with CFI systems was 0.36; in homes without ventilation systems it was 0.33 and in homes with HRVs it was 1.43.
- 50% of the homes in the study had natural air change rates of less than 0.35 ACH.
- A subset of the homes in the study was monitored for formaldehyde concentration. 62% of the homes monitored exceeded the California Air Resources Board guideline exposure concentration of 33 $\mu g/m^3$.

<u>Post-presentation discussion:</u>

The audience had several questions about the study; however due to the fact none of the authors of the report were present there were not answers forthcoming. The questions and comments were as follows:

- This data was from part of the study done in the summer. Bruce Wilcox said that the winter results (not yet published) include some different results that he cannot yet divulge.
- Joe Lstiburek and Philip Fairey felt that the number of houses in the sample presented was too small to have statistical significance, especially the HRV group (3 houses)
- The audience wanted to know more about the attributes of the homes that had high formaldehyde levels.

Speaker 2: Bill Rittelmann, PE, IBACOS, Inc., Pittsburgh, PA

<u>Presenter bio:</u> Bill Rittelmann is a Research Project Manager at IBACOS. He is a registered Professional Engineer, a Certified Energy Manager, and Certified in Plumbing Engineering. At IBACOS he is responsible for managing the domestic hot water and HVAC research projects. He graduated with a Bachelor's of Science in Architectural Engineering from Pennsylvania State University.

<u>Presentation Title:</u> *Room Air Temperature Uniformity of a Forced-Air System Relative to Runtime*

<u>Presentation Summary:</u>

Bill presented results from a project IBACOS had performed on the effects of air conditioner and furnace runtime on temperature distributions within a house. In this project, an HVAC system (along with a duct system) was installed within a finished 2-story house in Ft. Wayne, Indiana. One system consisted of high sidewall registers, and a second consisted of floor registers. Floor-to-floor and head-to-toe temperature stratification was measured over four months in winter, with and without minimum air handler runtimes. Results showed that the higher airflow of the high sidewall registers resulted in higher temperature air from the register. The floor registers had lower total airflow and the duct system was located between floors; therefore the delivered air temperature was lower. With high sidewall registers, floor-to-floor stratification was 0-4 degrees F and head-to-toe stratification (within the same room) was 0-3 degrees F. Lower outdoor temperatures and higher supply air temperatures increased the level of stratification. Additionally, lower supply air velocity increased the level of stratification as the supply air did not entrain room air. With floor registers, floor-to-floor stratification was 2-3 degrees F and decreased with decreasing outdoor temperature. Higher supply air temperatures increased the level of stratification. Finally, head-to-toe stratification was 0-3 degrees F and increased with decreasing outdoor temperature. Overall, lower supply air temperatures resulted in lower stratification due to higher velocities and longer runtimes.

IBACOS also performed tracer gas decay tests in the same house. The main conclusions from these tests were that single-point exhaust or supply ventilation was only marginally effective, and that continuous low-level supply to a central fan operating on low speed was effective.

<u>Post-presentation discussion:</u>

The audience agreed that the project's findings were not surprising.

Speaker 3: Keith Gawlik, National Renewable Energy Laboratory

<u>Presenter bio:</u> Keith Gawlik is a Senior Engineer at NREL. Since he joined NREL in 1992, his work has included experimental and numerical analysis of the fluid flow and heat transfer performance of transpired solar air heaters, geothermal binary cycle power plants, enhanced heat transfer surfaces, corrosion barrier polymer coatings, heat sinks for electronics modules, photocatalytic oxidizers, polymer heat exchangers, natural convection cooling towers, solar domestic hot water systems, building HVAC systems, and hydrogen venting systems. He has received R&D 100 and Federal Laboratory Consortium for Technology Transfer awards related to his work on polymer coatings. He is co-inventor on one patent related to the transpired collector, one on an enhanced heat transfer surface, and two on chemical application systems, the latter two from his experience as a mechanical engineer at a company designing and manufacturing water analysis equipment. He graduated from the Massachusetts Institute of Technology with S.B. and S.M. degrees in mechanical engineering, and earned his Ph.D. at the University of Colorado at Boulder.

<u>Presentation Title:</u> *CFD Evaluation of Air Distribution Systems for Residential Forced Air Systems in Cold Climates*

<u>Presentation Summary:</u>

Keith described a joint modeling and experimental approach at NREL to categorize the effect of throw from high sidewall registers. Fluent 6.2 was used for computational fluid dynamics (CFD) modeling, and a full-size experimental chamber was built to perform physical experiments as well. His results show that high supply air temperature causes more stratification, as does low supply air speed, and the effects combine. For example, high temperature, low speed supply air results in the highest level of stratification.

<u>Post presentation discussion:</u>

Low temperature, high speed supply air would be the best case from a stratification perspective. However there are limits to this case: high speed supply air causes noise and whistling at the supply register, and both high speed and low temperature supply air can cause uncomfortable conditions for the occupants in the space.

Speaker 4: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Corporation. He has worked for Building Science for over four years, where he focuses on all aspects of energy efficiency, building durability, and indoor air quality. Aaron holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University.

Presentation Title: *Update on Results of Field Measurements and CONTAM Simulations*

Presentation Summary:

A CONTAM[1] airflow network model was developed and compared to measurements from field tests of a production Building America house in Sacramento in January 2006. The field testing results had been presented in detail at a previous meeting (January 2006), and the CONTAM model had been presented in January and June 2007. Based on the simulation work, the previous presentations asked the question, "Can we quantify the difference in performance between different ventilation systems?"

In this current presentation (January 2008), questions raised at previous meetings were addressed. Specifically, Aaron addressed the question of what the relative exposures were under a wider set of assumptions about sources and occupancy behaviors (based on the cases presented in June 2007 by Max Sherman and Iain Walker of LBL), what the effect of the sizing assumption was (i.e. what happens if the space conditioning system was not sized according to Manual J), and what the effect was of various parameters that were varied (i.e. climate, central system type, duct leakage, minimum system runtime, and envelope tightness).

The contaminant source and occupant behavior included the following cases:

1. "Everybody Everywhere." Each zone has a contaminant with the same source strength, and the occupant is exposed to the air in each zone equally.
2. Volume Weighted Sources. Each zone has a contaminant with source strength proportional to its volume, and the occupant is exposed to the air in each zone equally. This source strength assumption meets the criteria for age of air analysis.

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[1] CONTAM is a multizone indoor air quality and ventilation analysis program, developed by NIST, designed to help you determine: airflows and pressures – infiltration, exfiltration, and room-to-room airflows and pressure differences in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by temperature differences between the building and the outside; contaminant concentrations – the dispersal of airborne contaminants transported by these airflows and transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces; and/or personal exposure – the prediction of exposure of building occupants to airborne contaminants for eventual risk assessment. CONTAM can be useful in a variety of applications. Its ability to calculate building airflows and relative pressures between zones of the building is useful for assessing the adequacy of ventilation rates in a building, for determining the variation in ventilation rates over time, for determining the distribution of ventilation air within a building, and for estimating the impact of envelope airtightening efforts on infiltration rates. (source: NISTIR 7251, CONTAM 2.4 User Guide and Program Documentation)

3. "Worst Case" Age of Air. Each zone has a contaminant source with strength proportional to its volume. The occupancy is one of three cases: (a) moves each hour to the most contaminated zone, (b) stays in the zone with the highest average contaminate level for the entire year, and (c) moves about according to a normal schedule, but sleeps in the most contaminated bedroom.
4. "I Stink." There is a single contaminant source, in the same room as the occupant. The occupant stays in the room that maximizes exposure over the course of the year.
5. "You Stink." There is a single contaminant source, in some other room than the occupant. The occupant stays in the room that maximizes exposure over the course of the year.

Even though there are substantial differences in the methodologies between the LBL (Max Sherman and Iain Walker) and BSC approaches, the relative exposure for each case examined came out similar. There is significantly more variation from case to case than there is from the LBL approach to the BSC approach.

The effect of system sizing is very small. If a system is oversized, it simply delivers the same amount of air in a shorter time period. Since even an undersized space conditioning system delivers significantly more air than a ventilation system or infiltration, the house stays mixed at about the same level independent of space conditioning system size. Aaron showed an example of a system sized by Manual J and a system sized at two times Manual J, and the pollutant concentration over the course of a day is nearly indistinguishable.

Variations in model inputs had the following effects:

- Climate has an effect, but less so at high ventilation rates or with tight houses. All other things being equal, climates with fewer infiltration degree days will have higher contaminant concentrations.
- The central system type does have an effect. With a reasonable amount of ventilation (at least 50% of the current 62.2 value), a house with no means to distribute ventilation air (i.e. no central system and a single-point ventilation system) will have the highest contaminant concentration. A ventilation system with a supply duct to each room and a central forced-air space conditioning system will have the lowest contaminant concentration. Single-point ventilation systems with a central forced-air space conditioning system fall in between the two.
- Duct leakage has an effect if the ducts are outside of conditioned space. If ducts are outside of conditioned space, increased duct leakage causes increased air change within the house, and therefore lowers the contaminant level. If ducts are within the conditioned space, duct leakage has a negligible effect on the contaminant level.
- Having a forced-air system minimum runtime lowers contaminant concentration levels. The effect is more pronounced if the ducts are located outside of conditioned space, as the additional runtime results in additional duct leakage and therefore more air change.
- Envelope leakage has a large effect—perhaps the largest of all the parameters studied. Houses with leaky envelopes have lower contaminant concentrations than houses with tighter concentrations.

<u>Post presentation discussion:</u>

Jamie Lyons and Terry Brennen asked if multiport exhaust systems had been examined with the model. They had not. Jamie asked for an educated guess at what the coefficient would be.

Aaron responded that he would guess 1.5 but would have to run the simulations. Terry and Phillip Fairey indicated that they would also guess 1.5 would be close. Paul Francisco stated that exhaust fans should be located in the zones where pollutants are generated, but other pointed out that we cannot predict where that will be, other than the kitchen and bathrooms (which we already do).

Max Sherman asked if airflow ratios could be calculated based on Case 1 exposure and occupant behavior. They could be but have not yet been.

Dennis Deitz pointed out that if we increase the required flowrate for exhaust-only systems, we exacerbate negative air pressure problems. Paul Francisco pointed out a need to differentiate where the ducts are located, that bad air from leaky ducts in a crawlspace should not be credited. He suggested that if a house has leaky ducts in a crawlspace it should not be able to claim a low coefficient.

GENERAL DISCUSSION

The general open discussion period was moderated by Joseph Lstiburek, Principal of Building Science Corporation.

- Bruce Wilcox wanted to see the coefficients with duct leakage taken out of consideration.
- Max Sherman pointed out the need to make sure that if the central system is used more that it won't increase contaminant levels.
- Someone asked if it makes a difference for a balanced system, if the system exhausts from each zone or if a single location is sufficient.
- Max Sherman agreed that the results from the LBL MTMS data are consistent with the BSC modeling results.
- Philip Fairey pointed out that the previous starting point for 62.2 assumed that the building had a certain amount of envelope leakage (i.e. the building was leaky).
- Paul Francisco suggested that the 62.2 standard be split for existing versus new buildings. He is okay with distribution credits for new buildings but does not want to see them required for existing buildings because he does not want to get rid of the infiltration credit.
- Max suggested that 62.2 could require the higher coefficient (2.0) for all systems and then allow lower coefficients if the house proves it has tight ducts, mixing, etc. Joe disagreed because he does not want to credit leakage, so 62.2 should start at 1.0 and go up if the building has an inferior ventilation system.

FOLLOW-UP WORK

As a result of the expert meeting, there was general consensus that the distribution coefficient concept was sound and could be implemented. Some members of the committee wanted additional systems or scenarios simulated. In order to accommodate this, BSC collaborated with Bruce Wilcox and Steve Emmerich to develop a simulation plan that, when executed, would provide the information necessary for the 62.2 committee to adopt the distribution coefficients at the next 62.2 committee meeting in June 2008.

A copy of the final simulation plan is attached as Appendix H.

Appendix A: Expert Meeting Agenda

INVITATION and AGENDA

Building America Expert Meeting

VENTILATION SYSTEM INTERACTIONS IN HOMES

Meeting Manager:	Armin Rudd, Building Science Corp.
Date/Time:	**Friday, 18 January 2008, 8:00 am to 12 pm**
Location:	New York City, ASHRAE Winter Meeting hotel Hilton New York, Beekman room

Featured Speakers:

- Bud Offermann, Indoor Environmental Engineering
- Bill Rittelmann, IBACOS
- Keith Gawlik, NREL
- Aaron Townsend, Building Science Corp.

Key questions regarding this meeting:

Mechanical ventilation is becoming an increasingly larger portion of the total space conditioning load in energy efficient homes. When contaminant source control is a first priority, and whole-house ventilation air distribution is assured, reduced ventilation requirements may be acceptable and advantageous. Hot and humid climates may benefit the most.

1. What does the latest research tell us about indoor air contaminants in homes?

2. How do thermal comfort requirements in energy efficient homes relate to whole-house ventilation air distribution; what are the systems interactions?

3. Should ventilation systems with better spatial distribution be credited for having more reliable whole-house performance relative to indoor air quality?

4. Can we use the information we currently have to account for ventilation air distribution for comfort and air quality to determine appropriate minimum residential ventilation requirements?

Invitees:

Participants will be key people working in the indoor air quality, comfort, and space conditioning fields. Participants are invited from the following groups: Building America teams, ASHRAE Standard 62.2 committee members and participants, residential HVAC and construction industry, national and state government laboratories and agencies, university researchers, energy efficiency organizations, and building consultants.

Meeting Agenda:

- 8:00 am to 8:05 am, Welcome and Meeting Introduction
- 8:05-8:15 Building America Zero Energy Home Overview (DOE/NREL)
- Presentations
    - 8:15 to 8:45, (30 min) Bud Offermann, *Window Usage, Ventilation, and IAQ in 108 New California Homes*
    - 8:45 to 8:55, (10 min) Questions and discussion
    - 8:55 to 9:25, (30 min) Bill Rittelmann, *Air distribution for thermal comfort in high-performance homes and its interaction with ventilation*
    - 9:25 to 9:35, (10 min) Questions and discussion
    - 9:35 to 10:05 (30 min) Keith Gawlik, *CFD evaluation of air distribution systems for residential forced air systems in cold climates*
    - 10:05-10:15 (10 Min) Questions and Discussion
    - 10:15 to 10:45, (30 min) Aaron Townsend, *CONTAM simulations to evaluate uniformity of ventilation air distribution and occupant exposure to indoor contaminants*
    - 10:45 to 10:55, (10 min) Questions and discussion
- General discussion, 10:55 to 11:45 (50 min), Joseph Lstiburek- discussion moderator
- Wrap up, action items, and follow-up plan, 11:45 to 12:00

Appendix B: Expert Meeting Attendee List (based on sign-in sheet)

Last name	First name	Company	Email
Baxter	Van	ORNL	baxtervd@ornl.gov
Bloemer	John	Research Products Corp.	jb@aprilaire.com
Brennan	Terry	Camroden Associates	terry@camroden.com
Crawford	Roy	Trane	roy.crawford@trane.com
Dietz	Dennis	American Aldes Ventilation	eng@aldes-us.com
Drumheller	Craig	NAHB Research Center	cdrumheller@nahbrc.org
Emmerich	Steve	NIST	steven.emmerich@nist.gov
Fairey	Philip	FSEC	pfairey@fsec.ucf.edu
Forest	Daniel	Venmar Ventilation	forestd@venmar.ca
Francisco	Paul	University of Illinois-UC	pwf@uiuc.edu
Gawlik	Keith	NREL	keith_gawlik@nrel.gov
George	Marquam	Blu Spruce Construction	marquam.george@uas.alaska.edu
Grimsrud	David		grimsrud@earthlink.net
Henderson	Hugh	CDH Energy	hugh@cdhenergy.com
Karg	Rick	R.J.Karg Associates	rjkarg@karg.com
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Werling	Eric	USEPA	werling.eric@epa.gov
Wettergren	Ola	Fantech	olwe@fantech.net
Wilcox	Bruce		bwilcox@lmi.net

Appendix C: Introductory Presentation

Appendix D: Presentation 1: Summary of the paper “Window Usage, Ventilation, and IAQ in New California Homes” by Francis (Bud) Offerman, presented by Armin Rudd

Appendix E: Presentation 2: Room Air Temperature Uniformity of a Forced-Air System Relative to Runtime, presented by Bill Rittelmann

Appendix F: Presentation 3: CFD Evaluation of Air Distribution Systems for Residential Forced Air Systems in Cold Climates, presented by Keith Gawlik

Appendix G: Presentation 4: Update on Results of Field Measurements and CONTAM Simulations, presented by Aaron Townsend

Appendix H: Final Simulation Plan

	Revised work plan for CONTAM modeling of ventilation air distribution		
	Model category	**Existing model assumptions**	**Revised model assumptions**
1	**Simulation time step**	5 min	No change
2	**Climates**	CZ 2A: Daytona Beach CZ 2B: Phoenix CZ 4C: Seattle CZ 4A (close to 3A): Raleigh CZ 6: Minneapolis	Same but add 2 more locations in California (Bruce to pick from TMY2 locations: Arcata, Bakersfield, Dagget, Fresno, Long Beach, Los Angeles, Sacramento, San Diego, San Francisco, Santa Maria)
3	**Temperature**	Outdoor temperature from TMY2 data Indoor temperature constant at 22 C (71.6)	No change
4	**Wind**	Wind speed and direction from TMY2 data; Wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings	No change
5	**Minimum AHU runtime criteria**	When central system is present and a minimum runtimer is used, central fan runs at least 10 minutes out of every 30 minutes.	When central system is present and a minimum runtimer is used, central fan runs at least long enough to provide 1 air change per hour.
6	**Central heating and cooling equipment sizing and fan flow**	Sizing per Manual J for each climate for cooling: cooling airflow 400 cfm/ton heating airflow 85% of cooling airflow	No change. Due to change in minimum runtime criteria, size will be self-correcting for minimum runtime just as it is for space conditioning. For example, a system oversized by 25% will reach 1 air turnover 25% faster than a system that is properly sized, and therefore provide the same amount of mixing.
7	**Activation of heating and cooling**	Linearly interpolate from 80% runtime to 0% runtime between outdoor design condition and balance point temperature. Heating balance point = 65 F Cooling balance point = 75 F Two cycles per hour, cycles rounded to nearest 5 minute increment.	No change
8	**Duct leakage**	6% of air handler flow, and 12% of air handler flow	Eliminate duct leakage. Redistribute effective leakage area to walls and ceiling in proportion to their relative leakage.
9	**Central system duct location**	1) No central duct system 2) In conditioned space 3) Outside of conditioned space	1) No central duct system 2) Outside of conditioned space (but no leakage)
10	**Building enclosure leakage rate**	R-2000 house: 1.5 ach50 Building America house: 3.5 ach50 Standard house: 7 ach50	No change
11	**Building enclosure leakage distribution**	Leakage distribution per ASHRAE Fundamentals, Chapter 27. Walls (range 18 to 50%; middle of range 35%) Windows & doors (range 6 to 22%; 15%) Ceiling details (range 3 to 30%; 18%) Fireplaces (range 0 to 30%; 12%) Nonoperating exhaust vents (range 2 to 12%; 5%) Air handler & ductwork (range 3 to 28%; 18%) Model combines in the following manner: Walls, windows, doors, fireplaces (all modeled as wall leakage, uniformly distributed by wall area): 62% Ceilings & nonoperating exhaust vents (all modeled as ceiling leakage, uniformly distributed by ceiling area): 23% Air handler & ductwork (modeled as duct leakage): 15%	Leakage distribution per ASHRAE Fundamentals, Chapter 27. Walls (range 18 to 50%; middle of range 35%) Windows & doors (6 to 22%; 15%) Ceiling details (3 to 30%; 18%) Fireplaces (0 to 30%; 12%) Nonoperating exhaust vents (2 to 12%; 5%) Air handler & ductwork (3 to 28%; 18%) Model combines in the following manner: Walls, windows, doors, fireplaces, plus proportionate share (2/3) of air handler & ductwork (all modeled as wall leakage, uniformly distributed by wall area): 68% Ceilings, nonoperating exhaust vents, plus proportionate share (1/3) of air handler & ductwork (all modeled as ceiling leakage, uniformly distributed by ceiling area): 32%
12	**Zones**	<u>1st Floor:</u> Living Room 1 Kitchen Bedroom 1 <u>2nd Floor:</u> Living Room 2 Bedroom 2 Bedroom 3 Master Bedroom	Add the following zones <u>1st Floor:</u> Laundry Room Bathroom 1 <u>2nd Floor:</u> Bathroom 2 Master Bathroom
13	**Airflow between zones[2] when interior doors are open**	Modeled by forcing small (0.1 C) temperature difference between neighboring zones	No change
14	**Pollutant generation**	Uniform generation of unique pollutant in each zone. Generation rate proportional to room area (1 $mg/hr/ft^2$).	No change, but additional post-processing as described below.
15	**Interior door scheduling**	Bedroom doors open except during sleeping period 10 PM to 7 AM	No change

16	**Ventilation system types**	1) Single-point exhaust from common area 2) Single-point exhaust from common area with minimum central fan runtime (10 min per hour) 3) Central-fan-integrated supply without minimum runtime 4) Central-fan-integrated supply with minimum runtime (10 min per hour) 5) Two-point balanced (supply into common area, exhaust from the same well-mixed common area) 6) Fully-ducted balanced (independent ventilation duct system, supply into the common area and each bedroom, exhaust from the common area)	1) Single-point exhaust from common area 2) Single-point exhaust from master bathroom 3) Single-point exhaust from common area with minimum central fan runtime[1] 4) Single-point exhaust from master bathroom with minimum central fan runtime[1] 5) Single-point supply to common area 6) Single-point supply to common area with minimum central fan runtime[1] 7) Central-fan-integrated supply without minimum runtime 8) Central-fan-integrated supply with minimum runtime[1] 9) Three-point exhaust, 1/3 from each bathroom continuously 10) Three-point exhaust, 1/3 runtime from each of the laundry, family bath, and master bath 11) Two-point balanced (supply into common area, exhaust from family bathroom) 12) Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, single exhaust from the common area)
17	**Ventilation rates**	Percent of 62.2 rate 7.5(Nbr+1)+0.01(CFA): 0, 50, 100, 150, 200	No change
18	**Occupant scheduling**	Same schedule for each occupant: 10 PM to 7 AM: in bedroom with door closed 7 AM to 9 AM: in kitchen 9 AM to 12 PM: in living room 12 PM to 1 PM: in kitchen 1 PM to 6 PM: in living room 6 PM to 10 PM: in other bedrooms	Change to: Same schedule for each occupant: 10 PM to 7 AM: in bedroom with door closed 7 AM to 7:30 AM: in the bathroom nearest to occupant's bedroom 7:30 AM to 9 AM: in kitchen 9 AM to 12 PM: in living room 12 PM to 1 PM: in kitchen 1 PM to 5 PM: in living room 5 PM to 7 PM: in kitchen 7 PM to 9:30 PM: in other bedrooms 9:30 PM to 10:00 PM: in the bathroom nearest to occupant's bedroom
19	**Post-processing**	Calculate annual exposure for each occupant in the house according to the occupant schedule, for each ventilation rate, and calculate distribution coefficient based on the occupant with the highest annual average exposure in each simulation	Calculate exposure and distribution coefficients for each ventilation system under the following scenarios: 1) As done previously, with new occupant schedule described above 2) As done previously, except 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 above Create table of distribution coefficients for each of the three enclosure leakage levels, for each of: 1) annual average exposure 2) monthly average exposure 3) weekly average exposure 4) sleeping hours (10 PM to 7 AM) annual average exposure
	Footnotes:		
	[1] the central fan operates for heating and cooling plus any amount needed to accomplish a minimum of one house air volume turnover per hour		
	[2] CONTAM does not handle gas diffusion between zones. All movement of contaminants from zone to zone are by air flow.		

		Distribution coefficients Based on: Sources uniformly distributed (volume weighted) Occupant schedule Occupant with highest exposure				Distribution coefficients Based on: Sources uniformly distributed (volume weighted) Occupants uniformly distributed ("Everybody Everywhere" scenario)				Distribution coefficients Based on: Sources: 1/3 master bathroom, 2/3 kitchen Occupant schedule Occupant with highest exposure			
Vent Sys #	Description	annual avg exposure	highest monthly avg exposure	highest weekly avg exposure	sleeping hrs annual avg exposure	annual avg exposure	highest monthly avg exposure	highest weekly avg exposure	sleeping hrs annual avg exposure	annual avg exposure	highest monthly avg exposure	highest weekly avg exposure	sleeping hrs annual avg exposure
1	Single-point exhaust from common area												
2	Single-point exhaust from master bathroom												
3	Single-point exhaust from common area with minimum central fan runtime												
4	Single-point exhaust from master bathroom with minimum central fan runtime												
5	Single-point supply to common area												
6	Single-point supply to common area with minimum central fan runtime												
7	Central-fan-integrated supply without minimum runtime												
8	Central-fan-integrated supply with minimum runtime												
9	Three-point exhaust, 1/3 from each bathroom continuously												
10	Three-point exhaust, 1/3 runtime from each of the laundry, family bath, and master bath												
11	Two-point balanced (supply into common area, exhaust from family bathroom)												
12	Fully-distributed balanced (independent ventilation duct system, supply into the common area and each bedroom, single exhaust from the common area)												