2.18.1. Substitute House Testing Trip Report

To: Memo of Record

From: Aaron Townsend

Date: November 17, 2006

Subject: Ventilation air flow measurements in Augustus

On Tuesday and Wednesday, November 14 and 15, 2006, I performed air flow and pressure measurements at a house in DR Horton's Augustus development in Lincoln, CA. These measurements are intended to assist in providing inputs to the CONTAM modeling of the tracer-gas testing Armin and I performed in January 3-10, 2006 in the same development. This report summarizes the measurements.

The house I tested was 1664 Markdale Lane, which is the same plan as the 2-story house located at 1117 Montague Lane that was tested in January. The only difference is that 1664 Markdale Lane has two additional bedrooms and an additional bathroom located over the garage, where 1117 Montague Lane did not. The floor plan comparison is shown in Figure 1 and Figure 2. 1117 Montague Lane has a total of 2961 square feet of living space, and 1664 Markdale Lane has a total of 3440 square feet of living space.

I intended to perform automated Zone Pressure Diagnostics (ZPD) tests using a program developed by Dave Bohac of the Minnesota Center for Energy and the Environment (MNCEE) and Colin Olson of the Energy Conservatory (TEC); however this program requires the use of TEC's Automated Performance Testing (APT) system, and the APT was damaged during shipping. Instead I performed several manual tests, as described in Table 1.

The furnace, air handler, and condenser are Goodman equipment. The furnace is rated at 93 AFUE. The condenser is model number CLQ48-1B, rated at 4 tons and 14 SEER.

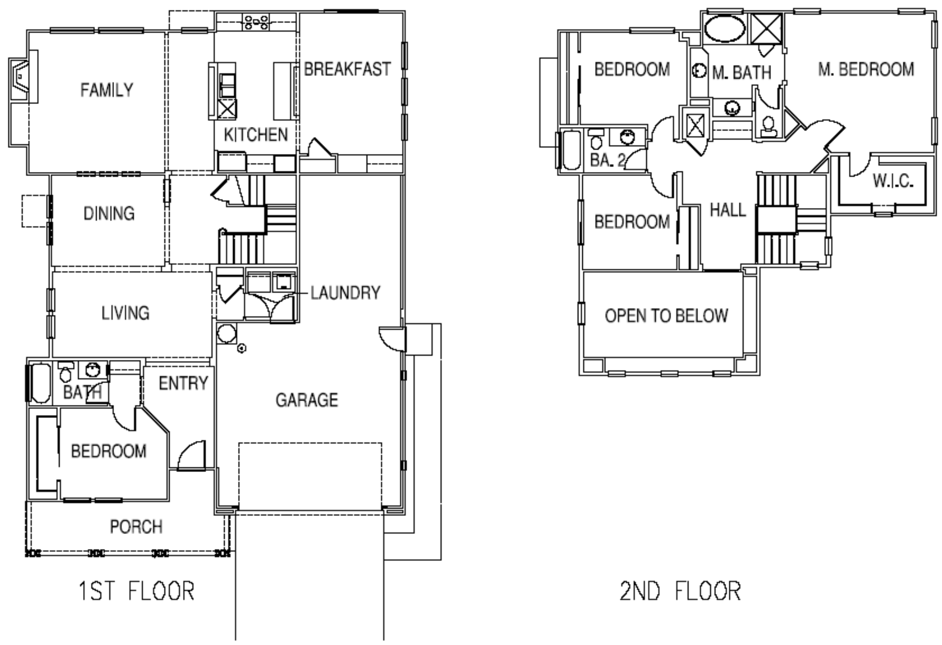


Figure 1: Floor plan of 1117 Montague Lane

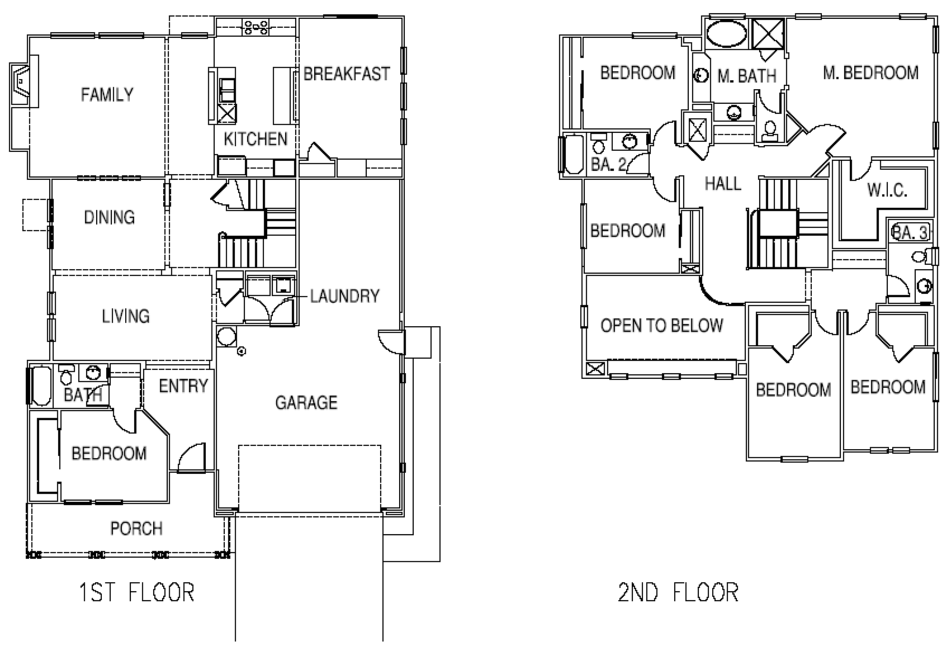


Figure 2: Floor plan of 1664 Markdale Lane

Table 1: Tests Performed This Trip

Test #	Test Description	Ducts	Transfer Grills	Bedroom Doors
1	Overall envelope leakage	Open	Open	Open
2	Room-by-room envelope leakage	Closed	Closed	Open
3	Room-by-room leakage to other rooms	Closed	Closed	Closed
4	Room-by-room leakage to main living space	Closed	Closed	Closed
5	Characterization of transfer grills	NA	NA	NA
6	Measure pressure field with laundry exhaust running	Closed	Closed	Closed
7	Measure pressure field with laundry exhaust running	Open	Closed	Closed
8	Measure pressure field with MBR exhaust running	Closed	Closed	Closed
9	Measure pressure field with MBR exhaust running	Open	Closed	Closed
10	Measure pressure field and supply flows with AHU on	Open	Closed	Closed
11	Measure pressure field and supply flows with AHU on	Open	Open	Closed
12	Overall duct leakage	Closed	NA	Open
13	Duct leakage to outside	Closed	NA	Open
16	Measure pressure field and duct and transfer grill flows with laundry exhaust running	Open	Open	Closed

Test Results

Test #1

Overall envelope leakage. This was measured by performing a standard multipoint blowerdoor test using TECTITE and a DG-700. The blower door was located in the door between the laundry room and the garage. The roll-up garage door was open. The following results were obtained: 1608 CFM50, C=124.4 (+/-1.8%), n=0.654 (+/-0.005), EqLA=165 square inches, ELA=87 square inches. Figure 3 shows the graph of the multipoint blowerdoor test.

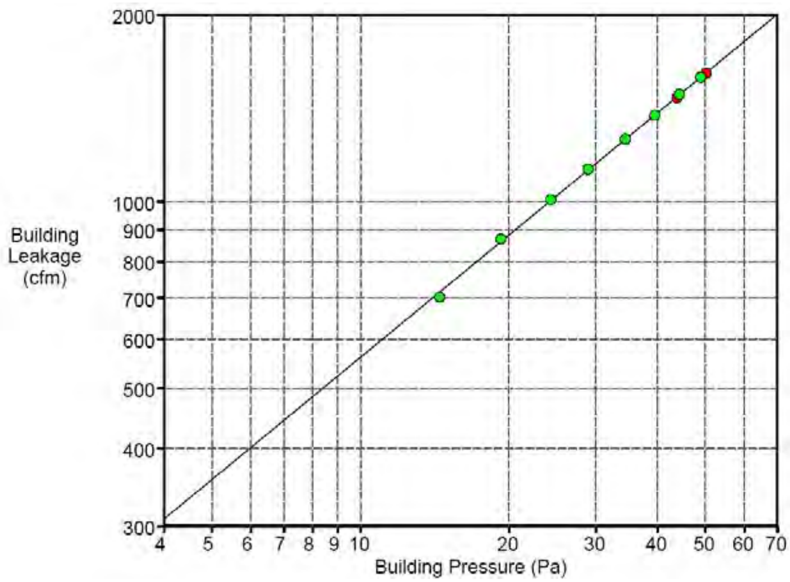


Figure 3: TECTITE building leakage graph

Test #2

Room-by-room envelope leakage. This test was performed similar to a duct-leakage-to-outside test. The house was brought to -50 Pa using the blower door, then one-by-one the zone leakages were measured using the duct blaster and a blower door frame and shroud in the door to that zone. For this test, all ducts and transfer grills were closed, and all doors except the zone being tested were opened.

Room	Pressure wrt living space (Pa) with shroud installed, no ductblaster flow	Ductblaster flow (cfm) required to zero pressure wrt living space
Master BR	(not recorded)	256
Bedroom 1	(not recorded)	65
Bedroom 2	+5.4	57
Bedroom 3	+6.2	60
Bedroom 4	+9.6	88
Bedroom 5	+9.0	87

For this test the baseline house pressure was -1.5 Pa. The house was taken to -50 Pa wrt outside. The sum of the leakage measured in the bedrooms is 613 cfm50 or 38% of the total leakage of 1608 cfm50. The remainder of the leakage is assumed to be to the main living area of the house. Therefore, the total leakage area of the building is distributed as below:

Room	Envelope leakage (cfm50)	Percentage of total leakage area	Flow Coefficient
Master BR	256	16%	20
Bedroom 1	65	4%	5
Bedroom 2	57	4%	4
Bedroom 3	60	4%	5
Bedroom 4	88	5%	7
Bedroom 5	87	5%	7
Main Living Space	995	62%	77
Total	1608	100%	124

Test #3

Room-by-room opening window to outside with all doors, ducts, and transfers closed and house at -50 Pa (originally). The blower door controller was not adjusted during this test. The results of the test show that each zone is isolated from the other zones. No two zones show correlation greater than 5%. This shows that the zones will leak primarily to the main living space when the ducts are not considered.

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Pressure wrt main living space	MBR	15.4	42.1	11.4	12.7	13	13.3	12.4
	BR1	3.7	3.1	40.6	3.1	3	3.2	3.1
	BR2	5.9	4.8	4.6	43.6	5.9	5.3	4.9
	BR3	5.5	5.1	4.2	5.1	44.8	4.8	4.4
	BR4	13.1	11.1	11.1	11.5	11.8	44.9	12.8
	BR5	8.1	6.7	6.3	7.1	7.2	8	42.7
Pressure wrt outside	Main living space	-51	-42.1	-40.5	-43.9	-43.6	-44.9	-43.4

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Pressure wrt outside	MBR	-35.6	0	-29.1	-31.2	-30.6	-31.6	-31
	BR1	-47.3	-39	0.1	-40.8	-40.6	-41.7	-40.3
	BR2	-45.1	-37.3	-35.9	-0.3	-37.7	-39.6	-38.5
	BR3	-45.5	-37	-36.3	-38.8	1.2	-40.1	-39
	BR4	-37.9	-31	-29.4	-32.4	-31.8	0	-30.6
	BR5	-42.9	-35.4	-34.2	-36.8	-36.4	-36.9	-0.7

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Percent of way to outside	MBR	30%	100%	28%	29%	30%	30%	29%
	BR1	7%	7%	100%	7%	7%	7%	7%
	BR2	12%	11%	11%	99%	14%	12%	11%
	BR3	11%	12%	10%	12%	103%	11%	10%
	BR4	26%	26%	27%	26%	27%	100%	29%
	BR5	16%	16%	16%	16%	17%	18%	98%

		With this zone open to outside:						
		None	MBR	BR1	BR2	BR3	BR4	BR5
Difference from no zones open	MBR	0%	70%	-2%	-1%	0%	-1%	-2%
	BR1	0%	0%	93%	0%	0%	0%	0%
	BR2	0%	0%	0%	88%	2%	0%	0%
	BR3	0%	1%	0%	1%	92%	0%	-1%
	BR4	0%	1%	2%	1%	1%	74%	4%
	BR5	0%	0%	0%	0%	1%	2%	83%

Test #4
Room-by-room leakage to main living space with doors, ducts, transfers closed. In this test, the house was taken to two different depressurization levels, with the doors, ducts, and transfer grills closed, and the pressure of the bedrooms with respect to the living space was recorded. The measured values are below:

	Pressure wrt living space (Pa)	
Room	with house at -15 Pa	with house at -51 Pa
Master BR	+3.4	+15.4
Bedroom 1	+0.8	+3.7
Bedroom 2	+1.2	+5.9
Bedroom 3	+1.1	+5.5
Bedroom 4	+3.2	+13.1
Bedroom 5	+1.7	+8.1

In this test, each room has a flow into it (from outdoors) and out of it (to the main living space), and these two flows are assumed to be equal. By using the flow equation twice (once for each flow), and using values previously established for the flow coefficient (C) (established in test #2) and pressure exponent (n) (established in test #1), the following system of equations results:

General flow equation: $Q = C * (\Delta P)^n$, where
- Q = flow rate of air (cfm)
- C = flow coefficient (cfm/Pa^n)
- ΔP = pressure difference along the flow path (Pa)
- n = pressure exponent for the flow path (unitless)

Apply the general flow equation to the exterior wall of a zone (the wall between the zone and the outdoors):

$Q_o = C_o * (\Delta P_o)$^n_o, where the subscripts indicate that the value is for the flow from the *outside*.

Now apply the general flow equation to the interior wall of a zone (the wall between the zone and the main living space):

$Q_i = C_i * (\Delta P_i)$^n_i, where the subscripts indicate that the value is for the flow to the *inside*.

Assuming these two flows are equal, and by using previously-established values of C and n for the exterior wall, we can then rearrange the equation to get:

$C_i = (\Delta P_o)$^n_o / (ΔP_i)^$n_i * C_o$

In this equation we have two unknowns: C_i and n_i. By running the test at two different pressures (ΔP_o and ΔP_o'), we have two equations with two unknowns, and can solve the system of equations for n_i and then plug the value into the equation above to solve for C_i.

$n_i = n_o * \ln(\Delta P_o' / \Delta P_o) / \ln(\Delta P_i' / \Delta P_i)$, and

By applying this system to each of the bedrooms, the flow coefficient and pressure exponent were found for leakage between the zone and the main living space. The table below shows the results. The pressure exponents are near 0.5, which is the value for orifice flow. This makes sense, since the dominant leakage path between the bedrooms and main living space is usually the door, particularly the door undercut. The differences between the flow coefficients are due to the door size, undercut amount, and flooring type present under each door. The master bedroom has a 3080 door, where the other bedrooms have 2668 doors. Additionally, all of the bedrooms have carpet flooring, but bedroom 1 is adjacent to a living space with wood flooring, which allows more air to flow through the door undercut.

Room	Flow Coefficient	Pressure Exponent
Master BR	54.3	0.485
Bedroom 1	32.0	0.514
Bedroom 2	22.5	0.486
Bedroom 3	24.8	0.482
Bedroom 4	18.2	0.541
Bedroom 5	28.2	0.491

Test #5

Transfer grill characterization. This test was intended to determine the pressure-flow characteristics of the transfer grills. The transfer grills consist of a louvered grill on either side of the wall above the bedroom door. The grill on each side of the wall are offset, with one being higher than the other. The gross area of each grill is approximately 5.5" by 9.5", with approximately 50% open area.

In order to determine the flow characteristics, a cardboard box was fixed on one side of a transfer grill, with the duct blaster duct exhausting air out of the box. The pressure and flow measurements are listed in Table 2 below. Figure 4 shows the results and provides a fit of the equation Q=C*(dP)^n, where for this case C=27 cfm/(Pa^n) and n=0.53. In hindsight I should have tested higher pressure differences, as later tests showed that the rooms were pressurized up to ten Pascals. Figure 5 shows the effect of the exponent at higher differential pressures. It is clear from Figure 6 that the flow exponent is definitely less than 0.65 and closer to 0.5.

Table 2: Bedroom 3 Transfer Grill Pressure-Flow Characteristics

Pressure difference (Pa)	Measured flow (cfm)
0.6	21
0.8	24
0.9	26
1.4	32
1.8	38

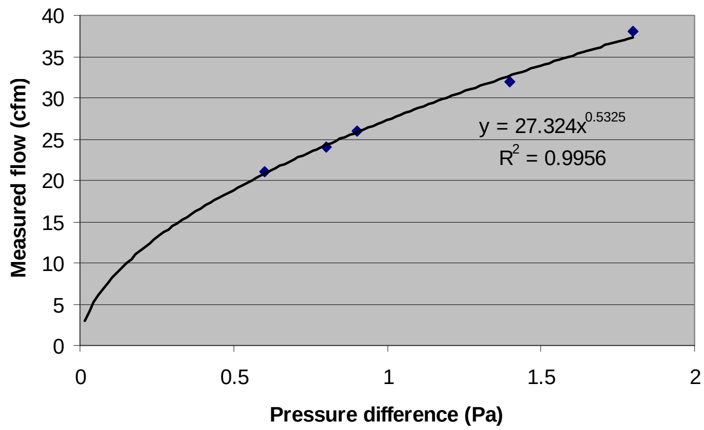


Figure 4: Curve-fit of tested data for transfer grill to bedroom 3

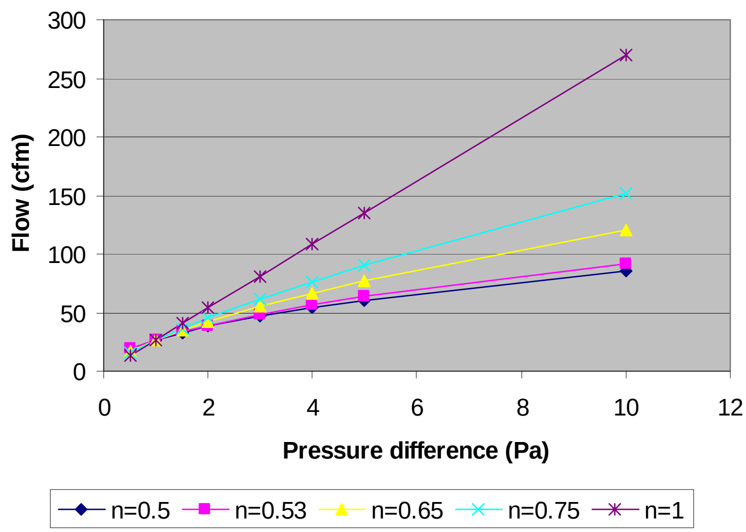


Figure 5: Extrapolation of flow to 10 Pa for different values of the flow exponent n

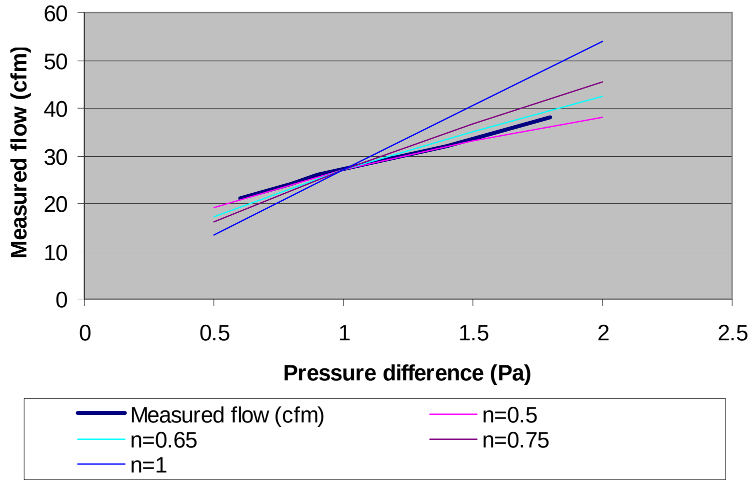


Figure 6: Comparison of measured flow to flow with several different flow exponents

The master bedroom transfer grill was also tested, as it is significantly different than the other bedroom transfer grills. The master bedroom transfer grill is in a chase that extends the full height of the wall. The gross grill size is approximately 13.5" by 9.5", with approximately 50% open area.

The same procedure as described above was performed, yielding the results described in the table and figure below. For this case, C=61 cfm/(pa^n) and n=0.62.

Table 3: Master Bedroom Transfer Grill Pressure-Flow Characteristics

Pressure difference (Pa)	Measured flow (cfm)
0.2	21
0.4	38
1.0	60
1.5	76

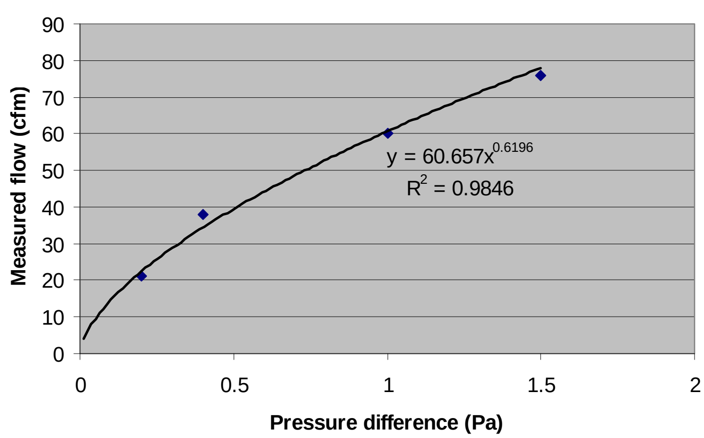


Figure 7: Curve-fit of tested data for transfer grill to master bedroom

The value of the flow exponent is significantly higher than the value for the previous test. Upon examination, it is clear that the first measurement, at 0.2 Pa, heavily influences the resulting curve-fit. Removing the 0.2 Pa measurement, which is the least accurate since the accuracy of the manometer is only 0.1 Pa, results in a flow exponent very close to the value found in the first test. After this step, C=61 cfm/Pa^n, and n=0.52.

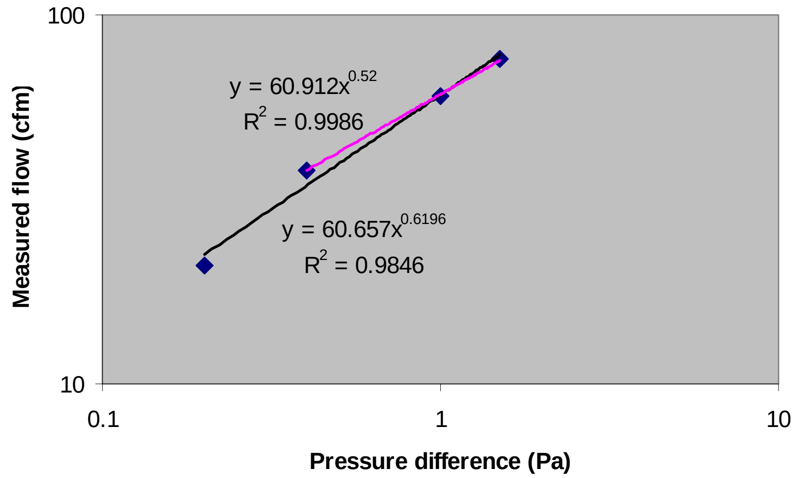


Figure 8: Log-log plot of pressure versus flow

Tests #6, 7, 16
The pressure field in the house was measured with laundry exhaust running, and the doors, ducts, and transfers closed or opened as described in the table. The results are below:

Test Number	6	7	16
Doors	Closed	Closed	Closed
Transfer grills	Closed	Closed	Open
Ducts	Closed	Open	Open
House Pressure wrt outside (Pa)	-0.5	Not recorded	-2.3
Baseline House Pressure wrt outside (Pa)	-0.1	-1.6	-1.6
Measured exhaust flow rate (cfm)	53	Not recorded	56
Room pressure wrt living space (Pa)			
Master BR	+0.1	0.0	0.0
Bedroom 1	+0.1	+0.2	+0.2
Bedroom 2	+0.1	0.0	+0.1
Bedroom 3	0.0	0.0	0.0
Bedroom 4	+0.2	0.0	0.0
Bedroom 5	+0.1	0.0	+0.1

Test 6 was conducted during the day, with relatively little stack effect present (baseline pressure -0.1 Pa). During this test, the bedrooms were more or less at the same pressure as the outside, to the accuracy of the manometer.

Tests 7 and 16 were conducted about 9:00 PM, with a higher indoor-outdoor temperature difference and therefore greater stack pressure (baseline pressure -1.6 Pa). During both of these tests, bedroom 1 (on the ground floor) was at +0.2 Pa, indicating that there was airflow from outside, through bedroom 1, to inside. Since bedroom 1 did not have a transfer grill in this house, tests 7 and 16 are nearly identical for this room (duct open but no transfer grill). The only difference between the tests is in the secondary or tertiary flow paths through the ducts to other bedroom and their transfer grills. Since the pressures changed very little in the other bedrooms, and these paths are not the primary airflow paths, these differences can be ignored.

For bedrooms 2 and 5, the results from tests 7 and 16 are counterintuitive. The results suggest that the bedrooms are more closely linked to outside when the transfer grills are open, which is not true. The measurements are within the uncertainty of the manometers (0.15 Pa in this range).

During test 16, the duct and transfer flows were measured with the Alnor Lo-Flow Hood. The Lo-Flow hood can measure flows only down to 10 cfm. These results are below:

Room	Pressure wrt living space (Pa)	Measured duct flow (cfm)	Measured transfer flow (cfm)
Master BR	0.0	0	0
Bedroom 1	+0.2	0	(no transfer grill present)
Bedroom 2	+0.1	0	0
Bedroom 3	0.0	0	0
Bedroom 4	0.0	0	0
Bedroom 5	+0.1	0	0
Bath 1	NA	0	NA
Bath 2	NA	0	NA
Bath 3	NA	0	NA
Breakfast	NA	0	NA
Family	NA	11 (supplying)	NA
Dining	NA	0	NA
Living	NA	0	NA
Laundry	NA	0	NA

Test #9

Pressure field in house with master bathroom exhaust fan running and AHU off, bedroom doors closed, transfer grills closed, and ducts open. The exhaust flow rate was measured with the Alnor Lo-Flow Hood.

Room	Pressure wrt living space (Pa)
Master BR	-0.9
Bedroom 1	+0.2
Bedroom 2	0.0
Bedroom 3	0.0
Bedroom 4	0.0
Bedroom 5	0.0
Bath 1	NA
Bath 2	NA
Bath 3	NA
Breakfast	NA
Family	NA
Dining	NA
Living	NA
Laundry	NA

During this test the pressure of the main living space wrt outdoors was -2.5 Pa with the master bathroom exhaust fan running. The measured exhaust flow rate was 85 cfm. Baseline pressure of the main living space wrt outdoors was approximately 2 Pa, estimated from baseline measurements for test 11 (1 hr before this test) and test 10 (10 minutes after this test).

The exhaust rate of 85 cfm would be expected to cause a pressure drop of about 1.25 Pa, given the flow parameters for the master bedroom calculated in test 4 (C=54.3, n=0.5, mainly via leakage past the bedroom door). Given the measured pressure drop of 0.9 Pa, the duct system is clearly providing an air flow path, which reduces the flow rate past the bedroom door and therefore the pressure drop. At 0.9 Pa, the door flow path would be expected to give approximately 52 cfm airflow, leaving approximately 33 cfm of airflow through the duct system.

Tests #10 and 11

Pressure field and supply flows in house with AHU on (cooling mode), bedroom doors closed, and transfer grills closed or open. Supply and transfer flows were measured with the Alnor Lo-Flow Hood.

Test Number	10		11		
Doors	Closed		Closed		
Transfer grills	Closed		Open		
Ducts	Open		Open		
House Pressure wrt outside (Pa)	-2.2		-1.9		
Baseline House Pressure wrt outside (Pa)	(not recorded)		-1.6		
Room	Pressure wrt living space (Pa)	Supply flow(s) (cfm)	Pressure wrt living space (Pa)	Supply flow(s) (cfm)	Transfer flow (cfm)
Master BR	+1.9	16, 18, 18, 14	+0.55	16, 19, 21, 14 (total 70)	36
Bedroom 1	(not recorded)	(not recorded)	+1.1	22	(no transfer)
Bedroom 2	+8.6 Pa	69	+3.6	76	38
Bedroom 3	+10.2 Pa	90	+5.1	100	39
Bedroom 4	+5.0	46	+1.5	49	31
Bedroom 5	+1.8	27	+0.4	26	18

In comparing tests 10 and 11, some reduction in supply flow is seen due to closing of the transfer grills. Significant pressurization of bedrooms 2, 3, and 4 is seen with the transfer grills closed, and even with the transfer grills open bedrooms 2 and 3 are pressurized above BSC's 3 Pa criteria.

During test 11, all of the supply flows in the house were measured with AHU on (cooling mode), bedroom doors closed, and transfer grills open.

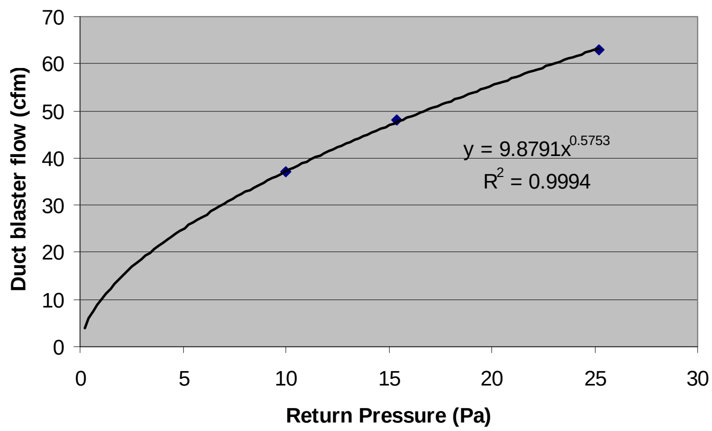
Room	Supply flow(s) (cfm)
Master BR	16, 19, 21, 14 (total 70)
Bedroom 1	22
Bedroom 2	76
Bedroom 3	100
Bedroom 4	49
Bedroom 5	26
Bath 1	26
Bath 2	21
Bath 3	17
Breakfast	207
Family	181
Dining	47
Living	133
Laundry	35

The total measured supply flow is 1010 cfm, only 63% of the design flow of 1600 cfm. Significant air flow through the door undercuts was observed in bedrooms 2 and 3.

Test #12

Overall duct leakage. Overall duct leakage was measured using the duct blaster exhausting from the return grill. The results are summarized in the table and figure below. The total leakage at 25 Pascals was 63 cfm, approximately 4% of design air handler flow (1600 cfm) and 6% of measured supply flow (1010 cfm).

Return Pressure (Pa)	Ductblaster flow (cfm)
0	0
-10.0	37
-15.4	48
-25.2	63



Test #13

Duct leakage to outside. A duct leakage to outside test was performed by depressurizing the house to -25 Pa. With the duct blaster off, the pressure in the return wrt the house was only +0.2 Pa. The duct leakage to outside was significantly below 20 cfm, the lowest measurable flow of the Ductblaster.

2.18.2. January 2007 Expert Meeting Summary Report

SYSTEMS ENGINEERING APPROACH TO DEVELOPMENT OF ADVANCED RESIDENTIAL BUILDINGS

13.B.2 FINAL EXPERT MEETING PLANS

RE: TASK ORDER NO. **KAAX-3-32443-13**
UNDER
TASK ORDERING AGREEMENT NO. **KAAX-3-32443-00**

MIDWEST RESEARCH INSTITUTE,
NATIONAL RENEWABLE ENERGY LABORATORY DIVISION,
1617 COLE BOULEVARD,
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CONSORTIUM LEADER:
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70 MAIN STREET, WESTFORD, MA
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BETSY@BUILDINGSCIENCE.COM

CONSORTIUM MEMBERS:

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ARTISTIC HOMES
BURLINGAME RANCH, LLC/SHAW CONSTRUCTION
CHRIS MILES
CHUCK MILLER CONSTRUCTION, INC.
COASTAL HABITATS
DAVID WEEKLEY HOMES
D.R. HORTON
EBSCO
FERRIER HOMES
FIREMAN'S FUND
GLOBAL GREEN
HAYMOUNT, LLC
ICI HOMES
ISM CONSTRUCTION, INC.
IDEAL HOMES
MCSTAIN COMMUNITIES
OAKLAND HOUSING
PULTE HOME CORPORATION / DEL WEBB
VENTURE, INC.

ANDERSEN WINDOWS
CARDINAL GLASS CO.
PANASONIC
THE DOW CHEMICAL COMPANY
CERTAINTEED
DUPONT NONWOVENS
FORTIFIBER
GEORGIA PACIFIC
HONEYWELL
HUBER ENGINEERED WOOD PRODUCTS
ICYNENE, INC.
JAMES HARDIE BUILDING PRODUCTS
LIPIDEX CORPORATION
JOHN MANSVILLE
MASCO
U. S. GREENFIBER, LLC
TAMLYN
RESEARCH PRODUCTS CORPORATION/APRILAIE

FEBRUARY 15, 2007

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AGENDA

Building America Expert Meeting

VENTILATION AIR DISTRIBUTION EFFECTS IN HOMES

Meeting Manager: Joseph Lstiburek, Building Science Corporation
Date/Time: **Friday, 26 January 2007, 8 am to 12 pm**
Location: Dallas, TX, **Adam's Mark, Houston Ballroom**
(ASHRAE Winter Meeting hotel)

Featured Speakers:

- Max Sherman, Lawrance Berkeley National Laboratory
- Bjarne Olesen, International Center for Indoor Environment and Energy, Denmark
- Ren Anderson, National Renewable Energy Laboratory
- Aaron Townsend, Building Science Corporation

Invitees:
Participants will be key people working in the indoor air quality field. 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 8:15 am, Welcome and Meeting Introduction – Joseph Lstiburek
- Presentations
    - 8:15 to 8:45, (30 min) Max Sherman, "Development of Metrics for Ventilation Distribution"
    - 8:45 to 8:55, (10 min) Questions and discussion
    - 8:55 to 9:25, (30 min) Bjarne Olesen, "Exposure and Risk"
    - 9:25 to 9:35, (10 min) Questions and discussion
    - 9:35 to 9:45 (10 min) Break/refreshments
    - 9:45 to 10:15, (30 min) Ren Anderson, "Contaminants and Control Strategies"
    - 10:15 to 10:25, (10 min) Questions and discussion
    - 10:25 to 10:55, (30 min) Aaron Townsend, "Field Measurements and Simulations"
    - 10:55 to 11:05, (10 min) Questions and discussion
- General discussion, 11:05 to 11:55 (50 min), Joseph Lstiburek-discussion moderator

- Whole-house ventilation air distribution is important to achieve reliable ventilation performance.
  - What are the metrics that can be used to quantify the effective differences between systems?
  - How can those metrics be applied to ASHRAE Standard 62.2?

- Wrap up, action items, and follow-up plan, 11:55 to 12:00

Key questions regarding this meeting:

Mechanical ventilation is becoming an increasingly larger portion of the total space conditioning load in high-performance buildings. Where contaminant sources are managed (for example, closed combustion) and ventilation air distribution is assured, reduced ventilation requirements may be acceptable and advantageous. Hot-humid climates may benefit the most.

1. What does the latest research tell us about ventilation effectiveness due to spatial air distribution?

2. Should not ventilation systems with better spatial distribution be credited for having more reliable whole-house performance relative to indoor air quality?

3. What are the best metrics to account for ventilation air distribution in determining appropriate minimum residential ventilation rates?

References/Supporting Documents

Hendron, R, Rudd, A., Anderson, R., Barley, D., Hancock, E., Townsend, A., 2006. "Field test of room-to-room uniformity of ventilation air distribution in two new houses." Submitted for publication to IAQ 2007, ASHRAE, December.

Lstiburek, J., Townsend, A., Rudd, A., 2006. "Engineering based guidelines for effective ventilation in new homes." Final report submitted to USDOE, December.

Table 1. List of confirmed attendees (not including speakers and BSC staff)

#	Last name	First name	Company	Email	Y/N response as of 1/5/07	62.2 status
1	Baxter	Van	ORNL	baxtervd@ornl.gov	Y	
2	Bloemer	John	Research Products Corp.	jb@aprilaire.com	Y	
3	Brennan	Terry	Camroden Associates	terry@camroden.com	Y	SSPC 62.2 vote
4	Chandra	Subrato	Florida Solar Energy Center	subrato@fsec.ucf.edu	Y	
5	Crawford	Roy	Trane	roy.crawford@trane.com	Y	SSPC 62.2 vote
6	Davis	John	Research Products Corp.	jgd@aprilaire.com	Y	
7	Drumheller	Craig	NAHB Research Center	cdrumheller@nahbrc.org	Y	SSPC 62.2 non-vote
8	Emmerich	Steve	NIST	steven.emmerich@nist.gov	Y	SSPC 62.2 vote
9	Fairey	Philip	FSEC	pfairey@fsec.ucf.edu	Y	
10	Ferris	Rob	Fantech	rofe@fantech.net	Y	
11	Forest	Daniel	Venmar Ventilation	forestd@venmar.ca	Y	
12	Francisco	Paul	University of Illinois-UC	pwf@uiuc.edu	Y	SSPC 62.2 vote
13	George	Marquam	Blu Spruce Construction	marquam.george@uas.alaska.edu	Y	SSPC 62.2 vote
14	Grimsrud	David		grimsrud@earthlink.net	Y	SSPC 62.2 vote
15	Heidel	Tom	Broan-Nutone	theidel@broan.com	Y	
16	Henderson	Hugh	CDH Energy	henderson@cdhenergy.com	Y	
17	Holton	John		jholton1@verizon.net	Y	SSPC 62.2 vote
18	Kosar	Douglas	University of Illinois-Chicago	dkosar@uic.edu	Y	
19	Lubliner	Mike	Washington State University	lublinerm@energy.wsu.edu	Y	
20	Olson	Collin	Energy Conservatory	colson@energyconservatory.com	Y	
21	Proctor	John	Proctor Engineering	john@proctoreng.com	Y	SSPC 62.2 vote
22	Rittelmann	Bill	IBACOS	brittelmann@ibacos.com	Y	
23	Ryan	William	University of Illinois-UC	wryan@uic.edu	Y	
24	Stevens	Don	Stevens & Associates	don.t.stevens@wavecable.com	Y	SSPC 62.2 vote
25	Stroud	Thomas	Health Patio & Barbeque Assoc	stroud@hpba.org	Y	SSPC 62.2 vote
26	Talbot	John		jmtalbott@comcast.net	Y	
27	Uselton	Dutch	Lennox	dutch.uselton@lennoxInd.com	Y	
28	Walker	Iain	LBNL	iswalker@lbl.gov	Y	SSPC 62.2 vote
29	Wilcox	Bruce		bwilcox@lmi.net	Y	SSPC 62.2 vote
30	Williams	Ted	AGA	twilliams@aga.org	Y	SSPC 62.2 vote

Appendices

METRICS

What do we need to know in order to add air distribution into ASHRAE Standard 62.2?

Max Sherman

OBJECTIVES

- To define some potential metrics that can be used to evaluate air distribution
  - But, first we need to look at implied metrics for acceptable Indoor Air Quality
- Suggest some approaches to evaluate metrics
  - Simulation
  - Experiment

Max's Metric Mantra:

Metrics must be meaningful and measurable

Pre-Metric: Acceptable IAQ

- Frames discussion of metrics
- Won't discuss this quantitatively, but operationally it should
  - Limit **damage**
  - Caused by **contaminants** of concern
  - To which people are exposed over some **time** period

Types of "DAMAGE"

- Comfort
  - Unpleasant Odors, Irritation *(covered by 62.2)*
  - Acoustics, lighting, thermal, etc. *(not covered)*
- Health
  - Reduced physiological functioning
  - Tissue damage
  - Increased susceptibility to disease

Contaminants of Concern

- Compounds and specifics: ***Bjarne***
- Whole-house ventilation looks at what?
  - Acute Mortality/Morbidity: No
    - E.g. we don't control phosgene with 62.2
  - Reduction in life-expectancy: Yes
    - E.g. carcinogenesis, mutagenesis, toxic loads
  - Reduction in quality of life: Yes
    - E.g. hours of discomfort, minor disease etc.

Timed Exposure

- Delay in absorption of contaminant
  - Important for short-term exposure
- Body can repair/adapt sometimes; e.g.
  - 10 ppm CO for 400 hours: small impact
  - 400 ppm CO for 10 hours: death
- But not others; e.g.
  - Irreparable tissue damage
  - Risk increases during exposure

Damage Equation:

- Linear (n=1) for many cumulative risks
  - Most cancer, metals, stable (e.g. DDT)
- n=3 for Chlorine
  - Typical of oxidants, poisons
- n>>1 represents a threshold
  - Time above threshold is important
- Linear approximation good if little variation

IAQ METRICS

- Peak concentration of contaminant
  - Good for high exposure levels/acute effects
  - Good for threshold-dominated contaminants
  - Focus on short-term dose
- Average concentration (e.g. linearized)
  - Good for cumulative exposures
  - Good for steady exposures above thresholds
  - Focus on long-term dose

Average Concentration It is

- Highly variable emission rates
  - Not well controlled by continuous ventilation
  - Need source control (e.g. exhaust ventilation)
- Contaminants of concern
  - Must be above thresholds to be "of concern"
  - Are the ones we expect to control with whole-house ventilation
- Metric is then long-term average concentration: DOSE

How Do We Get Concentration

- Depends on
  - Sources & sinks
  - Volumes
  - Ventilation & air transport
- Linked by Continuity Equation
- Need to proceed generically
  - No pollutant specifics (i.e. a tracer gas)
  - Ignore species-specific interactions

CONTINUITY EQUATION

- Locally Covariant Derivation
  - Good everywhere
  - Even near black holes
- Steady state, single zone expression:
  - S=emission rate (e.g. cfm)
  - Q= ventilation (e.g. cfm)

Getting Back to Distribution

- Air distribution is only relevant when it is not a single well-mixed zone.
  - Can't get too crazy (e.g. CFD)
  - Need to relate it to the simple result
- We use a multizone continuity equation
  - But we can assume the zones are well mixed
  - Need matrix formulation of continuity equation

MATRIX EQUATION

- Local Zonal Description
  - Matrix of flows
  - Independent sources
  - Zonal concentrations
- Psuedo-Steady State
  - Matrix inverse
  - Represents averages

MATRIX NOTATION

- For N zones: N rows & N columns
- Sum of all entries gives single zone value
- Diagonal element is total for zone
- Off-diagonal elements of Q matrix are (negative of) flow between zones
  - Ask about Volume matrix if you dare

Dose is our IAQ Metric

- A person can only be in one zone at a time
  - So, we define an activity variable.
- Source strength may vary zonally.
  - So, we define a source fraction for each zone
- Distribution impacts are relative
  - So, we define a relative dose v. perfect mixing

How Should We Use Metric

1. Evaluate Metric for distribution system of interest
2. Evaluate Metric for distribution in reference case (e.g. 62.2 default)
3. Adjust total rate by ratio to increase or decrease depending on system
   - Could be tabulated like in 62.1

DOSE

- *d* is dose
- ***s*** is fractional source strength
- ***a*** is fractional time spent in each zone
- **D** is Distribution Matrix

DISTRIBUTION MATRIX

- Couples emission in one zone to exposure in all other zones; e.g.
  - All entries the same (1) for fully mixed
  - Matrix diagonal for isolated zones
- ***Independent*** of sources, activities, etc
- So, we could base final metric on it
  - If we define activity/source distribution

3-Zone Example (PFT data)

- Q Matrix=>
  - m^3/hr
  - Q_o=726 m^3/hr

653	-291	0
-130	448	-206
-17	-23	292

- D Matrix =>
  - Dimensionless
  - D_o=9.54

1.30	0.88	0.62
0.43	1.97	1.39
0.11	0.21	2.63

Metric Choices

- Need to determine how to use the Distribution Matrix in a way that does not depend on knowing activity/sources.
- What is appropriate for a standard?
  - Best case?
  - Worst case?
  - Typical case?
    - What is that??

Extreme Metrics

- The best and worst cases of the metric will be when the contaminant of concern is emitted in a single zone
- Worst case: Highest value in matrix; e.g. someone generates contaminants and lives in same zone: 2.63 in example
- Best case: lowest value: e.g. live in most isolated room: 0.11 in example

Distributed Distribution

- Assume sources are fully dispersed and activity is spread between all zones
- d=1.06 in example
- Tends toward perfect mixing result because of source distribution and activity patterns

Inactivity Patterns

- Suppose sources were distributed but someone spent all their time in the worst zone
- Relative dose would then be from the row of Distribution Matrix with highest sum.
- From example
  - 0.93, 1.26, 0.98
  - RMS mean=1.07

Deviation from Perfection

- Suppose we have no clue on activity patterns or source distributions
- We can measure the "distance" from perfect mixing using RMS deviation
- d=1.80 for example case

Which Metric Option?

- Fully distributed sources & activities (1.06)
  - Air distribution effect will be minimal
- Worst zone; distributed sources (1.26)
  - Is reasonable? (RMS=1.07)
- Clueless: (1.80)
  - Robust, but semi-empirical; conservative
- Worst case: (2.63)
  - Appropriate for minimum standard?

METRICS ARE WORTHLESS

Unless you can measure them, of course

- Direct Field Measurement
  - Measure response in real configuration
  - Can really only be done with tracer gas
- Simulation
  - More practical; allows parametrics
  - But must be believable
    - See "Direct Field Measurement" above

HOW TO MAKE THE MEAUSURMENTS

The diagnostics necessary to measured air distribution effects

TWO TRACER APPROACHES

- Simplified for the Metric of Choice; e.g.
  - Inject tracer in reference source pattern
  - Sample in reference activity pattern
- Complete Characterization
  - Measure all flows to/from zones
  - Can be used to compare metrics
    - And derive simplified approach
  - Can be used to verify simulations

TRACER CONTINUITY

- Same Continuity equation, but
  - this time we know concentrations
  - and are looking to determine the flows
- Unfortunately, no direct solution
  - N^2 unknowns, but only N equations
  - Need to get more information

THREE APPROACHES

- Time Series in Non-steady State
  - Fit time series data over changing conditions (e.g. decay) to solve differential equation
- Series (Single-Tracer) Steady-state Tests
  - N tests are done one at a time
- Simultaneous Multi-Tracer Tests
  - Use N tracer gases to run simultaneous tests (e.g. inject one in each zone)

TIME SERIES

- Fit data to=>
- To find eigenvalues
- "A"s are relevant air change rates
  - N of the them; C_{ij} are their eigenvectors
  - Slowest is whole-building air change rate
  - Quickest determines uncertainty
- This approach never works in real buildings
  - Mixing issues obscure vital information
  - KIDS: DON'T DO THIS AT HOME

MIXING KILLS

- In all real experiments mixing will obscure short-term information with noise
- Don't differentiate---INTEGRATE
- Even in single-zone situations, fitting decay data is inferior to integrating under the curve
- In multizone situations it is much worse
  - Alternative approaches are needed

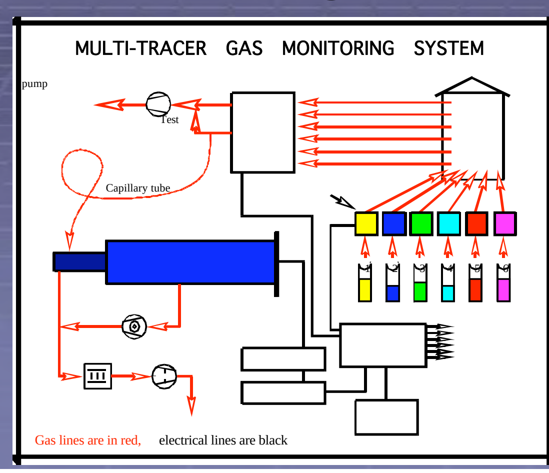
MULTIPLE EXPERIMENTS

- Do N different experiments & integrate/average
  - inject in N independent ways
    - E.g. in 1 zone different zone each experiment
- Add to Matrix equation
  - Can be inverted now

SERIES OR PARALLEL

- Series Option
  - Can be done with one tracer gas
  - Very sensitive to changes in air flows
- Parallel (MultiTracer) Option
  - Can accurately find average flow
  - Takes less time
  - LBL's MTMS uses this approach

MTMS



WHAT TO DO NOW?

- Some discussion on options for Metrics
- Measurement of possible metrics in real buildings for various real systems
  - LBL & BSC planning on doing so this year
- Simulate wider variety of options
  - Significant differences between systems????
  - Field diagnostics even needed????
- Implement in 62.2 as appropriate

DISCUSSION

International Centre for Indoor Environment and Energy

VENTILATION AIR DISTRIBUTION EFFECTS IN HOMES

Indoor Air Quality-Exposure and Risk

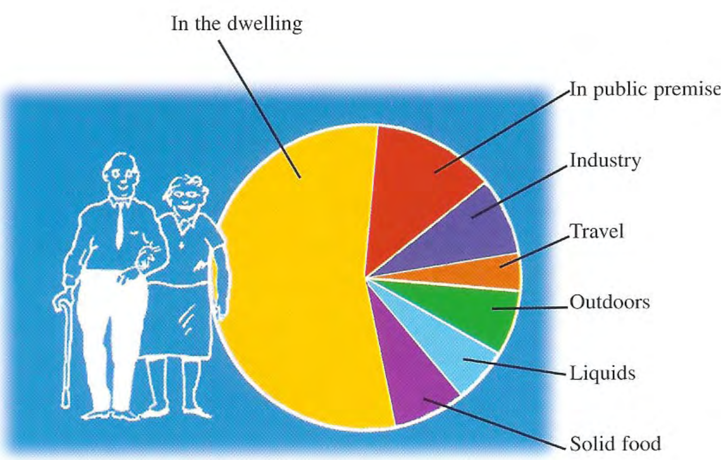
Professor Bjarne W. Olesen, Ph.D.

www.ie.dtu.dk

Technical University of Denmark

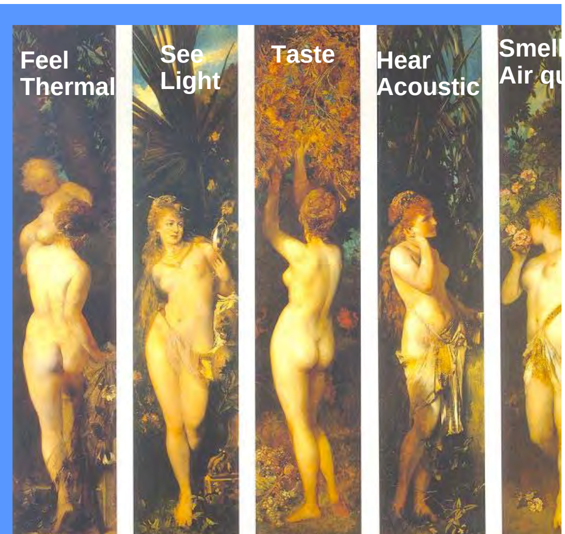
INDOOR - OUTDOOR

- Highest exposure to the indoor environment
- People spend ~90 % of the time indoors during work, during transportation and at home



Relative exposure of air during a normal life.

5 SENSES



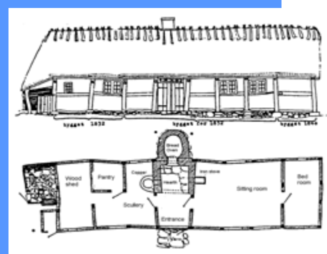
HEALTH

In developing regions 5000 persons die per day due to poor IAQ

(WHO)

Experiments in two houses at Lejre Experimental Centre for Archaeolog
Professor Kirk Smith, UC-Berkeley

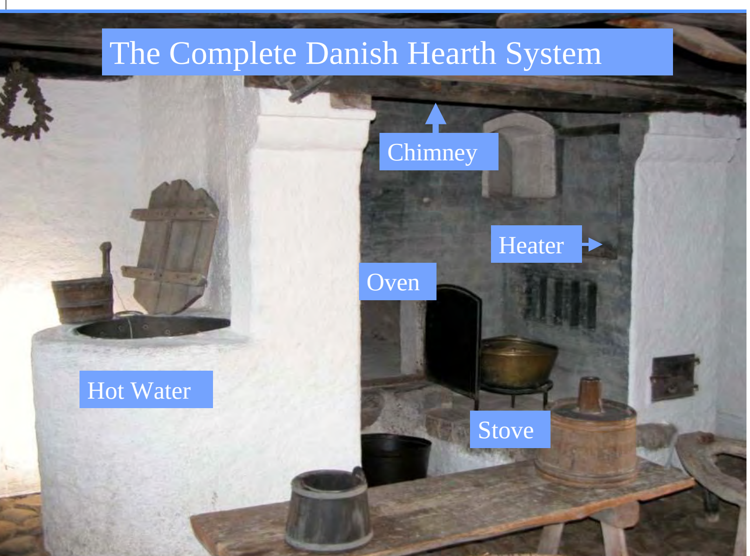
- How does the Danish hearth system perform?
- Will the system be useable in developing countries, e.g. Nepal, so that peoples exposure to smoke from indoor fireplaces can be reduced?



Not so long ago, Denmark was a low-technology wood-burning society
not able to afford much metal.

How did its people solve the smoke problem?

The Complete Danish Hearth System

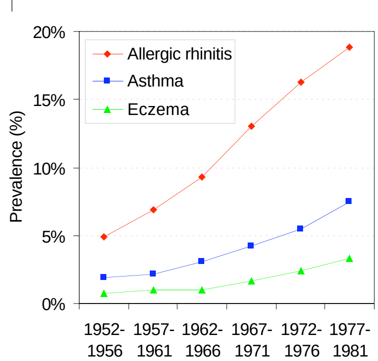


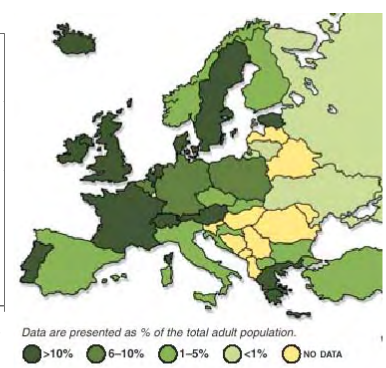
Monitoring of CO and fine particles in house during use of fireplace (cooking, heating, boiling water)

Asthma and Allergy

In several industrial countries 50% of school children is suffering from Asthma or Allergy. This number has doubblet within the last 20 years

International Centre for Indoor Environment And Energy

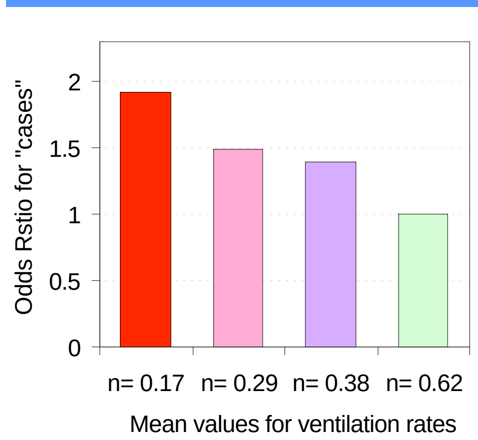




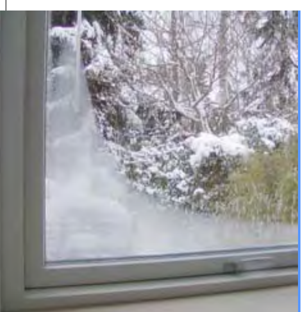
Left: Trends for allergic rhinitis, asthma and eczema among male conscripts (17-20 years age) in Sweden (Bråbäck et al., 2004).
Right: Current data on prevalence of asthma in adults in Europe (Loddenkemper et al., 2

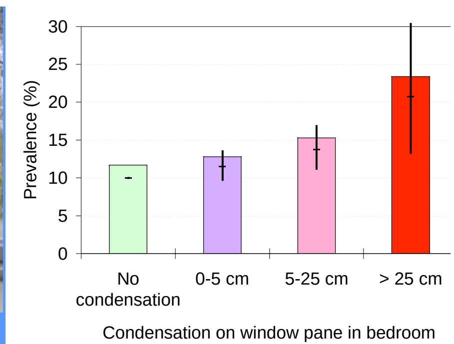
In a large study with 11.000 children the relation between asthma and the indoor air quality was investigated.
In 200 houses with children suffering from asthma and in 200 houses with healthy children we made detailed chemical, physical, biological and medical measurements.

International Centre for Indoor Environment And Energy



Odds ratio for being a “case”, children with at least two sym of possible three (wheezing, r eczema) as a function of vent rates, in single family houses. (Bornehag et al., 2003).

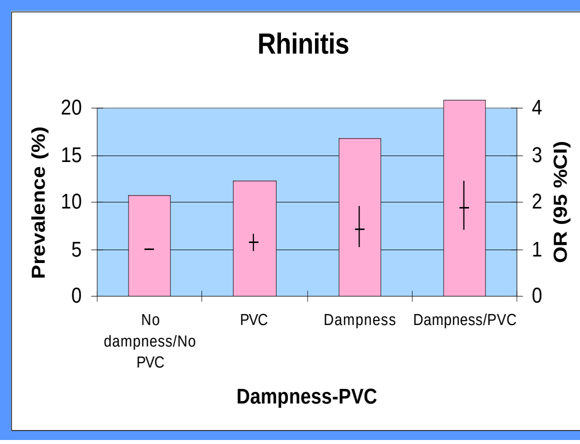


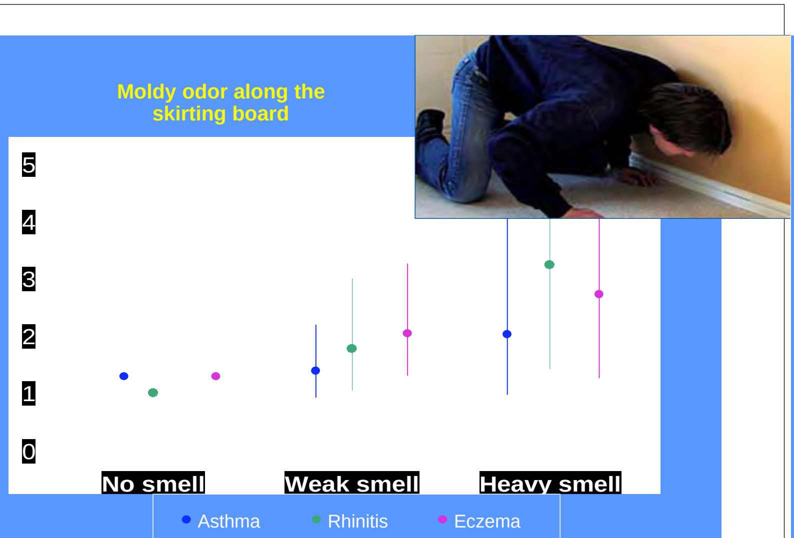


Left: Window water condensation is often a sign of poor ventilation in dwelling

Right: Prevalence and odds ratio for rhinitis among children versus condensatio window pane in a bedroom (source: DBH-study group, in press).

Combination of Dampness in floor and PVC



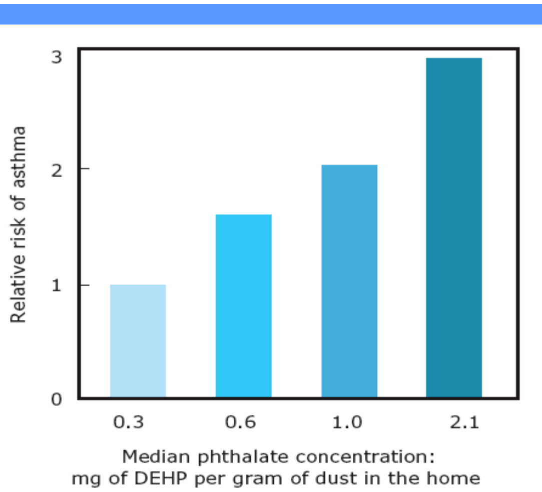


THE RIDDLE OF ALLERGIES

- ALLERGIES ARE INCREASING!
- Up to 50% of children has or have had symptoms of allergic disease
- IN SWEDEN more in the north!
- IN EUROPE more in the west!
- IN USA more among the poor!
- MOST in countries that speak ENGLISH (UK, New Zeeland, Australia
- Also high in Peru...

THE ROLE OF INDOOR AIR?

Appendix II



DEHP: di(2-ethylhexyl) phthalate.

Plasticizers fr
polyvinyl chlor
in dwellings
increase the ri
of asthma amo
children.

Each column
represents abo
90 dwellings.

The ALLHOME study

Objectives

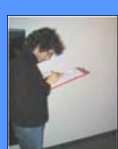
•To map the housing conditions regarding indoor environment in two representative urban areas of Bulgaria (Sofia and Burgas).

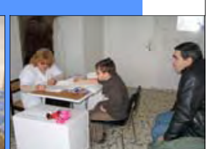
•To explore the associations between housing condition and symptoms in airways, eyes, nose and skin in children age 2 to 7.

The ALLHOME-2 study

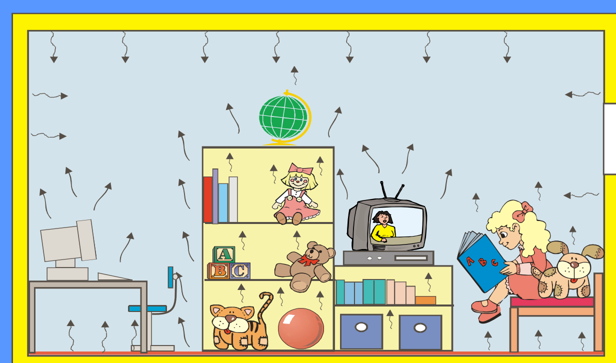
- Nested case-control study, including medical and engineering measurements
- Case and control children selected based on the ALLHOME-1 study
- December-March 2005
- Medical and engineering measurements:
  - •Building inspection, 24h-CO_2, RH, T; dust samples,
  - •Examination, Skin Prick Test (10 allergens), urine
- •Collected data: 215 children (111 cases, 114 controls), 211 houses

Analyses are ongoing

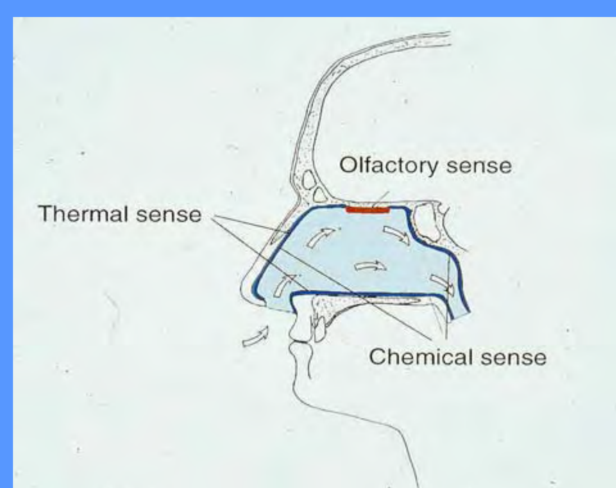




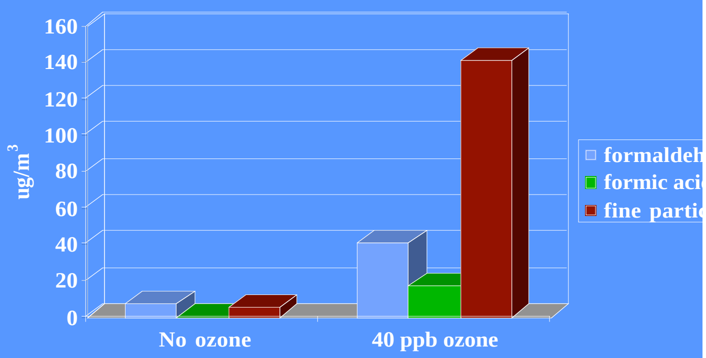
Homes



List of 350 common volatile organic compounds in indoor air



Mixture of 23 VOCs (including d-limonene and α-pinene)

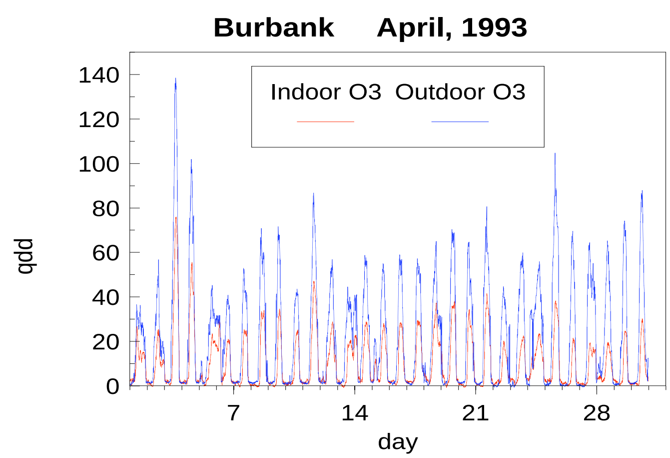


Indoor Chemistry

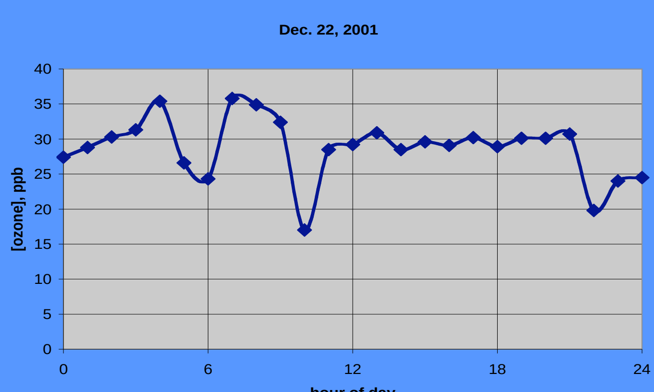
- Indoor chemistry can influence the kind and concentration of organic chemicals in indoor air

Ozone

- Sources
  - outdoor to indoor transport
  - photocopiers
  - laser printers
  - ozone generators
- Indoor levels normally smaller than outdoor
- Large variations with time of day, day of week and season

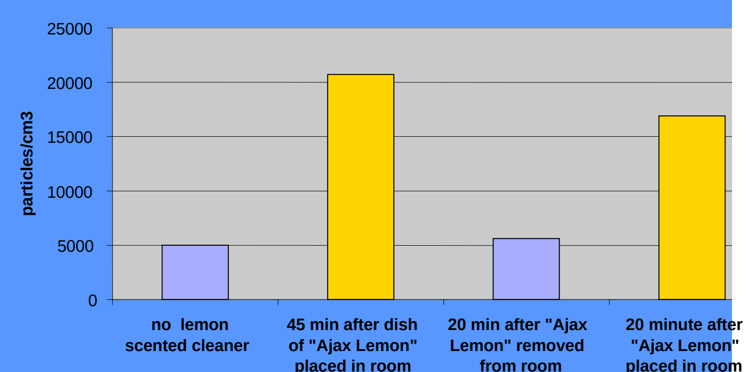


Even in Scandinavia During the Winter Outdoor Ozone Can Exceed 35 ppb



Office in Copenhagen; Dec. 19, 2001

[outdoor ozone] = 28 ppb



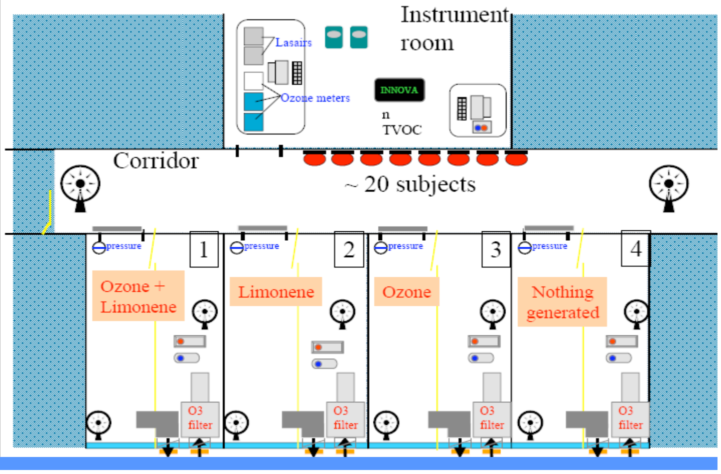
Examples of common indoor pollutants that react with ozone in the air

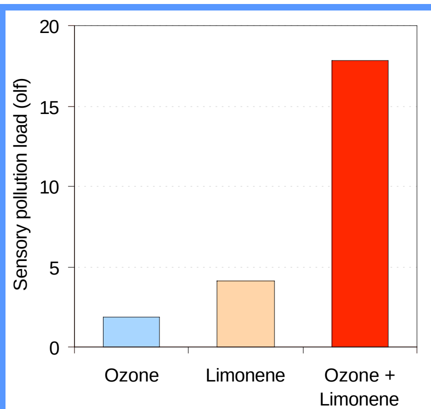
- Nitric oxide, nitrogen dioxide

- Terpenoids (e.g., d-limonene, α-pinene, linalool)

- Unsaturated fatty acids (e.g., oleic, linoleic)

Sensory effects from ozone + limonene





The sensory pollution load in an office where either ozone (15 ppb) or limonene (83 pp were present separately or both ozone and limonene (15 ppb+83 ppb respectively) we mixed in the office air (Tamás et al., 2005); the increased sensory pollution load is due to the presence of reaction products in the office air.

When is Indoor Chemistry Most Likely to Happen

- When indoor ozone levels are elevated (oxidation)
- When the humidity is elevated (hydrolysis)
- When temperatures are elevated
- When ventilation rates are low (gas phase)
- When terpene levels are high
- When surfaces are “dirty”

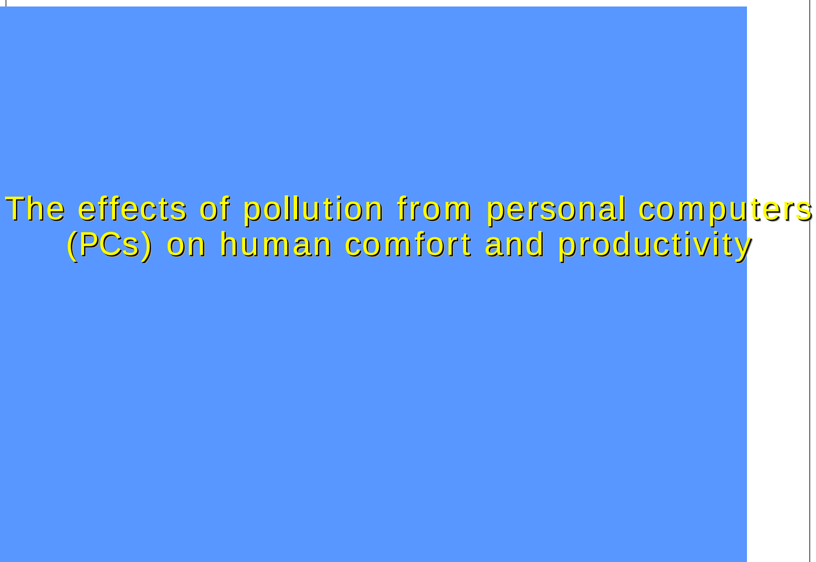
Generation of pollution from occupants

	Sensory pollution load olf/ occupant	Carbon dioxide l/(h· occupant)	Carbon monoxide [1] l/(h· occupant)	Water vapour [2] g/(h· occupan
Sedentary, 1-1.2 met				
0% smokers	1	19		50
20% smokers [3]	2	19	$11 \cdot 10^{-3}$	50
40% smokers [3]	3	19	$21 \cdot 10^{-3}$	50
Physical exercise				
Low level, 3 met	4	50		200
Medium level, 6 met	10	100		430
high level (athletes), 10 met	20	170		750
Children				
Kindergarten, 3-6 years, 2,7 met	1,2	18		90
School, 14-16 years, 1-1,2 met	1,3	19		50

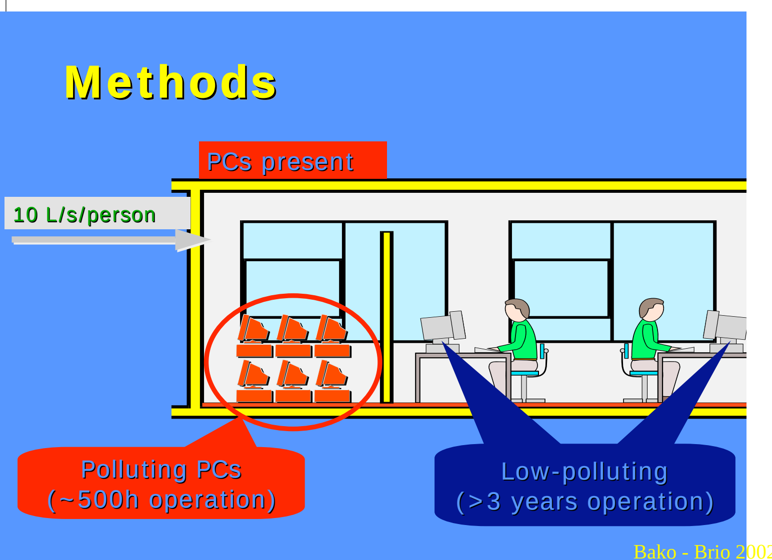
[1] from tobacco smoking
[2] applies for persons close to thermal neutrality
[3] average smoking rate 1,2 cigarettes/hour per smoker, emission rate 44 ml CO/cigarette

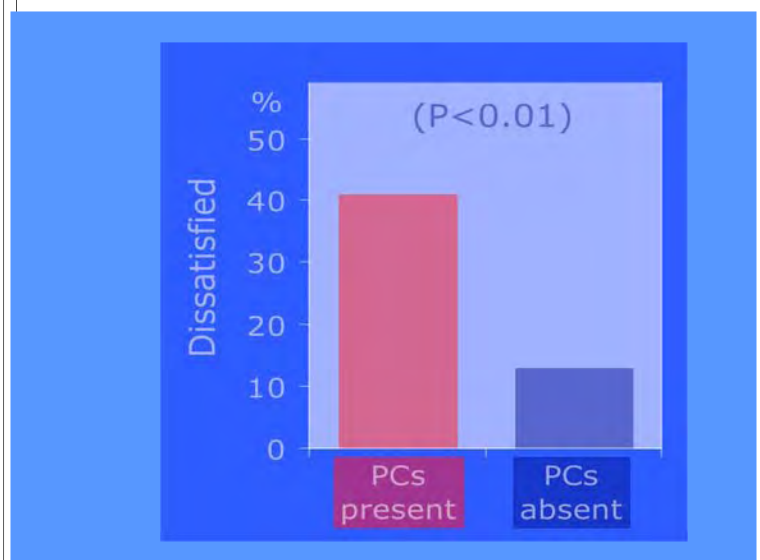
POLLUTANT FROM BUILDING, FURNISHING AND SYSTEM	Sensory pollution lo olf/m_	
	Average	Range
Existing buildings		
Offices [a]	0,3 [d]	0,02-0,9
Offices [b]	0,6 [c]	0 - 3
Class rooms [a]	0,3	0,12-0,5
Kindergarten [a]	0,4	0,20-0,7
Auditorium [a]	0.3 [d]	0,13-1,3
New buildings (No-smoking)		
Low polluting buildings	0,1	
Not-low polluting buildings	0,2	
Very low polluting buildings	0.02	

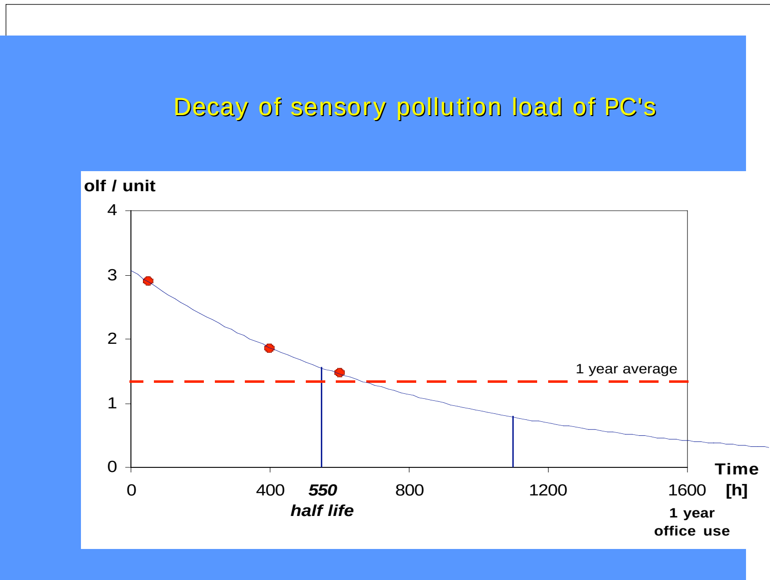
[a] Data from more than 40 mechanical ventilated buildings in Denmark.
[b] Data from an European Audit program, 1992-1995.
[c] Includes pollutant load from smokers
[d] Includes pollutant from earlier smoking.

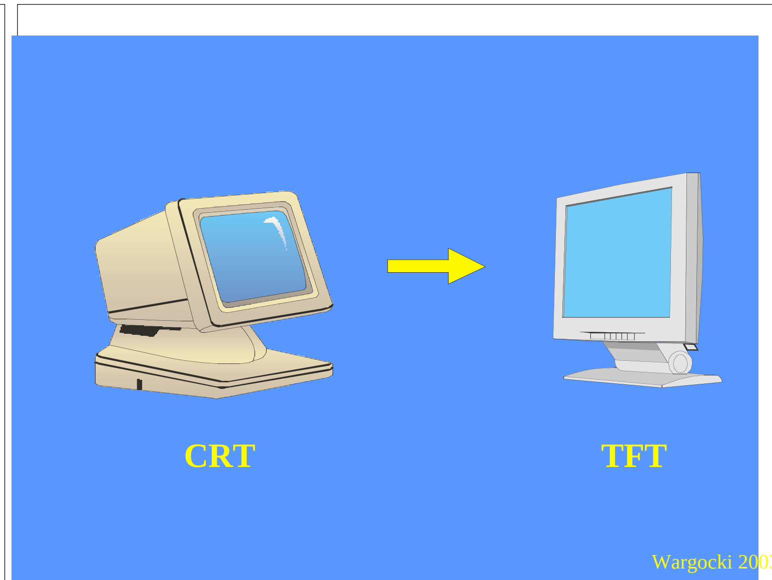

The effects of pollution from personal computers
(PCs) on human comfort and productivity

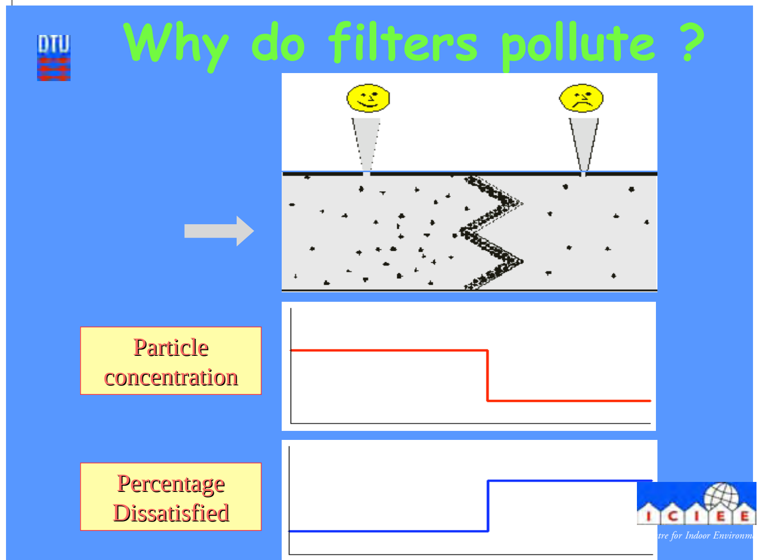

PCs are pr
s
The estimate
is more than
PCs are an indispensable tool in a
modern office


Methods
PCs present
10 L/s/person
Polluting PCs
(~500h operation)
Low-polluting
(>3 years operation)
Bako - Brio 2002

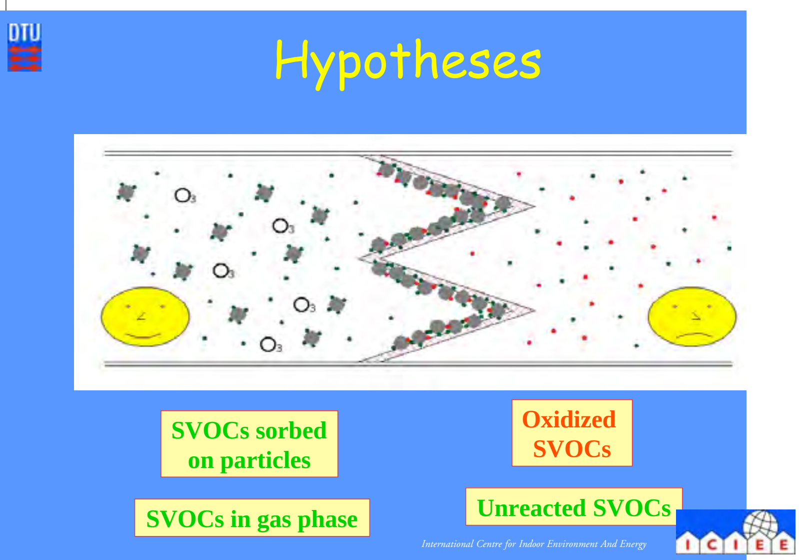

%
(P<0.01)
Dissatisfied
50
40
30
20
10
0
PCs
present
PCs
absent


Decay of sensory pollution load of PC's
olf / unit
4
3
2
1
0
1 year average
0
400
550
half life
800
1200
1600
Time
[h]
1 year
office use

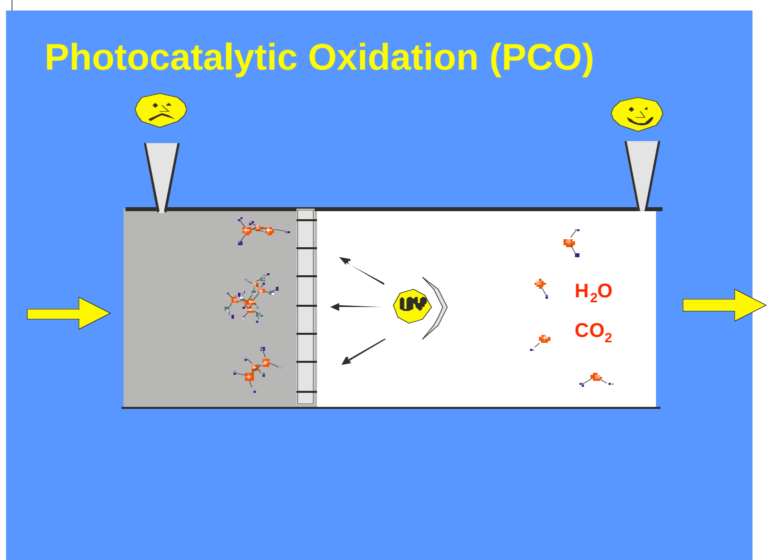

CRT
TFT
Wargocki 2003



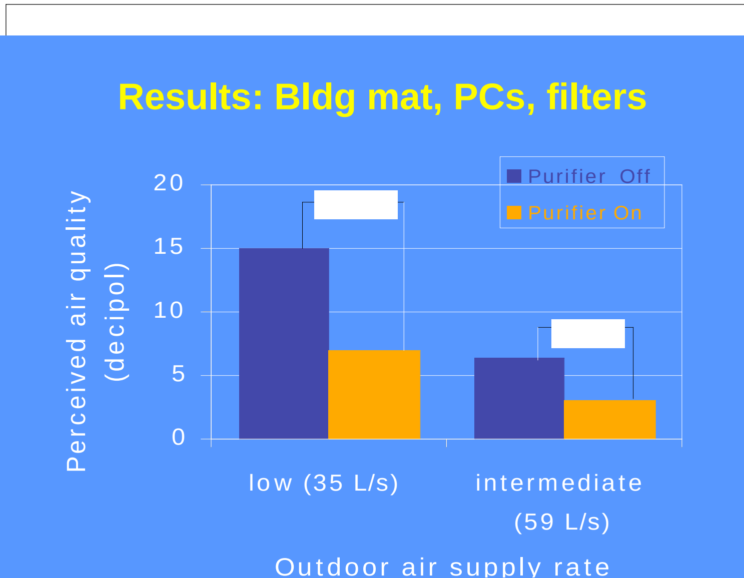
Why do filters pollute ?
Particle concentration
Percentage Dissatisfied



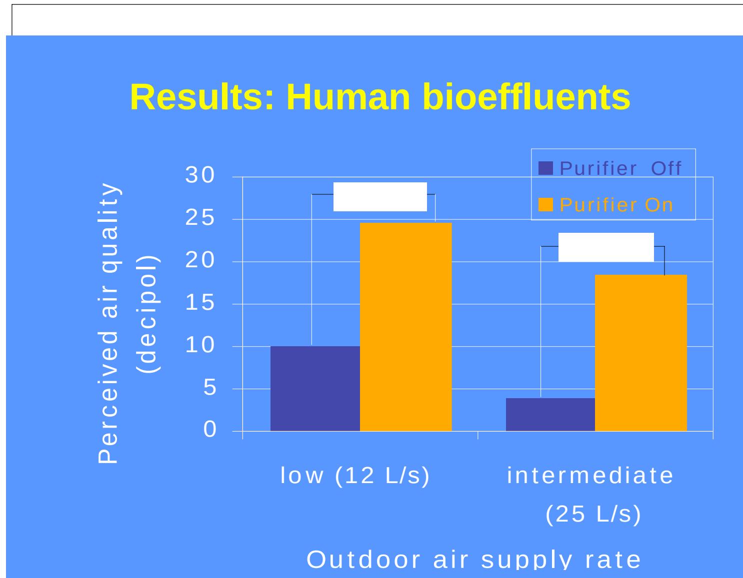
Hypotheses
SVOCs sorbed on particles
Oxidized SVOCs
SVOCs in gas phase
Unreacted SVOCs
International Centre for Indoor Environment And Energy



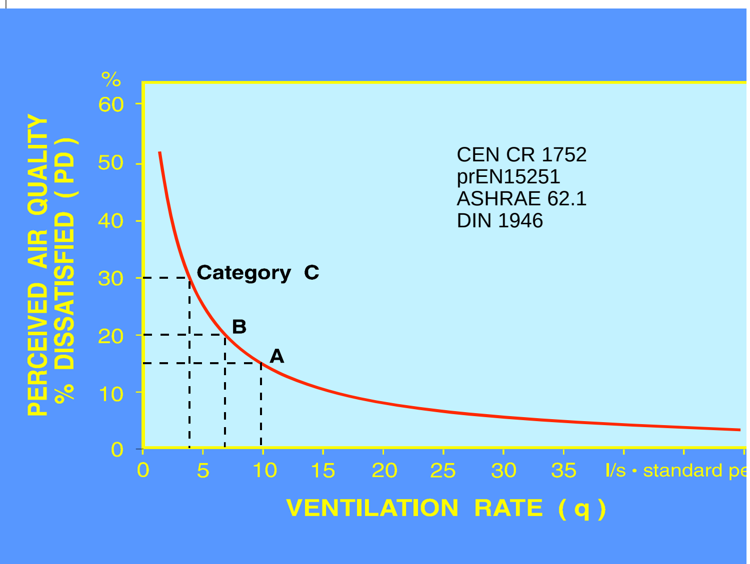
Photocatalytic Oxidation (PCO)
UV
H_2O
CO_2



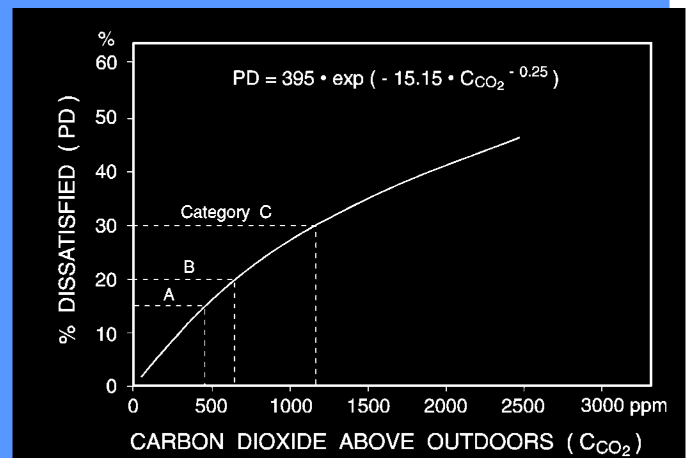
Results: Bldg mat, PCs, filters
Perceived air quality (decipol)
20
15
10
5
0
Purifier Off
Purifier On
low (35 L/s)
intermediate (59 L/s)
Outdoor air supply rate



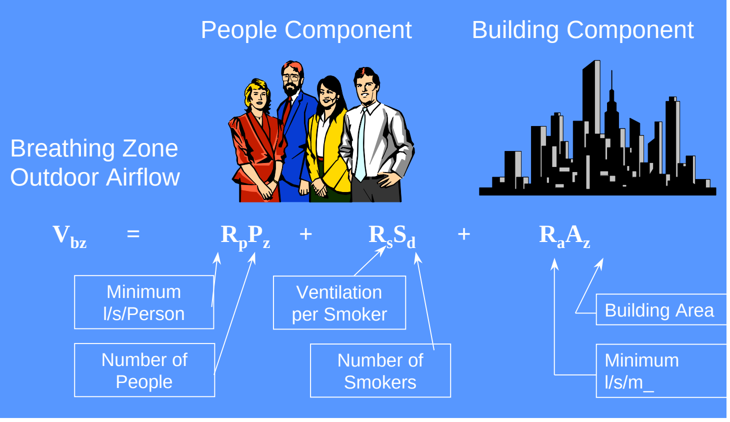
Results: Human bioeffluents
Perceived air quality (decipol)
30
25
20
15
10
5
0
Purifier Off
Purifier On
low (12 L/s)
intermediate (25 L/s)
Outdoor air supply rate



CO2 as reference



Concept for calculation of design ventilation rate



Recommended ventilation rates for non-residential buildings with default occupant density for three categories of pollution from the building itself.
If smoking is allowed the last column gives the additional required ventilation rate

Type of building or space	Category	Floor area m²/person	q_p	q_B	q_{tot}	q_B	q_{tot}	q_B	q_{tot}	smoking
			l/s, m² for occupancy	l/s,m² for very low polluted building		l/s,m² for low polluted building		l/s,m² for non-low polluted building		l/s,m²
Single office	A	10	1,0	0,5	1,5	1,0	2,0	2,0	3,0	0,7
	B	10	0,7	0,3	1,0	0,7	1,4	1,4	2,1	0,5
	C	10	0,4	0,2	0,6	0,4	0,8	0,8	1,2	0,3
Landscaped office	A	15	0,7	0,5	1,5	1,0	1,7	2,0	2,7	0,7
	B	15	0,5	0,3	1,0	0,7	1,2	1,4	1,9	0,5
	C	15	0,3	0,2	0,6	0,4	0,7	0,8	1,1	0,3
Conference room	A	2	5,0	0,5	1,5	1,0	6,0	2,0	7,0	5,0
	B	2	3,5	0,3	1,0	0,7	4,2	1,4	4,9	3,6
	C	2	2,0	0,2	0,6	0,4	2,4	0,8	2,8	2,0

DTU

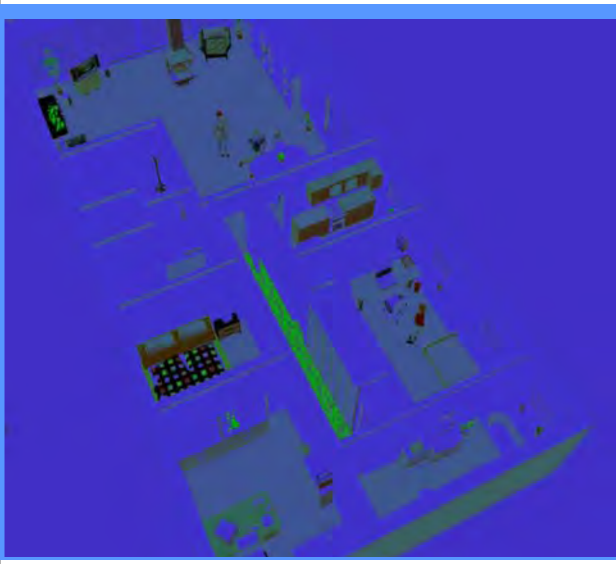
Type building/ space	Occupancy person/m²	Category CEN	Occupants only l/s person		Additional ventilation for building (add only one) l/s ?m²			Total l/s ?m²
			ASHRAE Rp	CEN	CEN low-polluting building	CEN *Non*-low-polluting building	ASHRAE Ra	CEN Low Pol.
Single office (cellular office)	0,1	A	2,5	10	1,0	2,0	0,3	2
		B		7	0,7	1,4		1,4
		C		4	0,4	0,8		0,8
Land-scaped office	0,07	A	2,5	10	1,0	2,0	0,3	1,7
		B		7	0,7	1,4		1,2
		C		4	0,4	0,8		0,7
Conference room	0,5	A	2,5	10	1,0	2,0	0,3	6
		B		7	0,7	1,4		4,2
		C		4	0,4	0,8		2

1 l/s m² = 0.2 cfm/ft²

International Centre for Indoor Environment And Energy

Residential buildings

Category	Air change rate [1]		Living room and bedrooms, mainly outdoor air flow		Exhaust air flow, l/s		
	l/s,m² (1)	ach	l/s, pers[2] (2)	l/s/m² (3)	Kitchen (4a)	Bathrooms (4b)	To (4
I	0,49	0,7	10	1,4	28	20	14
II	0,42	0,6	7	1,0	20	15	10
III	0,35	0,5	4	0,6	14	10	7



Concentration of carbon dioxide measured in 12 locations within the house shown in Figure

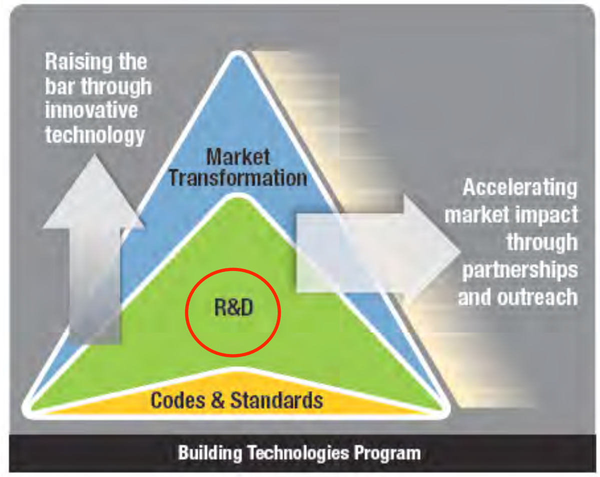
Requirements for Residential Ventilation

Dr. Ren Anderson, NREL

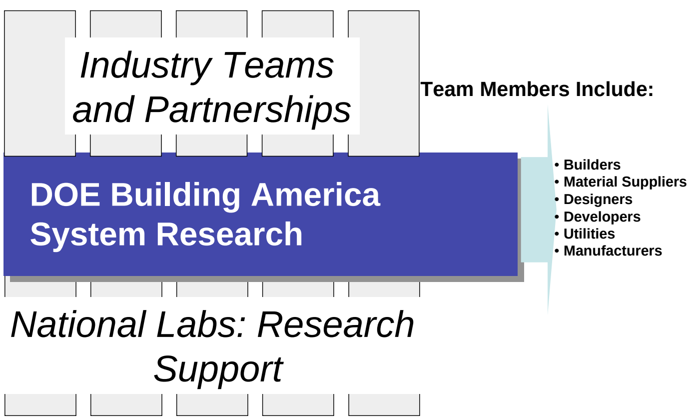
ASHRAE Winter Meeting
Ventilation Expert Meeting
January 26, 2007, Dallas, CA

Research Funded in Part by USDOE

NREL is operated by Midwest Research Institute • Battelle

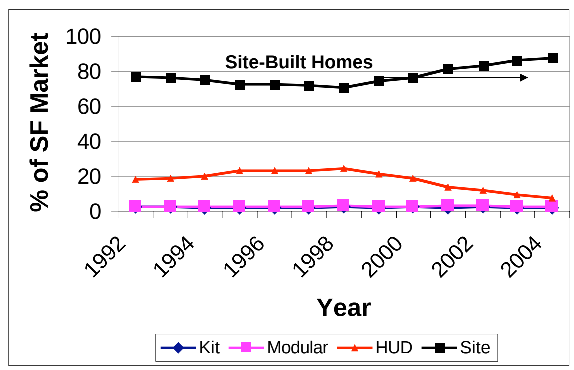


Cost Shared R&D Approach



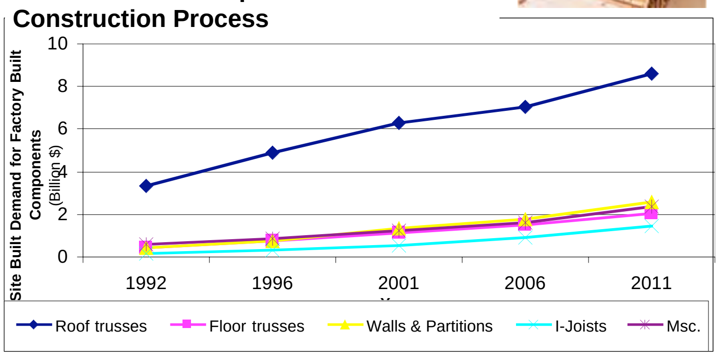
EEBA, Energy Star, Engineered for Life, ComfortWise, CEC, CEE Lighting for Tomorrow, SMUD, RESNET, NAHB and Others are Deployment Partners

Market Context: Site Builders Currently Account for Nearly 90% of All New Homes Built in the US Each Year



U. S. Census Bureau, Residential Construction Characteristics

Market Context: Production Builders are Rapidly Shifting to the Use of Standardized, Pre-Manufactured Components to Reduce Onsite Labor and Speed the Construction Process



"The Factory Built Components Industry Is Almost as Large as the Softwood Lumber Industry", Al Schuler, **STRUCTURAL BUILDING COMPONENTS MAGAZINE, April 2003.**

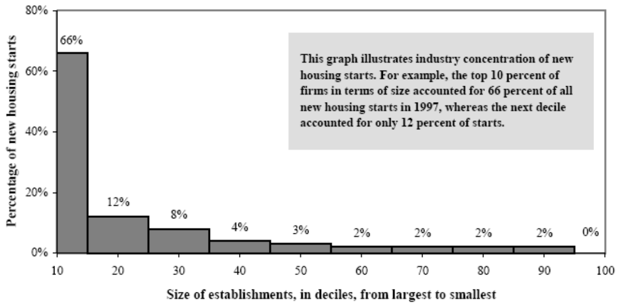
Residential construction is a highly automated process:

-A multi-step construction process that is managed across multiple homes, and

-"Just in Time" delivery of the systems, skills, and materials required for each step of the construction process

Production Building Techniques Have Standardized Construction Practices and Enabled Consolidation of the Homebuilding Industry:

The top 20% of Homebuilders Account for Over 78% of all of the Homes Built in the US Each Year



Source: Calculated from U.S. Census Bureau, 1997 Economic Census--Construction Sector Special Study, Housing Start Statistics (January 2000).

Review of Residential Ventilation Design Options

↓

Packaged System ? | **Custom Design ?**

The Winner is:
"Packaged" System.
Simplest Approach.
No Site Assembly or Extra Construction Steps Required

↓

Simplifications Provided by This Approach:
-System Will Work Independently of Individual House Geometry
-System Does Not Require Case by Case Engineering Design

Packaged System

↓

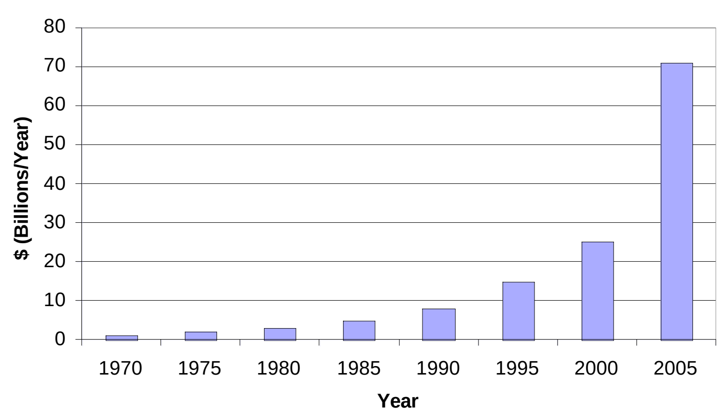
No Source Control? | **Source Control?**

Builders and Contractors Tend to Embrace Changes That:

- Reduce risks,
- Reduce costs,
- Reduce complaints,
- Reduce training requirements
- Increase the reliability of suppliers, materials and equipment, and
- Reduce planning steps or approvals

Risk Minimization is a Residential Design Requirement

US Catastrophic Insurance Losses



Packaged System With Source Control

Best Practice Recommendations:
- Local bath and kitchen exhaust
- Install radon mitigation in high risk areas
- Use closed combustion appliances
- Use low emission materials and furnishings
- Remove materials with known risks from consumer products used in homes
- Support research on risks of total exposures to air contaminants

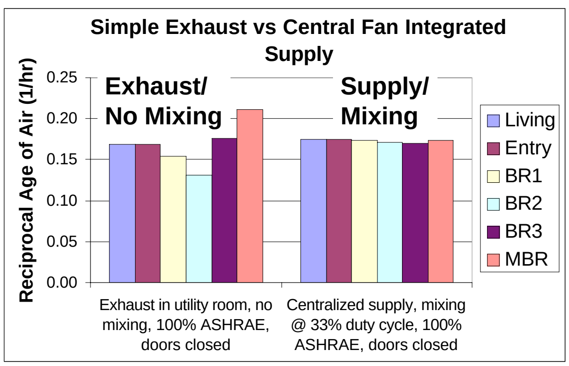
Benefits of This Approach:
- Overall risks are minimized; reliability is increased; simple, low cost, standard practice solutions are possible
- IAQ control decoupled from ventilation
- Ventilation rate determined primarily by odor and comfort control
- Easily controlled and understood by occupants
- IAQ sensors not required
- Air treatment not required

Packaged System With Source Control

Mixed System?

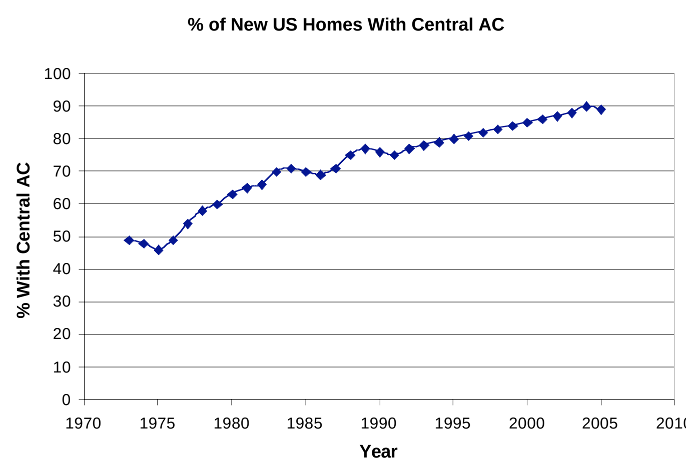
Unmixed System?

Evaluation of Distribution Performance



Evaluation of Uniformity of Distribution of Outside Air, NREL Test Method

US Homebuyers Have Already Made This Decision!



Packaged System With Source Control And Mixing

Best Practice Recommendations:
- Use low resistance duct designs, efficient air handlers, high EER AC, efficient furnaces
- Operate air handler on 20-30% duty cycle during periods with low sensible loads

Benefits of This Approach:
- Directly applicable to 90% of US market
- Solution meets requirements for use by production builders
- Provides uniform comfort and uniform ventilation air distribution

Final Reality Check: Compatible with Residential Requirements?

Level 1- Meets Minimum Residential Performance Requirements:
Technology meets minimum availability, reliability, O&M and durability requirements and provides high potential value to builders, contractors, and homeowners.

Reality Check: Compatible with Residential Requirements?

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Technology meets minimum availability, reliability, O&M and durability requirements and provides high potential value to builders, contractors, and homeowners.

Level 2- Can Be Integrated with the Residential Construction Process:
Best practice design details and construction sequencing are known and accepted by builders, contractors, and local code officials. Costs and benefits have been validated based on construction of one or more pilot homes.

Level 1- Meets Minimum Residential Performance Requirements:
Technology meets minimum availability, reliability, O&M and durability requirements and provides high potential value to builders, contractors, and homeowners.

Level 2- Can Be Integrated with the Residential Construction Process:
Best practice design details and construction sequencing are known and accepted by builders, contractors, and local code officials. Costs and benefits have been validated based on construction of one or more pilot homes.

Level 3- Can Be Built on a Production Basis:
Quality assurance requirements, quality control requirements, and training requirements are understood and individual responsibilities are accepted by suppliers, builders and subcontractors.

Conclusions:

Homes are not high end commercial, industrial, or laboratory buildings

- **Limited custom engineering**
- **Limited custom design**
- **Limited commissioning**
- **No sophisticated controls or sensors**
- **No operating engineers**
- **Limited maintenance**

Therefore, while there are certainly lots of possible ventilation approaches that could work,

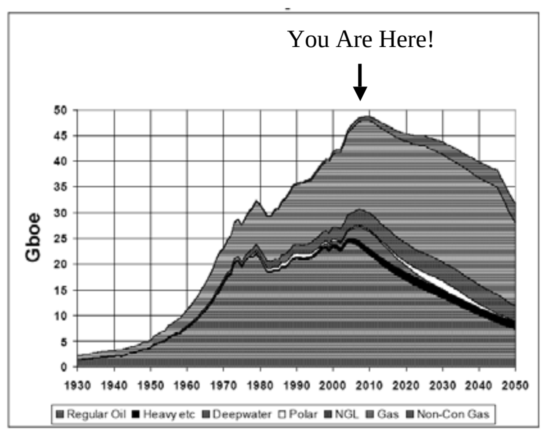
---

There is only one approach that is compatible with broad US market needs and also provides predictable, uniform performance that is independent of individual home geometry:

Central exhaust or supply with mixing and best practice source control.**

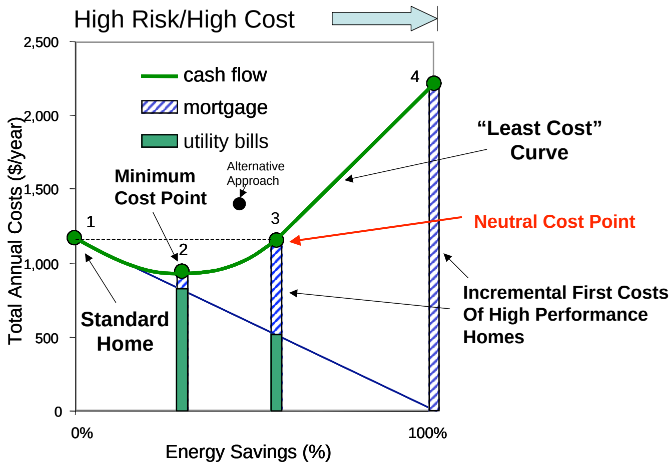
****Note. This problem can also be solved using more complicated approaches.**

Global Context: Resources are Constrained Efficient Resource Use is a Design Requirement



The Association for the Study of Peak Oil and Gas, October 2005 Newsletter, www.peakoil.ie

Overall Homeowner Costs vs. Benefits



Please see our website at:
www.buildingamerica.gov

Ren_Anderson@nrel.gov
NREL
1617 Cole Blvd
Golden, Colorado 80401

Field Measurements and Simulations

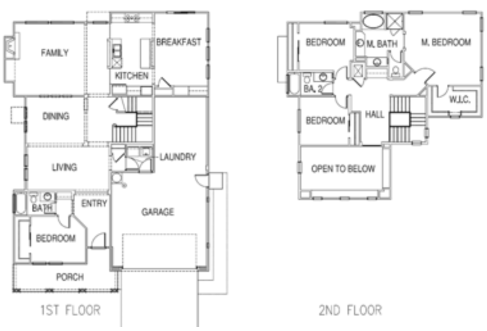
Ventilation Experts Meeting

Aaron Townsend

January 26, 2007

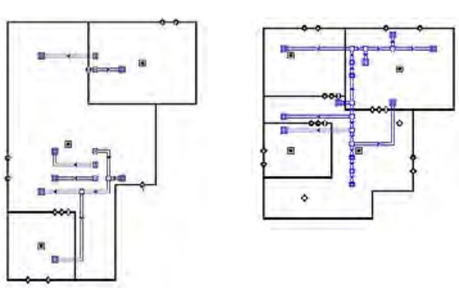
- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- ELA = 2.5 square inches per 100 square feet
- January 2006

Floor Plan



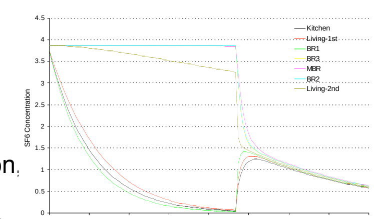
Zones

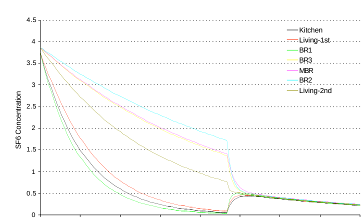
CONTAM Model



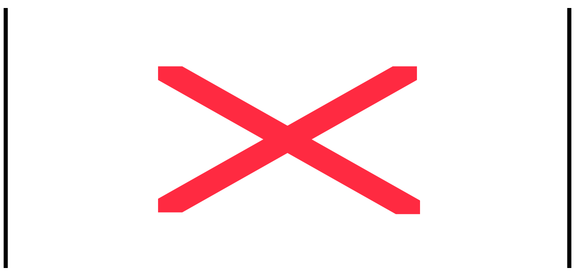
Results of the model very sensitive to certain inputs:

- Number, location, and size of leakage paths in each room
- Vertical elevation of leakage paths critical
- Indoor and outdoor temperatures

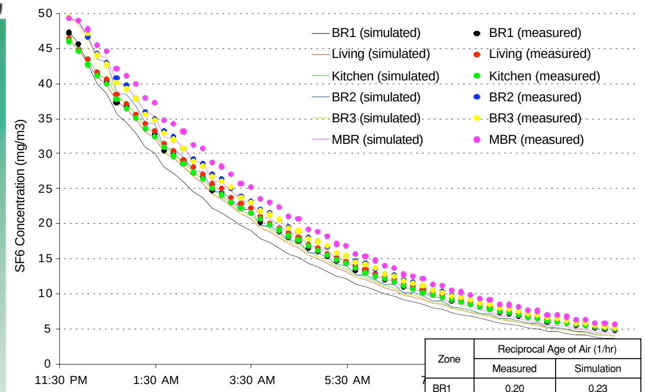




- Wind was neglected
  - Relatively low speed (0-4 mph)
  - Direction was not recorded
  - Uncertainty in wind pressure coefficient values and shielding by neighboring houses
- Results show good agreement with measured data

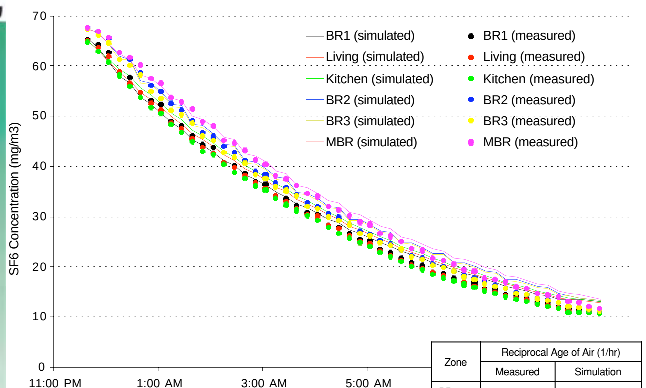


CFI, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open



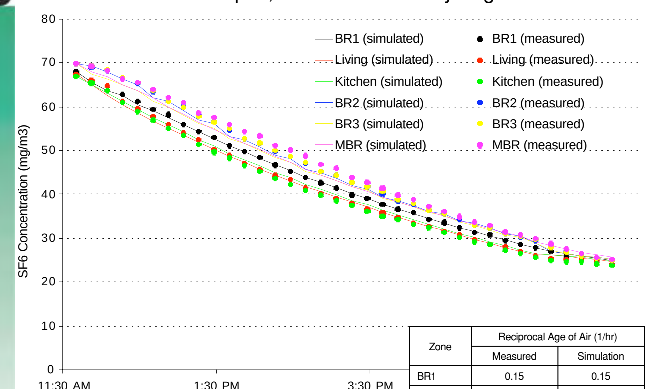
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.20	0.23
Living	0.19	0.22
Kitchen	0.20	0.21
BR2	0.20	0.22
BR3	0.20	0.22
MBR	0.19	0.21

CFI, 60% of 62.2 Rate, Doors Closed, Transfer Grills Closed



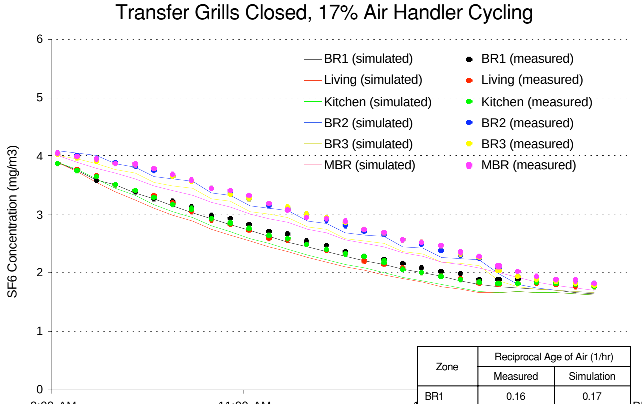
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.19	0.17
Living	0.19	0.17
Kitchen	0.19	0.17
BR2	0.19	0.17
BR3	0.19	0.17
MBR	0.18	0.16

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Air Handler Cycling



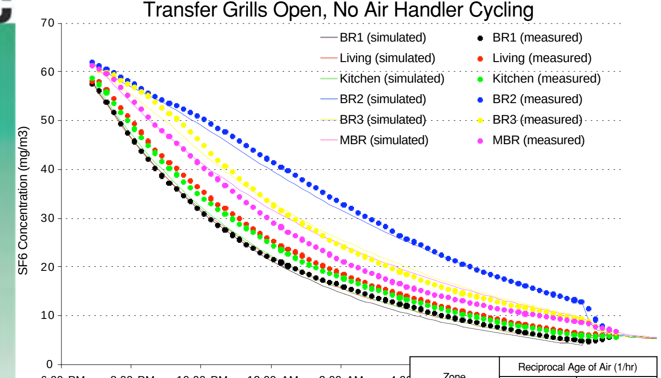
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.15	0.15
Living	0.16	0.15
Kitchen	0.16	0.15
BR2	0.15	0.15
BR3	0.15	0.15
MBR	0.14	0.15

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Closed, 17% Air Handler Cycling



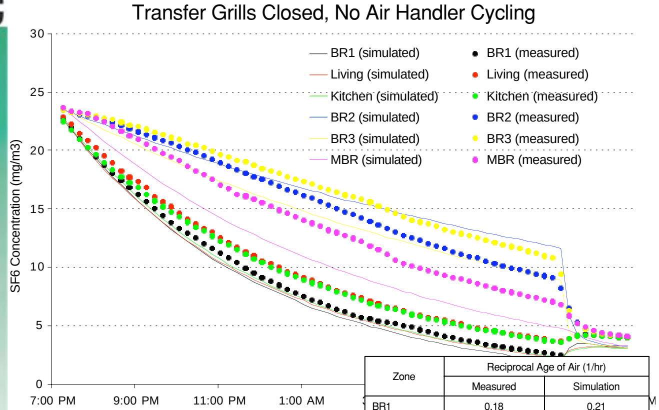
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.16	0.17
Living	0.17	0.19
Kitchen	0.17	0.19
BR2	0.13	0.14
BR3	0.13	0.14
MBR	0.13	0.15

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Air Handler Cycling



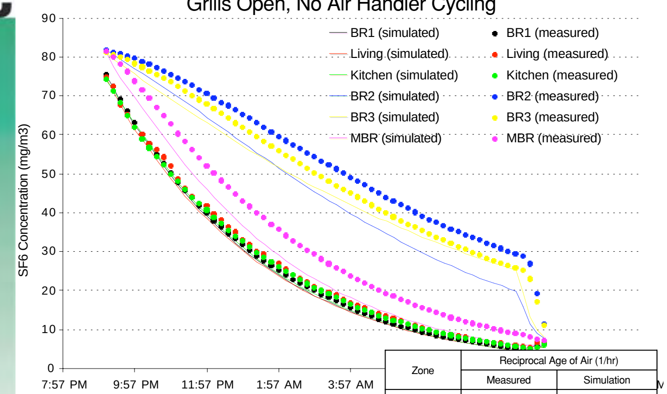
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.19
Living	0.16	0.18
Kitchen	0.16	0.18
BR2	0.11	0.11
BR3	0.13	0.13
MBR	0.14	0.13

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Closed, No Air Handler Cycling



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.21
Living	0.15	0.19
Kitchen	0.15	0.19
BR2	0.08	0.06
BR3	0.07	0.08
MBR	0.10	0.13

Master Bath Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Air Handler Cycling



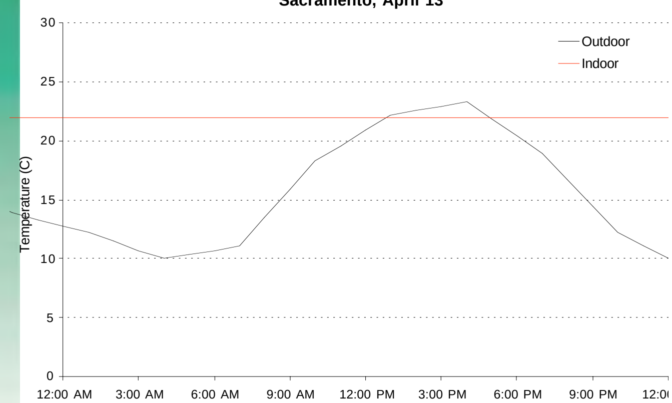
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.24	0.25
Living	0.22	0.25
Kitchen	0.23	0.24
BR2	0.09	0.12
BR3	0.10	0.10
MBR	0.19	0.23

Extension to Other Systems

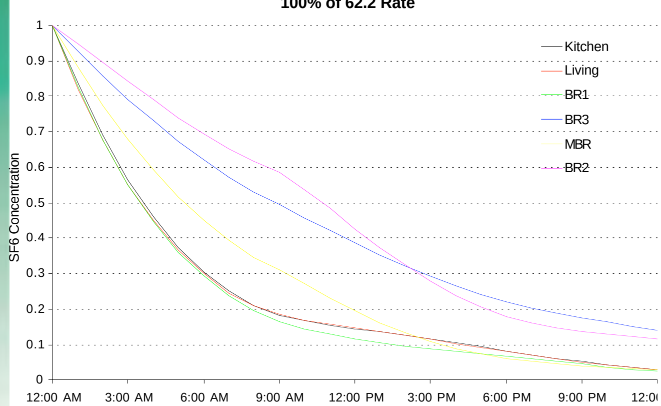
Six Systems Evaluated & Compared:

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

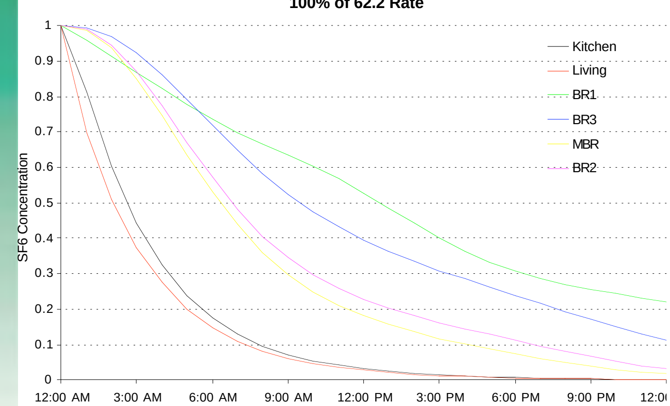
Indoor and Outdoor Temperature
Sacramento, April 13

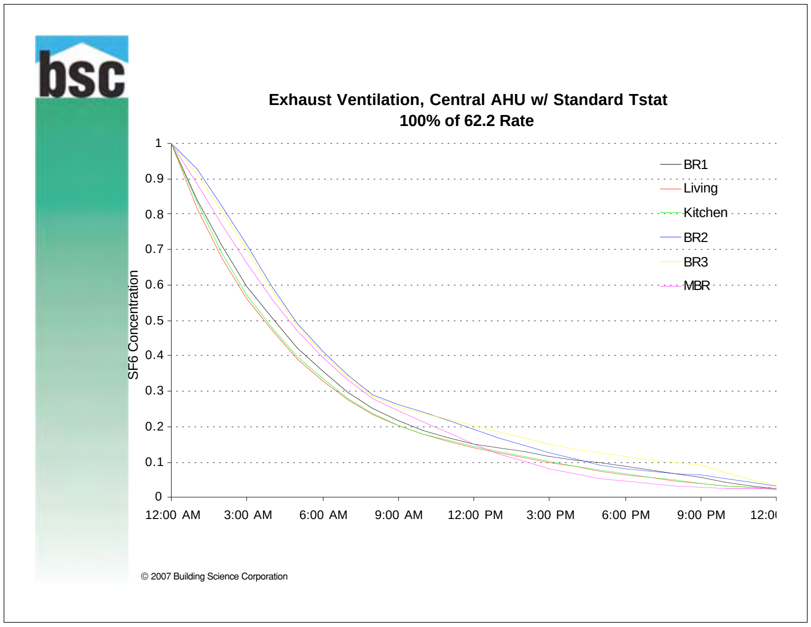


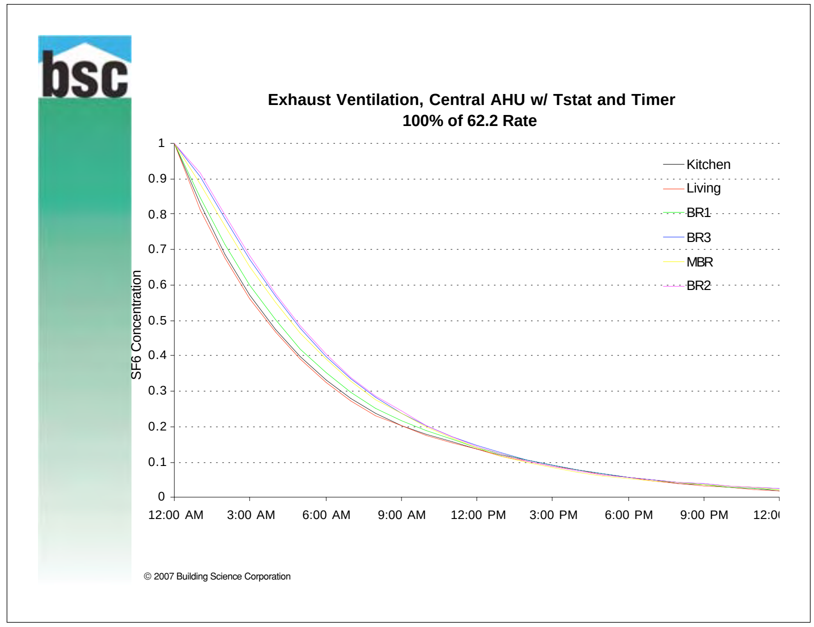
Exhaust Ventilation, No Central System
100% of 62.2 Rate

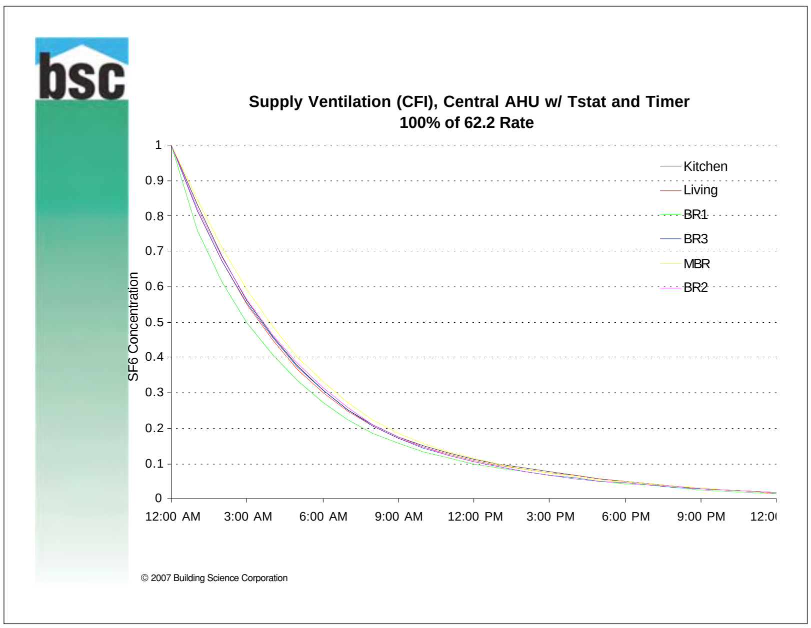


Supply Ventilation, No Central System
100% of 62.2 Rate




bsc
Exhaust Ventilation, Central AHU w/ Standard Tstat
100% of 62.2 Rate
SF6 Concentration
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
BR1
Living
Kitchen
BR2
BR3
MBR
© 2007 Building Science Corporation


bsc
Exhaust Ventilation, Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
Kitchen
Living
BR1
BR3
MBR
BR2
© 2007 Building Science Corporation


bsc
Supply Ventilation (CFI), Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
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6:00 PM
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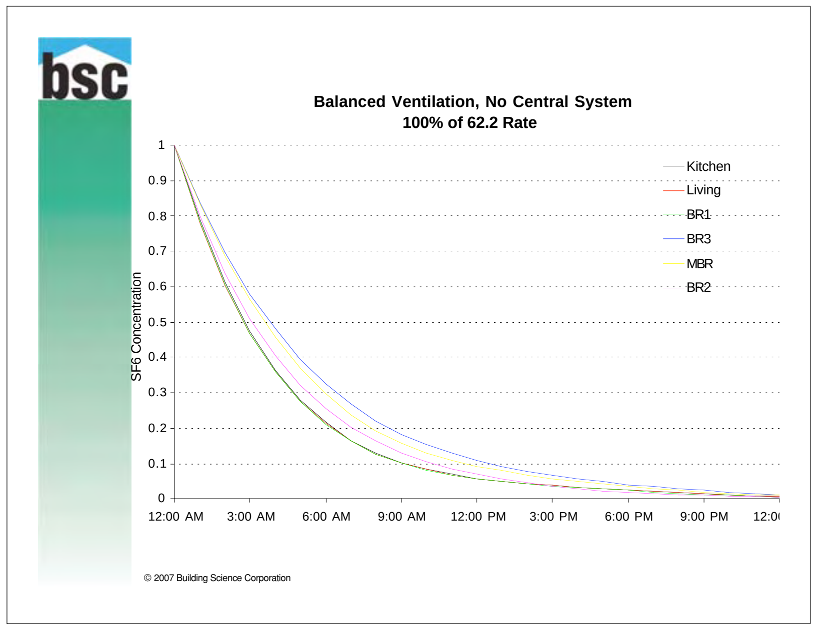
Kitchen
Living
BR1
BR3
MBR
BR2
© 2007 Building Science Corporation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Balanced Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
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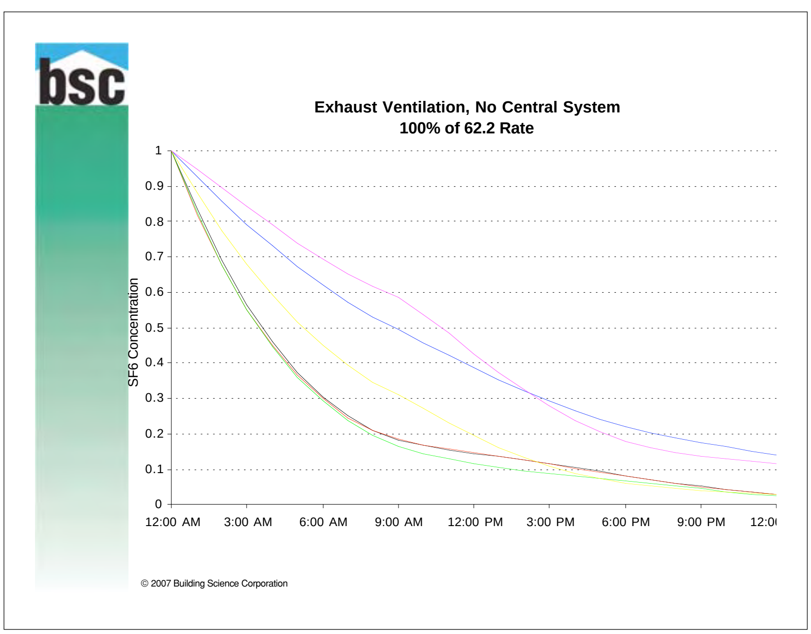
6:00 PM
9:00 PM
Kitchen
Living
BR1
BR3
MBR
BR2
© 2007 Building Science Corporation


bsc
Exhaust Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
0
0.1
0.2
0.3
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0.5
0.6
0.7
0.8
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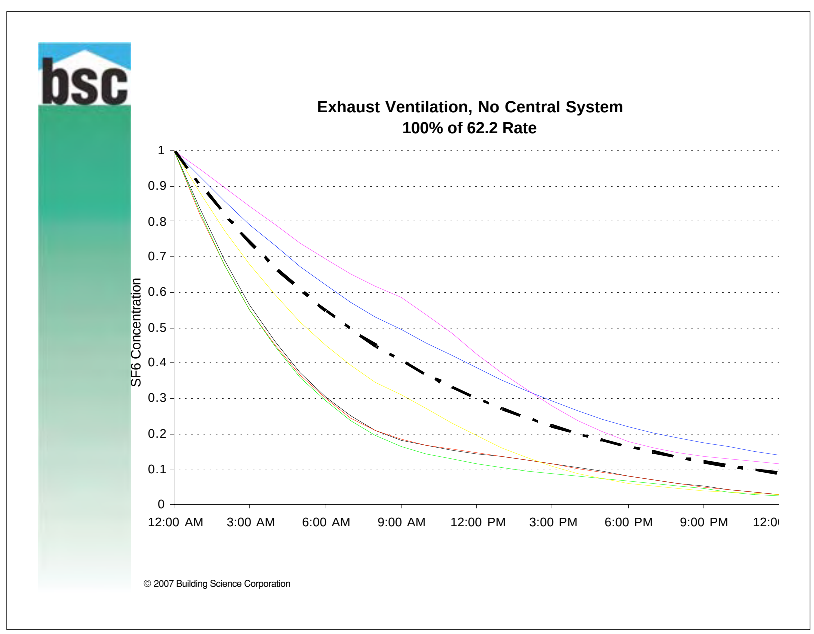
© 2007 Building Science Corporation


bsc
Exhaust Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
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0.1
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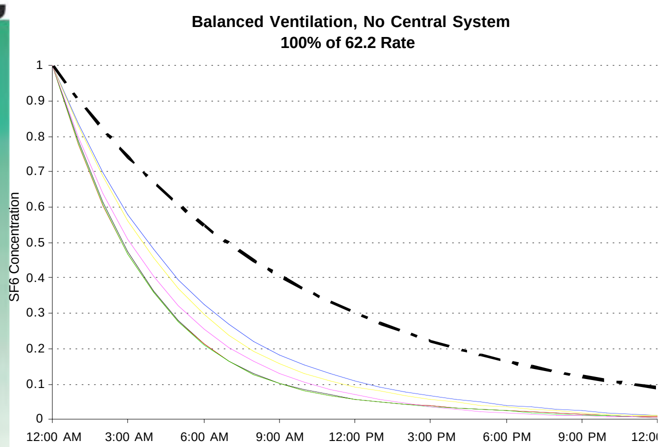
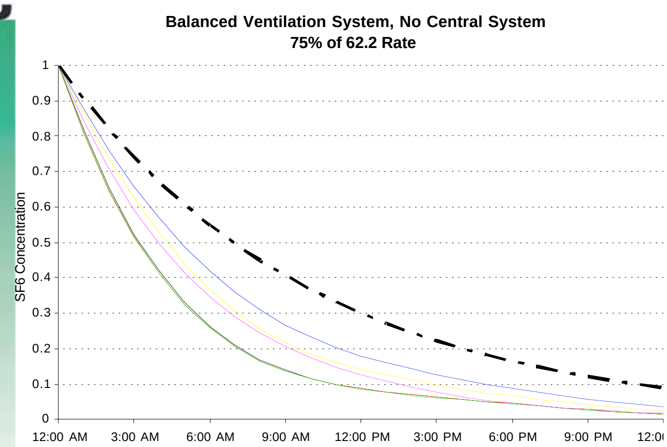
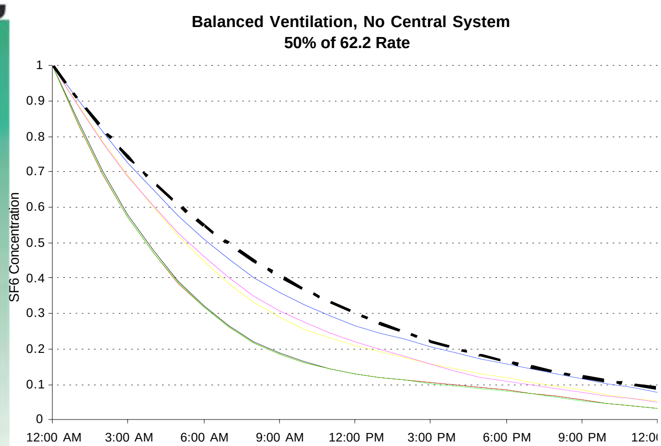
© 2007 Building Science Corporation







Coefficient of Distribution (C_D)

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

2.18.3. June 2007 Expert Meeting Summary Report

SYSTEMS ENGINEERING APPROACH TO DEVELOPMENT OF ADVANCED RESIDENTIAL BUILDINGS

13.B.3 Final Expert Meeting Summary: Ventilation Effectiveness In Residential Systems

RE: TASK ORDER NO. **KAAX-3-32443-13**
UNDER
TASK ORDERING AGREEMENT NO. **KAAX-3-32443-10**

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ARTISTIC HOMES	ANDERSEN WINDOWS
BURLINGAME RANCH, LLC/SHAW CONSTRUCTION	APPLIED DEHUMIDIFICATION, INC.
CHUCK MILLER CONSTRUCTION, INC.	CARDINAL GLASS CO.
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DAVID WEEKLEY HOMES	THE DOW CHEMICAL COMPANY
D.R. HORTON	CERTAINTEED
EBSCO	DUPONT NONWOVENS
FERRIER HOMES	FORTIFIBER
FIREMAN'S FUND	GEORGIA PACIFIC
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PHILLIPS BUILDERS LLC	TAMLYN
PULTE HOME CORPORATION / DEL WEBB	RESEARCH PRODUCTS CORPORATION/APRILAIRE

August 4, 2007

INTRODUCTION

The Building Science Consortium held two Expert Meetings on Ventilation Air Distribution Effectiveness in Residential Systems on 26 January 2007 at the Adam's Mark Hotel in Dallas, Texas, and on 21 June at the Renaissance Hotel in Long Beach, California. Both expert meetings were 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 32 in attendance. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by discussion with the expert audience.

The final agendas for these meetings are listed in Appendix A1 and A2.. A list of attendees for the first meeting is given in Appendix B.

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

26 January 2007
PRESENTATIONS

Speaker 1: Max Sherman, Lawrence Berkeley National Laboratory

Presenter bio: Max Sherman, Ph.D, is Group Leader of the Energy Performance of Buildings Group at LBNL. He is an ASHRAE Fellow and a long-time recognized expert in the field of indoor air.

Presentation Title: *Development of Metrics for Ventilation Distribution*

Presentation Summary:

In order to add ventilation air distribution to ASHRAE Standard 62.2 we need an appropriate metric to evaluate and compare different systems on the basis of acceptable air quality and health. The metric must be both useful and measurable. Evaluation and comparison could be by simulation or measurement or both. The metric should limit damage caused by contaminants of concern to which people are exposed over some time period. The damage may be a negative effect on comfort or health. Effects on comfort may include unpleasant odors and irritation which are covered by 62.2, and acoustics and thermal which are not covered by 62.2. Effects on health may include reduced physiological functioning, tissue damage, and increased susceptibility to disease.

To put this in perspective, whole-house ventilation does not address acute mortality or morbidity. For example, Standard 62.2 ventilation will not control for a release of phosgene gas. Standard 62.2 does intend to control for a reduction in life-expectancy, e.g. carcinogenesis, mutagenesis, and toxic loads. Standard 62.2 also intends to control for reduction in quality of life, e.g. hours of discomfort and minor disease.

An IAQ metric can focus on the peak concentration of a contaminant or the average concentration. For peak concentration the focus is on short-term dose and it is good for evaluating high exposure levels/acute effects and threshold-dominated contaminants. For average concentration the focus is on long-term dose and is good for cumulative exposures and steady exposures above thresholds. For the purposes of whole-house ventilation in the context of 62.2, the metric should be long-term average concentration, or dose. The contaminants of concern that we expect to control with whole-house ventilation must be above thresholds to be "of concern". Highly variable emission rates are not well controlled by whole-house ventilation and need source control by local exhaust.

Air distribution is only relevant when we are NOT working with a single well-mixed zone. A matrix formulation of the continuity equation allows for multiple zones where we can assume that each zone is individually well mixed. A local zonal matrix equation was described for a matrix of air flows, independent contaminant sources, and zonal concentrations. For psuedo-steady state conditions, the matrix inverse represents averages.

With dose as the IAQ metric, an activity variable is defined acknowledging that a person can only be in one zone at a time, a source fraction for each zone is defined since source strength may vary zonally, and since distribution impacts of different ventilation systems are relative, a relative dose versus perfect mixing is defined. The metric can be used to adjust the total ventilation rate by a ratio to increase or decrease it depending on the ventilation system.

The best and worst cases of the metric will be when the contaminant of concern is emitted in a single zone. The worst case, represented by the highest value in the matrix, represents the case where contaminants are generated in a single zone and someone stays in that same zone. The best case, represented by the lowest value in the matrix, represents the case where someone stays in the zone most isolated from the zone where contaminants are generated.

The range of metric options is as follows, with example ratios that would increase the ventilation flow rate to show equivalent performance to perfect mixing:

1. Evenly distributed sources and activities (ratio=1.06). In this case, the effect of ventilation air distribution would be minimal because there is no concentrated contaminant generation and people keep moving around all the time, so their exposure is smoothed or averaged. This would not represent sleeping in the same room overnight, for example.
2. Evenly distributed sources, but someone stays in the worst zone (1.26), such as sleeping in the least ventilated zone overnight.
3. If we have no clue on activity patterns or source distributions, we can measure the “distance” from perfect mixing using RMS deviation (1.80).
4. The worst ventilated zone is also where the highest source generation is and someone stays there (2.63). While this is certainly possible, this may be too extreme to be appropriate for a minimum standard.

Unless you can measure the metric it will be worthless. Direct field measurement can give the response in actual constructed configurations. This can only be done with tracer gas. Simulations are more practical and allow parametrics, but they must be verified by direct measurement to be believable.

A simplified or complete characterization tracer gas measurement method can be used. The simplified method requires that a reference source pattern and a reference activity pattern be established for a metric of choice (for example 1 through 4 above). The complete characterization method measures all flows to and from each zone. That can be used to compare different metrics, verify simulations, and derive a simplified approach.

Three measurement approaches are as follows:

1. Time Series, Single-tracer, Non-steady State: A single tracer gas is injected and uniformly mixed throughout all zones, then the time series tracer gas decay data are fit over the changing conditions to solve the differential equation.
2. Series, Single-tracer, Steady-state Tests: Multiple steady-state (constant injection) tests are done with a single tracer gas, in multiple zones, but only in one zone at a time. A single tracer is injected in a single zone and the response is measured in all zones.
3. Parallel, Multi-tracer, Steady-state Tests: Simultaneous steady-state tests are conducted with multiple tracer gases. A different tracer is injected into each zone simultaneously and the responses of all tracers are measured in all zones.

The Multi-Tracer Monitoring System developed at LBNL uses the third approach. Measurement of possible metrics in real buildings for various real systems are being planned for this year. This will be a collaboration between LBNL and Building Science Corp, under Building America.

Post-presentation discussion:

What defines a zone? There is no definition. It could be based on area, door closure, air handler service, or other factors. General consensus was to start by defining a zone to be any room that can be closed off with a door (except bathrooms and laundry) and the common area of each floor level.

Are the coefficients (ratios) independent of building/room geometry and duct layout? Unknown.

Standard 62.2 assumed continuous ventilation fan operation with uniformly distributed sources and occupants in a single well-mixed zone. Door closure, intermittent ventilation fan operation, and intermittent mixing via central air handler operation will give different answers than are currently built into 62.2.

Will temperature difference between rooms and floors make a difference? Thermal buoyancy will matter, but building enclosure leakiness will matter more.

Speaker 2: Bjarne Olesen, International Center for Indoor Environment and Energy, Technical University of Denmark

Presenter bio: Bjarne Olesen, Ph.D., is Professor at the International Centre for Indoor Environment and Energy. He has more than 30 years experience from University and Industry in research on the impact of the indoor environment on people, energy performance of buildings, and HVAC-systems. He has obtain several ASHRAE awards including the Ralph Nevins Award (1982), Distinguished Service Award (1997), Fellow Award (2001), and Exceptional Service Award. He is active in several ASHRAE-CEN-ISO-DIN standard committees regarding indoor environment and energy performance of HVAC systems. He has published more than 250 papers including more than 40 in peer reviewed journals.

Presentation Title: *Exposure and Risk*

Presentation Summary:

The highest human exposure to air contaminants is in the indoor environment. People spend about 90% of the time indoors including work, transportation, and at home. Over 50% of their relative exposure to air in a normal lifetime is in the dwelling.

In developing regions 5,000 persons die per day due to poor indoor air quality (WHO). In several industrial countries 50% of school children are suffering from Asthma or Allergy. This number has doubled within the last 20 years. Trends for the prevalence of allergic rhinitis, asthma and eczema among male conscripts (17-20 years age) in Sweden have continually increased from 1952 to 1981 (Bråbäck et al., 2004).

A large study looked at the relationship between asthma and indoor air quality. There were 11,000 children studied from 200 single-family houses with children suffering from asthma and from 200 single-family houses with healthy children. Detailed chemical, physical, biological and medical measurements were made. It was found that the likelihood (odds ratio) of having at least two out of three symptoms (wheezing, rhinitis, eczema) went continually down as ventilation rate increased from 0.17 air changes per hour (ach) to 0.62 ach (Bornehag et al., 2003). Houses that had a detectible bad odor had the highest prevalence of asthma, indicating that a person's sense of smell can be a good detector of some indoor air conditions that are bad for them. It was previously thought that the prevalence of asthma was higher in western Europe than in eastern Europe, but it was found that the prevalence was about the same in both.

Water condensation on windows is often a sign of poor ventilation in dwellings. Observation of condensation on bedroom window panes increased the prevalence and odds ratio for rhinitis among children (DBH-study group). The prevalence of rhinitis increases with the presence of PVC materials and with floor dampness in dwellings. The prevalence of asthma, rhinitis, and eczema goes up with increased mold odor smelled at wall baseboards (Hägerhed-Engman et al., 2005). Good ventilation should at least eliminate condensation on windows and bad odors.

Allergies are increasing also. Up to 50% of children have or have had symptoms of allergic disease. In Sweden, this is more so in the north. In Europe, this is more so in the west. In the USA, this is more so among the poor. This is more so in countries that speak English (UK, New Zeeland, Australia). There is also a high prevalence in Peru. The role of indoor air in this is mostly unknown. There are essentially no studies in residential buildings that establish the background of pollutants without people activities.

Indoor chemistry can influence the kind and concentration of organic chemicals in indoor air. Ozone reacts readily with other chemicals and creates fine particles in the air. Reactions between ozone and limonene are especially important. Fortunately that reaction has a higher odor effect, making it easier to detect by smell. Primary ozone sources are: outdoor to indoor transport; photocopiers; laser printers; and ozone generators. Indoor levels of ozone are normally lower than outdoor, but there are large outdoor variations with time of day, day of week, and season.

Indoor chemistry is most likely to happen when:

- indoor ozone levels are elevated (oxidation)
- humidity is elevated (hydrolysis)
- temperatures are elevated
- ventilation rates are low (gas phase)
- terpene levels are high
- surfaces are "dirty"

A new desktop computer emits enough pollutant to equal three people. That diminishes over the first year. The flame retardant used on CRT monitors is the most offending. Flat panel monitors are much better. The presence of computers can have a large negative impact on the perception of indoor air quality in offices.

A study of the effect of air filtration on perceived air quality (based on smell) was conducted. Fiber or cloth media type filters were observed to lower a person's perception of air quality. As the particle concentration in the airstream went down after the filter, the percentage dissatisfied went up. In other words, the air smelled better before it went through the filter. The reason was determined to be that unreacted SVOC's sorbed on particles on the filter react with ozone and become oxidized SVOC's with higher odor detection. Air treated by photocatalytic (UV) air cleaners was perceived to be better if the chemical loading was low, but worse if the chemical loading was high.

When designing for ventilation flow rate, you need to decide whether you are designing for adapted occupants in a space or for unadapted visitors to the space. There can be a three times factor difference between the answers. There should be a people component and a building component to the ventilation rate. The building component is still being worked on for commercial buildings where there is more measured data and more consensus than there is for residential buildings. Classes of buildings were proposed as: very low polluted, low polluted, and non-polluted. The typical ventilation rate in dwellings in Denmark is 0.5 air changes per hour. It is important to get ventilation air to the sleeping rooms since they have the highest pollutant levels all night.

Speaker 3: Ren Anderson, National Renewable Energy Laboratory

<u>Presenter bio:</u> Ren Anderson, Ph.D, is Residential Section Leader at NREL. At NREL since 1983, he has been involved the development of advanced window coatings, building energy design tools, advanced desiccant cooling and heat recovery systems, BCHP (Building Cooling, Heating, and Power) systems, and residential ventilation systems. Ren is currently working on the development of least cost approaches to the design of zero energy homes and is providing training on sustainable construction techniques for reconstruction of homes in disaster areas.

<u>Presentation Title:</u> *Performance Requirements for Residential Ventilation Systems*

<u>Presentation Summary:</u>

The Building America approach is one of raising the bar through innovative technology. Market transformation is supported by research and development which leads codes and standards. The market impact is accelerated by industry partnerships and educational outreach.

Site builders currently account for nearly 90% of all new homes built in the U.S. 80% of the homes are built by 20% of the builders. Production builders are rapidly shifting to the use of standardized, pre-manufactured components to reduce onsite labor and speed the construction process.

When it comes to ventilation, packaged systems will win over custom designs. Packaged systems are the simplest approach, with no site assembly or extra construction steps required. The successful packaged system should work Independently of individual house geometry and not require case-by-case engineering design. Source control in combination with the packaged ventilation system is the best way to minimize risk, which is a residential design requirement. Builders and contractors tend to embrace changes that:

- Reduce risks,
- Reduce costs,
- Reduce complaints,
- Reduce training requirements
- Increase the reliability of suppliers, materials and equipment, and
- Reduce planning steps or approvals

Best Practice recommendations for the source control side are:

- Local bath and kitchen exhaust
- Install radon mitigation in high risk areas
- Use closed combustion appliances
- Use low emission materials and furnishings
- Remove materials with known risks from consumer products used in homes
- Support research on risks of total exposures to air contaminants

A primary benefit of this approach is that IAQ control decoupled from ventilation. Source control takes care of the IAQ health concerns and ventilation with mixing takes care of odor and comfort control. The whole-house ventilation rate can then be determined primarily by odor and comfort. With this approach, overall risks are minimized, reliability is increased, simple low-cost standard-practice solutions are possible, the system is easily controlled and understood by occupants, and IAQ sensors and air treatment are not required.

Using a previously presented tracer gas measurement and analysis approach to evaluate the uniformity of outside air distribution performance, the clear benefit of ventilation with central system mixing versus simple exhaust has been shown. It appears that the U.S. market has already figured that out – 90% of new U.S. homes have central heating and cooling systems.

Best Practice recommendations for the packaged ventilation system side are:

- Use low resistance duct designs, efficient air handlers, high EER AC, efficient furnaces
- Operate air handler on 20-30% duty cycle during periods with low loads

Primary benefits of this approach are that it is directly applicable to 90% of the U.S. market, it is a solution that meets requirements for wide use by production builders, and it provides uniform comfort at the same time that it provides uniform ventilation air distribution.

Post presentation discussion:

Why do people buy central air conditioning? Is it for the uniformity of air distribution or do the builders make that choice for them? Builders provide what people expect.

Higher Building America savings goals may lead toward getting away from central forced air systems.

What about running the fan on low speed all the time? That has a dramatic negative effect on moisture control in humid climates as the wet cooling coil is constantly dried off again after cooling cycles.

How do you size the outside air duct if the central air handler operates at different speeds? If necessary, that can be handled as it is in commercial buildings with a modulating damper and outside air duct pressure control.

Speaker 4: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Consulting. He holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University. His work focuses on all aspects of energy efficiency, building durability, and indoor air quality.

Presentation Title: *Field Measurements and Simulations*

Presentation Summary:

A CONTAM[1] airflow network model was developed and compared to measurements from testing a production Building America house in Sacramento in January 2006. The testing results had been presented in detail at the previous meeting in June 2006.

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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)

Results from the model were very sensitive to certain inputs, including: the number, location, and size of leakage paths in each room; the vertical elevation of leakage paths; and indoor and outdoor temperatures. Wind was neglected for this work, at this time, because wind speed was relatively low (0-4 mph) during the testing, the wind direction was not recorded, and there was considerable uncertainty in establishing wind pressure coefficient values and accounting for the impact of shielding by neighboring houses. Despite neglecting wind effects, the modeled results showed good agreement with measured data.

After establishing that the model could adequately represent the measured condition, the model was extended to evaluate other systems. Six systems were evaluated and compared:

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

The systems without a central duct system showed wide variation in ventilation air distribution between zones (each bedroom and the common area on each floor was defined as a zone). Adding a central duct system with the air handler controlled by a standard thermostat reduced the variation significantly. Adding a minimum runtime timer to make sure that the air handler operated one-third of each hour reduced the variation between zones to almost nothing.

Taking the first system (exhaust with no central duct system) as the reference system, and taking the average of the decays curves for the bedroom zones as the reference curve, all of the other systems were modeled parametrically to find the ventilation airflow rate that would give equivalent results compared to the reference curve. In this way, the relative ventilation air distribution performance of each system could be compared via a ratio of the subject ventilation system's ventilation rate at the point where it matched the reference curve to the ventilation flow rate of the reference system.

The distribution coefficients in Table 1 show the resulting relative performance of each system, with the third system (exhaust with a central duct system and standard thermostat) arbitrarily given a coefficient of 1.0.

Table 1. Coefficient of Distribution (C_{dist})

Exhaust ventilation, without central duct system	C_{dist}=1.25
Supply ventilation, without central duct system	C_{dist}=1.25
Exhaust ventilation, with central ducts, AHU controlled by standard thermostat	C_{dist}=1.0
Exhaust ventilation, with central ducts, AHU controlled by thermostat with timer	C_{dist}=0.75
Supply ventilation, with central ducts, AHU controlled by thermostat with timer	C_{dist}=0.75
Fully ducted balanced ventilation system, without central duct system	C_{dist}=0.50

GENERAL DISCUSSION

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

A wider range of boundaries needs to be considered. Generate a list, including:

- Provision for multiple fans, and multiple speeds
- Ducts not just in conditioned space, but not leaky ducts.
- Reconsider not neglecting wind (two people for and one against).
- Model people moving around the house for contaminant exposure.
- Basements should also be a zone

NIST can make tools available to run CONTAM in batch mode to make it easier to look at more options. NIST also has a suite of prepared CONTAM models that were designed to represent a range of the housing market.

Europeans ask questions about people first. North Americans consider the building first. Lowering the ventilation is increasing risk. However, with relatively few houses currently going in with any whole-house ventilation system at all, just getting them in at any level will by default raise ventilation rates.

It is too complex to estimate residential contaminant sources and occupant exposure. Look at systems that get more ventilation where people spend their time. One-half air change per hour is recommended but that is not needed in each space all the time, put it where needed.

Standard 62.2 is a ventilation standard, not an energy standard, so lowering ventilation rates to save energy is not a concern of 62.2. Yet, in practice, they are both combined. No ventilation systems go in without concern for the energy impact.

The metric should be average exposure over a year. It can't be annual average exposure. Who would accept living in a smelly house in Spring knowing that it would get better in Winter? The exposure metric is for health not odor. More ventilation can be worse for odor if there is high outdoor ozone – reactions with indoor chemicals.

If exposure is to be the metric, and we know that there is a large difference in exposure between interior doors closed and open, how do you decide which doors are open or closed, and when and for how long? Prescriptive compliance is what most people will want to use, but exposure as a metric requires a complex performance approach. Simply requiring distribution by mixing eliminates the unnecessary complexity.

What happens when the central system ducts become part of the contaminant source? Would mixing be a benefit in that case? Duct and coil maintenance is part of source control which should be a prerequisite to an effective ventilation strategy.

The impacts of infiltration and duct leakage should be broken apart from distribution effects. Need to do simulations to see whether we need to merge or separate ventilation and infiltration. Lumping them into common systems is where we are right now.

A task force on distribution efficiency should be convened to assemble a matrix of all the take backs and give backs. The outcome of that would likely require a revision of 62.2.

The Indoor Environment Research Program at NRC may be interested in following the LBNL testing protocol which could provide additional data (contact Morad Atif).

We need to consider giving credit for systems that tell people when the ventilation system is working or not. That is more important than distribution. Moving toxics around can be worse than leaving them alone.

A straw vote was taken on how to break up zones within a house. The vote was almost unanimous to consider each bedroom with the door closed as a zone, and at least one zone for the common area on each floor level, and a basement if applicable.

A straw vote was taken on whether to use annual average exposure or uniform distribution of outside air as the primary metric. The vote was split down the middle. Consensus was to do both since the exposure method would also provide the uniformity of air distribution information. The attendees were all invited to continue their valued participation by emailing any further comments and ideas to us. They were also asked to plan to attend another expert meeting on this topic on Friday morning before the ASHRAE 62.2 meetings in Long Beach in June 2007.

21 June 2007
PRESENTATIONS

Building America Program introduction by Terry Logee, U.S. Department of Energy

Speaker 1: Max Sherman and Iain Walker, Lawrence Berkeley National Laboratory

Presenter bio: Max Sherman, Ph.D, is Group Leader of the Energy Performance of Buildings Group at LBNL. He is an ASHRAE Fellow and a long-time recognized expert in the field of indoor air.

Iain Walker, Ph.D, is Scientist in the Energy Performance of Buildings Group at LBNL. His focus as a researcher is related to energy use, moisture issues, comfort, and health in buildings. He serves on a number of ASHRAE and ASTM committees.

Presentation Title: *Measurements of Multizone Air Distribution: What's Distribution got to do with it?*

Presentation Summary:

A review of perceived consensus from previous meetings is that we want to give air distribution systems appropriate "credit" towards ventilation rates, and that "Credit" is couched in terms of impact on longer-term exposure to contaminants (on the order of days at least).

A key question is, "What is the impact of different air distribution strategies on dose received by occupants?" The answer is not simple because we don't know many important parameters, such as: where the sources are in home; where the occupants are in the home; how internal doors are operated (which effectively breaks houses up into multiple zones); and, how much infiltration air leakage there is (higher infiltration diminishes the impact of mechanical air distribution).

A defined goal, and a defined strategy to meet it, is needed. Are we striving to achieve something in addition to minimizing exposure for health reasons? For example, you may want perfect mixing so that exposure to contaminants would be uniform, and lower on average, for all occupants. Or you may accept that some occupants will have higher exposure to contaminants so that other occupants can be perfectly isolated from those sources.

Distribution of sources can be: 1) spread equally in each zone, or equivalently, completely unknown; 2) weighted by zone volume, such as is the case when using "Age of Air" source distribution; 3) concentrated and depending on occupant location; and 4) concentrated and independent of occupant location.

In a similar way, distribution of occupants can be: 1) spread equally in each zone, or equivalently, completely unknown; 2) weighted by zone volume; 3) concentrated and independent of sources; and 4) concentrated and correlated to sources.

"Age-of-air" is a special case metric. Age-of-air can be measured more easily than what is involved with the LBNL Multi-Tracer Monitoring System (MTMS), but it has some limitations. While it provides a good estimate of how long air has been in the zone, it assumes sources are distributed by volume weighting, and is only applicable to metrics that are based on volume distribution of indoor sources. In other words, it assumes that each unit of air has the same contaminant source as every other unit of air. Age-of-air also rolls together ventilation rate and air distribution information such that it is not possible to know the independent impact of each.

LBNL research is taking two approaches. The first approach is as follows:

a) Develop potential norms that may represent typical contaminant sources and occupant activities;
b) Develop a Relative Exposure metric that evaluates how good or bad a particular system is, using a home that is a single well-mixed zone as the reference (assumption built into 62.2); and
c) Develop a Distribution Matrix that contains all the relevant information about air flows for finding the Relative Exposure.

The second approach is as follows:

a) Measure multi-zone air flows in real houses with systems that span a range of proposed distribution technologies, in both tight and leaky houses, with both open and closed interior doors;
b) Measure flows to and from all zones in real time; and
c) Use a distribution matrix to evaluate the measurements for a range of metrics (best to worst cases) using the theoretically perfectly mixed case as a reference.

Using the LBNL Multi-Tracer Monitoring System (MTMS) two houses were tested so far this year. One house had a very leaky building enclosure, and leaky ducts, and was tested in winter conditions near Lake Tahoe. The other house was had a tight building enclosure, and tight ducts, and was tested in mild spring conditions near Sacramento. All interzonal air flows were measured for an exhaust ventilation system and an intermittent central-fan-integrated supply ventilation system in each house. The ventilation systems were sized to meet 62.2 flow requirements. Multiple tests were run with a range of open and closed interior doors and mechanical air mixing strategies. Each test was run for 4 hours.

Three systems were analyzed using MTMS system. These systems were intended to bracket the range of ventilation air distribution impacts on long-term relative exposure, from most to least:

1. Simple single-point exhaust with no central system air handler operation. This involved a continuously operating exhaust fan in a single zone with no mechanical distribution at all, such as might be the case in a house with baseboard heating and no central cooling.
2. Central-fan-integrated supply (CFI) with a central system air handler that runs at a minimum programmed rate.
3. Single-point exhaust with continuous central air handler operation.

Based on the MTMS measurements, seven metric cases were analyzed using the distribution matrix approach. These cases were intended to bracket the range of possibility for ventilation air distribution impacts on long-term relative exposure. The exposures were calculated as typical for the whole year based on the flows measured in the 4 hour tests. The relative exposure ratios are ratios of the concentration in a zone to the concentration if it were all a single perfectly mixed zone. A relative exposure ratio of 1.0 signifies that you would have the same exposure as if it were a single, perfectly mixed zone. Ratios below 1.0 mean that it is better than single zone perfect mixing because of plug-flow displacement ventilation from a first to second floor. The metric cases analyzed, and their respective results for the tight house, were as follows:

1. Equal source in each zone and occupant spends equal time in each zone.
    a. Nicknamed “Everything and Everybody Everywhere”. Assumes equal contaminant generation in every zone the occupant moves around equally between zones. This case could also be said to assume random occupant movement that is uncorrelated to changes in source strengths in various zones.
    b. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 40% greater to match the long-term occupant exposure of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be over 2 times greater to match the long-term occupant exposure of the other systems.
2. Volume weighted sources and occupant spends equal time in each zone.
    a. Because the source strengths are weighted by zone volume, this case can be used for comparison to age-of-air results. This is equivalent to volume weighted

average age-of-air for a given total ventilation rate when occupants spend equal time in every zone.

   b. **Results:** If all interior doors are left open, then all systems perform about the same. If interior doors are closed, then the simple exhaust ventilation flow rate should be about 20% greater to match the long-term occupant exposure of the other systems.

3. Volume weighted sources and occupant stays in the least ventilated zone.
   a. Because of the volume weighted sources, this case meets the age-of-air assumptions. Assumes that an occupant spends all their time in the zone with the lowest age-of-air.
   b. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 10% greater to match the long-term occupant exposure of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be almost 2 times greater to match the long-term occupant exposure of the other systems.
4. Sources concentrated in the least ventilated zone and the occupant stays in that zone all the time (Worst Case)
   a. Nicknamed "I Stink". Assumes occupant is the direct or indirect generator of the contaminant and assumes occupant stays in the worst zone. This case may useful for evaluating a special limiting cases, such as home offices or in-law quarters, and can be useful for comparison to non-worst case metrics, but is probably too limiting for a minimum standard.
   b. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be over 2 times greater to match the long-term occupant exposure of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be almost 9 times greater to match the long-term occupant exposure of the other systems.
5. Sources are concentrated in a zone that is remote from the zone where the occupant stays, and the zone where the occupant stays is the least ventilated zone.
   a. Nicknamed "You Stink". Assumes that the contaminant of concern is concentrated in a different zone than the occupant is localized in. This would be applicable where the contaminant of concern is localized in a zone not frequented often by occupants.
   b. **Results:** Regardless of whether all interior doors are open or closed, the simple exhaust ventilation flow rate should be over 2 times greater to match the long-term occupant exposure of the other systems.

The metric of Cases 6 and 7 is not directly relative exposure, instead, it measures deviation (root-mean square) from a desired outcome. The deviation will always be greater than 1. Case 6 measures deviation from perfect mixing, while Case 7 measures deviation from perfect isolation.

6. "Perfection" Metric, where the contaminants are perfectly averaged.
   a. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 50% greater to match the deviation from perfect mixing of the other systems. If all interior doors are closed, then the simple exhaust ventilation flow rate should be 4 times greater to match the deviation from perfect mixing of the other systems.
7. "Isolation" Metric, where ventilation air is supplied to each zone and the zones don't communicate with each other.
   a. **Results:** If all interior doors are open, then the simple exhaust ventilation flow rate should be about 20% greater to match the deviation from perfect isolation of the other systems. If all interior doors are closed, then the deviation from perfect isolation is about the same for all systems.

While opening interior doors significantly reduces variation in relative exposure, it was found that, with interior doors closed, there is not much air flow through door undercuts and room-to-hall jump ducts or transfer grilles unless the central air handler operates. That result is consistent with age-of-air results previously presented by NREL and BSC.

Mechanical ventilation air distribution impacts are small in houses with high building enclosure leakage, because infiltration acts like additional ventilation, further diluting contaminant concentrations and reducing relative exposure.

Low variations in relative exposure occur when sources and occupants are uniformly distributed and when age-of-air is averaged. Large variations in relative exposure occur when sources and occupants are not uniformly distributed but are correlated. In other words, if people keep moving around the house, and contaminant sources are not concentrated, then mechanical ventilation air distribution makes only small improvements in relative exposure. However, if people spend significant amounts of time in a single place or if contaminant sources are concentrated, then mechanical ventilation distribution can have a large impact on relative exposure.

Speaker 2: Bob Hendron, National Renewable Energy Laboratory

Presenter bio: Bob Hendron, Senior Engineer, has been at the National Renewable Energy Laboratory since 1999, and currently supports the technical efforts for the U.S. Department of Energy's Building America program. Building America works in partnership with the residential building industry to develop and implement innovative building processes and technologies that save homeowners millions of dollars in energy costs. NREL serves as Field Manager for the program, oversees the work of five Building America teams, provides R&D and field test support, and plays a national leadership role in bioclimatic design for residential buildings. Bob's efforts have been focused on performance analysis and field testing of advanced energy systems in new and existing homes.

Presentation Title: *Procedure for Evaluating Outside Air Distribution Using a Single-Tracer Gas, and Results from Three New Test Sites*

Presentation Summary:

The NREL team acknowledges the participation of several Building America teams in this work: BSC, CARB, IBACOS, and BAIHP.

Objectives of this work are to develop a practical field test procedure to quantitatively compare the uniformity of outside air distribution for alternate mechanical ventilation schemes, and to add the procedure to NREL's standard package of short-term field tests for Building America houses. The test would be repeated in several homes in various climates to evaluate its applicability to relevant ASHRAE Standards (129 and 62.2)

Building America/NREL is trying to work out a test procedure to apply to tight houses that is as simple as possible but accurate enough to show the meaningful differences between ventilation air distribution of different spaces. We want to evaluate the house itself because that is all a builder can control. We are not trying to determine contaminant exposure because that is unknowable (i.e. where the contaminants will be generated at what level and where the people will be at any given time).

Local mean age of air, which is equal to the average length of time air molecules at a specific location have resided within a test space, is the primary result. The performance metric is an Effective Ventilation Rate (EVR). The EVR was defined by the NREL team as the reciprocal of the local mean age-of-air in a well-mixed zone, which is equal to the ACH for the limiting case when the whole house is a single, well-mixed zone. It quantifies the average rate at which outside air reaches each zone during the test period, regardless of the path taken, including both ventilation and infiltration. What the EVR does not tell us is the amount of air provided to each zone by ventilation compared to infiltration, the inter-zonal airflow rates, the length of time air molecules have been in each zone, and occupant contaminant exposure.

The EVR test procedure includes the following steps:

1. Thoroughly mix air and SF_6 tracer gas throughout the test space
2. Turn off whole-house mixing fans but continue mixing within each individual zone
3. Establish ventilation system operating conditions of interest
4. Monitor decay rate in each zone
5. Run test until slowest decay reaches <20% of initial concentration (~1.5 air changes)
6. Re-mix entire test space
7. Calculate average ACH for whole house
8. Examine decay curves to determine if conditions sufficiently reached steady state
9. Calculate local age-of-air and EVR for each zone

Some cautions for applying the EVR test method are that: weather conditions must be stable and/or the infiltration rate must be very small, the whole-house must be initially very well-mixed, the test must be run until all zones are in the exponential decay regime (if the zone decay curves are observed to rise and fall, or flatten out, or cross over each other, then exponential decay is not reached).

The RDI house was tested with two exhaust fans as the whole-house ventilation system, and was tested with and without a 4 in^2 window opening in each of the two secondary bedrooms. Natural infiltration was also measured and was found to be very low (<0.05 ach) and relatively even between zones. With the exhaust fans on, and interior doors closed, there was a wide variation in EVR (over 100%) between the two secondary bedrooms and the living room and master bedroom zones. Very little variation existed if interior doors were kept open. The secondary bedrooms had the lowest EVR without any window opening, but had the highest EVR with a 4 in^2 window opening (a 32 inch wide window opened 1/8th inch).

The 2-story Fort Wayne house was tested with exhaust, single-point supply, and central-fan-integrated supply ventilation. The kitchen and dining zones always had the highest EVR. The inter-zonal variation in EVR was not large for any of the systems tested, except for the reduced flow rate exhaust test.

The Burlingame 2-story test house (attached on one side to an adjoining dwelling unit) was tested with a Heat Recovery Ventilator (HRV) and a bathroom exhaust fan. The HRV supplied ventilation air to the bedrooms and exhausted from one bathroom. The exhaust fan was located in the second bathroom. EVR varied widely in all tests with bedroom doors closed, and varied significantly even with bedroom doors open. The master bedroom had the highest ERV except in the Bath 2 exhaust test.

The following conclusions were drawn from all of the EVR testing thus far:

- Opening doors tends to provide good mixing regardless of ventilation type
- Central fan operation at duty cycles as low as 17% provides good mixing regardless of ventilation type even with doors closed
- Central fan integrated supply ventilation results in much better mixing of outside air than single-point exhaust ventilation
- Small window openings (4 in^2) greatly increase the outside air provided to bedrooms for point exhaust ventilation
- By design, an HRV supplying ventilation air to bedrooms does not necessarily result in uniform mixing, but ensures that key areas of the house (bedrooms) are not under-ventilated

EVR measurement is one method to quantify uniformity of air distribution for alternative ventilation systems and operating conditions in a field test setting. EVR results may be useful for developing air distribution correction factors for ASHRAE 62.2.

Speaker 3: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Consulting. He holds a bachelor's degree in mechanical engineering from the University of Texas and a master's degree in mechanical engineering from Stanford University. His work focuses on all aspects of energy efficiency, building durability, and indoor air quality.

Presentation Title: *Results of multi-zone, multi-city CONTAM modeling*

Presentation Summary:

CONTAM modeling was conducted to determine annual average contaminant exposure for different ventilation rates, ventilation systems, and air handler unit (AHU) operation schedules. The ventilation systems modeled were:

- single-point exhaust with and without AHU operation
- single-point supply with and without AHU operation
- central-fan-integrated supply with AHU operation
- balanced ventilation with and without AHU operation

In review, previous testing in two Sacramento, CA houses showed the following conclusions:

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance but the effect is not predictable
- Central-fan-integrated supply ventilation with 33% air handler operation and one-third the ASHRAE Standard 62.2 ventilation rate, gave a uniform Effective Ventilation Rate (EVR) throughout the house that exceeded the EVR of the least ventilated rooms using single-point exhaust providing 100% of the 62.2 ventilation rate.

Computer modeling was used to replicate field testing (tune the model) and to predict performance of systems not tested in the field. The tuned model was then applied to other systems not tested. Conclusions were as follows:

1. Ventilation systems do not perform equally just because they have equal nominal airflow
2. Airflow requirements could be adjusted based on performance of each system
3. Further simulations are needed to predict year-round performance to help distribution coefficients that would modify the required 62.2 airflow

The current modeling effort is focused on expand the previous modeling from 1 day in 1 house in 1 climate to a full-year with various house characteristics (leakage, mechanical systems, etc) and different climates. The methodology of simulations changed from decay to contaminant exposure. Uniform generation of pollutant within house was modeled. An assumed occupancy schedule was created that assumed people were home on weekends and at night, and were at work or school during weekdays. Average exposures were calculated on a 3-hr, 8-hr, and annual basis.

A description of the modeling assumptions is as follows:

1. Weather

    a. Temperature: outdoor temperature from hourly TMY2 data, indoor temperature constant at 22 C
    b. Wind: speed and direction from hourly TMY2 data, wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings
2. HVAC equipment
    a. Heating and cooling system sizing per Manual J for each climate
    b. Duty cycle each hour based on the outdoor temperature and the design temperature for the climate, maximum 80% runtime at design conditions, heating balance point = 65 F, cooling balance point = 75 F, two cycles per hour, cycle time rounded to nearest 5 minute increment to match the simulation time step of 5 minutes
3. Building enclosure air leakage
    a. Distribution: leakage distribution per ASHRAE Fundamentals Chapter 27 with:
        i. Walls, windows, doors = 62%
        ii. Ceilings and non-operating exhaust vents = 23%
        iii. Ducts = 15%
        iv. Total leakage varied as follows:
            1. 1.5 ACH50 (R-2000)
            2. 3.5 ACH50 (Building America)
            3. 7 ACH50 (standard construction)
4. Pollutant generation
    a. Uniform generation of unique pollutant in each room
    b. Generation rate proportional to room square footage (1 mg/hr/sf)
    c. Pollutants unique, but assumed identical in analysis presented later
5. Occupant schedules (same schedule for each occupant)
    a. 10 PM to 7 AM in bedroom with door closed
    b. 7 AM to 9 AM in kitchen
    c. 9 AM to 12 PM in living room
    d. 12 PM to 1 PM in kitchen
    e. 1 PM to 6 PM in living room
    f. 6 PM to 10 PM in other bedrooms
    g. Bedroom doors open except during sleeping period 10 PM to 7 AM
6. Varied paramenters
    a. Climate: Minneapolis, Seattle, Phoenix
    b. Central air handler unit: not present, in conditioned space, outside of conditioned space
    c. AHU Schedule: standard thermostat, minimum runtime per hour (10 on/20 off)
    d. Duct Leakage: 6% of air handler flow, 12% of air handler flow
    e. Ventilation systems: single-point exhaust, single-point supply, dual-point balanced, fully-ducted balanced
    f. Ventilation Rate: percentage of current 62.2 rate 0%, 50%, 100%, 150%

Taking the fully ducted, balanced ventilation system as a performance reference to compare other systems to, what ratio of airflows do other systems need to provide equal yearly average exposure? Table 2 shows the resulting ventilation rate ratios as a range and approximate median.

Table 2. Ventilation rate ratios to show equivalent annual contaminant exposure with the fully ducted balance ventilation system taken as the reference

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

Post-presentation discussion:

Was there a programmed temperature difference between zones? There is concern about the model sensitivity when doors are open if there is no temperature difference between rooms (as there would be in reality). Yes, it was found that a 0.1 C temperature difference between bedrooms and the common area drove a significant amount of air mixing through the open door.

Over-sizing of furnace units should be considered by simulating more than Manual J sizing cases. RESNET standards, Energy Star standards, and a number of progressive building codes refer to correct sizing using Manual J. How many instances of bad design can we allow for and still get anything useful done?

The ASHRAE Standard 136 method of combining ventilation and air infiltration should be used. We need to separate out the effects of building leakage and duct leakage from ventilation. The current modeling may not be specific enough to those details, but it is hard to tell since they are combined. This modeling may be tailored to tight houses with tight ducts, which 62.2 does not force. While ventilation air distribution matters less in houses with leaky enclosures or leaky ducts, we should acknowledge that the future of construction is tight enclosures and tight ducts. Really leaky buildings don't need mechanical ventilation. The results of this testing and modeling provide us with enough information to get within at least 75% of the right answer on the ventilation air distribution issue. Over the next several years it may evolve somewhat, but in the meantime, we will be much farther ahead to acknowledge that not all ventilation systems perform the same and apply distribution coefficients to 62.2.

Building America Expert Meeting

VENTILATION AIR DISTRIBUTION EFFECTS IN HOMES

Meeting Manager: Joseph Lstiburek, Building Science Corporation
Date/Time: **Friday, 26 January 2007, 8 am to 12 pm**
Breakfast refreshments begin at 7:30 am
Location: Dallas, TX, **Adam's Mark, Houston Ballroom A**
(ASHRAE Winter Meeting hotel)
Featured Speakers:

- Max Sherman, Lawrence Berkeley National Laboratory
- Bjarne Olesen, International Center for Indoor Environment and Energy, Denmark
- Ren Anderson, National Renewable Energy Laboratory
- Aaron Townsend, Building Science Corporation

Invitees:
Participants will be key people working in the indoor air quality field. 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:

- 7:30 am to 8:00 am, Breakfast refreshments
- 8:00 am to 8:15 am, Welcome and Meeting Introduction – Joseph Lstiburek

- Presentations
  - 8:15 to 8:45, (30 min) Max Sherman, "Development of Metrics for Ventilation Distribution"
  - 8:45 to 8:55, (10 min) Questions and discussion

  - 8:55 to 9:25, (30 min) Bjarne Olesen, "Exposure and Risk"
  - 9:25 to 9:35, (10 min) Questions and discussion

- o 9:35 to 9:45 (10 min) Break/refreshments

- o 9:45 to 10:15, (30 min) Ren Anderson, "Performance Requirements for Residential Ventilation Systems"

- o 10:15 to 10:25, (10 min) Questions and discussion

- o 10:25 to 10:55, (30 min) Aaron Townsend, "Field Measurements and Simulations"
- o 10:55 to 11:05, (10 min) Questions and discussion

- General discussion, 11:05 to 11:55 (50 min), Joseph Lstiburek-discussion moderator
    - o Whole-house ventilation air distribution is important to achieve reliable ventilation performance.
    - o What are the metrics that can be used to quantify the effective differences between systems?
    - o How can those metrics be applied to ASHRAE Standard 62.2?

- Wrap up, action items, and follow-up plan, 11:55 to 12:00

Key questions regarding this meeting:

Mechanical ventilation is becoming an increasingly larger portion of the total space conditioning load in high-performance buildings. Where contaminant sources are managed (for example, closed combustion) and ventilation air distribution is assured, reduced ventilation requirements may be acceptable and advantageous. Hot-humid climates may benefit the most.

1. What does the latest research tell us about ventilation effectiveness due to spatial air distribution?

2. Should not ventilation systems with better spatial distribution be credited for having more reliable whole-house performance relative to indoor air quality?

3. What are the best metrics to account for ventilation air distribution in determining appropriate minimum residential ventilation rates?

References/Supporting Documents

Hendron, R, Rudd, A., Anderson, R., Barley, D., Hancock, E., Townsend, A., 2006. "Field test of room-to-room uniformity of ventilation air distribution in two new houses." Submitted for publication to IAQ 2007, ASHRAE, December.

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Rudd, A., Lstiburek, J., 2000. “Measurement of ventilation and interzonal distribution in single-family homes.” ASHRAE Transactions 2000, MN-00-10-3, V. 106, Pt.2.

USDOE Building America Sponsored Expert Meeting on Ventilation Air Distribution

21 June 2007
Long Beach

Agenda

- BA program introduction by Terry Logee
- "Measurements of Multizone Air Distribution" by Dr. Max Sherman of Lawrence Berkeley National Laboratory
- "Procedure for Evaluating Outside Air Distribution Using a Single-Tracer Gas, and Results from Three New Test Sites" by Bob Hendron of the National Renewable Energy Laboratory
- "Results of multi-zone, multi-city CONTAM modeling" by Aaron Townsend of Building Science Consulting
- Dr. Joseph Lstiburek will lead discussions concerning the presentations and on the application of ventilation air distribution coefficients for use in the ASHRAE Standard 62.2.

Appendix B: 26 January 2007 Expert Meeting Attendee List (based on sign-in sheet)

#	Last name	First name	Company	Email
1	Anderson	Ren	NREL	ren_anderson@nrel.gov
2	Baxter	Van	ORNL	baxtervd@ornl.gov
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4	Brennan	Terry	Camroden Associates	terry@camroden.com
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6	Crawford	Roy	Trane	roy.crawford@trane.com
7	Drumheller	Craig	NAHB Research Center	cdrumheller@nahbrc.org
8	Emmerich	Steve	NIST	steven.emmerich@nist.gov
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11	Forest	Daniel	Venmar Ventilation	forestd@venmar.ca
12	Francisco	Paul	University of Illinois-UC	pwf@uiuc.edu
13	George	Marquam	Blu Spruce Construction	marquam.george@uas.alaska.edu
14	Grimsrud	David		grimsrud@earthlink.net
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18	Jackson	Mark	Lennox	mark.jackson@lennoxintl.com
19	Kosar	Douglas	University of Illinois-Chicago	dkosar@uic.edu
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27	Ryan	William	Univ of Illinois	wryan@uic.edu
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What's *Distribution* got to do with it?

Max Sherman
Iain Walker
LBL

June 22, 2007

Overview

- Objectives for today
- Background & Review
- Issues needing to be addressed
- LBL Approach
- Experiment and MTMS Data
- Analysis of Experimental Data

Objectives

- Approaches to understanding air distribution impacts
- Framing of key issues
- Review of case study of two houses
- Discussion of possible metrics
- Some consensus
- Maybe recommendations for SSPC 62.2

DON'T MAKE ME DO IT

- Why long-term exposure should be the norm for ventilation standards
- The types and range of contaminants of concern
- Matrix definitions of air flows and the continuity equation
- Derivation of multizone age of air

Review of Consensus

- Want to give air distribution systems appropriate "credit" towards ventilation rates.
- "Credit" is couched in terms of impact on longer-term exposure to contaminants
  - Days/weeks/months not minutes/hours
- Many contaminants of concern
  - Not always known, but of known classes

Measurement Review

- Need system of providing credit that does not require complex measurements
  - No tracer gas techniques for user
- Need accurate R&D to determine appropriate values for standard
  - Tracer gas techniques for researchers
- Simplified techniques may work
  - If they measure the right thing

KEY QUESTION

What is impact of different air distribution strategies on dose received by occupants?

- Not that simple because we don't know…
  - Where sources are in home
  - Where occupants are in home
  - How internal doors are operated
  - How much leakage there is

CONTINUITY EQUATION

- Zonal Description
  - Matrix of flows
  - Independent sources
  - Zonal concentrations

$$\underline{\underline{V}} \cdot \dot{\underline{C}} + \underline{\underline{Q}}\,\underline{C} = \underline{S}$$

- Psuedo-Steady State
  - Matrix inverse
  - Represents averages

$$\underline{C} = \underline{\underline{Q}}^{-1} \cdot \underline{S}$$

DISTRIBUTION MATRIX

- For N zones: N rows & N columns
- Sum of all entries gives single zone value
- Distribution Matrix contains normalized information

$$Q_o \equiv \sum_{i,j} Q_{ij}$$

$$\underline{\underline{D}} = Q_o \underline{\underline{Q}}^{-1}$$

Need to Define Strategy

- Are we striving to achieve something in addition to minimizing exposure:
  - Perfect mixing or perfect isolation?
  - Air delivery or pollutant removal?
  - Accuracy or robustness?
- Base Case: Where are we starting from?
  - i.e. for 62.2: What do we currently assume

LBL Research Approach 1

- Develop potential norms and metrics
  - Reviewed last time and will do more later
- Relative Exposure metric evaluates how good or bad a particular system is
  - Reference is single zone home
- Distribution Matrix contains all relevant information about air flows for finding RE

LBL Research Approach 2

- Measure multizone air flows in real houses
  - Span range of proposed distribution technologies
  - Both tight and leaky houses
  - Open & closed internal doors
  - Flows to/from all zones in real time
- Use measurements with metrics to find out what it all means

Measurements

IAIN WALKER

Field Measurements

- Tested two houses: one leaky, one tight
- Leaky house had leaky ducts (40%), tight house had tight ducts (<6%)
- Leaky in winter, tight in spring (no ΔT)
- Multi-Tracer Multi-Sample (MTMS) system for interzonal air flows
- Exhaust and intermittent Central Fan Integrated Supply sized to meet 62.2

Test Summary – Tahoe Leaky

CFIS operates 10 minutes out of every 30

- Furnace Fan Auto
  - Natural Infiltration, open doors
  - Natural Infiltration, closed doors
  - Exhaust, open doors
  - Exhaust, closed doors
  - CFIS, open doors
  - CFIS, closed doors
  - Ex + CFIS, open doors
  - Ex + CFIS, closed doors
- Co-Heat
  - Natural Infiltration, open doors
  - Natural Infiltration, closed doors
  - *Exhaust, open doors*
  - *Exhaust, closed doors*
  - *Exhaust + continuous furnace fan, open doors*
  - *Exhaust + continuous furnace fan, closed doors*
  - *CFIS, open doors*
  - *CFIS, closed doors*
  - Alternate Exhaust, open doors
  - Alternate Exhaust, closed doors

Test Summary – Sparks Tight

No heating or cooling central fan operation
No Co-heating
CFIS operates 15 minutes out of every 30

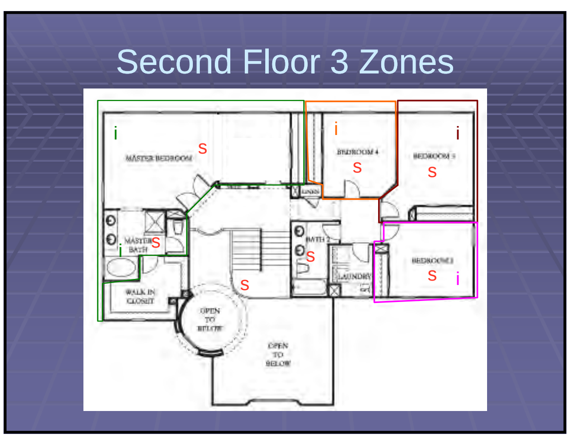
- Natural Infiltration, doors open
- Natural Infiltration, doors closed
- *Exhaust, doors open*
- *Exhaust, doors closed*
- *CFIS, doors closed*
- *CFIS, doors open*
- *Exhaust + continuous furnace fan, doors open*
- *Exhaust + continuous furnace fan, doors closed*
- CFIS + continuous furnace fan, doors open
- CFIS + continuous furnace fan, doors closed
- Exhaust + CFIS, doors closed

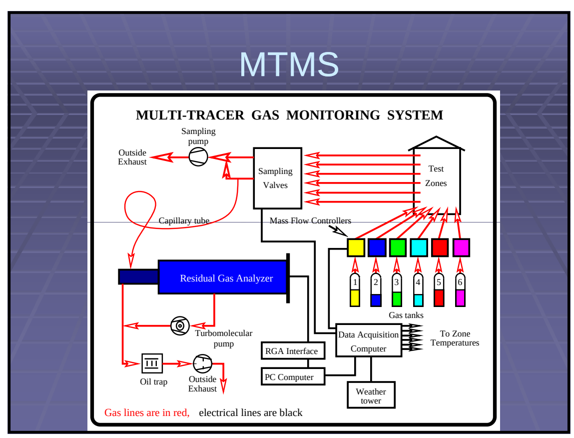

Ceiling fan used
to aid mixing
Leaky ceiling
Trees
Oscillating fan
Used for injection


Central Fan Integrated Supply at three times 62.2,
on 1/3 of the time - need big fixed flow


0.1 ACH w/o mech. vent.
0.2 ACH with mech. Vent
0.15 ACH added for 62.2
Q50 =1350 cfm


Ground floor all one zone
KITCHEN
NOOK
FAMILY ROOM
DINING ROOM
ENTRY
PORCH
LIVING ROOM
THREE CAR TANDEM GARAGE


Second Floor 3 Zones
MASTER BEDROOM
BEDROOM 4
MASTER BATH
WALK IN CLOSET
BATH 2
LAUNDRY
OPEN TO BELOW


MTMS
MULTI-TRACER GAS MONITORING SYSTEM
Sampling pump
Outside Exhaust
Sampling Valves
Test Zones
Capillary tube
Mass Flow Controllers
Residual Gas Analyzer
1
2
3
4
5
6
Gas tanks
Turbomolecular pump
Data Acquisition Computer
To Zone Temperatures
RGA Interface
PC Computer
Oil trap
Outside Exhaust
Weather tower
Gas lines are in red, electrical lines are black

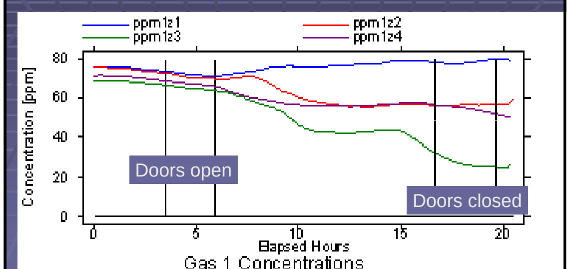
MTMS

- Inject different tracer in each zone at fixed rate
- Sample from several locations in each zone
- Each zone well mixed with fans

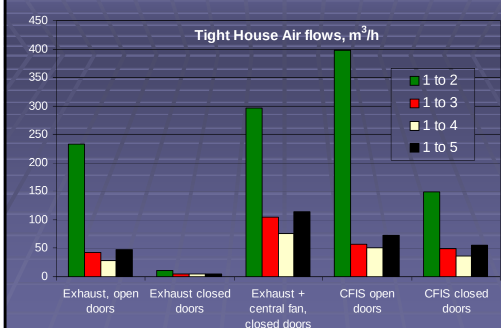
MTMS

- Residual Gas Analyzer
- Each zone sampled every 4 minutes
- Each experiment lasts several hours – to allow steady-state analysis

Exhaust only



Zone to zone air flows



Questions on Measurements?

Otherwise Max comes back

MEASUREMENTS TO METRICS AND NORMS

How do we use these measurements to evaluate air distribution systems

Distribution of Sources

- Spread Equally in Each Zone
  - Or, equivalently completely unknown
- Weighted by Zone Volume
  - "Age of Air" source distribution
- Concentrated
  - Dependent on occupant location
  - Independent of occupant location

Distribution of Occupants

- Spread Equally in Each Zone
  - Or, equivalently completely unknown
- Weighted by Zone Volume
- Concentrated
  - Independent of sources
  - Correlated (Anti-correlated) to source

Age of Air Metric

- Using "Age of Air" is a special case
  - Good estimate of how long air has been "inside"
- Assumes sources distributed by volume
  - Applicable to norms/metrics that are based on volume distribution of indoor sources
- Convolves rate and distribution information
  - Can be measured more easily than MTMS

Systems Analyzed

- Simple Exhaust: No blower operation
  - Continuously operating exhaust fan in a single zone; no mechanical distribution at all
- CFI: Normal operation
  - Blower runs always at programmed rate
- Exhaust with continuous blower operation
  - Upper limit of distribution impact

CASES ANALYZED

1. Fully distributed sources and activities
2. Volume weighted sources (Average)
3. Worst case "age of air" (NREL/BSC)
4. Worst case (worst case)
5. Remote contaminants (worst case)
6. "Perfection" Metric
7. "Isolation" Metric

Case 1: Everybody Everywhere

- Assume equal source in every zone
- Assume equal time by occupant in every zone
- Or assume random movement uncorrelated to changes in source strengths in various zones

Everybody Everywhere Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.06	1.64	1.16	1.36	1.13	1.18
1.37	2.43	1.01	1.10	1.03	1.05

Case 2: Volume Weighted

- Similar to Case 1
- Source strengths are weighted by volume
  - Therefore meets Age of Air assumptions
- Equal time in every zone
- Equivalent to volume weighted average age of air given total ventilation rate

Volume Weighted Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
0.95	1.14	1.01	1.04	1.00	0.99
1.05	1.20	1.00	1.00	1.00	0.99

Case 3: Worst Age of Air

- Assumes volume weighted sources
  - Meets Age of Air assumptions
- Assumes person spends all their time in the zone with the lowest age of air
- Cf. results presented by BSC last time

NREL/BSC Age of Air Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.05	1.59	1.06	1.18	1.06	1.05
1.09	1.83	1.01	1.03	1.01	1.02

Case 4: "I Stink"

- Assumes occupant is the direct or indirect generator of the contaminant
- Assumes occupant stays in worst zone
- Worst case, but may be useful for comparison
- Applicable e.g. home office, in-law, etc.

"I Stink" Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
3.25	10.85	2.96	7.22	3.14	5.19
4.25	24.80	1.94	2.83	1.88	2.21

Case 5: "You Stink"

- Assumes that the contaminant of concern is concentrated in a different zone than the occupant is localized in.
- Worst case choice of zones
- Applicable if contaminate is localized in zone not frequented often by occupants.

"You Stink" Relative Exposures

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.88	1.04	2.04	0.90	1.28	0.94
2.95	2.53	1.20	1.16	1.14	1.13

Cases 6 & 7: Not RE

- Metrics, but not directly relative exposure
- Measure (root-mean square) deviation from a desired outcome. Can not be better (i.e. metric never less than 1)
- Case 6: Measures deviation from perfect mixing.
- Case 7: Measures deviation from perfect isolation: (aka Greta Garbo case)

Deviation from Perfect Mixing Performance Metric

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.89	4.20	1.80	3.29	1.69	2.45
1.96	6.32	1.28	1.57	1.28	1.40

Greta Garbo Performance Metric

Simple Exhaust		CFI		Exhaust w/mixing	
open	closed	open	closed	open	closed
1.77	1.43	1.83	1.40	1.74	1.51
2.25	1.84	1.84	1.81	1.85	1.82

Simple Results: Sources

- Low variations when sources and occupants are distributed.
  - Averaging Age of Air gets rid of differences
- Big variations when source and occupants are correlated
- Cases 5 & 7 behave opposite to others
  - Mixing is “bad” for these approaches

Simple Results: Tightness

Infiltration acts like air distribution

- Leaky houses perform better when there is no mechanical air distribution
  - More so for cases 5 & 7
- Air leakage makes mechanical air distribution perform worse
  - Except cases 5 & 7

Best Systems: Tightness

	LEAKY	TIGHT
1	Exhaust (open)	Any mixing
2	Any open doors	Any mixing
3	Any mixing or open	Any mixing
4	Any open doors	Any mixing
5	Closed doors	Mixing
6	Open doors	Open doors & mixing
7	Closed doors	Closed doors or mixing

Air Distribution Results

- For leaky house with open interior doors, air handler operation does little
  - Benefit for closed door
    - Penalty for close doors for cases 5 & 7
- For tight houses air handler operation can improve mixing significantly
  - Whether that is good or bad depends on which case you care about

Simple Results: Open Doors

- Opening doors improves mixing
  - Good except in cases 5 & 7
- Impact big when sources are localized
- Impact big when no air distribution
  - No significant impact when air handler on
- Transfer grilles/jump ducts not the same as open doors.

Conclusions

- Mixing helps most cases
- Open doors are mixing aid
  - Especially in leaky house
- Relative performance of systems depends in detail on metric chosen
  - Range: 2% to 300%
  - But some generalizations are possible

What to do?

- **Option 1:** Ignore mixing credit/debit issues. Too complicated for a standard.
- **Option 2:** Agree on fixed metric and base case assumptions. Derive (and validate) credit/debits. Include in standard.
- **Option 3:** Use broad approach to eliminate "bad actors" through minimum requirements. No quantitative credit/debit.

DISCUSSION

Max's Metric Mantra:

Metrics must be meaningful and measurable

What is Acceptable IAQ?

- Won't discuss this quantitatively, but operationally is it
  - Limiting **damage**
  - Caused by **contaminants** of concern
  - To which people are exposed over some **time** period

Types of DAMAGE

- Comfort
  - Unpleasant Odors, Irritation *(covered by 62.2)*
  - Acoustics, lighting, thermal, etc. *(not covered)*
- Health
  - Reduced physiological functioning
  - Tissue damage
  - Increased susceptibility to disease

Contaminants of Concern

- Compounds and specifics: ***Various***
- Whole-house ventilation looks at what?
  - Acute Mortality/Morbidity: No
    - E.g. we don't control phosgene with 62.2
  - Reduction in life-expectancy: Yes
    - E.g. carcinogenesis, mutagenesis, toxic loads
  - Reduction in quality of life: Yes
    - E.g. hours of discomfort, minor disease etc.

Timed Exposure

- Delay in absorption of contaminant
  - Important for short-term exposure
- Body can repair/adapt sometimes; e.g.
  - 10 ppm CO for 400 hours: small impact
  - 400 ppm CO for 10 hours: death
- But not others; e.g.
  - Irreparable tissue damage
  - Risk increases during exposure

Damage Equation: $D \cdot (C/C_c)^n$

- Linear (n=1) for many cumulative risks
  - Most cancer, metals, stable (e.g. DDT)
- n=3 for Chlorine
  - Typical of oxidants, poisons
- n>>1 represents a threshold
  - Time above threshold is important
- Linear approximation good if little variation

IAQ METRICS

- Peak concentration of contaminant
  - Good for high exposure levels/acute effects
  - Good for threshold-dominated contaminants
  - Focus on short-term dose
- Average concentration (e.g. linearized)
  - Good for cumulative exposures
  - Good for steady exposures above thresholds
  - Focus on long-term dose

Average Concentration It is

- Highly variable emission rates
  - Not well controlled by continuous ventilation
  - Need source control (e.g. exhaust ventilation)
- Contaminants of concern
  - Must be above thresholds to be "of concern"
  - Are the ones we expect to control with whole-house ventilation
- Metric is then long-term average concentration

How Do We Get Concentration

- Depends on
  - Sources & sinks
  - Volumes
  - Ventilation & air transport
- Linked by Continuity Equation
- Need to proceed generically
  - No pollutant specifics (i.e. a tracer gas)
  - Ignore species-specific interactions

CONTINUITY EQUATION

- Locally Covariant Derivation
  - Good everywhere
  - Even near black holes

$$J_\mu \cdot \partial G = \Lambda$$

- Steady state, single zone expression:
  - S=emission rate (e.g. cfm)
  - Q= ventilation (e.g. cfm)

$$C_o = S/Q$$

Getting Back to Distribution

- Air distribution is only relevant when it is not a single well-mixed zone.
  - Can't get too crazy (e.g. CFD)
  - Need to relate it to the simple result
- We use a multizone continuity equation
  - But we can assume the zones are well mixed
  - Need matrix formulation of continuity equation

MATRIX EQUATION

- Zonal Description
  - Matrix of flows
  - Independent sources
  - Zonal concentrations

$$\underline{\underline{V}} \cdot \underline{\dot{C}} + \underline{\underline{Q}}\,\underline{C} = \underline{S}$$

- Psuedo-Steady State
  - Matrix inverse
  - Represents averages

$$\underline{C} = \underline{\underline{Q}}^{-1} \cdot \underline{S}$$

MATRIX NOTATION

- For N zones: N rows & N columns
- Sum of all entries gives single zone value
- Diagonal is total for zone
- Off-diagonal elements of Q matrix are (negative of) flow between zones

$$Q_o \equiv \sum_{i,j} Q_{ij}$$

Exposure not Concentration

- A person can only be in one zone at a time
  - So, we define an **a**ctivity variable.
- Source strength may vary zonally.
  - So, we define a **s**ource fraction for each zone
- Distribution impacts are relative
  - So, we define a relative dose v. perfect mixing

How Should We Use Metric

1. Evaluate Metric for distribution system of interest
2. Evaluate Metric for distribution in reference case (e.g. 62.2 default)
3. Adjust total rate by ratio to increase or decrease depending on system
   - Could be tabulated like in 62.1

RELATIVE DOSE METRIC

$$d = 1 + \frac{1}{N}\sqrt{\sum_{i \neq j} D_{ij}^2}$$

- *d* is relative dose
- **s** is fractional source strength
- **a** is fractional time spent in each zone

- **D** is Distribution Matrix

$$\underline{\underline{D}} = Q_o \underline{\underline{Q}}^{-1}$$

DISTRIBUTION MATRIX

- Couples emission in one zone to exposure in all other zones; e.g.
  - All entries the same (1) for fully mixed
  - Matrix diagonal for isolated zones
- ***Independent*** of sources, activities, etc
- So, we could base final metric on it
  - If we define activity/source distribution

3-Zone Example (PFT data)

- Q Matrix=>
  - m^3/hr
  - Q_o=726 m^3/hr

653	-291	0
-130	448	-206
-17	-23	292

- D Matrix =>
  - Dimensionless
  - D_o=9.54

1.30	0.88	0.62
0.43	1.97	1.39
0.11	0.21	2.63

Metric Choices

- Need to determine how to use the Distribution Matrix in a way that does not depend on knowing activity/sources.
- What is appropriate for a standard?
  - Best case?
  - Worst case?
  - Typical case?
    - What is that??

Extreme Metrics

- The best and worst cases of the metric will be when the contaminant of concern is emitted in a single zone
- Worst case: Highest value in matrix; e.g. someone generates contaminants and lives in same zone: 2.63 in example
- Best case: lowest value: e.g. live in most isolated room: 0.11 in example

Distributed Distribution

- Assume sources are fully dispersed and activity is spread between all zones

$$d = D_o/N^2$$

- d=1.06 in example
- Tends toward perfect mixing result because of source distribution and activity patterns

Inactivity Patterns

- Suppose sources were distributed but someone spent all their time in the worst zone
- Relative dose would then be from the row of Distribution Matrix with highest sum.
- From example
  - 0.93, 1.26, 0.98
  - RMS mean=1.07

Deviation from Perfection

- Suppose we have no clue on activity patterns or source distributions
- We can measure the "distance" from perfect mixing using RMS deviation

$$d = 1 + \frac{1}{N}\sqrt{\sum_{i,j}(D_{ij} - 1)^2}$$

- Not actually Relative Exposure

Deviation from Isolation

- Suppose we have no clue on activity patterns or source distributions
- We can measure the "distance" from non-mixing using RMS deviation

$$d = 1 + \frac{1}{N}\sqrt{\sum_{i\neq j} D_{ij}^2}$$

- Not actually Relative Exposure

HOW TO MAKE THE MEAUSURMENTS

The diagnostics necessary to measured air distribution effects

TWO TRACER APPROACHES

- Simplified for the Metric of Choice; e.g.
  - Inject tracer in reference source pattern
  - Sample in reference activity pattern
- Complete Characterization
  - Measure all flows to/from zones
  - Can be used to compare metrics
    - And derive simplified approach
  - Can be used to verify simulations

TRACER CONTINUITY

- Same Continuity equation, but
  - this time we know concentrations
  - and are looking to determine the flows
- Unfortunately, no direct solution
  - N^2 unknowns, but only N equations
  - Need to run under N different conditions

THREE APPROACHES

- Time Series in Non-steady State
  - Fit time series data over changing conditions (e.g. decay) to solve differential equation
- Simultaneous Multi-Tracer Tests
  - Use N tracer gases to run simultaneous tests (e.g. inject one in each zone)
- Series (Single-Tracer) Tests
  - N tests are done one at a time

TIME SERIES

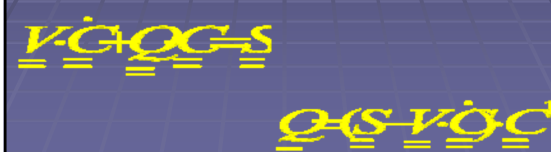
- Fit data to=>
- To find eigenvalues
- "A"s are relevant air change rates
  - N of the them; C_{ij} are their eigenvectors
  - Slowest is whole-building air change rate
  - Quickest determines uncertainty
- This approach never works in real buildings
  - Mixing issues obscure vital information
  - DON'T DO THIS AT HOME

MIXING KILLS

- In all real experiments mixing will obscure short-term information with noise
- Don't differentiate---INTEGRATE
- Even in single-zone situations, fitting decay data is inferior to integrating under the curve
- In multizone situations it is much worse
  - Alternative approaches are needed

MULTIPLE EXPERIMENTS

- Do N different experiments & integrate/average
  - inject in N independent ways
    - E.g. in 1 zone different zone each experiment
- Add to Matrix equation
  - Can be inverted now

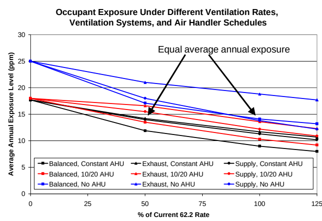


SERIES OR PARALLEL

- Series Option
  - Can be done with one tracer gas
  - Very sensitive to changes in air flows
- Parallel (MultiTracer) Option
  - Can accurately find average flow
  - Takes less time
  - LBL's MTMS uses this approach

DISCUSSION

Results of Multi-, Multi-, Multi-CONTAM Modeling



Aaron Townsend

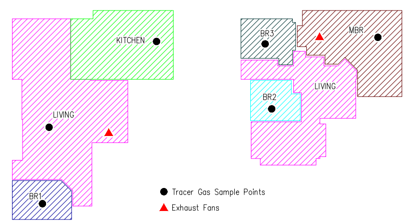
June 22, 2007

Sacramento Tracer Gas Testing January 2006

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- Supply and exhaust ventilation tested, with and without mixing via central air handler
- Each test 4-14 hours long
- Weather conditions slightly different during each test

Floor Plan - 2 Story House

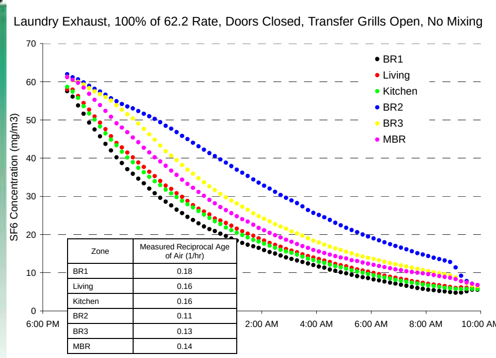
Zones – 2 Story House



- These were tracer gas decay tests—establish uniform concentration of tracer gas and then activate ventilation system to remove it.
- Reciprocal age-of-air can be calculated from decay curves (if weather conditions are sufficiently constant)

Example Results of Sacramento Tracer Gas Testing

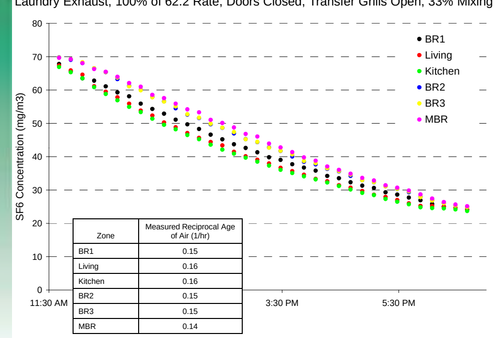
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.18
Living	0.16
Kitchen	0.16
BR2	0.11
BR3	0.13
MBR	0.14

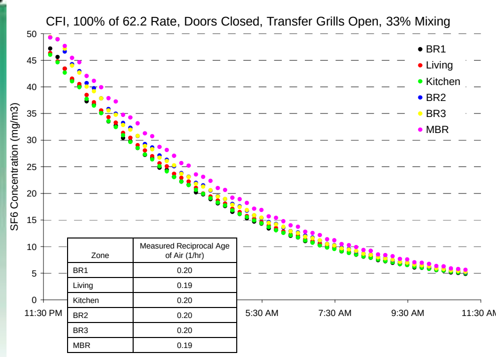
Example Results of Sacramento Tracer Gas Testing

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.15
Living	0.16
Kitchen	0.16
BR2	0.15
BR3	0.15
MBR	0.14

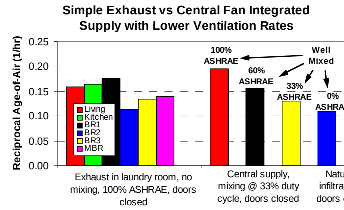
Example Results of Sacramento Tracer Gas Testing



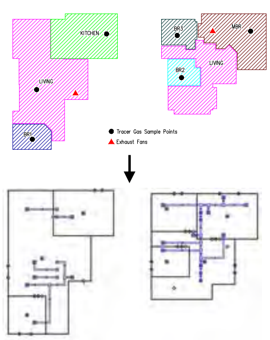
Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.20
Living	0.19
Kitchen	0.20
BR2	0.20
BR3	0.20
MBR	0.19

Conclusions From Sacramento Tracer Gas Testing

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance but the effect is not predictable

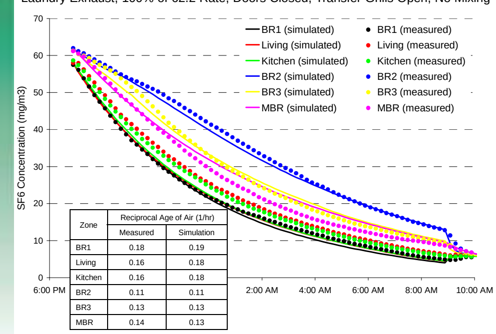


CONTAM Modeling, Nov. 2006-Jan. 2007



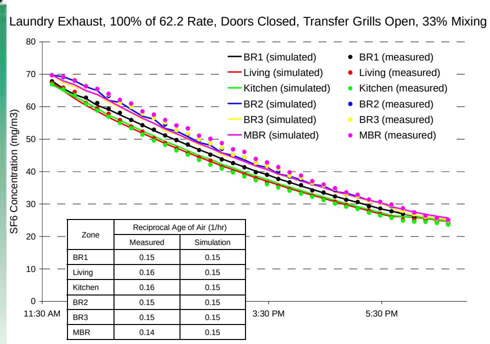
Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

Example Results of Tuned CONTAM Model



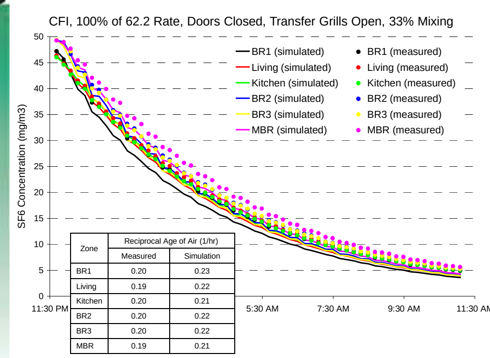
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.19
Living	0.16	0.18
Kitchen	0.16	0.18
BR2	0.11	0.11
BR3	0.13	0.13
MBR	0.14	0.13

Example Results of Tuned CONTAM Model



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.15	0.15
Living	0.16	0.15
Kitchen	0.16	0.15
BR2	0.15	0.15
BR3	0.15	0.15
MBR	0.14	0.15

Example Results of Tuned CONTAM Model



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.20	0.23
Living	0.19	0.22
Kitchen	0.20	0.21
BR2	0.20	0.22
BR3	0.20	0.22
MBR	0.19	0.21

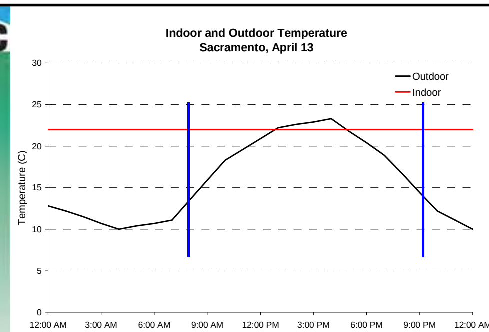
bsc

Tuned CONTAM Model Applied to Other Systems

Six Systems Evaluated & Compared:

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

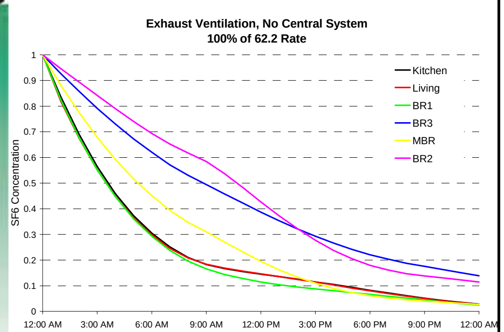
bsc



Simulation allows identical weather conditions for each system (generally not possible in field tests).

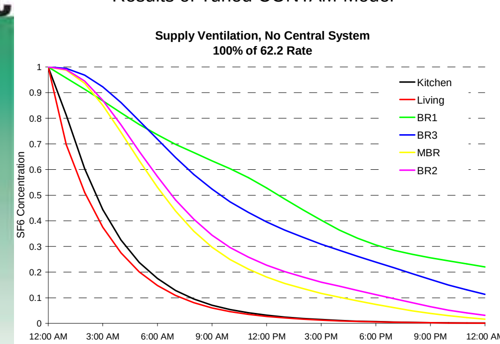
bsc

Results of Tuned CONTAM Model



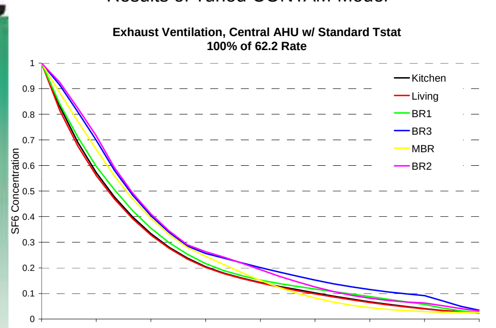
bsc

Results of Tuned CONTAM Model



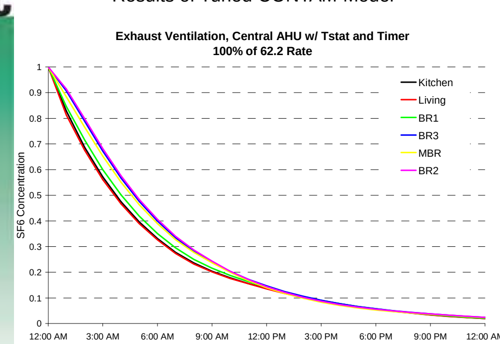
bsc

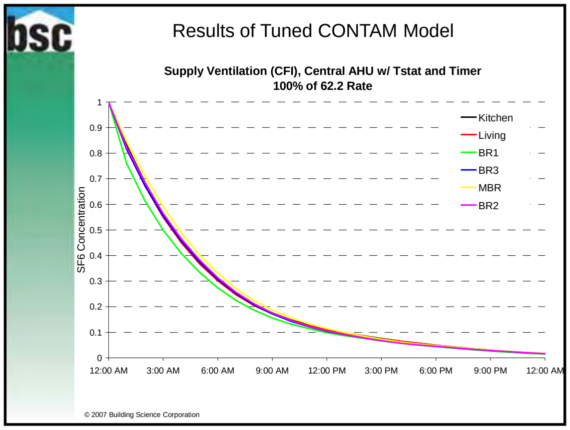
Results of Tuned CONTAM Model

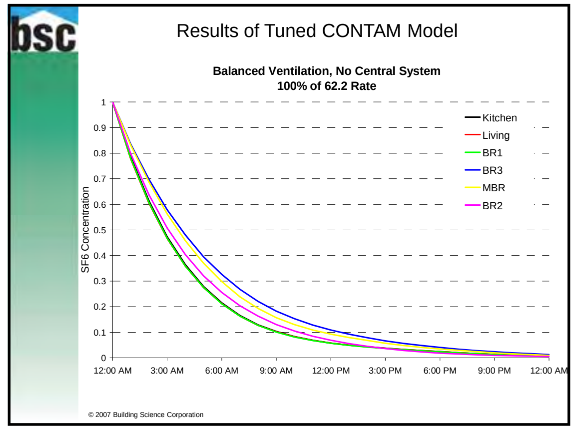


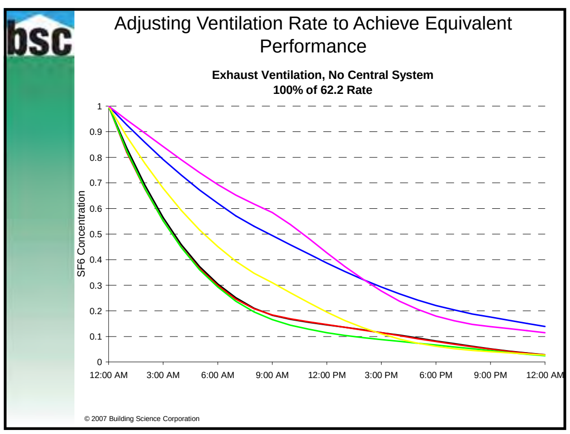
bsc

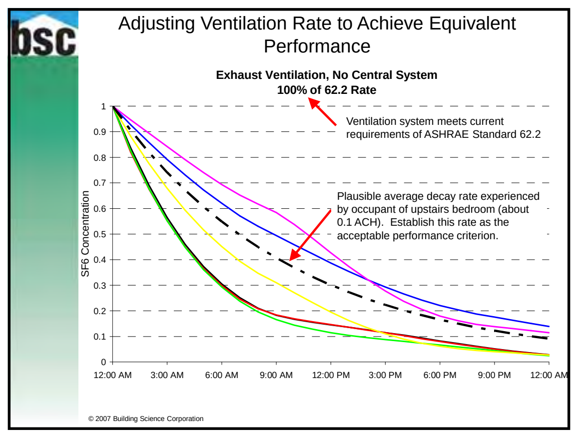
Results of Tuned CONTAM Model

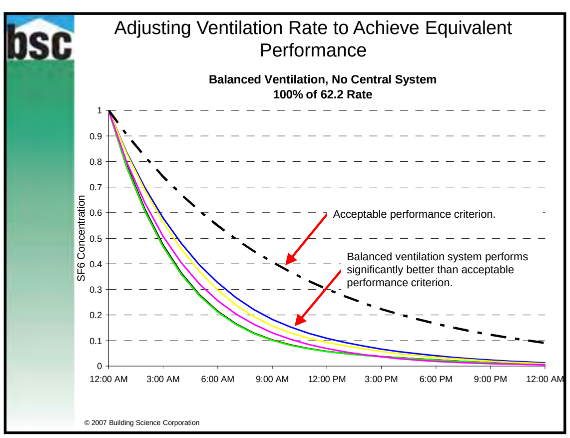


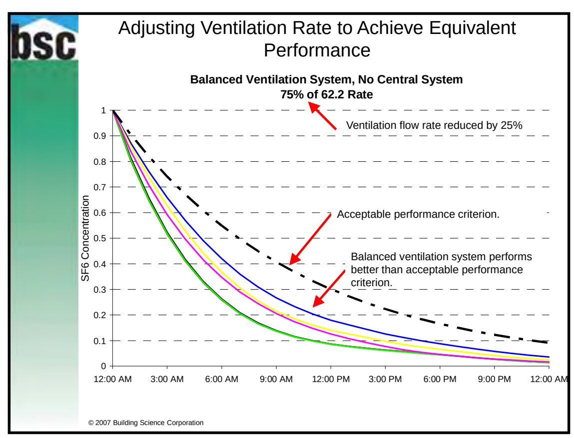

Results of Tuned CONTAM Model
Supply Ventilation (CFI), Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
9:00 PM
12:00 AM
© 2007 Building Science Corporation


Results of Tuned CONTAM Model
Balanced Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
© 2007 Building Science Corporation

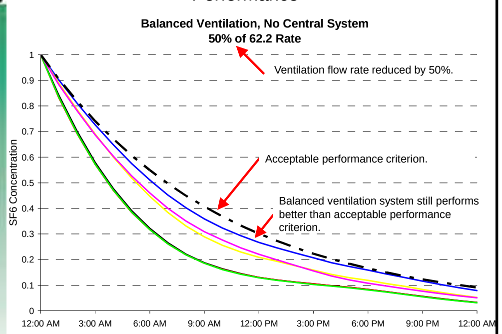

Adjusting Ventilation Rate to Achieve Equivalent Performance
Exhaust Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
© 2007 Building Science Corporation


Adjusting Ventilation Rate to Achieve Equivalent Performance
Exhaust Ventilation, No Central System
100% of 62.2 Rate
Ventilation system meets current requirements of ASHRAE Standard 62.2
Plausible average decay rate experienced by occupant of upstairs bedroom (about 0.1 ACH). Establish this rate as the acceptable performance criterion.
SF6 Concentration
© 2007 Building Science Corporation


Adjusting Ventilation Rate to Achieve Equivalent Performance
Balanced Ventilation, No Central System
100% of 62.2 Rate
Acceptable performance criterion.
Balanced ventilation system performs significantly better than acceptable performance criterion.
SF6 Concentration
© 2007 Building Science Corporation


Adjusting Ventilation Rate to Achieve Equivalent Performance
Balanced Ventilation System, No Central System
75% of 62.2 Rate
Ventilation flow rate reduced by 25%
Acceptable performance criterion.
Balanced ventilation system performs better than acceptable performance criterion.
SF6 Concentration
© 2007 Building Science Corporation

Adjusting Ventilation Rate to Achieve Equivalent Performance



Conclusions from Tuned CONTAM Model

1. Ventilation systems do not perform equally just because they have equal nominal airflow
2. Airflow requirements can be adjusted based on performance of each system
3. Further simulations were needed to predict year-round performance for general guidance
4. Can we create a “distribution coefficient” to modify the required airflow?

Current Work

1. Comparison of 1 day in 1 house in 1 climate is useful but needs to be expanded before establishing general guidelines.
2. Expand modeling from 1 day in 1 house in 1 climate to full-year with various house characteristics (leakage, mechanical systems, etc) and different climates.
3. Methodology of simulations changed from decay to exposure
   1. Uniform generation of pollutant within house
   2. Assumed occupancy schedule
   3. Calculated 3-hr, 8-hr, and yearly average exposures

Model Characteristics

1. Specific model became more general
2. Vary certain parameters to cover reasonable subset of current construction
3. Include effects of:
   1. Wind
   2. Stack effect
   3. Ventilation systems
   4. Occupant schedule
   5. Pollutant generation

Modeling Assumptions: Weather

1. Temperature
   1. Outdoor temperature from TMY2 data
   2. Indoor temperature constant at 22 C
2. Wind
   1. Wind speed and direction from TMY2 data
   2. Wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings

Model Assumptions: Air Handler

1. Sizing per Manual J for each climate
2. Duty cycle each hour based on temperature and design temperature for the climate
   1. Maximum 80% runtime at design conditions
   2. Heating balance point = 65 F
   3. Cooling balance point = 75 F
3. Two cycles per hour
   1. Cycles rounded to nearest 5 minute increment (simulation time step = 5 minutes)

Model Assumptions: Envelope Leakage

1. Distribution
   1. Leakage distribution per ASHRAE Fundamentals Chapter 27
      1. Walls, windows, doors: 62%
      2. Ceilings & nonoperating exhaust vents: 23%
      3. Ducts: 15%
2. Total leakage varied as described later

Model Assumptions: Pollutant Generation

1. Uniform generation of unique pollutant in each room
   1. Generation rate proportional to room square footage (1 mg/hr/sf)
   2. Pollutants unique, but assumed identical in analysis presented later

Model Assumptions: Occupant Schedules

1. Assume similar schedule for each occupant:
   1. 10 PM to 7 AM: in bedroom with door closed
   2. 7 AM to 9 AM: in kitchen
   3. 9 AM to 12 PM: in living room
   4. 12 PM to 1 PM: in kitchen
   5. 1 PM to 6 PM: in living room
   6. 6 PM to 10 PM: in other bedrooms
2. Bedroom doors open except during sleeping period 10 PM to 7 AM

Varied Parameters

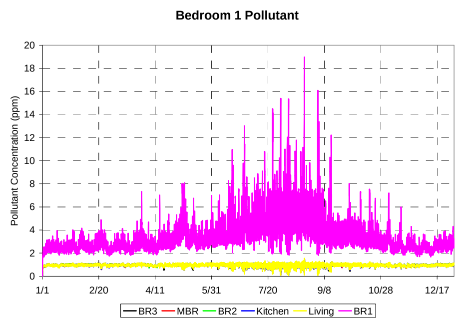
1. Climate
   1. Minneapolis
   2. Seattle
   3. Phoenix
2. Envelope leakage
   1. 1.5 ACH50 (R-2000)
   2. 3.5 ACH50 (Building America)
   3. 7 ACH50 (standard construction)

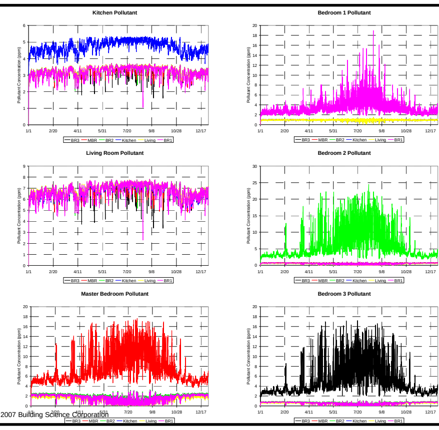
Varied Parameters

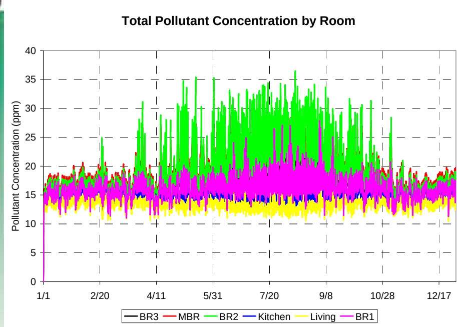
3. Central AHU System
   1. Not present
   2. In conditioned space
   3. Outside of conditioned space
4. AHU Schedule
   1. Standard thermostat
   2. Minimum runtime per hour (10 on/20 off)
5. Duct Leakage
   1. 6% of air handler flow
   2. 12% of air handler flow

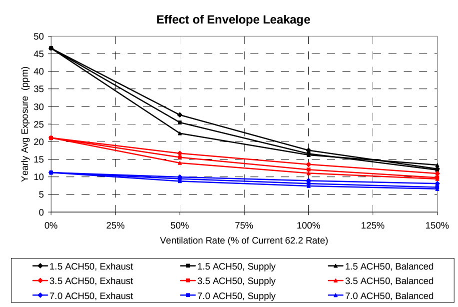
Varied Parameters

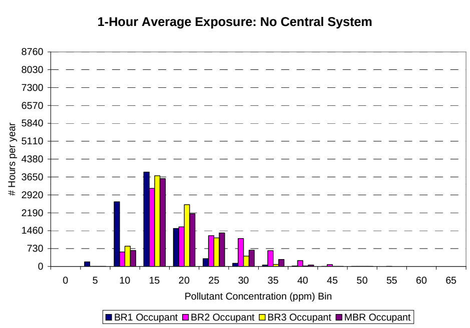
6. Ventilation System
   1. Single-point exhaust
   2. Single-point supply
   3. Dual-point balanced
   4. Fully-ducted balanced
7. Ventilation Rate
   1. 0, 50, 100, 150% of current 62.2 rate

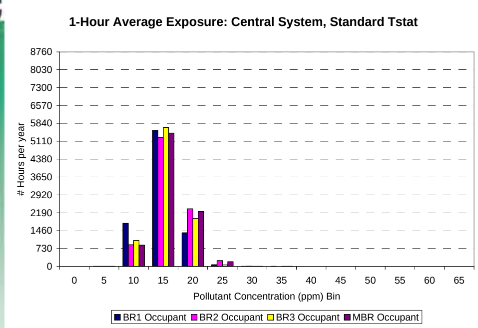

Bedroom 1 Pollutant
Pollutant Concentration (ppm)
20
18
16
14
12
10
8
6
4
2
0
1/1
2/20
4/11
5/31
7/20
9/8
10/28
12/17
BR3
MBR
BR2
Kitchen
Living
BR1

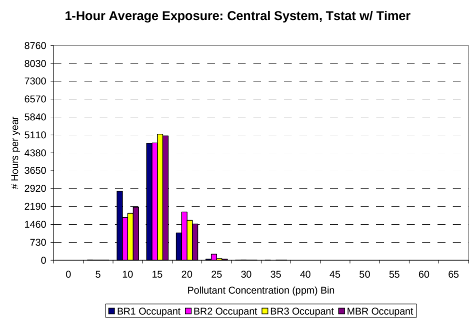

Kitchen Pollutant
Bedroom 1 Pollutant
Living Room Pollutant
Bedroom 2 Pollutant
Master Bedroom Pollutant
Bedroom 3 Pollutant


Total Pollutant Concentration by Room
Pollutant Concentration (ppm)
40
35
30
25
20
15
10
5
0
1/1
2/20
4/11
5/31
7/20
9/8
10/28
12/17
BR3
MBR
BR2
Kitchen
Living
BR1


Effect of Envelope Leakage
Yearly Avg Exposure (ppm)
50
45
40
35
30
25
20
15
10
5
0
0%
25%
50%
75%
100%
125%
150%
Ventilation Rate (% of Current 62.2 Rate)
1.5 ACH50, Exhaust
1.5 ACH50, Supply
1.5 ACH50, Balanced
3.5 ACH50, Exhaust
3.5 ACH50, Supply
3.5 ACH50, Balanced
7.0 ACH50, Exhaust
7.0 ACH50, Supply
7.0 ACH50, Balanced

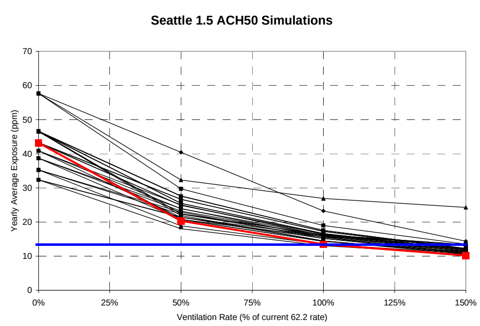

1-Hour Average Exposure: No Central System
Hours per year
8760
8030
7300
6570
5840
5110
4380
3650
2920
2190
1460
730
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Pollutant Concentration (ppm) Bin
BR1 Occupant
BR2 Occupant
BR3 Occupant
MBR Occupant

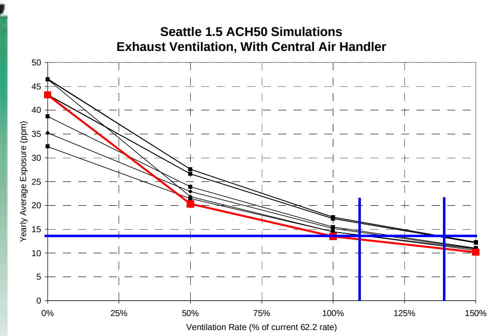

1-Hour Average Exposure: Central System, Standard Tstat
Hours per year
8760
8030
7300
6570
5840
5110
4380
3650
2920
2190
1460
730
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Pollutant Concentration (ppm) Bin
BR1 Occupant
BR2 Occupant
BR3 Occupant
MBR Occupant



Reference System

- Best available system: fully ducted, balanced ventilation system
- Compare other systems to this system: what ratio of airflows do other systems need to provide equal yearly average exposure?





Airflow Ratios—All Simulations

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

2.18.4. January 2008 Expert Meeting Summary Report

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

Building Science Corporation Industry Team

March 3, 2008

Work Performed Under Funding Opportunity Number:
DE-FC26-08NT00601

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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 always 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

Presenter bio: 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.

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

Presentation Summary:

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 $\mu g/m^3$.

Post-presentation discussion:

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

Presenter bio: 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.

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

Presentation Summary:

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 confirmed what they would have assumed about the systems presented.

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.

Post presentation discussion:

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.

[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.

<u>Key questions regarding this meeting:</u>

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
Langan	Glen	Gulf Power-Southern Co.	gplangan@southernco.com
Lstiburek	Joseph	Building Science Corp.	joe@buildingscience.com
Lyons	Jamie	Newport Partners, LLC	jameslyons@newportpartnersllc.com
Moore	Mike	Newport Partners, LLC	mmoore@newportpartnersllc.com
Nelson	Gary	Energy Conservatory	gnelson@energyconservatory.com
Olson	Collin	Energy Conservatory	colson@energyconservatory.com
Poirier	Bertrand	Fantech	bepo@fantech.ca
Prahl	Duncan	IBACOS	dprahl@ibacos.com
Puttagunta	Srikanth	Steven Winter Associates	sri@swinter.com
Raymer	Paul		paul.raymer@heysol.com
Rittelmann	Bill	IBACOS	brittelmann@ibacos.com
Rudd	Armin	Building Science Corp.	arudd@buildingscience.com
Sherman	Max	LBNL	mhsherman@lbl.gov
Stevens	Don	Panasonic	stevensd@us.panasonic.com
Stroud	Thomas	Health Patio & Barbeque Assoc	stroud@hpba.org
Talbot	John		jmtalbott@comcast.net
Taylor	Sam	DOE	samuel.taylor@ee.doe.gov
Townsend	Aaron	Building Science Corp.	aaron@buildingscience.com
Walker	Iain	LBNL	iswalker@lbl.gov
Werling	Eric	USEPA	werling.eric@epa.gov
Wettergren	Ola	Fantech	olwe@fantech.net
Wilcox	Bruce		bwilcox@lmi.net

Appendix C: Introductory Presentation

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable
Building Technologies Program

Building America
U.S. Department of Energy
Research Leading to Zero Energy Homes

Building America Expert Meeting

Ventilation System Interactions In Homes

Hilton New York
18 January 2008
8 am to noon

<u>Meeting Agenda:</u>

Welcome and Meeting Introduction
Building America Zero Energy Home Overview (DOE/NREL)

1. Francis (Bud) Offerman, *Window Usage, Ventilation, and IAQ in New California Homes*

2. Bill Rittelmann, *Air distribution for thermal comfort in high-performance homes and its interaction with ventilation*

3. Keith Gawlik, *CFD evaluation of air distribution systems for residential forced air systems in cold climates*

4. Aaron Townsend, *CONTAM simulations to evaluate uniformity of ventilation air distribution and occupant exposure to indoor contaminants*

General discussion, Joseph Lstiburek-discussion moderator

Wrap up, action items, and follow-up plan

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

Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions

Francis Offermann PE CIH, Principal Investigator
Jonathan Robertson CIH and Teresa Woo EIT
Indoor Environmental Engineering, San Francisco, CA www.iee-sf.com
Steve Brennan PE and Dave Springer
Davis Energy Group, Davis, CA

Window usage

- People opened their windows about the same amount in houses with no mechanical ventilation system as they did in houses with supply ventilation (outdoor air ducted to the central return).
- People in houses with HRV ventilation systems opened their windows about twice as much as people in houses with either no mechanical ventilation or supply ventilation.

Table 2. Window and door opening expressed as the average opening in square feet over the 24-hour air quality sampling period and the average of the previous seven 24-hour periods in new single-family detached homes in California; with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)		DOA Mechanical Outdoor Air [b] Homes (n=8)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)	Test Day 24 hr Average (ft^2)	Week 24 hr Average (ft^2)
Minimum	0.0	0.0	0.0	0.2	12.1	14.2
25% Quartile	1.7	1.9	3.3	5.0	16.4	16.5
50% Median	7.9	8.5	10.4	7.8	20.7	18.8
75% Quartile	17.5	19.2	19.2	23.9	33.6	28.7
Maximum	102.0	52.5	52.8	43.7	46.4	38.6

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Building enclosure leakage

- All of the house groups had about the same range of building air tightness as tested by blower door, about 4 to 5 ach50, or 2 to 3 SLA.

Table 4. Building envelope air leakage area as calculated from building envelope depressurization tests and as expressed as ACH_{50} and SLA in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)		DOA Mechanical Outdoor Air [b] Homes (n=7)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	ACH_{50} (ach)	SLA	ACH_{50} (ach)	SLA	ACH_{50} (ach)	SLA
Minimum	3.5	1.7	3.2	1.4	4.3	2.1
25% Quartile	4.0	2.4	4.0	2.5	4.4	2.2
50% Median	4.7	2.7	4.3	2.8	4.6	2.4
75% Quartile	5.3	3.0	5.0	3.0	4.8	2.6
Maximum	8.4	5.5	6.1	3.7	4.9	2.8

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 7 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems (one home without blower door measurements excluded)
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Ventilation flow rates

- Houses with supply ventilation had about the same estimated outside air exchange rate as houses with no mechanical ventilation.
- Only one of the eight supply ventilation houses had a fan cycling control to assure a minimum fan duty cycle (11 minutes every 30). That house was lumped with all the others for reporting the air exchange results so there was no way to differentiate performance due to a programmed minimum fan duty cycle.
- The median estimated outside air flow rate for the supply systems was 40 cfm, and the median fan runtime was 18%. That was the equivalent of 7 cfm continuous.

Ventilation flow rates (cont.)

- The median outside air flow rate for the HRV houses was 153 cfm and 100% runtime. Therefore, the median HRV system delivered about 20 times more outside air than the median supply ventilation system over the test period.
- The median house size was 2,260 ft2, assuming 3 bedrooms, the median HRV ventilation rate was 3 times the 62.2 rate.

Table 3. Exhaust and outdoor air fan ventilation as expressed as expressed as the average air changes per hour (ach) over the 24-hour air quality sampling period as well as the average of the previous seven 24-hour periods in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)	DOA Mechanical Outdoor Air [b] Homes (n=8)		HRV Mechanical Outdoor Air [c] Homes (n=3)	
	Exhaust Fan 24 hr Average (ach)	Exhaust Fan 24 hr Average (ach)	Mechanical Outdoor Air 24 hr Average (ach) / (%ON) / (cfm)	Exhaust Fan 24 hr Average (ach)	Mechanical Outdoor Air 24 hr Average (ach) / (%ON) / (cfm)
Minimum	0.00	0.00	0.00 / 0 / 27	0.11	0.12 / 32 / 149
25% Quartile	0.00	0.00	0.01 / 0 / 30	0.23	0.38 / 66 / 151
50% Median	0.01	0.00	0.02 / 18 / 40	0.35	0.44 / 100 / 153
75% Quartile	0.01	0.02	0.04 / 25 / 48	0.43	0.46 / 100 / 156
Maximum	0.10	0.03	0.07 / 40 / 71	0.51	0.47 / 100 / 159

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

PFT measured air change rate

- As measured by PFT, houses with the supply ventilation system had a slightly higher 24 hour average air exchange rate compared to houses with no mechanical outdoor air, 0.36 ach compared to 0.33 ach.
- Houses with HRV systems had four times that amount, 1.43 ach.
- In all, 50% of the 62 homes with PFT measurements had outdoor air exchanges rates below 0.35 ach.

Table 5. Average 24-hour outdoor air exchange rates as calculated from passive PFT tracer gas measurements in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=41)	DOA Mechanical Outdoor Air [b] Homes (n=8)	HRV Mechanical Outdoor Air [c] Homes (n=3)
	Outdoor Air Exchange Rate (ach)	Outdoor Air Exchange Rate (ach)	Outdoor Air Exchange Rate (ach)
Minimum	0.13	0.10	0.33
25% Quartile	0.20	0.20	0.88
50% Median	0.33	0.36	1.43
75% Quartile	0.66	0.46	2.86
Maximum	6.47	0.58	4.28

a.) 41 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems (one home without a PFT measurement excluded).
b.) 8 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems.
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.

Formaldehyde concentrations

- The median 24 hour average formaldehyde concentration was 38 µg/m^3 for the 42 houses with no mechanical ventilation. It was about 50% higher for the 7 houses with supply ventilation (59 µg/m^3), and about four times less for the 3 HRV houses (10 µg/m^3).
- In all, 62% of the 61 homes with formaldehyde measurements had indoor concentrations that exceeded the California Air Resources Board exposure guideline of 33 µg/m^3.

Table 6. Average 24-hour indoor formaldehyde concentrations in new single-family detached homes in California with and without mechanical outdoor air ventilation.

	No Mechanical Outdoor Air [a] Homes (n=42)	DOA Mechanical Outdoor Air [c] Homes (n=7)	HRV Mechanical Outdoor Air [c] Homes (n=3)	Outdoor All [d] Homes (n=23)
	Indoor Formaldehyde Concentrations (µg/m^3)	Indoor Formaldehyde Concentrations (µg/m^3)	Indoor Formaldehyde Concentrations (µg/m^3)	Outdoor Formaldehyde Concentrations (µg/m^3)
Minimum	4.7	34.6	7.8	0.7
25% Quartile	22.2	42.2	8.9	1.5
50% Median	38.3	58.5	10.0	2.2
75% Quartile	73.8	87.0	23.4	3.1
Maximum	143.6	135.5	36.7	8.0

a.) 42 homes with no mechanical outdoor air systems and no nighttime ventilation cooling systems.
b.) 7 homes with operational mechanical ducted outdoor air (DOA) ventilation systems and no nighttime ventilation cooling systems (one home with a formaldehyde sample failure excluded)
c.) 3 homes with operational mechanical heat recovery ventilator (HRV) outdoor air ventilation systems and no nighttime ventilation cooling systems.


Discussion?
Building Science Consortium

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

Room Air Temperature Uniformity of a Forced-Air System Relative to Runtime

BA Ventilation Experts Meeting
January 18, 2008
IBACOS, Inc.
Bill Rittelmann

Overview

- Project Description
- Runtime vs. Temperature Uniformity
- Ventilation Tracer Gas
- Conclusions

Space Conditioning in High Performance Homes

Project Overview

- Project Partners – Carrier Corporation and Cardinal Glass
- Features – Redundant forced-air systems in high-performance house – Perimeter floor and high sidewall
- Focus – Thermal comfort performance of high sidewall diffusers using low-temperature supply air in the heating mode
- Target Climates – All climates requiring heat
- Location – Fort Wayne, IN

Floor Diffuser System

- 2-stage gas-fired furnaces were installed that are capable of delivering supply air temperatures as low as 95ºF (25ºF rise @ 70ºF).
- Fancoil is setup to supply air at 84ºF, 99ºF, & 113ºF at a constant volume of 1100 cfm, which is equal to cooling.

Space Conditioning in High Performance Homes

High Sidewall SAO System

Ductwork inside envelope

Adjustable Vane Diffusers

Space Conditioning in High Performance Homes

High Sidewall SAO System

- Diffusers were mounted near interior walls and sized using current ASHRAE guidelines for cooling
- $T_{50} / L = 1.5$
- To achieve required throw velocity, only one diffuser per room was used

Space Conditioning in High Performance Homes

High Sidewall SAO System

Room airflows were calculated as an average of the peak heating and cooling room airflows.

Each diffuser was balanced to achieve the desired flow

$$CFM_{bal} = \frac{CFM_{Hpeak} + CFM_{Cpeak}}{2}$$

Standards & Guidelines

ACCA – Manual D, Residential Duct Systems

This reference can't be found in Manual B.

Manual B (Principles of Air Conditioning) is no longer published by ACCA.

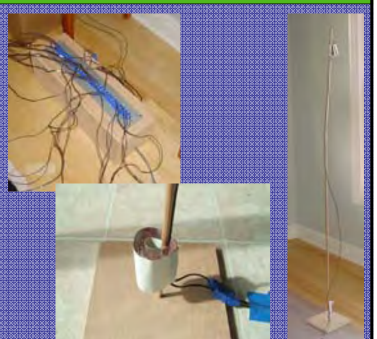
It was last published in 1970.

…there should not be more than a 2ºF temperature difference between any two rooms. However, as explained below, it is difficult, if not impossible, to satisfy this requirement with a single zone air distribution system for some homes. (As per ***Manual B****, 2ºF is ideal, but the maximum allowable difference is equal to 4ºF).*

Temperature Measurements

Test measures a volumetric grid of air temperatures to determine temperature distribution in a room relative to system operation and load

Apparatus is designed for quick assembly and compliance with ASHRAE measurement protocols



Current Research

Heating Season Cases

- Fancoil/High Sidewall Diffusers
  - Stage 1, 1,222 CFM, 5 kW
  - Stage 2, 1,222 CFM, 10 kW
  - Stage 3, 1,222 CFM, 15 kW
- Furnace/Floor Diffusers
  - Stage 1, 474 CFM
  - Stage 2, 680 CFM

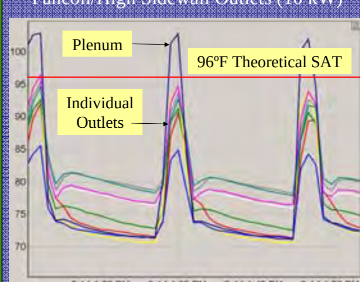
High Sidewall SAO System

Outlet temperatures approach steady-state by end of cycle and are relatively equal

Plenum temperature is high due to location of sensor relative to heating coils

1,222 cfm

Heating Supply Air Temperatures
Fancoil/High Sidewall Outlets (10 kW)



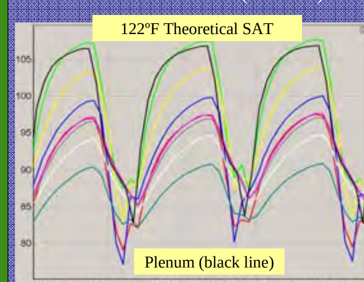
Floor Diffuser System

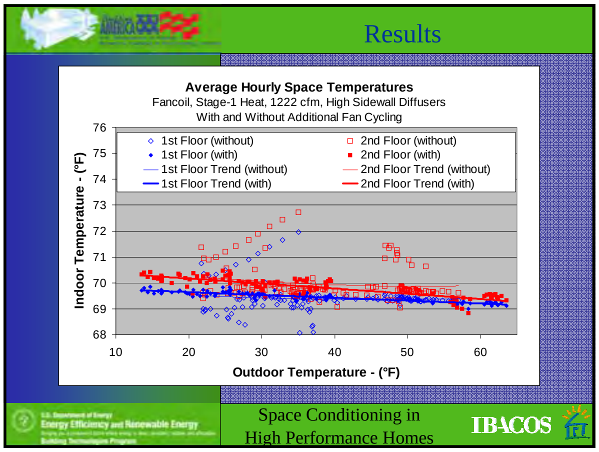
Outlet temperatures are nowhere near steady-state by end of cycle and the are relatively diverse

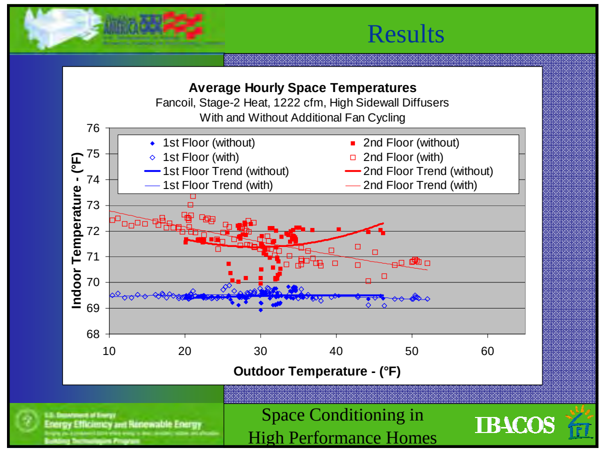
Duct mass, thermal losses, and low outlet velocity leads to longer cycles

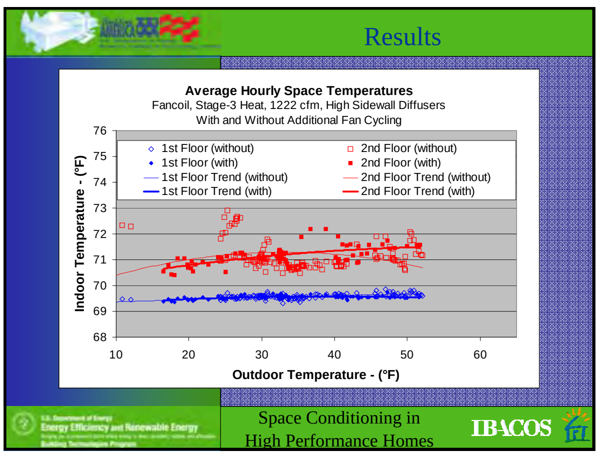
680 cfm

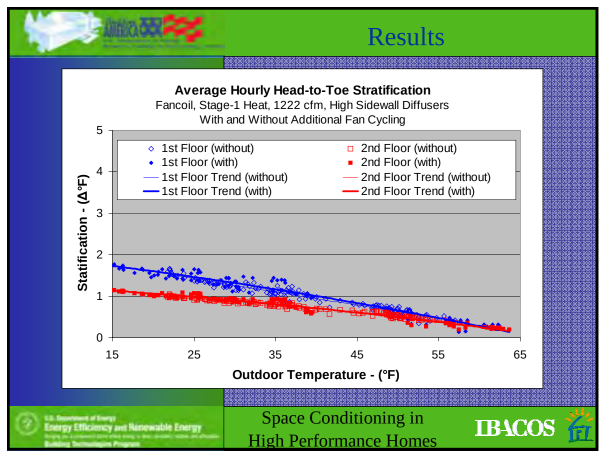
Heating Supply Air Temperatures
Furnace/Floor Outlets (38 MBH)

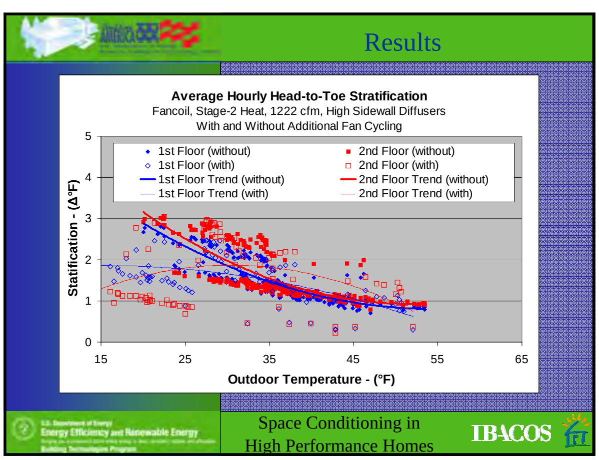


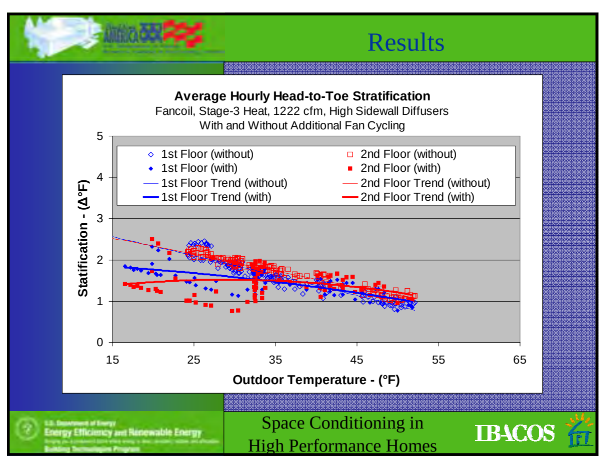

Results
Average Hourly Space Temperatures
Fancoil, Stage-1 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Space Conditioning in
High Performance Homes
IBACOS

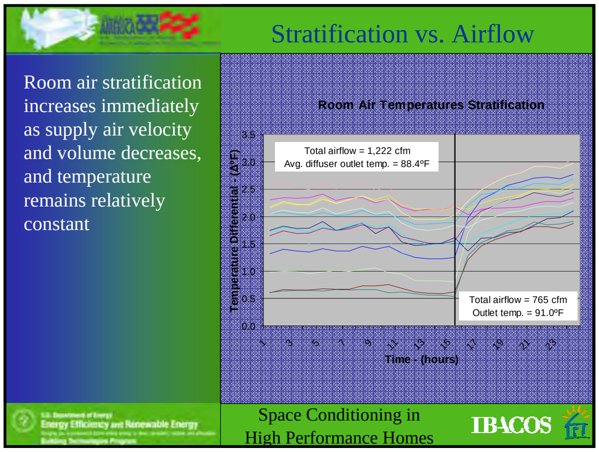

Results
Average Hourly Space Temperatures
Fancoil, Stage-2 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Space Conditioning in
High Performance Homes
IBACOS

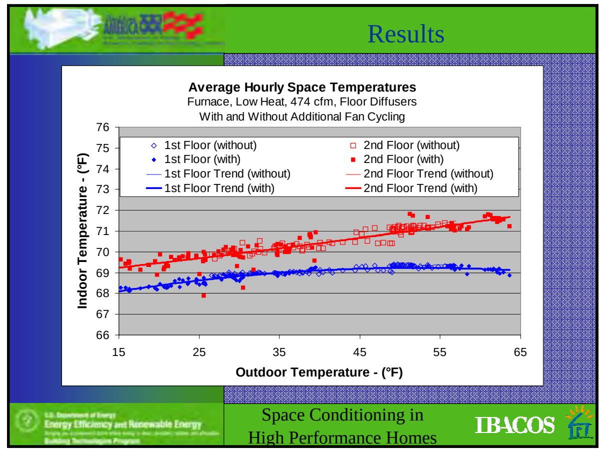

Results
Average Hourly Space Temperatures
Fancoil, Stage-3 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Space Conditioning in
High Performance Homes
IBACOS

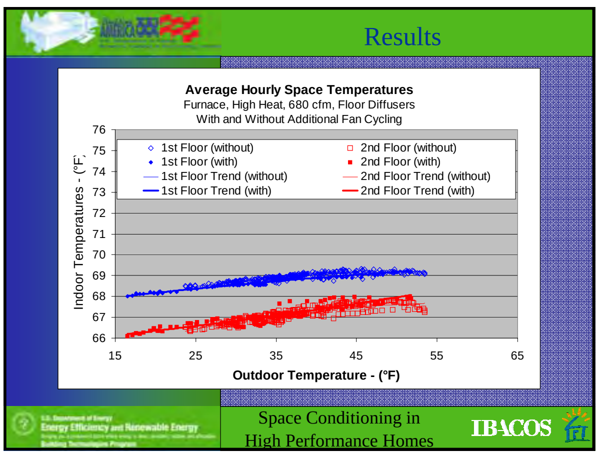

Results
Average Hourly Head-to-Toe Stratification
Fancoil, Stage-1 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
Statification - (Δ°F)
Outdoor Temperature - (°F)
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Space Conditioning in
High Performance Homes
IBACOS

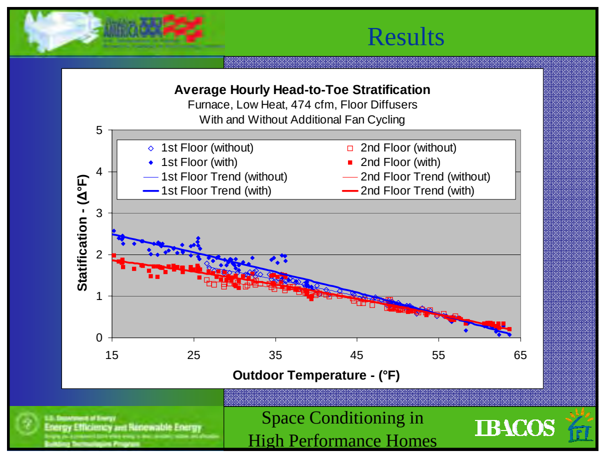

Results
Average Hourly Head-to-Toe Stratification
Fancoil, Stage-2 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
Statification - (Δ°F)
Outdoor Temperature - (°F)
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Space Conditioning in
High Performance Homes
IBACOS

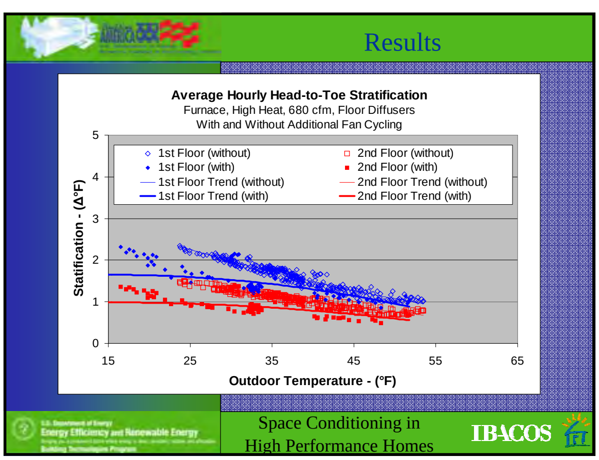

Results
Average Hourly Head-to-Toe Stratification
Fancoil, Stage-3 Heat, 1222 cfm, High Sidewall Diffusers
With and Without Additional Fan Cycling
Statification - (Δ°F)
Outdoor Temperature - (°F)
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Space Conditioning in
High Performance Homes
IBACOS

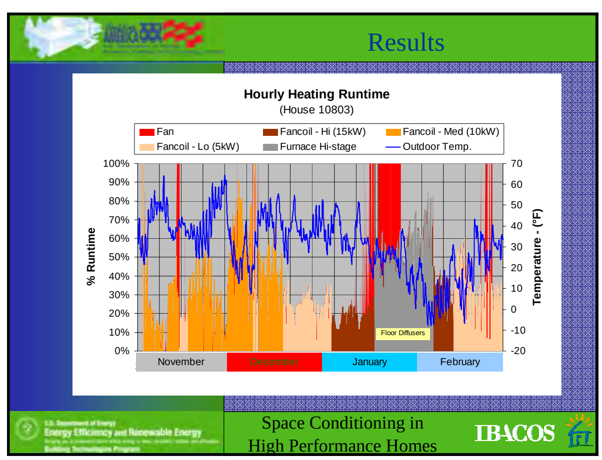

Stratification vs. Airflow
Room air stratification increases immediately as supply air velocity and volume decreases, and temperature remains relatively constant
Room Air Temperatures Stratification
Total airflow = 1,222 cfm
Avg. diffuser outlet temp. = 88.4°F
Total airflow = 765 cfm
Outlet temp. = 91.0°F
Temperature Differential - (Δ°F)
Time - (hours)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Space Temperatures
Furnace, Low Heat, 474 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Indoor Temperature - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS

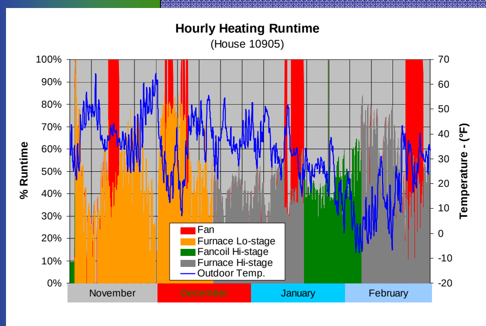

Results
Average Hourly Space Temperatures
Furnace, High Heat, 680 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Indoor Temperatures - (°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Head-to-Toe Stratification
Furnace, Low Heat, 474 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Stratification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Average Hourly Head-to-Toe Stratification
Furnace, High Heat, 680 cfm, Floor Diffusers
With and Without Additional Fan Cycling
1st Floor (without)
1st Floor (with)
1st Floor Trend (without)
1st Floor Trend (with)
2nd Floor (without)
2nd Floor (with)
2nd Floor Trend (without)
2nd Floor Trend (with)
Statification - (Δ°F)
Outdoor Temperature - (°F)
Space Conditioning in
High Performance Homes
IBACOS


Results
Hourly Heating Runtime
(House 10803)
Fan
Fancoil - Hi (15kW)
Fancoil - Med (10kW)
Fancoil - Lo (5kW)
Furnace Hi-stage
Outdoor Temp.
% Runtime
Temperature - (°F)
Floor Diffusers
November
January
February
Space Conditioning in
High Performance Homes
IBACOS

Results



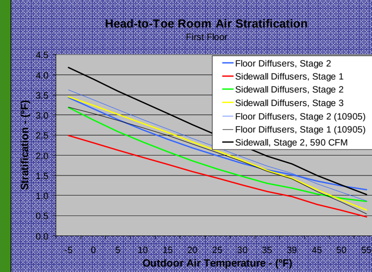
Space Conditioning in High Performance Homes

IBACOS

Summary

All conditions were well within ASHRAE criteria of 3ºC (5.4ºF)

First and second stage of the high sidewall system outperformed the floor outlet system due to lower outlet temperatures



Space Conditioning in High Performance Homes

IBACOS

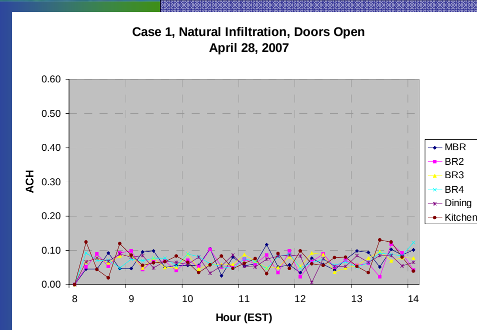
Tracer Gas Results

Case	Central Air (cfm)	Ventilation Supply (cfm)	Ventilation Exhaust (cfm)	Interior Doors
1	**0**	**0**	**0**	**Open**
2	**0**	**0**	**0**	**Closed**
3	350	70	0	Open
4	**350**	**70**	**0**	**Closed**
5	350	70	Up Bath	Open
6	350	70	Up Bath	Closed
7	350	70	Down Bath	Open
8	**350**	**70**	**Down Bath**	**Closed**
9	**350**	**0**	**70**	**Closed**
10	**350**	**0**	**0**	**Closed**
11	**350**	***70***	**0**	**Closed**
12	**0**	**0**	**55**	**Closed**

Space Conditioning in High Performance Homes

IBACOS

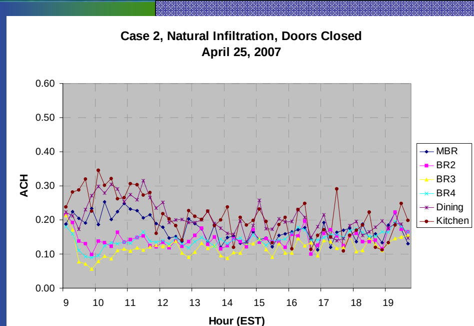
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

Tracer Gas Results



Space Conditioning in High Performance Homes

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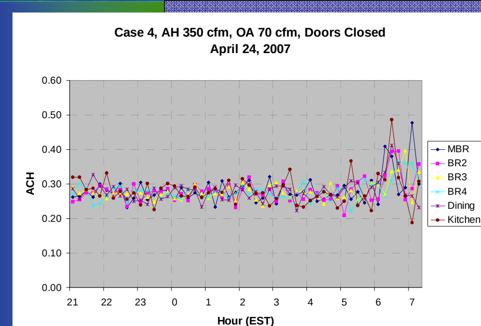
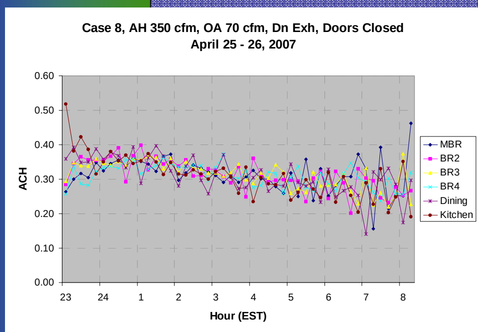
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

Tracer Gas Results



Space Conditioning in High Performance Homes

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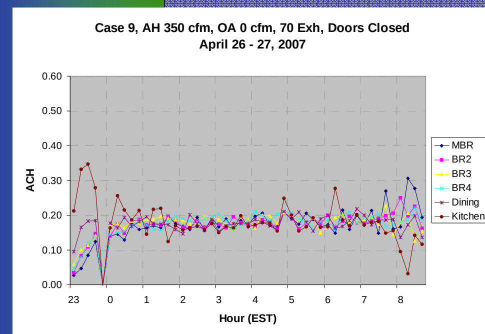
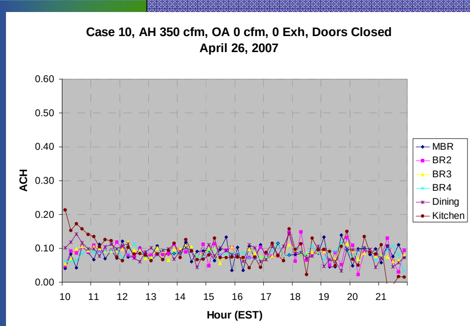
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

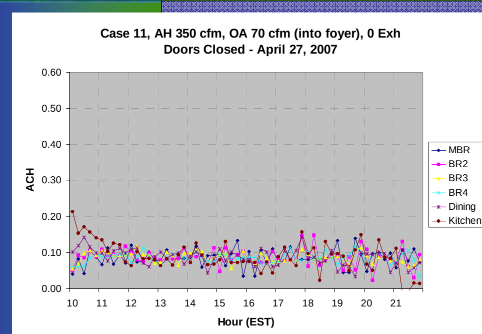
Tracer Gas Results



Space Conditioning in High Performance Homes

IBACOS

Tracer Gas Results



Space Conditioning in High Performance Homes

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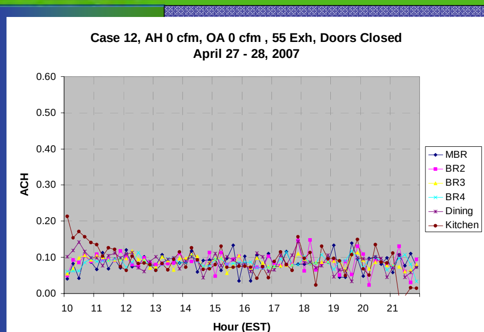
Tracer Gas Results



Space Conditioning in High Performance Homes

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Conclusions

Additional fan operation appears to:

- Reduce extreme space temperature excursions under most operating conditions, but general trends are not noticeably affected
- Reduce head-to-toe temperature stratification under almost all operating conditions – more noticeable at higher supply air temperatures and lower outdoor air temperatures.

Space Conditioning in High Performance Homes

IBACOS

Conclusions

Additional fan operation appears to:

Be less effective in “ironing out” temperature differences using floor diffusers.

Space Conditioning in High Performance Homes

IBACOS

Conclusions

Tracer Gas

Continuous low-volume central air provides adequate and uniform distribution of ventilation air when OA is injected into return air stream

Single-point unbalanced ventilation systems appear to be only marginally effective whether they are supply or exhaust

Space Conditioning in High Performance Homes

IBACOS

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

CFD Evaluation of Air Distribution Systems for Residential Forced Air Systems in Cold Climates

Keith Gawlik
NREL

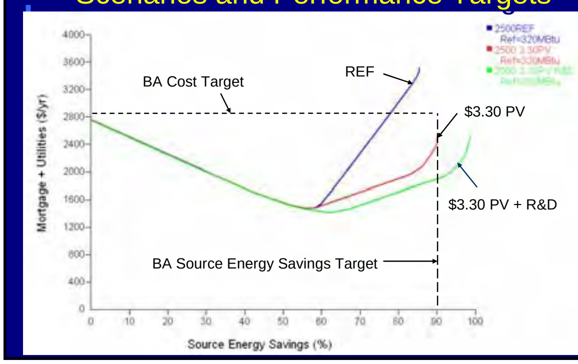
Outline

- Context of this project in ZEH research
- Review of past simulation work
- Results and correlation development
- Comparisons between test and simulation

Background

- Neutral cost of ZEH by 2020
- Improved shell (R30-R60-R5) + best available equipment = 50% by 2015
- ZEH shell + PV + ZEH systems by 2020

Scenarios and Performance Targets



How to maintain comfort?

- ZEH shells:
  - 50% less HVAC capacity
  - 50% smaller duct cross sections and registers
  - 50% less CFM
- Need integrated comfort conditioning for thermal, odor, humidity control

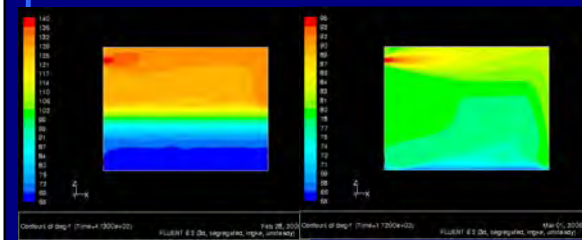
A least cost option

- Use A/C system for integrated comfort conditioning
- 80% market penetration of A/C, so systems available
- Uniform distribution of ventilation air

Major barriers

- Heating airflows less than cooling airflows
- Good supply air mixing not assured in heating mode unless carefully designed
- Stratification possible

Good air mixing required



Stratified Well mixed

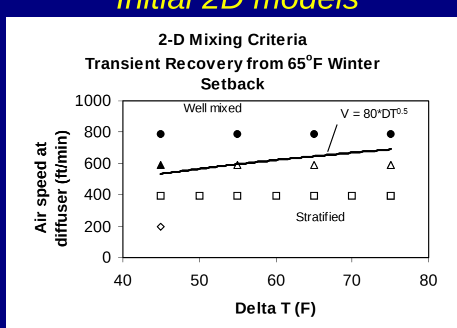
Objective

Develop demonstrated numerical models in collaboration with IBACOS to provide initial design guidance on mixing performance and direct experimental plans

Past work

- Recovery from 65ºF setback
- Variety of room sizes, diffuser sizes, air flowrates, supply temperatures
- 2D and 3D models
- Performance parameters defined
- Correlation developed

Initial 2D models



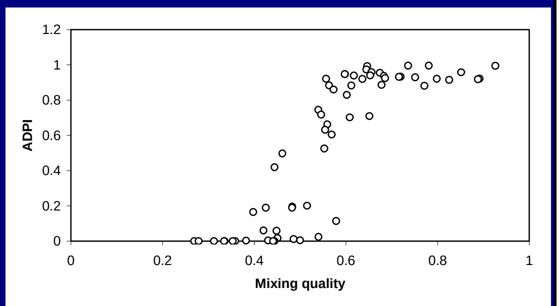
Performance criteria

- Displacement efficiency, η_d
- Mixing quality $Q = (1-\eta_d)/(0.368)$
- Air diffuser performance index (ADPI)
  - Draft temperature between -1.5º and 1ºC

$$\theta = T - T_{avg} - 8(V - 0.15)$$

  - Air speed less than 0.35 m/s

3D model results

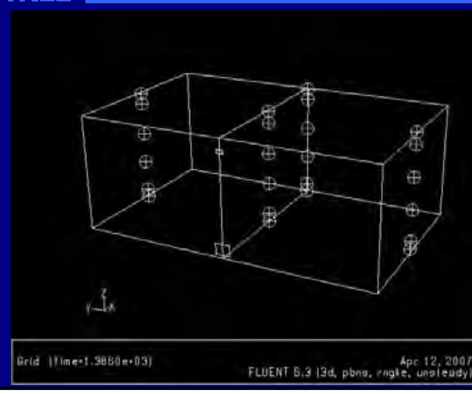


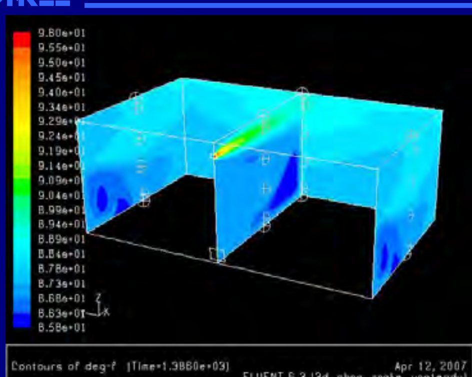
Comparison between test and simulation

- Experimental data from Ventilation Test Facility
- Field test data from IBACOS and Cardinal Glass house in Ft. Wayne

NREL Ventilation Test Room

- Two cases chosen for modeling
- Low flow, high temp. (L3)
  - 87 cfm, 102ºF SAT
- Medium flow, low temp. (M2)
  - 122 cfm, 96ºF SAT

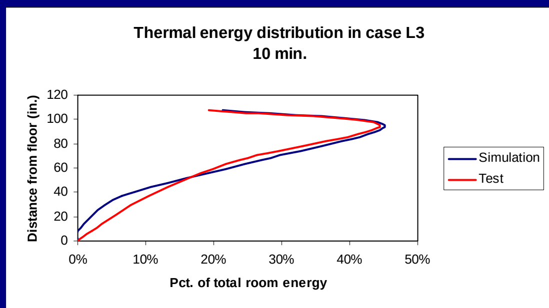




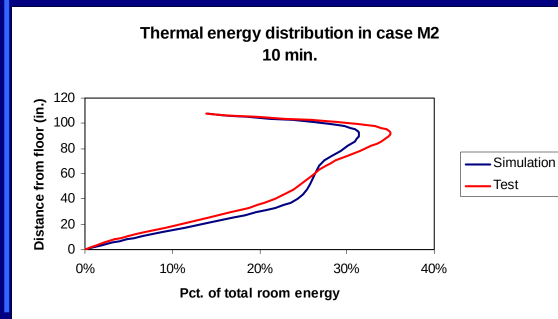
NREL Ventilation Test Room

- Stratification effects explored via relative energy content in room

NREL Ventilation Test Room



NREL Ventilation Test Room



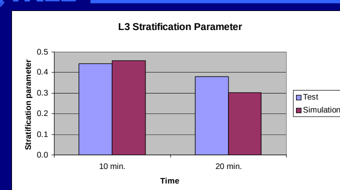
NREL Ventilation Test Room

- Stratification parameter:

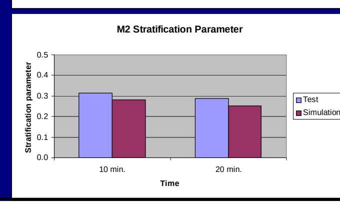
$(T_{ceiling}-T_{floor})/T_{weighted\ average}$

0: perfectly mixed

>1: extremely stratified



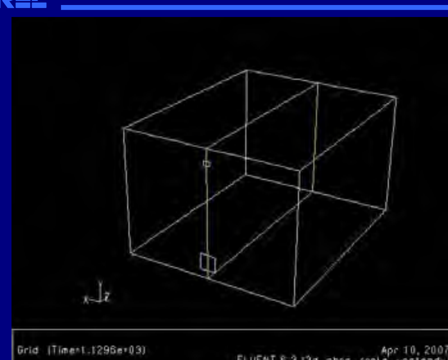
L3: 3 % diff. at 10 min.

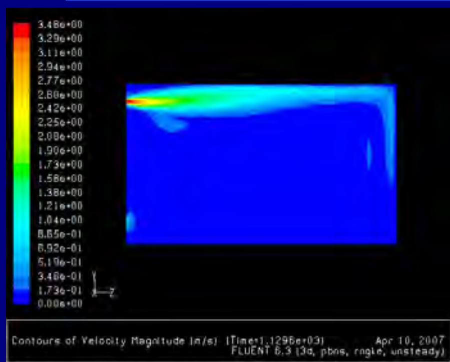


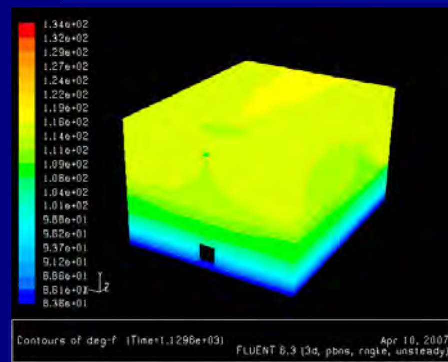
M2: -11 % diff. at 10 min.

Ft. Wayne Test Room

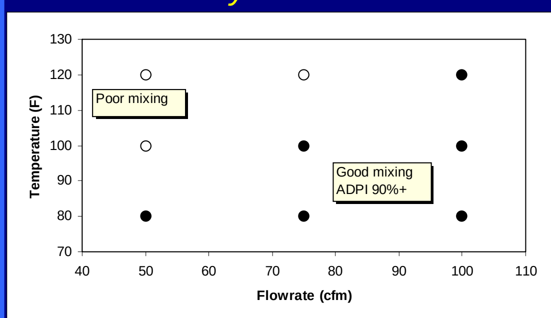
- Bedroom supplied by single 6" by 4" high sidewall diffuser
- Range of flowrates modeled (design 71 cfm)
- Supply temperatures fixed and functions of return temperature







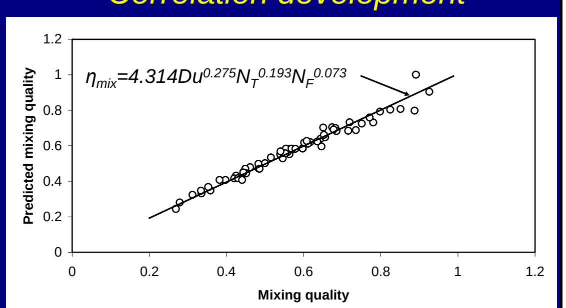
Ft. Wayne Test Room



Correlation development

- Geometry
  - Duct fineness ratio, N_F = *(height/width)*
  - Isothermal throw ratio, N_T = *(X/L)*,
- Air kinetic energy / thermal energy, $Du=V^2/\{c_p(T-T_o)\}$

Correlation development



Summary

- 2D and 3D models developed and used to predict mixing performance
- Good agreement between simple model and ventilation test room data

Future work

- Compare model to Ft. Wayne data
- Determine thermostatic control effects for select cases
- Develop design guidelines

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

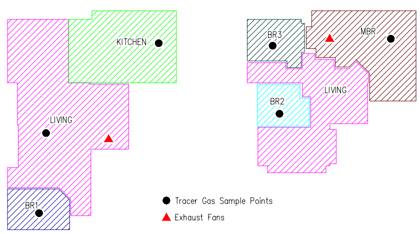
Update on Results of Field Measurements and CONTAM Simulations

Aaron Townsend
January 18, 2008

Tracer Gas Testing Sacramento January 2006

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- Supply and exhaust ventilation tested, with and without mixing via central air handler
- Each test 4-14 hours long

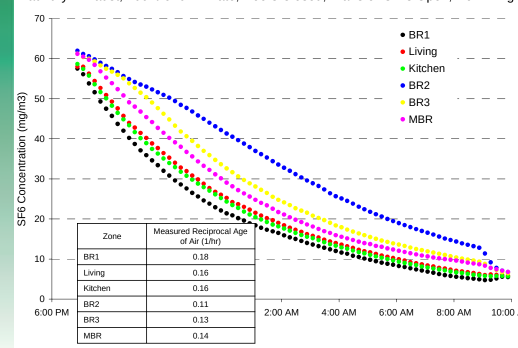
Zones – 2 Story House



- These were tracer gas decay tests—establish uniform concentration of tracer gas and then activate ventilation system to remove it.
- Reciprocal age-of-air can be calculated from decay curves (if weather conditions are sufficiently constant)

Example Results of Sacramento Tracer Gas Testing

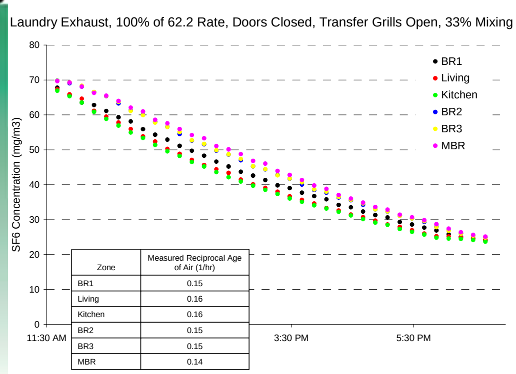
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.18
Living	0.16
Kitchen	0.16
BR2	0.11
BR3	0.13
MBR	0.14

Example Results of Sacramento Tracer Gas Testing

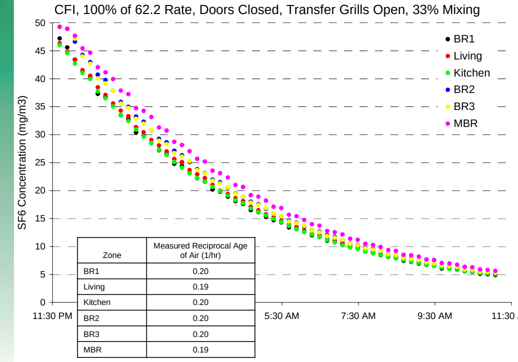
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.15
Living	0.16
Kitchen	0.16
BR2	0.15
BR3	0.15
MBR	0.14

Example Results of Sacramento Tracer Gas Testing

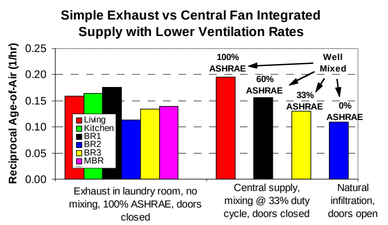
CFI, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



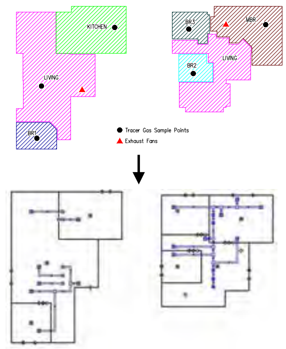
Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.20
Living	0.19
Kitchen	0.20
BR2	0.20
BR3	0.20
MBR	0.19

Conclusions From Sacramento Tracer Gas Testing

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance but the effect is not predictable



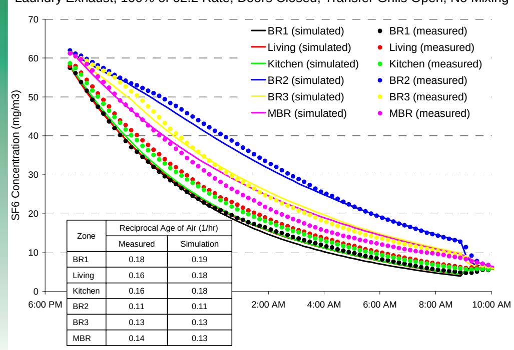
CONTAM Modeling, Nov. 2006-Jan. 2007



Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

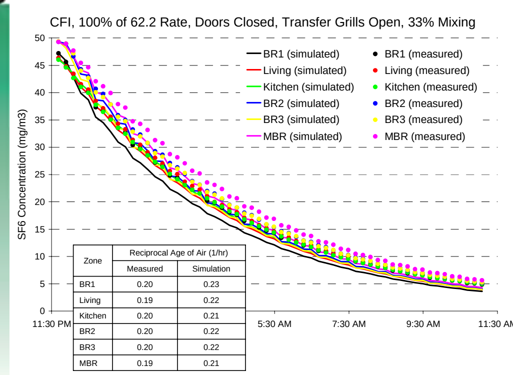
Example Results of Tuned CONTAM Model

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing



Example Results of Tuned CONTAM Model

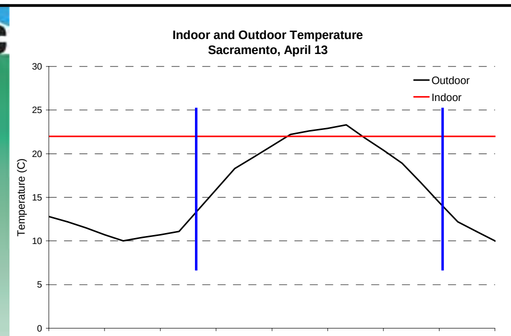
CFI, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, 33% Mixing



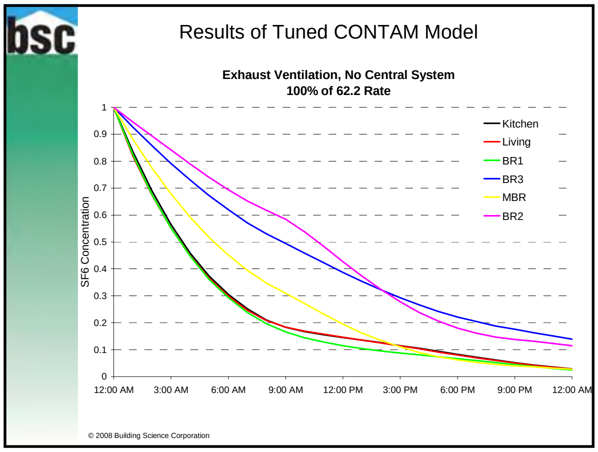
Tuned CONTAM Model Applied to Other Systems

Six Systems Evaluated & Compared:

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



Simulation allows identical weather conditions for each system (generally not possible in field tests).


bsc
Results of Tuned CONTAM Model
Exhaust Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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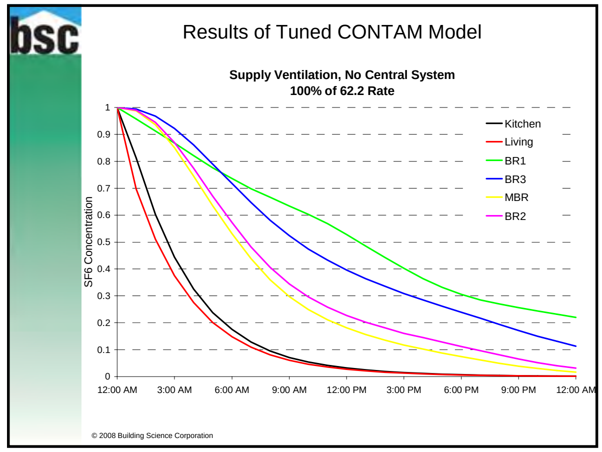
bsc
Results of Tuned CONTAM Model
Supply Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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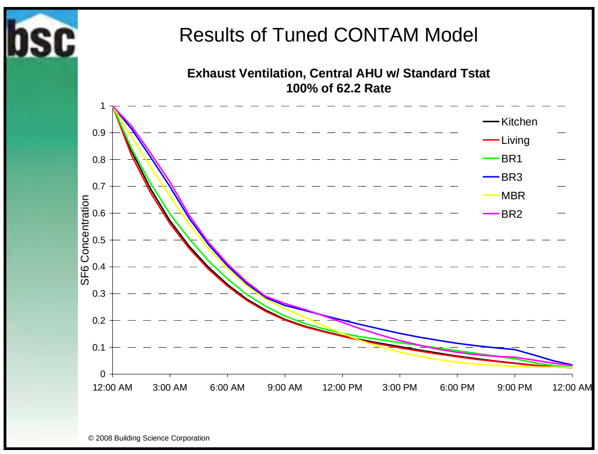
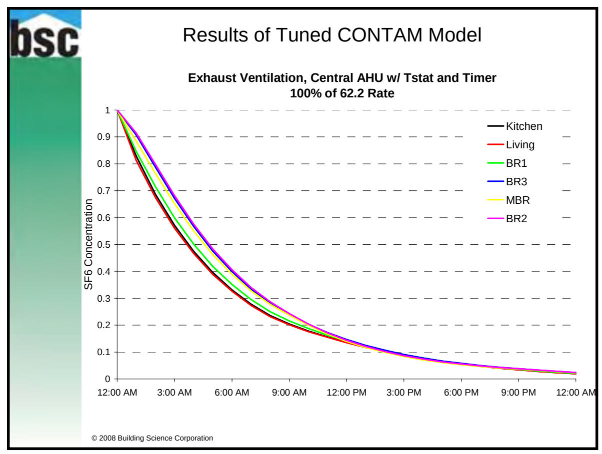

bsc
Results of Tuned CONTAM Model
Exhaust Ventilation, Central AHU w/ Standard Tstat
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
© 2008 Building Science Corporation


bsc
Results of Tuned CONTAM Model
Exhaust Ventilation, Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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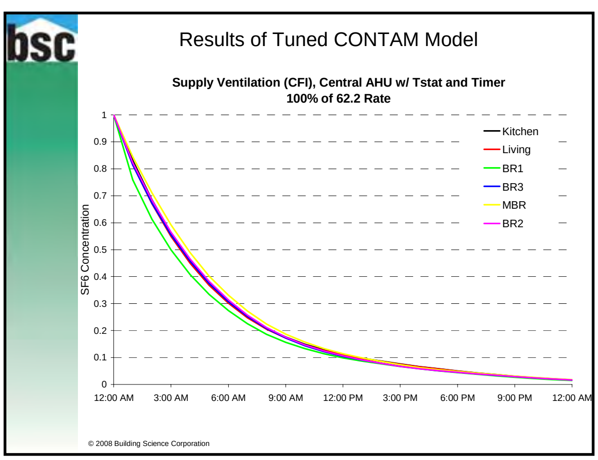
bsc
Results of Tuned CONTAM Model
Supply Ventilation (CFI), Central AHU w/ Tstat and Timer
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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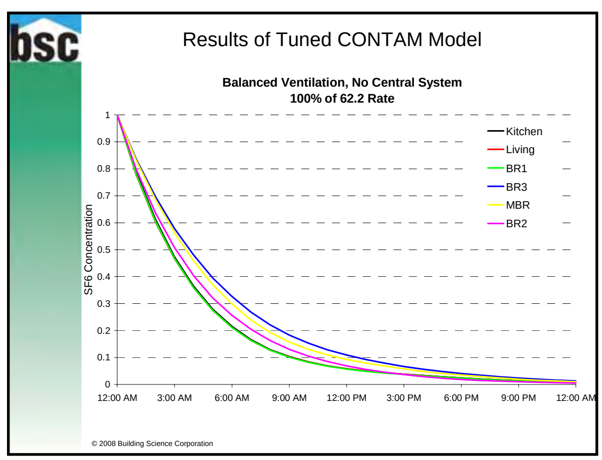
bsc
Results of Tuned CONTAM Model
Balanced Ventilation, No Central System
100% of 62.2 Rate
SF6 Concentration
Kitchen
Living
BR1
BR3
MBR
BR2
12:00 AM 3:00 AM 6:00 AM 9:00 AM 12:00 PM 3:00 PM 6:00 PM 9:00 PM 12:00 AM
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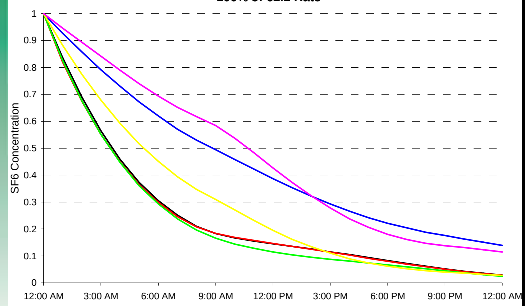
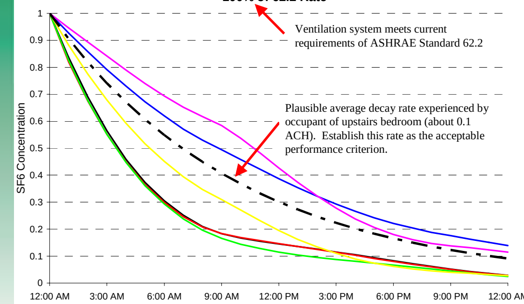
Adjusting Ventilation Rate to Achieve Equivalent Performance

Exhaust Ventilation, No Central System
100% of 62.2 Rate



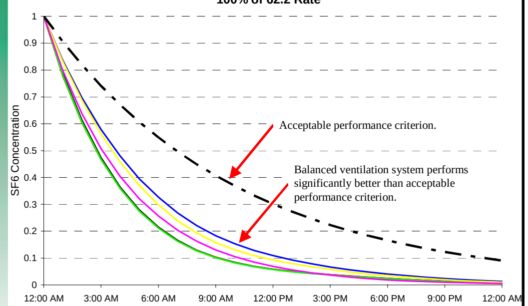
Adjusting Ventilation Rate to Achieve Equivalent Performance

Exhaust Ventilation, No Central System
100% of 62.2 Rate



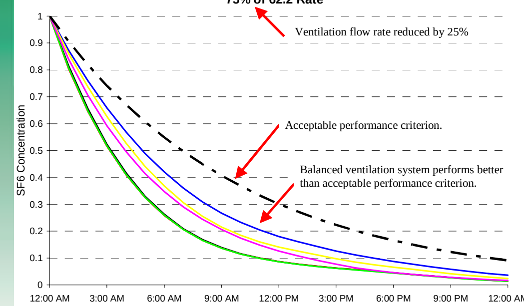
Adjusting Ventilation Rate to Achieve Equivalent Performance

Balanced Ventilation, No Central System
100% of 62.2 Rate



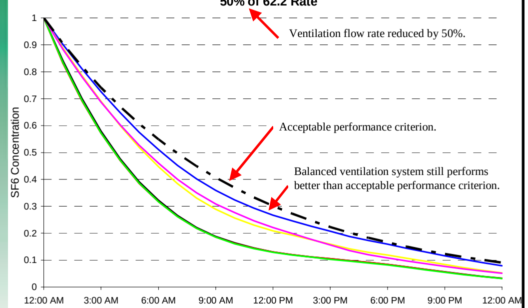
Adjusting Ventilation Rate to Achieve Equivalent Performance

Balanced Ventilation System, No Central System
75% of 62.2 Rate



Adjusting Ventilation Rate to Achieve Equivalent Performance

Balanced Ventilation, No Central System
50% of 62.2 Rate



Conclusions from Tuned CONTAM Model

1. Ventilation systems do not perform equally just because they have equal nominal airflow
2. Airflow requirements can be adjusted based on performance of each system
3. Further simulations were needed to predict year-round performance for general guidance
4. Can we create a “distribution coefficient” to modify the required airflow?

Next Steps

1. Comparison of 1 day in 1 house in 1 climate is useful but needs to be expanded before establishing general guidelines.
2. Expand modeling from 1 day in 1 house in 1 climate to full-year with various house characteristics (leakage, mechanical systems, etc) and different climates.
3. Methodology of simulations changed from decay to exposure
    1. Uniform generation of pollutant within house
    2. Assumed occupancy schedule
    3. Calculated 3-hr, 8-hr, and yearly average exposures

Model Characteristics

1. Specific model became more general
2. Vary certain parameters to cover reasonable subset of current construction
3. Include effects of:
    1. Wind
    2. Stack effect
    3. Ventilation systems
    4. Occupant schedule
    5. Pollutant generation

Modeling Assumptions: Weather

1. Temperature
    1. Outdoor temperature from TMY2 data
    2. Indoor temperature constant at 22 C
2. Wind
    1. Wind speed and direction from TMY2 data
    2. Wind shielding model and modifiers as described in ASHRAE Fundamentals 2005 Chapters 16 and 27 for typical suburban surroundings

Model Assumptions: Air Handler

1. Sizing per Manual J for each climate
2. Duty cycle each hour based on temperature and design temperature for the climate
    1. Maximum 80% runtime at design conditions
    2. Heating balance point = 65 F
    3. Cooling balance point = 75 F
3. Two cycles per hour
    1. Cycles rounded to nearest 5 minute increment (simulation time step = 5 minutes)

Model Assumptions: Envelope Leakage

1. Distribution
    1. Leakage distribution per ASHRAE Fundamentals Chapter 27
        1. Walls, windows, doors: 62%
        2. Ceilings & nonoperating exhaust vents: 23%
        3. Ducts: 15%
2. Total leakage varied as described later

Model Assumptions: Pollutant Generation

1. Uniform generation of unique pollutant in each room
    1. Generation rate proportional to room square footage (1 mg/hr/sf)
    2. Pollutants unique, but assumed identical in analysis presented later

Model Assumptions: Occupant Schedules

1. Assume similar schedule for each occupant:
   1. 10 PM to 7 AM: in bedroom with door closed
   2. 7 AM to 9 AM: in kitchen
   3. 9 AM to 12 PM: in living room
   4. 12 PM to 1 PM: in kitchen
   5. 1 PM to 6 PM: in living room
   6. 6 PM to 10 PM: in other bedrooms

2. Bedroom doors open except during sleeping period 10 PM to 7 AM

Varied Parameters

1. Climate
   1. Orlando (Daytona Beach)
   2. Minneapolis
   3. Seattle
   4. Phoenix
   5. Raleigh
2. Envelope leakage
   1. 1.5 ACH50 (R-2000)
   2. 3.5 ACH50 (Building America)
   3. 7 ACH50 (standard construction)

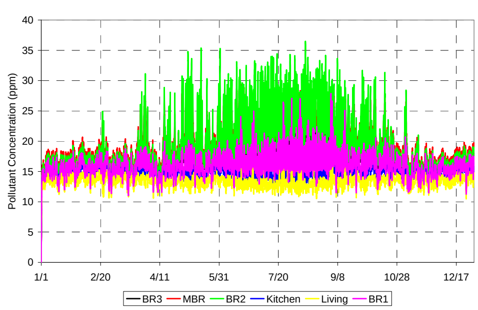
Varied Parameters

3. Central AHU System
   1. Not present
   2. In conditioned space
   3. Outside of conditioned space
4. AHU Schedule
   1. Standard thermostat
   2. Minimum runtime per hour (10 on/20 off)
5. Duct Leakage
   1. 6% of air handler flow
   2. 12% of air handler flow

Varied Parameters

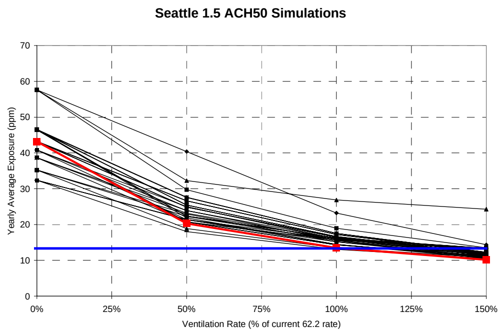
6. Ventilation System
   1. Single-point exhaust
   2. Single-point supply
   3. Dual-point balanced
   4. Fully-ducted balanced
7. Ventilation Rate
   1. 0, 50, 100, 150, 200% of current 62.2 rate

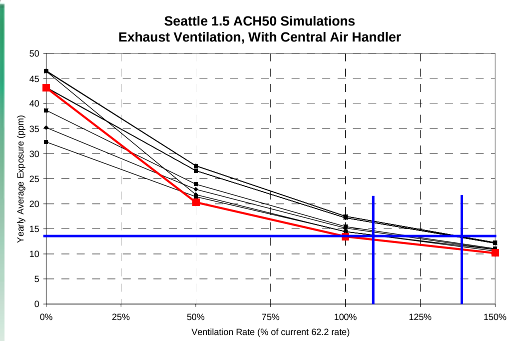
Total Pollutant Concentration by Room



Reference System

- Best available system: fully ducted, balanced ventilation system
- Compare other systems to this system: what ratio of airflows do other systems need to provide equal yearly average exposure?





Airflow Ratios—All Simulations

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

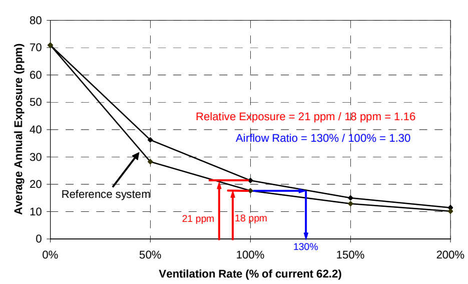
Questions From Long Beach

- How do these cases compare to the LBL cases (Iain & Max's cases)?
- What about oversized space conditioning systems?
- What is the effect of _____?

Comparison to LBL Metrics

- Relative Exposure vs Airflow Ratio
- Both are ratios used to help quantify effectiveness of different ventilation systems
- Relative Exposure: Ratio of exposures at the same nominal airflow (usually 100% of 62.2)
- Airflow Ratio: Ratio of airflows at the same exposure level (usually at the exposure at 100% of 62.2 of the reference system)

Relative Exposure vs Airflow Ratio



LBL Cases for Source & Occupant Distribution

1. Fully distributed sources & activities
2. Volume weighted sources, distributed activities
3. Worst case age-of-air (3 options)
4. Worst case
5. Remote contaminants

Ventilation Systems Compared

- Simple Exhaust
  - Single-point exhaust, no central mechanical system
- Central Fan Integrated
  - Central mechanical system with 10 minutes per 30 minute runtime, outside air duct to return plenum
- Exhaust With Constant Mixing
  - Single-point exhaust, with central system that runs 100% of the time

Apples and Oranges

LBL	BSC
Field measurements & calculation	Simulation from tuned model
Individual field tests (~4-12 hour duration each)	Year-long simulation
“Steady-state” for-real weather	TMY2 data
Leaky house in Tahoe	Leaky house in 5 climates
Tight house in Reno	Tight house in 5 climates
Different house plans	Same plan all climates
Separate tests with doors open and closed	Doors open and close on a daily schedule

Case 1: “Everybody Everywhere”

- Equal source in each zone (source strengths independent of zone sizes)
- Occupants spend equal time in each zone
- Exposure each hour is average of all zones

Case 1: “Everybody Everywhere”

Relative Exposure versus an identical house with perfect mixing

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

Case 2: Volume Weighted Sources

- Source strengths proportional to volume of each zone (meets age of air assumptions)
- Occupants spend equal time in each zone
- Exposure each hour is average of all zones

Case 2: Volume Weighted

Relative Exposure versus an identical house with perfect mixing

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

Case 3: Worst Age of Air

- Source strengths proportional to volume of each zone (meets age of air assumptions)
- Varying degrees of worst case:
  - Case A: Occupant in worst zone each hour
  - Case B: Occupant always in zone with worst yearly average
  - Case C: Occupant has worst exposure of all occupants in the house, assuming a daily schedule

Case 3: Worst Age of Air

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

Case 4: "I Stink"

- Single source in same zone as occupant
- Occupant stays in worst zone

Case 4: "I Stink"

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

Case 5: "You Stink"

- Single source different zone than occupant
- Worst combination of source zone and occupied zone

Case 5: "You Stink"

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

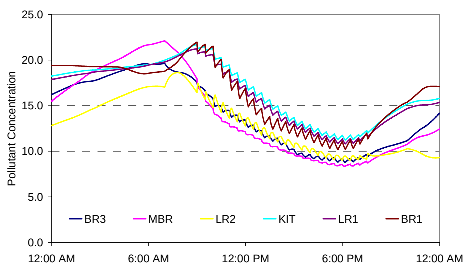
Exhaust with Mixing

	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

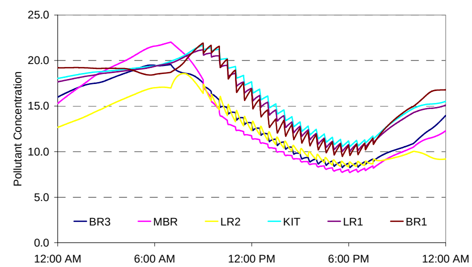
Effect of Oversized Systems

- Sizing generally doesn't matter (for mixing)
- Volume of air delivered to zone depends on:
  - Space conditioning load
  - Temperature of supply air
- Unless there is a minimum runtime, in which case the zone gets more mixing
  - But most zones are already well mixed by right-sized systems

Manual J Sizing

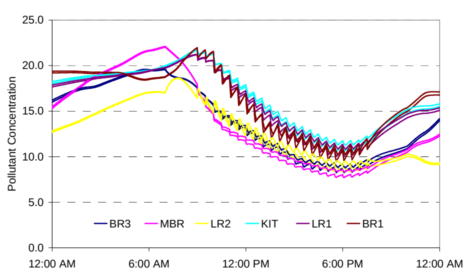


2x Manual J Sizing



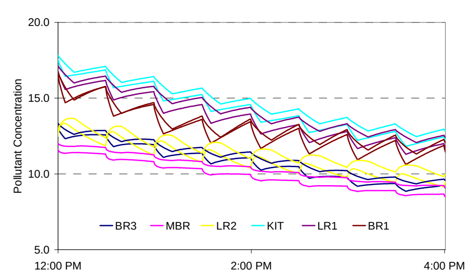
Notice any difference?

1x and 2x Manual J



Still need help?

Look Closely

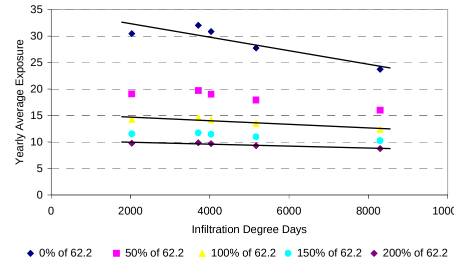


Oversizing means mixing happens faster but stops sooner—giving nearly identical results

What is the effect of ____?

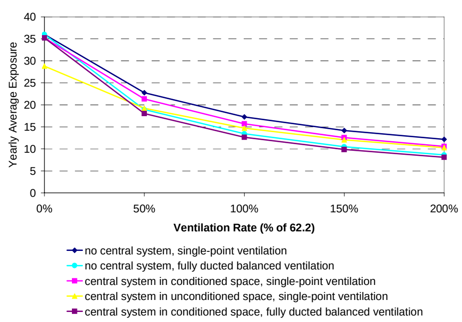
- Climate
- Central System
- Duct Leakage
- Minimum central system runtime
- Envelope tightness

Climate

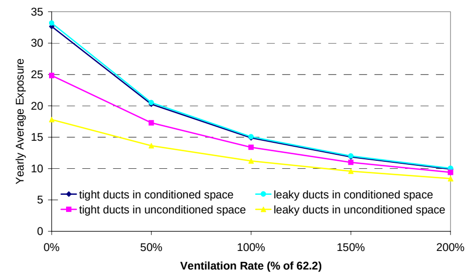


- Climate matters, but less so at high ventilation rates or with tight houses

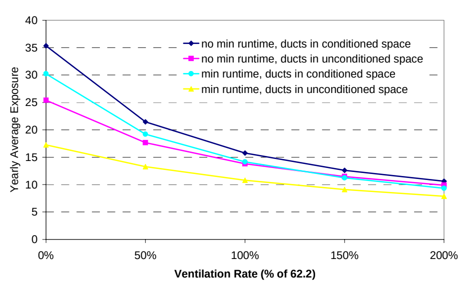
Central System



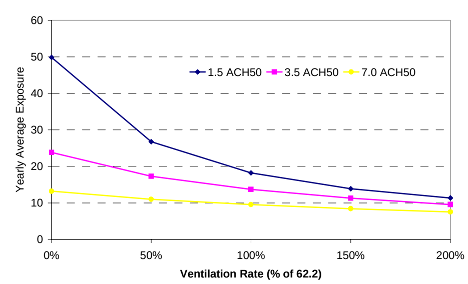
Duct Leakage



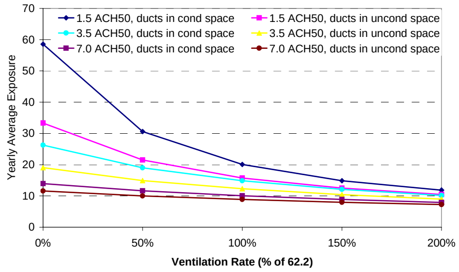
Minimum Runtime



Envelope Leakage



Envelope Leakage & Duct Leakage



- Similar results with minimum runtime (more difference with tight envelope)

Appendix H: Final Simulation Plan

Revised Simulation Plan and Assumptions for CONTAM Modeling

revision date 2/25/08

Model category	**Existing model assumptions**	**Revised model assumptions**
Simulation time step	5 min	No change
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)
Temperature	Outdoor temperature from TMY2 data Indoor temperature constant at 22 C (71.6)	No change
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
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.
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.
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
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.
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)
Building enclosure leakage rate	R-2000 house: 1.5 ach50 Building America house: 3.5 ach50 Standard house: 7 ach50	No change
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%
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
Airflow between zones[2] when interior doors are open	Modeled by forcing small (0.1 C) temperature difference between neighboring zones	No change
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.
Interior door scheduling	Bedroom doors open except during sleeping period 10 PM to 7 AM	No change

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)
Ventilation rates	Percent of 62.2 rate 7.5(Nbr+1)+0.01(CFA): 0, 50, 100, 150, 200	No change
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
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.

Revised Simulation Plan Output Table

		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)												

2.18.5. January 2009 Expert Meeting Summary Report

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

Building Science Corporation Industry Team

February 20, 2009

Work Performed Under Funding Opportunity Number:
DE-FC26-08NT00601

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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 23 January 2009 at the Hilton Hotel in Chicago, Illinois. 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 Dr. Jeffrey Siegel and Dr. Atila Novoselac of the University of Texas at Austin 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 always do.

5. Conclusions: The key gaps that remain are concerns by certain members of the 62.2 committee to certain aspects of the proposed changes, particularly assumptions about the contaminant sources and decisions regarding the appropriate magnitude of the system coefficients, and drafting and approval of a change to the ASHRAE Standard 62.2. The next steps involve continuing the dialogue with the committee members to further identify and address their concerns, and drafting and submission of a change proposal to the 62.2 committee. After these steps are complete, the ASHRAE 62.2 committee will be given the opportunity to adopt the suggested revisions into 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 23 January 2009 at the Hilton Hotel in Chicago, Illinois. 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 31 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 meeting is given in Appendix B. The presentations are included in Appendices C through F.

PRESENTATIONS

Speaker 1: Dr. Jeffrey Siegel, Department of Civil, Architectural, and Environmental Engineering, the University of Texas at Austin

Presenter bio: Dr. Jeffrey A. Siegel is an associate professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. He received his B.S. in Engineering from Swarthmore College in 1995 and his Ph.D. from U.C. Berkeley in Mechanical Engineering in 2002. Dr. Siegel and his research team have ongoing research on HVAC filtration, portable and passive air cleaners, particle resuspension, human exposure, and particle transport and deposition in HVAC systems. He is the recipient of the Early Career Award from the International Society for Exposure Assessment /American Chemistry Council, the 3M Non-Tenured Faculty Grant, and the ASHRAE New Investigator Award. He is the co-director of the National Science Foundation funded Integrative Graduate Education and Research Traineeship (IGERT) graduate program in Indoor Environmental Science and Engineering at The University of Texas. He is a voting member of TC 2.4, TC 6.3, SSPC 52.2, research subcommittee chair of TC2.4, and PI of RP1299 (Energy Implications of Filters in Residential and Light Commercial Buildings).

Presentation Title: *Pollutant Sources and Occupant Activities*

Presentation Summary:

Dr. Siegel presented the results of a literature review of indoor air contaminant sources. He gave examples of different categories of contaminant sources, such as area sources, point sources, and occupant-associated sources.

Dr. Siegel made the following key points during his presentation:

- Sources can roughly be divided into three categories: area sources, point sources, and occupant-associated sources; however these areas are roughly defined and some sources could be grouped in more than one category depending on the specific criteria used.
- The effect of an exposure to a contaminant depends on the contaminant and for many contaminants on the individual exposed as well. Because of this it is difficult to compare the impact of different contaminants.
- Area sources can be the dominant source of certain contaminants. These types of sources often decline in strength over time.
- Depending on the specific contaminant, point sources may decline over time or may remain constant.
- Occupant sources are very activity and contaminant dependent. The source strength of contaminants associated with an occupant's activities varies widely. The sources due to one occupant appear to be a point source from other occupants' perspectives.
- The National Human Activity Survey (NHAPS) is a significant resource for analyzing effects of human sources.
- The occupants are disproportionately exposed to occupant-generated sources due to their proximity and non-uniform mixing in the zone.
- There is little in the literature to suggest that fugitive emissions from items stored in kitchens and bathrooms (cleaning products, for example) are a significant source. Many of the emissions that occur in kitchens and bathrooms are a result of the occupant's activities while in those rooms. Cleaning products, etc, generally need ozone to react with to form harmful byproducts, and there is generally little ozone in the cabinets where they are stored.
- There is evidence that increasing ventilation rates causes higher emission rates from formaldehyde sources, such that the formaldehyde concentration does not change substantially.
- Dr. Siegel concludes that occupant-associated sources are often the dominant cause of exposure in homes.
- Dr. Siegel would like to see actual pollutants modeled instead of a single tracer-gas contaminant.
- Dr. Siegel would currently assume occupant activities account for 50-75% of total exposure.

<u>Questions and discussion during and after the presentation:</u>

The audience had several questions and comments during and after the discussion, which Dr. Siegel answered or discussed. The questions and comments were as follows:

- Q: How did the work presented define pollutant? A: Chemicals that are known to be harmful to humans.
- Q: How does one differentiate between emissions from humans themselves and emissions from their activities? A: It is mostly the activities, very little we personally emit is harmful.
- Q: How aggressive or conservative is this analysis? A: 50% would be the absolute lowest percentage exposure Dr. Siegel would expect to be due to occupant-generated sources.
- Q: What size particles did the analysis consider? A: PM10, PM2.5, ultrafine (1 nm)
- Q: Which contaminant species are the current dominant long-term health risks in residential settings? A: Formaldehyde and paradichlorobenzene.

- Q: Is there disproportionate exposure to either of these chemicals? A: Studies indicate no disproportionate exposure to formaldehyde but the Hispanic population is disproportionately exposed to paradichlorobenze, presumably due to higher tendencies to use the types of products that contain the chemical
- Q: How much difference is there between the occupant-generated emissions based on the actual activity level? Are the emissions while sleeping and moving around substantially different? A: The emissions rates are substantially higher while moving around but it is difficult to quantify how much. The NHAPS might be a good resource to try to determine occupant activities and typical locations.
- Q: Is the higher exposure of the Hispanic population due to increased use of moth crystals? A: Only one study looked at this question and it suggested that increased use of toilet bowl deodorizers was the most likely reason.

Speaker 2: Dr. Atila Novoselac, Department of Civil, Architectural, and Environmental Engineering, the University of Texas at Austin

Presenter bio: Dr. Atila Novoselac is an assistant professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. His research encompasses analysis of pollutant transport in indoor environments, human exposure studies, and development and experimental validation of models for air and particle dynamics. He has developed several indoor air quality indicators for evaluation of various air mixing and stratified ventilation systems. His current work includes studies related to the effects that the human microenvironment and ventilation type have on human exposure to gaseous and particulate contaminants. Dr. Novoselac is very active in ASHRAE indoor environmental modeling and room air distribution technical committees (voting member in TCs 5.3 and 4.10). He is also a corresponding member of TCs 4.3 and 4.7, and PI on the RP1416 project sponsored by ASHRAE (Development of Internal Surface Convection Correlations for Energy and Load Calculation Methods).

Presentation Title: *Contaminant Generation and Spatial Ventilation Effectiveness: How do Sources Relate to Human Exposure?*

Presentation Summary:

Dr. Novoselac presented data on the impact of the thermal plume that exists around a person sitting in a still air environment. This thermal plume draws contaminants into the person's breathing zone that would otherwise remain outside the breathing zone.

Dr. Novoselac made the following key points during his presentation:

- Personal exposure depends on the local concentration of the pollutants in a person's breathing zone.
- The local concentration of pollutants in a person's breathing zone can be different than the average concentration in the room, due to the thermal plume caused by the person's body heat.
- The thermal plume is important when the air is still, but is not when there is a fan or other mechanism for actively moving air within the space.

- His research includes both computer modeling (CFD) and physical testing.
- The location of a source in relation to the person and thermal plume has an important impact on the person's exposure to the contaminant.
- In a test house, their work determined that buoyancy-driven flow (i.e. the thermal plume) was the dominant flow mechanism when the central air handler was not operating.
- An assumption of well-mixed zones may be a bad assumption in a house without an operating air handler. Non-uniform mixing will generally increase the exposure to the occupant.

Questions and discussion during and after the presentation:

Dr. Novoselac answered the following questions and comments after his presentation:

- Q: What is a typical air velocity in the thermal plume? A: Approximately 0.5 feet per second.

Speaker 3: Aaron Townsend, Building Science Corporation

Presenter bio: Aaron Townsend is an Associate with Building Science Corporation. He has worked for Building Science for five years, where he focuses on 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: *System Coefficients: Where Have We Been and Where Are We Going?*

Presentation Summary:

Townsend reviewed the work to date towards establishing a system coefficient for the 62.2 standard. This history includes:

- Development of a CONTAM airflow network model and comparison to measurements from field tests of a production Building America house in Sacramento in January 2006
- Presentation of these results at the ventilation expert meeting in January 2006
- Modification and presentation of results for and after expert meetings in January and June 2007 as well as in January and June 2008
- Conference calls in between meetings to consult with participating 62.2 committee members and present results of additional work

Townsend also presented the results of one additional ventilation system that was modeled since the previous meeting. This system was a two-point exhaust system with an exhaust point on each of the two floors in the house. Townsend then presented a sensitivity analysis on effect of the source scenario on the ventilation system coefficients. Townsend made the following points during this part of the presentation:

- The sensitivity analysis examined the effect of mixing the three initial (or "pure") source assumptions in different ratios.
- The first pure scenario (volume-weighted sources) has about 25% of the emissions in the kitchens and bathrooms.
- The third pure scenario (occupant-generated sources) has about 15% of the emissions in the kitchens and bathrooms.

- Seven blends of the pure scenarios were presented. The blends chosen ranged from heavily dominated by volume-weighted and occupant-generated contaminants (50-50 split) to evenly divided between the volume-weighted, kitchens and bathrooms, and occupant-generated sources (1/3 each).
- The resulting coefficient tables for each of the pure and blended scenarios were presented and discussed. Increasing the ratio of occupant-generated contaminants resulted in lower system coefficients for ventilation systems with minimum turnover requirements and higher system coefficients for ventilation systems without a central air handling system.

<u>Questions and discussion during and after the presentation:</u>

Townsend answered the following questions and comments after his presentation:

- Q: Have there been more houses compared to this model? A: Yes, the results presented by Max Sherman and Iain Walker of LBNL were compared to results from this model, with good agreement given the differences in approach.
- Q: The sources in the model do not vary with time? A: Correct, the sources in the current model do not vary with time. It is within the model's capabilities but was not done in order to keep the results independent of a particular contaminant species.

GENERAL DISCUSSION

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

- A proposal was made to assign system coefficient values simply: all systems with minimum turnover or balanced ventilation get values of 1.0 and all others get values of 1.5. The general response to this proposal was that it was too general and ignored some of the differences between systems, such as the effect of ducting.
- A proposal was made to use the blended scenario with 1/3 of each of the pure scenarios, but to scale the coefficients down such that all the values of 1.33 became 1.25 and all the values of 1.65 became 1.5. The general response to this proposal was positive, in that the audience was receptive to the idea of reducing the penalty of the poorer-performing systems.
- Another proposal was made to have 3 categories: a balanced ventilation system with a minimum turnover has a coefficient of 1.0; a system that is either balanced or has a minimum turnover (but not both) has a coefficient of 1.25; and a system with neither balanced nor minimum turnover has a coefficient of 1.5. The general response to this proposal was mixed, as it ignores some differences seen in the presented results.

FOLLOW-UP WORK

Further discussion and work occurred after the SSPC 62.2 meeting. The concept of scaling back the magnitude of the coefficients to the range of 1.0 to 1.5 is being pursued. BSC is collaborating with Bruce Wilcox and Steve Emmerich to present the data in different ways (as requested by the committee) and to advance the proposed change to the 62.2 standard.

Appendix A: Expert Meeting Agenda

INVITATION and AGENDA

Building America Expert Meeting

CONTAMINANT GENERATION AND SPATIAL VENTILATION EFFECTIVENESS

Meeting Manager: Armin Rudd, Building Science Corp.
Date/Time: **Friday, 23 January 2009, 8:00 am to 12 pm**
(light breakfast refreshments after 7:30 am)
Location: Chicago, ASHRAE Winter Meeting
Hilton Hotel, **Grant Park** meeting room

Featured Speakers:

- Jeffrey Siegel and Atila Novoselac, Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin
- Aaron Townsend, Building Science Corp.

The objective of this session is to present and discuss recent experimental and modeling research on indoor air quality, with a particular focus on occupant activity, sources associated with occupants, and exposure to pollutants in residential indoor environments. The goal is to describe the state-of-the-art research in this field so that the Building America and Standard 62.2 communities can make informed decisions in assessing ventilation systems and distribution of ventilation air.

Key questions regarding this meeting:

1. What are the main pollutant sources and how do they relate to occupant activities? (Siegel)
The goal of this part of the presentation is to summarize recent literature on important sources of pollutants in homes. Many of the sources are either emitted directly by occupants or caused by their activities. This has important ramifications for assessing human exposure and the impact of ventilation. Pollutant sources will be associated with data from the National Human Activity Pattern Survey (NHAPS) which characterizes the duration and nature of occupant activities in their homes.

2. How do sources relate to human exposure? (Novoselac)
Given that many important sources are caused by the occupants themselves, this part of the presentation will show recent and ongoing research that demonstrates that for many of the pollutants associated with human activities, occupants have higher exposures than are usually assumed. Factors that increase exposure include air flows driven by thermal plumes, non-uniform mixing, and source-occupant proximity. The connection

between exposure, source position, ventilation flow rates and air distribution will also be explored.

3. How should source generation scenarios be treated for use in determining spatial ventilation effectiveness factors in ASHRAE Standard 62.2? (Townsend)
The ASHRAE SSPC 62.2 Committee has evaluated a number of iterations of CONTAM modeling results on this topic. Analysis and discussion continues to inform the process.

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

- Presentations

    - 8:05 to 8:35, (30 min) Jeffrey Siegel, *Indoor pollutant sources and their relation to occupant activities*.
    - 8:35 to 8:45, (10 min) Questions and discussion

    - 8:45 to 9:15, (30 min) Atila Novoselac, *Indoor pollutant sources and their relation to human exposure*.
    - 9:15 to 9:25, (10 min) Questions and discussion

    - 9:25 to 9:40, (15 min) Break

    - 9:40 to 10:10 (30 min) Aaron Townsend, *CONTAM simulations to evaluate the effect of ventilation system interactions on occupant exposure to indoor contaminants*
    - 10:10 to 10:20 (10 Min) Questions and Discussion

- Group discussion, 10:20 to 11:45

- Wrap up, action items, and follow-up plan, 11:45 to 12:00

Bios

Dr. Jeffrey A. Siegel is an associate professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. He received his B.S. in Engineering from Swarthmore College in 1995 and his Ph.D. from U.C. Berkeley in Mechanical Engineering in 2002. Dr. Siegel and his research team have ongoing research on HVAC filtration, portable and passive air cleaners, particle resuspension, human exposure, and particle transport and deposition in HVAC systems. He is the recipient of the Early Career Award from the International Society for Exposure Assessment /American Chemistry Council, the 3M Non-Tenured Faculty Grant, and the ASHRAE New Investigator Award. He is the co-director of the National Science Foundation funded Integrative Graduate Education and Research Traineeship (IGERT) graduate program in Indoor Environmental Science and Engineering at The University of Texas. He is a voting member of TC 2.4, TC 6.3, SSPC 52.2, research subcommittee chair of TC2.4, and PI of RP1299 (Energy Implications of Filters in Residential and Light Commercial Buildings).

Website: http://www.ce.utexas.edu/prof/siegel/
IGERT Website: http://www.caee.utexas.edu/igert/

Dr. Atila Novoselac is an assistant professor in the Department of Civil, Architectural, and Environmental Engineering at The University of Texas at Austin. His research encompasses analysis of pollutant transport in indoor environments, human exposure studies, and development and experimental validation of models for air and particle dynamics. He has developed several indoor air quality indicators for evaluation of various air mixing and stratified ventilation systems. His current work includes studies related to the effects that the human microenvironment and ventilation type have on human exposure to gaseous and particulate contaminants. Dr. Novoselac is very active in ASHRAE indoor environmental modeling and room air distribution technical committees (voting member in TCs 5.3 and 4.10). He is also a corresponding member of TCs 4.3 and 4.7, and PI on the RP1416 project sponsored by ASHRAE (Development of Internal Surface Convection Correlations for Energy and Load Calculation Methods).

Website: http://www.ce.utexas.edu/prof/novoselac/

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

Building America Ventilation Expert Meeting
Invitee/Attendee List
Building Science Corporation
January 23, 2009

Last name	First name	Company	Present 1/23/2009
Anderson	Ren	NREL	
Atif	Morad	NRC	
Baxter	Van	ORNL	x
Bloemer	John	Research Products Corp.	
Brandt	Donald	Brandt Training	
Brennan	Terry	Camroden Associates	
Cardenal	Bernardo	Rocamar Engineering	
Carlson	Steve	CDH Energy	
Chandra	Subrato	Florida Solar Energy Center	
Christensen	Dane	NREL	x
Christensen	Dane	NREL	x
Crawford	Roy	Trane	x
Delaquila	David	GAMA	
DeLaura	Lance	Southern California Gas Co.	
Dietz	Dennis	American Aldes Ventilation	x
Dobbs	Gregory	United Technologies Research Center	x
Drumheller	Craig	NAHB Research Center	
Emmerich	Steve	NIST	x
Fairey	Philip	FSEC	x
Ferris	Rob	Fantech	
Flynn	Victor	Panasonic	
Forest	Daniel	Venmar Ventilation	x
Francisco	Paul	University of Illinois-UC	x
Fugler	Don	Canada Mortgage and Housing Corp.	
Gawlik	Keith	NREL	
George	Marquam	Blu Spruce Construction	
Glenn	Langan	Southern Company	
Goel	Rakesh	Lennox	
Griffiths	Dianne	Steven Winter Associates	
Grimsrud	David		
Hammon	Rob	Consol	
Harrell	John	American Aldes Ventilation	
Hedrick	Roger	Gard Analytics	
Heidel	Tom	Broan-Nutone	x
Henderson	Hugh	CDH Energy	
Hendron	Robert	NREL	x
Hoeschele	Marc	Davis Energy	x
Hoeschele	Marc	Davis Energy Group	x
Holton	John		
Jackson	Mark	Lennox	x
James	George	USDOE	
Karg	Rick	R.J.Karg Associates	
Keller	Fred	Carrier	
Kenney	Tom	NAHB Research Center	
Kosar	Douglas	University of Illinois-Chicago	x
LaLiberte	Mark	Building Knowledge	
Langan	Glenn	Gulf Power-Southern Co.	x

Logee	Terry	USDOE	
Lstiburek	Joseph	Building Science Corp.	x
Lubliner	Mike	Washington State University	
Lyons	Jamie	Newport Partners	
Malone	Jane	Alliance for Healthy Homes	
Moore	Mike	Newport Partners	x
Neilsen	Patrick	Broan-Nutone	
Nelson	Gary	Energy Conservatory	x
Novoselac	Atila	UT-Austin	
Oberg	Brad	IBACOS	
Offermann	Bud	Indoor Environmental Engineering	
Olesen	Bjarne	Denmark Technical University	
Olson	Collin	Energy Conservatory	
Patenuaude	Raymond	The Holmes Agency	
Persily	Andrew	NIST	
Pettit	Betsy	Building Science Corp.	
Phillips	Bert	Unies Ltd.	
Poirier	Bertrand	Fantech	x
Pollock	Ed	USDOE	
Prahl	Duncan	IBACOS	
Price	David	USEPA	
Proctor	John	Proctor Engineering	
Puttagunta	Srikanth	Steven Winter Associates	x
Ranfone	James	AGA	
Rashkin	Sam	USEPA	
Raymer	Paul	Heyoka Solutions	x
Reardon	James	National Research Council Canada	
Rittelmann	Bill	IBACOS	
Rudd	Armin	Building Science Corp.	
Ryan	William	Univ of Illinois	
Sachs	Harvey	ACEEE	
Sagan	Kenneth	NAHB	
Schumacher	Chris	Building Sceince Consulting	
Shah	Raj	Carrier	
Sherman	Max	LBNL	x
Siegel	Jeffrey	UT-Austin	
Springer	David	Davis Energy Group	
Stamatopoulos	Anthony	IBACOS	
Stevens	Don	Panasonic	x
Straube	John	Building Science Corp.	
Stroud	Thomas	Health Patio & Barbeque Assoc	
Talbot	John		
Taylor	Sam	USDOE	x
Thompson	Rob	USEPA	
Townsend	Aaron	Building Science Corp.	x
Uselton	Dutch	Lennox	
Walker	Iain	LBNL	x
Weber	Mark	ASHRAE	
Werling	Eric	USEPA	x
Wettergren	Ola	Fantech	
Wilcox	Bruce		x
Williams	Ted	AGA	x
Wojcieson	Ray	Lennox	

Appendix C: Introductory Presentation

Building America Expert Meeting

CONTAMINANT GENERATION AND SPATIAL VENTILATION EFFECTIVENESS

Friday, 23 January 2009
8:00 am to 12 pm
in conjunction with the ASHRAE Winter Meeting
Chicago, Hilton Hotel, Grant Park meeting room

Featured Speakers

- Jeffrey Siegel and Atila Novoselac

  Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin
- Aaron Townsend

  Building Science Corp.

Key questions

- *What are the main pollutant sources and how do they relate to occupant activities?*
- *How do sources relate to human exposure?*
- *How should source generation scenarios be treated for use in determining spatial ventilation effectiveness factors in ASHRAE Standard 62.2?*

Development of BA Dehumidification Performance Standard

- Field testing ongoing 2008
- Lab testing to begin at NREL
- Working Group meetings June and October 2008
  - Longer term goal of industry based test procedure
    - need to establish industry partnerships to move this forward
  - Focus on development and consensus for:
    - Workable strategy for standards development/improvement
      - ANSI-ARI 210/240 (Performance Rating Of Unitary Airconditioning And Airsource Heat Pump Equipment)
      - ASHRAE 37 (Methods of Testing for Rating Electrically Driven Unitary Air-Conditioning and Heat Pump Equipment)
    - Indoor humidity control criteria
    - Field test design
    - Lab test design
- Expert Meeting: 2009 ASHRAE Summer Annual Meeting
- BA Quarterly Meeting October 2009
  - Draft Industry-based Test Procedure
- Industry Test Procedure by October 2010

Appendix D: Presentation 1

Pollutant Sources and Occupant Activities

Jeffrey Siegel
Department of Civil, Architectural, and Environmental Engineering
The University of Texas at Austin

IGERT: Indoor Environmental Science & Engineering
The University of Texas

Motivation

- How much residential indoor pollution is associate with occupant activities?
- Framework for exploring this question
- Literature and research that informs answer
  - National Human Activity Pattern Survey (NHAPS)
  - Indoor sources of interest
- Specific comments for Standard 62.2 about sources

My Confession

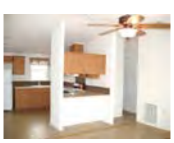
I ♥ dirty filters

An Anecdote

- Collecting used filters to explore their role as "passive" samplers
  - Subject filter cake to a variety of chemical and biological tests

  Noris et al. (2008) *Indoor Air 2008 Proc.*, Noris et al. (2009) *ASHRAE Trans.*
- Conducted tests in eight residences
- Conducted follow-up measurements in unoccupied test house
  - Test house is near two major highways
  - Minimal activity (occasional visits by students)

UTest House



- Two systems
  - 910±60 CFM each system
  - Fans ran continuously
  - High-efficiency (MERV 11) filters
  - Filter ΔP (Pa) after 30 days

	Clean	Dirty
Upflow	76±1.1	79±1.1
Downflow	83±1.2	85±1.2

Hypothesis

- Occupants are responsible for most indoor air pollution
  - Details of exact split are building, occupant, and pollutant specific

Framework

Source → Exposure → Impact

Other fates:
Exfiltration
Removal by ventilation
Chemical reaction
Deposition

Very difficult to "equate" pollutants

Functions of space and time

Different Types of Sources

- Area sources
  - Examples: new carpet, paint (Brown, 2002, *Indoor Air*)
- Point sources
  - Examples: cleaning products, plug-in air freshener (Nazaroff and Weschler, 2004, *Atmos. Environ.*; Singer et al., 2006, *Indoor Air*)
- Occupant sources
  - Examples: vacuuming, walking, cooking, showering (Corsi et al., 2008, *JOEH*; Thatcher and Layton, 1995, *Atmos. Environ.*; Qian and Ferro, 2008, *AS&T*; Wallace et al., 2008, *ES&T*; Moya et al., 1999, *ES&T*)
- Acknowledgment: Lots of grey areas

Area Sources

1. **Can** be dominant source of a pollutant
2. Tend to decline with age (Brown, 2002, *Indoor Air*)
   - Texanol from paint (Lin and Corsi, 2007, *Atmos. Environ.*)
   - VOCs from carpet (Brown, 2002, *Indoor Air*)
   - Not exclusively true (Hodgson et al., 2000, *Indoor Air*)

Point Sources

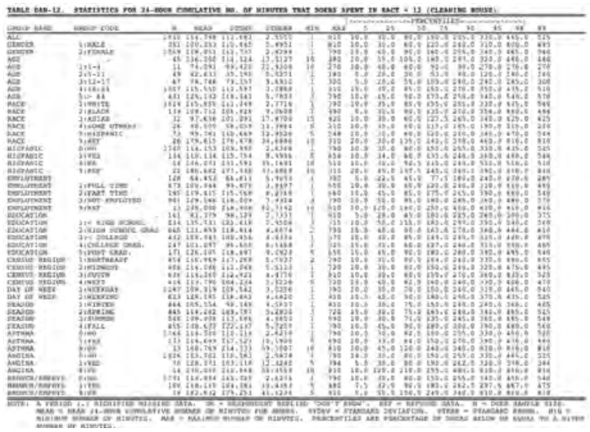
1. Some decline with age
   - VOCs (many) from computers (Destaillats, 2008, *Atmos. Environ.*)
   - Formaldehyde emissions from furniture
2. Others stay approximately constant
   - Ozone emissions from air cleaners (Waring et al, 2008, *Atmos. Environ.*)
   - Plug-in air fresheners (Singer et al., 2006, *Indoor Air*)
   - Particles from scented candles (Lee et al., 2006, *Atmos. Environ.*)

Occupant Sources

1. Very activity and pollutant dependent
   - Cooking as a source of ultrafine particles and NO_x (Wallace et al., 2008, *ES&T*; Baxter et al., 2007, *JESEE*)
   - Walking (resuspension) as a source of allergens (Thatcher and Layton, 1995, *Atmos. Environ.*; Qian and Ferro, 2008, *AS&T*)
   - Ozone reactions with personal care products and skin oils (Corsi et al., 2007, *Atmos Environ*; Wisthaler et al., 2005 *ES&T*)
2. Looks like a point source to other occupants

What do we know about human activities?

- Activities → Occupant sources
- National Human Activity Pattern Survey
  - 9,386 subjects (diverse regionally and demographically)
  - Two types of questions: detailed diaries and survey questions
  - Huge dataset - lots of tools for analyzing
  - Good summary: Klepeis et al. (1999) *Environ. Health Persp.*
  - Canadians have successfully infiltrated: Leech (2002) *JEAEE*
  - Detailed data: Tsang and Klepeis (1996) *EPA/600/R-96/148*



Analysis

$$avg.\ time\ spend\ doing\ activity = \frac{\#\ of\ \ doers}{sample\ size} \times avg.\ time$$

- Extremely conservative assessment: 100 min/day
- Does not account for
  - Others exposed to source (e.g., eating in kitchen)
  - Activities that aren't characterized enough or at all in NHAPS (e.g., housework)
  - Sources that are hard to assess (ozone reactions)

Why focus on occupant sources?

1. Area sources often decline with age
   - Diminishes their importance
2. Occupants spend time near point sources
   - If you are ventilating for occupants, you will get these sources
3. Many/most of our activities generate pollution
4. We are disproportionally exposed to occupant sources

What is the split?

- It depends ...
- If you consider potency and proximity and activity
  - 50 - 75% of all exposure is directly related to us "dirty beasts"

Standard 62.2 Comments

- Why focus on kitchens and bathrooms, rather than on occupants?
- Kitchens
  - Occupant sources: cooking, dishwashing, cleaning, dishwashers
  - Point sources: Cleaning product storage - closed containers, limited ozone reactions
- Bathrooms
  - Occupant sources: showering, personal care, cleaning
  - Point sources: Personal care product storage

Why focus on single pollutant approach?

- Pollutants deposit/sorb/react - transport properties are very different
- Pollutant health effects are dramatically different and generally not well studied
  - Not even sure of a suitable comparison metric

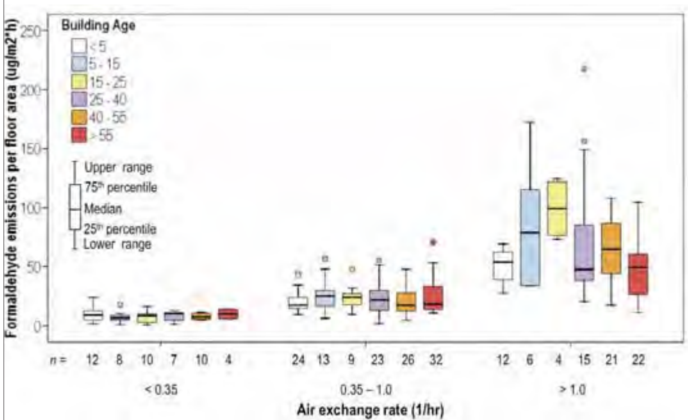
Transport

Pollutant	Example/Source	Typ. Loss Rate
1 nm particle	Cooking	5/hr
0.1 μm particle	Candle	0.05/hr
10 μm particle	Vacuuming	4/hr
Reactive Gas	Ozone/outdoors	2.8 - 4/hr
Unreactive Gas	CO_2/occupants	~0

Transport influences exposure and ventilation

Health Effects

- Data from RIOPA study
  - ~300 homes in Houston, Elizabeth, Los Angeles
  - Indoor, outdoor, personal concentration measurements
- Dominant cancer risks (VOCs and aldehydes only)
  Hun et al. (2008) *Indoor Air Conf.*
  - Formaldehyde (personal conc. > indoor conc.)
  - *para*-dichlorobenzene
    - Snake repellent, moth crystals, toilet bowl deodorizers
    - Hispanic population is particularly exposed



Conclusions

- Occupant sources are important and are often dominant causes of exposure in homes
  - Ventilation strategies should reflect this fact
- A single-pollutant approach is not likely to yield correct answers in any model

Appendix E: Presentation 2

Contaminant Generation and Spatial Ventilation Effectiveness

How do Sources Relate to Human Exposure?

Presenter: Atila Novoselac
The University of Texas at Austin

Building America Expert Meeting
Chicago, January 23rd 2009

INTRODUCTION

Personal exposure depending on:

Indoor airflow
- Ventilation rate
- Airflow distribution

Pollutant characteristics
- Properties
  - Gases: reactive noncreative
  - Particles: different sizes
- Position

Occupant activity
- Movement
- Breathing

OBJECTIVES

Specific presentation objectives:

- Show the impact that thermal plume has on airflow and pollutant concentration in human vicinity
- Present the transport mechanisms from source location to the occupant breathing zone for different pollutants and airflows
- Point out the impact that ventilation effectiveness and pollutant source have on human exposure

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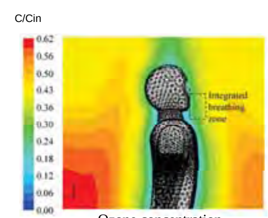
RESEARCH METHODOLOGY

We use advantage of both:

1) Experiments
- Realistic environment
- Reliable first-hand data

2) Numerical Simulations
- Detailed results
- Perfect repeatability

Particle exposure

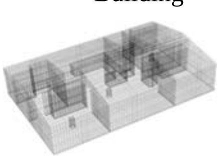


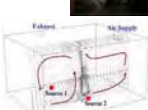
Ozone concentration

RESEARCH METHODOLOGY

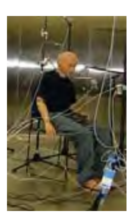
Different scales:

Building





Room



Occupant vicinity

RESULTS

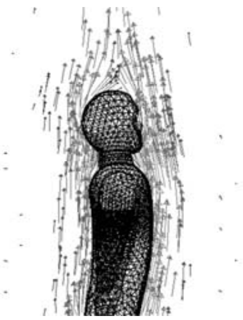
Examples from studies related to:

1) Transport of Particulate and Gaseous Pollutants in the Vicinity of a Human Body under Mixing and Buoyancy Driven Flow

2) Ventilation Effectiveness as an Indicator of Occupant Exposure to Indoor Pollutants

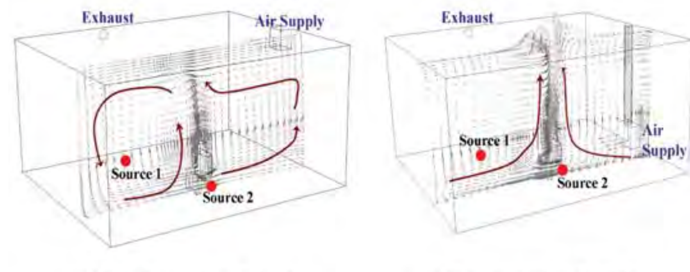
3) Pollutant Distribution in Multizone Residential Buildings with Portable Air Cleaning Devices

RESULTS: Effect of Thermal Plume



RESULTS: Effect of room airflow

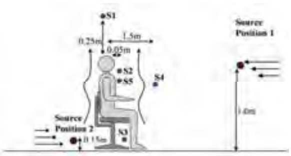
Example of airflow patterns in a space with dominant a) forced and b) natural convection



(a) Forced convection air supply — (b) Low-momentum air supply

HVAC on: mixed flow — Infiltration: stratified flow

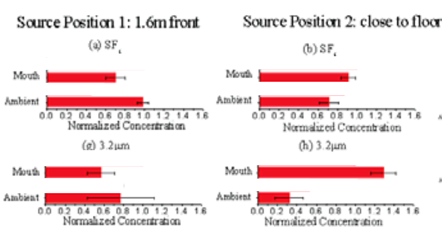
RESULTS: Effect of: Airflow & Source Position



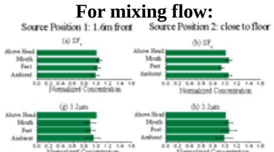
Constant Source Intensity

Ambient: Concentration in the vicinity of the thermal manikin but without the thermal plume

For stratified (buoyancy driven) flow:

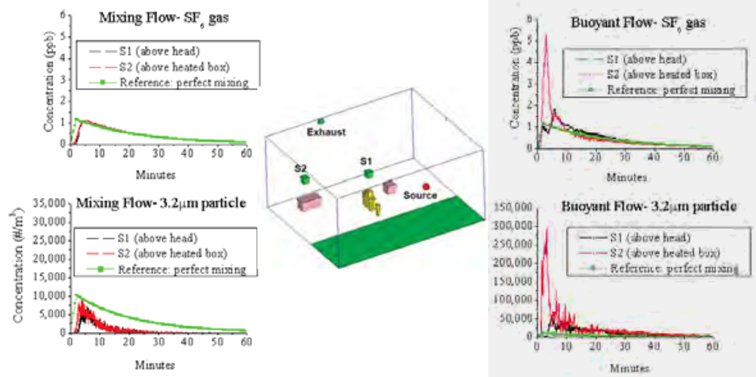


For mixing flow:



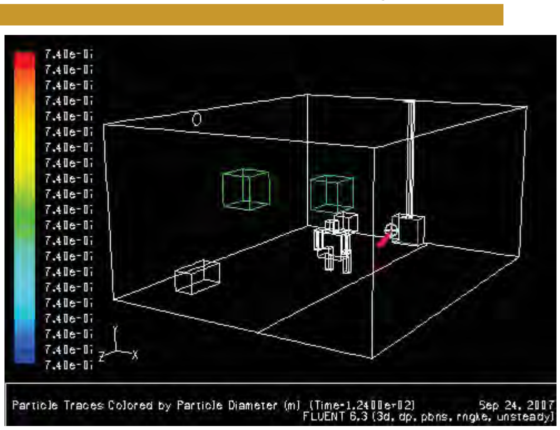
RESULTS: Effect of Source Dynamics

Short Source Emission 2 min



Same flow rate

RESULTS: Effect of Source Dynamics



Intermittent source and buoyancy driven flow result in higher exposure

RESULTS: Ventilation Effectiveness (VE)

Air-change Effectiveness as exposure indicator ?

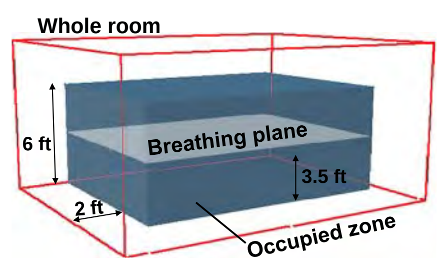
Air-change Effectiveness

$$\frac{\text{Average age of air in space}}{\text{Age of air at exhaust}}$$

For perfect mixing:
Air-change Effectiveness = 1

Exposure to most common:

1) Gaseous pollutants
2) Particles



Differences of Air-change Effectiveness defined for room occupied zone and breathing plane vary up to 25%

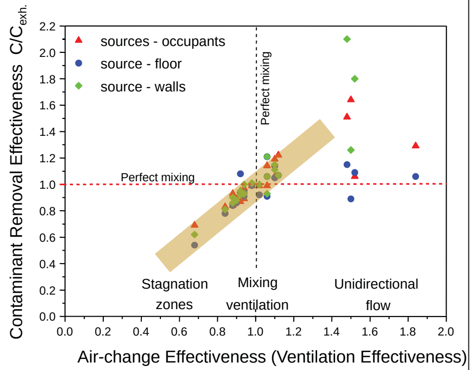
RESULTS: Ventilation Effectiveness (VE)

For Gases

Space types:
- personal office
- cubical office
- classroom
- residential room

Ventilation strategies:
- mixing
- stratified flow

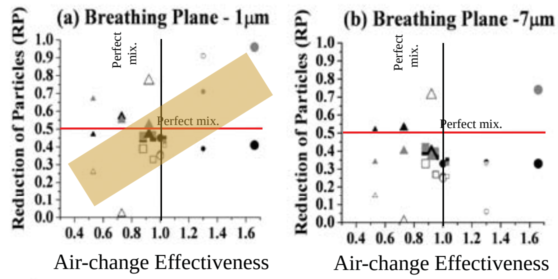
Different sources:
- occupants
- floor
- walls



RESULTS: Ventilation Effectiveness (VE)

For Particles

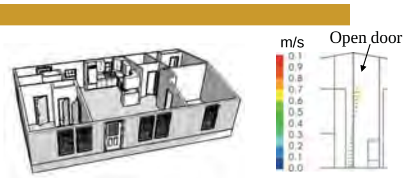
$$RP = \frac{1}{1 + \int C/C_{perf.mix}}$$



Airflow pattern (Symbol shape)	Air exchange rate (Symbol size)	Source location (Symbol color)
● Floor Supply	• $1.9 hr^{-1}$	● Floor Source
■ Ceiling Supply	● $3.9 hr^{-1}$	● Occupant thermal plume
▲ All Air-heating	● $7.7 hr^{-1}$	○ Momentum source

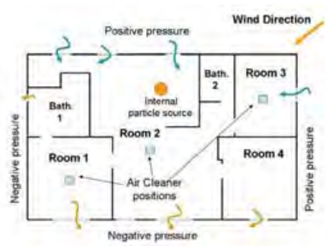
RESULTS: Pollutant Distribution in Homes

Air and particle mixing in a residence with and without portable air cleaning devices



House with open doors ~ heavily partitioned space

Analyzed :
- particle concentrations
- for cases with HVAC off

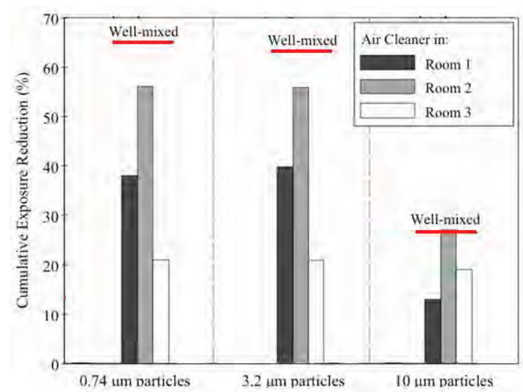


Cumulative exposure reduction

$$\int_0^{120\,min} \left(1 - \frac{C_{with\ AC}}{C_{without\ AC}}\right) dt$$

AC effectiveness

RESULTS: Pollutant Distribution in Homes



Buoyancy driven flow dominates in homes when HVAC is off

SUMMARY

Thermal plume has significant impact on the pollutant transport, positive or negative. Air mixing can decrease this effect of the thermal plume.

Exposure shows a strong dependency on source location. Sources in the vicinity of occupants almost always cause higher exposure.

Use of Air-change Effectiveness as a pollutant exposure indicator is valid to certain point for gases. However, it is not relevant for large particles.

Assumption of perfect mixing in human exposure studies should be used carefully. With HVAC fan off, pollutant concentration in homes can be very nonuniform.

Appendix F: Presentation 3

System Coefficients

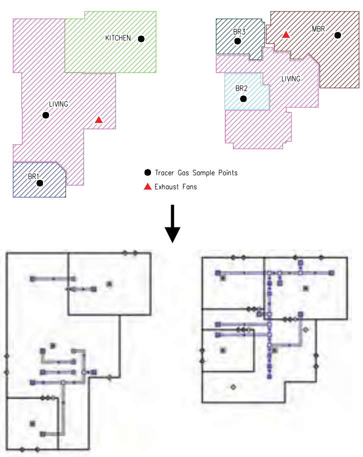
Where Have We Been
and Where Are We Going?

Aaron Townsend
January 23, 2009

Tracer Gas Testing Sacramento January 2006

- Tracer gas test of production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2600 square feet
- Tested two ventilation systems, with and without mixing via central air handler
- Results published by NREL (Bob Hendron) at IAQ 2007

CONTAM Modeling, Nov. 2006-Jan. 2007



Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

Expert Meeting, Dallas, January 2007

1. Presented:
   1. Tracer gas testing and results
   2. Calibrated model and results
   3. Coefficients ranging from 0.5 to 1.25 based on a reference of an exhaust-only system with a central AHU controlled by a thermostat only
2. Results:
   1. Committee wanted to see annual simulations, and a wider number of climates and house characteristics (leakage rates, ventilation systems, etc).

Expert Meeting, Long Beach, June 2007

1. Presented:
   1. First parametric study
   2. 3 climates, 3 enclosure leakage levels, 3 options for AHU, 2 options for AHU control, 2 options for duct leakage, 4 ventilation systems, ventilation rate 0-150% of 62.2
   3. Volume-weighted sources only
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Committee wanted to see more climates, and had questions about how the various parameters affected the results

Expert Meeting, New York, January 2008

1. Presented:
   1. Second parametric study
   2. 5 climates, 3 enclosure leakage levels, 3 options for AHU, 2 options for AHU control, 2 options for duct leakage, 4 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources only
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
   5. Comparison of exposure ratios from BSC's simulations to LBL's field testing & calculations
   6. Effect of AHU size
   7. Effect of parameters: climate, enclosure leakage, etc.
2. Results:
   1. Committee wanted no duct leakage, very leaky results, effect of sources in kitchens & bathrooms, and many more ventilation systems

Conference Calls, April-June 2008

1. April 18, 2008
   1. Revised simulation plan for third parametric study
2. June 10, 2008
   1. Presented third parametric study
   2. 8 climates, 4 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, ~10 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources or kitchens & bathrooms sources
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system

Meeting, Salt Lake City, June 2008

1. Presented:
   1. Third parametric study
   2. 8 climates, 4 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, 36 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources or kitchens & bathrooms sources
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Committee wanted another enclosure leakage level (5 ach50), occupant-generated sources, and a few more ventilation systems

Conference Call, October 30 2008

1. Presented:
   1. Fourth parametric study
   2. 8 climates, 5 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, ~12 ventilation systems, ventilation rate 0-200% of 62.2
   3. Volume-weighted sources, kitchens & bathrooms sources, or occupant-generated sources; also a combination of volume-weighted and occupant-generated
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Participants wanted to see a sensitivity analysis of the effect of source scenario

Conference Call, December 12 2008

1. Presented:
   1. Sensitivity analysis
   2. 8 climates, 5 enclosure leakage levels, 2 options for AHU, 2 options for AHU control, ~12 ventilation systems, ventilation rate 0-200% of 62.2
   3. Different combinations of volume-weighted sources, kitchens & bathrooms sources, and occupant-generated sources
   4. Coefficients ranging from 1.0 to 2.0 based on a reference of a fully-ducted balanced ventilation system
2. Results:
   1. Participants disagree or need more information regarding appropriate assumptions for pollutant sources
   2. One additional ventilation system was requested

New System

- New ventilation system:
  - Two-point exhaust system
  - Exhaust points in hall bathrooms upstairs and downstairs
  - Without AHU, with AHU, and with AHU and minimum turnover

New System

- Results: 3.5 ach50, average of climates

Scenario A

Description	no central system	with central system	with min turnover
Single-point continuous exhaust from first floor common area	2.17	1.79	1.40
Single-point continuous exhaust from second floor master bathroom	2.88	2.15	1.45
Two-point continuous exhaust from 1st and 2nd floor hall bathrooms	2.30	1.87	1.39
Three-point continuous exhaust, 1/3 from each bathroom	2.25	1.72	1.26
Four-point continuous exhaust 1/4 from kitchen and each bathroom	2.00	1.61	1.26

New System

- Results: 3.5 ach50, average of climates

Scenario C

Description	no central system	with central system	with min turnover
Single-point continuous exhaust from first floor common area	2.10	1.87	1.76
Single-point continuous exhaust from second floor master bathroom	2.56	2.34	2.26
Two-point continuous exhaust from 1st and 2nd floor hall bathrooms	2.16	1.83	1.55
Three-point continuous exhaust, 1/3 from each bathroom	1.65	1.49	1.37
Four-point continuous exhaust 1/4 from kitchen and each bathroom	1.43	1.38	1.34

New System

- Results: 3.5 ach50, average of climates

Scenario E

Description	no central system	with central system	with min turnover
Single-point continuous exhaust from first floor common area	2.36	1.79	1.04
Single-point continuous exhaust from second floor master bathroom	3.46	2.08	0.82
Two-point continuous exhaust from 1st and 2nd floor hall bathrooms	2.55	1.94	1.08
Three-point continuous exhaust, 1/3 from each bathroom	2.71	1.80	0.95
Four-point continuous exhaust 1/4 from kitchen and each bathroom	2.45	1.73	0.94

Sensitivity Analysis

- Effect of mixing 3 “pure” scenarios in different ratios
- Pure scenarios:
  - A: Volume-weighted sources
  - C: Sources in kitchens & baths only
  - E: Occupant-generated sources only

Scenario	A	C	E
% K&B zones	25%	100%	0%
% Other zones	75%	0%	0%
% Occupants	0%	0%	100%

Sensitivity Scenarios

- Sensitivity scenarios:
  - F, G1 through G6

Scenarios as a mix of “pure” scenarios

Scenario	F	G1	G2	G3	G4	G5	G6
% VW	50	40	30	50	50	33	20
% K&B	0	10	20	10	20	33	20
% Occ.	50	50	50	40	30	33	60

Sensitivity Scenarios

- Sensitivity scenarios:
  - K&B have volume—how much?
  - 25% in K&B, 75% elsewhere

Scenario emissions by zones & occupants

Scenario	F	G1	G2	G3	G4	G5	G6
% K&B	13	20	28	23	33	41	25
% Other	38	30	23	38	38	25	15
% Occ.	50	50	50	40	30	33	60

Sensitivity Scenarios

- Sensitivity scenarios:
  - Occupants move around—where are their emissions?
  - 15% in K&B, 85% elsewhere

Total emissions by emission location

Scenario	F	G1	G2	G3	G4	G5	G6
% in K&B	20	28	35	29	37	46	34
% in Other	80	73	65	72	63	53	66

Scenario A

(25% in K&B, 75% in other zones, 0% from occupants)

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

Scenario C

(100% in K&B, 0% in other zones, 0% from occupants)

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
	not fully ducted	1.35	1.65	2

*Any fully-ducted balanced system with returns from all K&B has a coefficient of 1.0

Scenario E

(0% in K&B, 0% in other zones, 100% from occupants)

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

Scenario F

(13% in K&B, 38% in other zones, 50% from occupants)

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

Scenario G1

(20% in K&B, 30% in other zones, 50% from occupants)

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

Scenario G2

(28% in K&B, 23% in other zones, 50% from occupants)

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

Scenario F

(13% in K&B, 38% in other zones, 50% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
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

Scenario G3

(23% in K&B, 38% in other zones, 40% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
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

Scenario G4

(33% in K&B, 38% in other zones, 30% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
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

Scenario G5

(41% in K&B, 25% in other zones, 33% from occupants)

Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
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

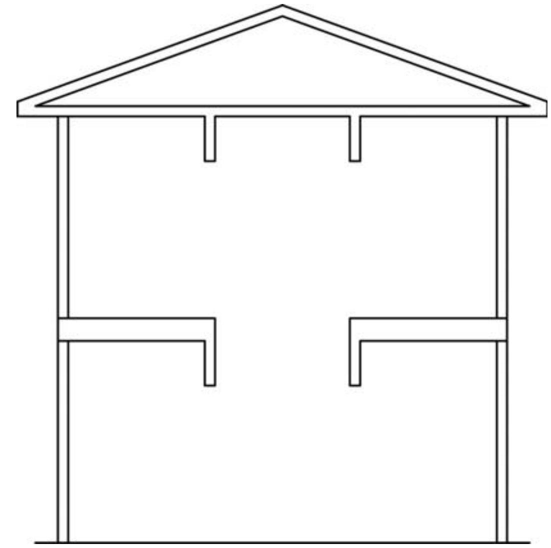
Scenario G6

(25% in K&B, 15% in other zones, 60% from occupants)

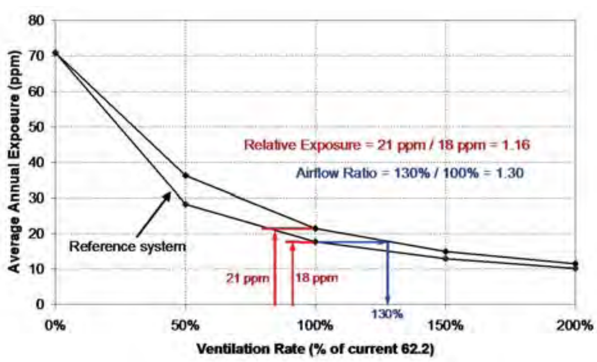
Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Supply	fully ducted	1	1	1.35
	not fully ducted	1	1.35	1.65
Exhaust	fully ducted	1	2	2
	not fully ducted	1	2	2
Balanced	fully ducted	1	1	1.35
	not fully ducted	1	2	2

Scenarios G2, G5, G6

		Ventilation type	Ventilation ducting	With AHU: With Min Turnover	With AHU: Without Min Turnover	Without AHU
Scenario	**G2**	Supply	fully ducted	1	1.35	1.35
% K&B	28		not fully ducted	1	1.35	1.65
% Other	23	Exhaust	fully ducted	1	1.65	2
% Occ.	50		not fully ducted	1.35	2	2
		Balanced	fully ducted	1	1	1.35
			not fully ducted	1	1.65	2
Scenario	**G5**	Supply	fully ducted	1	1.35	1.35
% K&B	41		not fully ducted	1.35	1.65	1.65
% Other	25	Exhaust	fully ducted	1.35	1.65	2
% Occ.	33		not fully ducted	1.35	2	2
		Balanced	fully ducted	1	1	1
			not fully ducted	1	1.65	2
Scenario	**G6**	Supply	fully ducted	1	1	1.35
% K&B	25		not fully ducted	1	1.35	1.65
% Other	15	Exhaust	fully ducted	1	2	2
% Occ.	60		not fully ducted	1	2	2
		Balanced	fully ducted	1	1	1.35
			not fully ducted	1	2	2



Relative Exposure vs Airflow Ratio



Relevant Sections of 62.2

- Forward, paragraph 8 (62.2 does not address certain events such as cleaning or other high-polluting events)
- Section 2.2 “[Acceptable indoor air quality] will not necessarily be achieved even if all requirements [of 62.2] are met”
  - Diversity of sources and susceptibility
  - Other factors: temperature, RH, etc
  - Outdoor air quality
  - Poor operation or maintenance
  - During high-polluting events

2.18.6. 2009 ASHRAE Transactions 11, Paper #1 Presentation

A Calibrated Multi-Zone Airflow Model for Extension of Ventilation System Tracer Gas Testing

Aaron Townsend, P.E.
Armin Rudd
Joseph Lstiburek, Ph.D., P.Eng.
Building Science Corporation

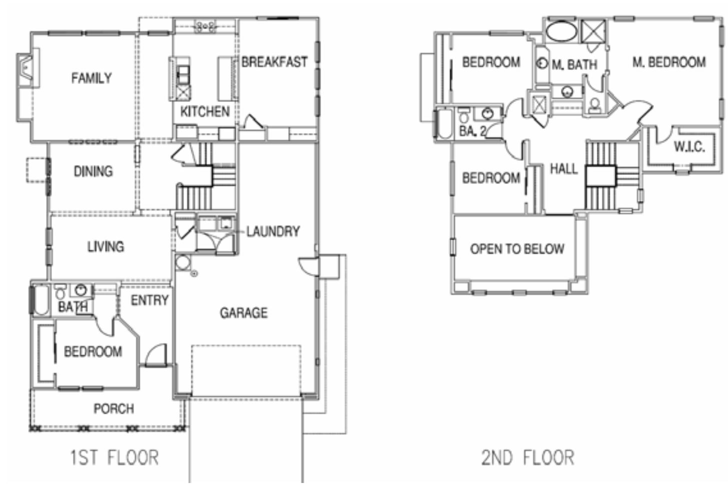
Introduction

- A software model was calibrated to reproduce field test results from tracer gas testing of ventilation systems

House Characteristics

- 2 story, 4 bedroom, 2600 ft^2 (240 m^2)

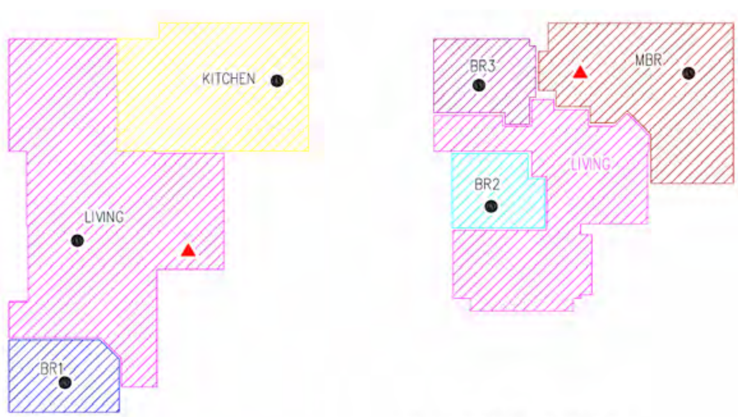
Floor Plan



Tracer Gas Testing

- 17 tests of ventilation systems under different conditions:
  - System (single-point exhaust or central-fan integrated supply)
  - Duty cycle of central fan (single-point exhaust only)
  - Ventilation rate (CFIS only)
  - Bedroom doors open or closed
  - Transfer grills open or closed

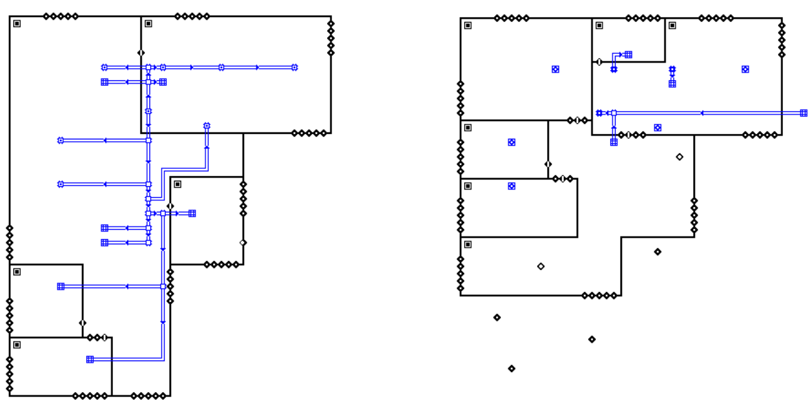
Zones



CONTAM Modeling Software

- Commonly-used multi-zone air flow network model software by NIST
- User specifies zones, air flow paths, contaminant sources and sinks, temperatures, weather, etc.
- Software determines flows and contaminant concentrations

CONTAM Screenshot



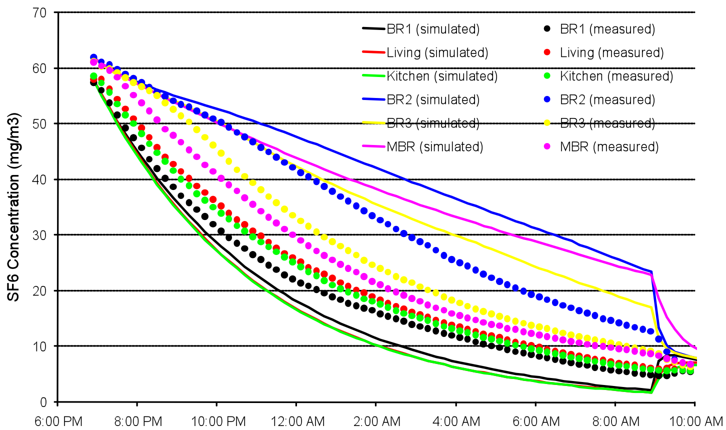
Modeling Procedure

- Initial guess values taken from testing of a similar house
- Simulation performed and educated guesses made to correct visual differences between tested results and simulated results
- No formal error function
- Not an optimized or unique solution

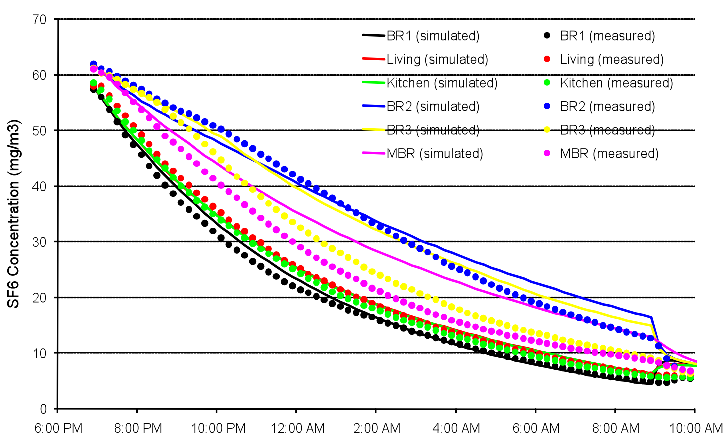
Modeling Procedure, II

- The most difficult tests to reproduce behavior were those with large differences between rooms
- One test used to calibrate model, remaining tests used to evaluate quality of calibration
- Calibration process stopped when visual behavior deemed sufficient (subjective)

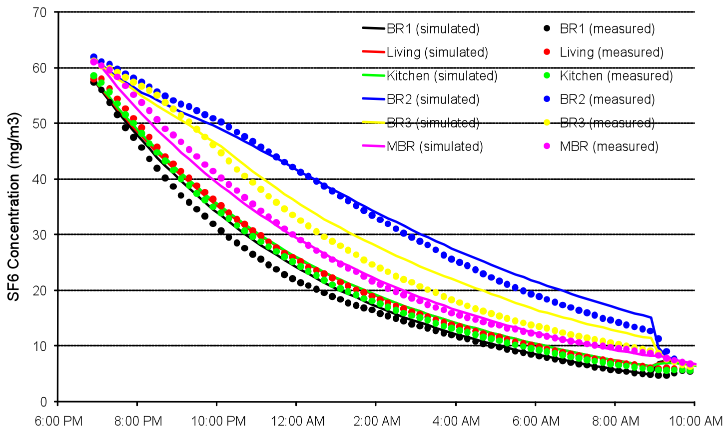
Results of Initial Guess



Mid-Calibration



Results of Final Calibration



Modeling Procedure, III

- Remaining tests simulated and compared to experimental results

Statistical Evaluation of Results

- ASTM D5157-97 Standard Guide for Statistical Evaluation of Indoor Air Quality Models used to evaluate quality of calibration.

ASTM D5157

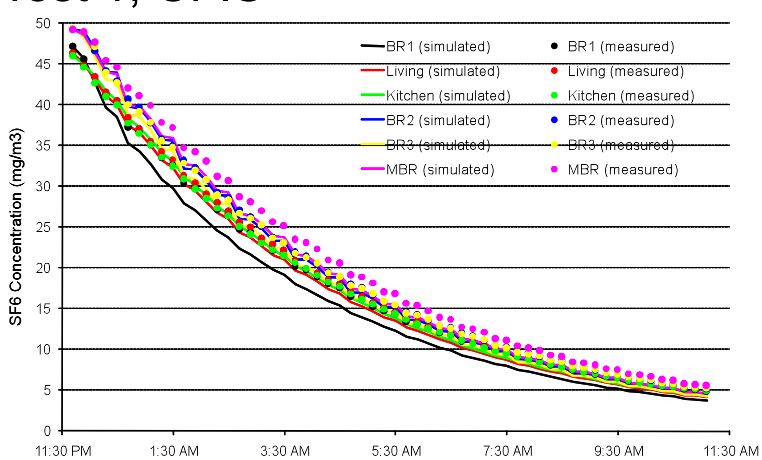
- Three criteria for evaluating models:
  - Data used for evaluation should be separate from data used for developing model
  - A set of quantitative parameters calculated from the modeled and observed data sets
  - Visual comparison of plotted data sets

ASTM D5157 Quantitative Parameters

- Correlation coefficient (should be >0.9)
- Best-fit line of regression components: m and b (0.75 < m < 1.25, $b/C_{o,avg}$ < 0.25)
- Normalized mean square error (NMSE < 0.25)
- Fractional bias (FB < 0.25)
- Index of variance bias (FS < 0.5)

Modeling Results

- Test 1, CFIS

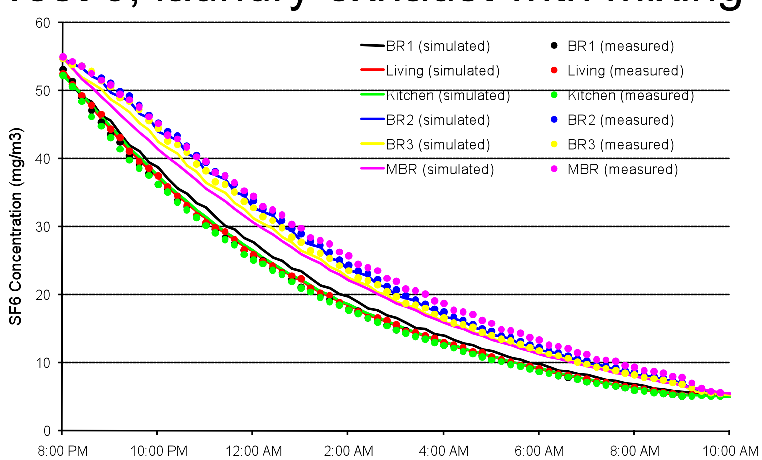


ASTM D5157 Parameters for Test 1

ASTM D5157 parameter	r	m	b/Co	NMSE	FB	FS
ASTM D5157 “adequate” range	>0.9	0.75 to 1.25	<0.25	<0.25	<0.25	<0.5
BR1	1.00	0.99	-0.09	0.01	-0.10	-0.01
Living	1.00	1.01	-0.07	0.00	-0.05	0.01
Kitchen	1.00	1.04	-0.05	0.00	-0.01	0.04
BR2	1.00	1.02	-0.05	0.00	-0.02	0.02
BR3	1.00	1.01	-0.06	0.00	-0.05	0.01
MBR	1.00	1.00	-0.06	0.00	-0.07	0.00

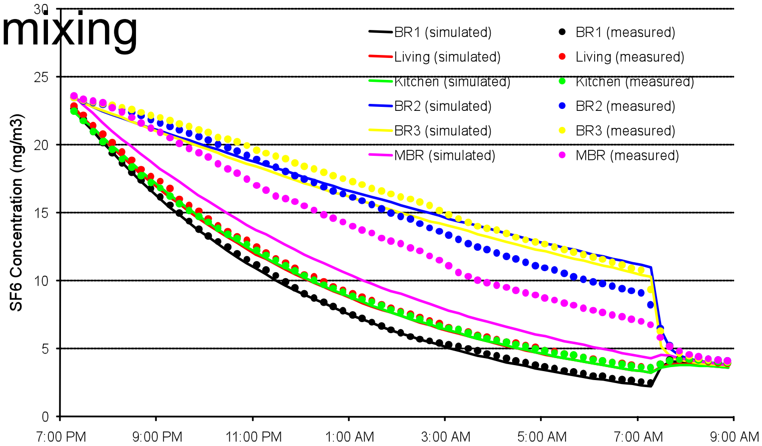
Modeling Results

- Test 6, laundry exhaust with mixing



Modeling Results

- Test 10, laundry exhaust without mixing



Modeling Results

- Good agreement between modeled and physical results
- Greatest agreement for cases with mixing due to central fan
- Least agreement for natural infiltration cases
- Most statistical parameters well within suggested limits

Discussion of Error

- Numerical and graphical comparisons of data sets indicate general agreement
- Some shapes in graphical comparison not replicated
- High number of assumptions about leakage distribution, effect of wind

Extension to Other Systems

- Calibrated model used to compare performance of systems not tested in physical testing
- Balanced, supply, and exhaust systems under identical environmental conditions
- Effective decay rate calculated as comparative metric

Extension Cases Studied

Case Number	Description
1	CFIS, AHU 20 min off/10 min on
2	Laundry exhaust, AHU 20 min off/10 min on
3	Laundry exhaust, AHU off
4	Balanced, AHU 20 min off/10 min on
5	Balanced, AHU off

- Cases 1, 2, & 4 mixed
- Cases 4 & 5 balanced

Extension Cases Results

- Effective decay rate of each system:

Case	BR1	Living	Kitchen	BR2	BR3	MBR
1	0.21	0.20	0.20	0.20	0.20	0.20
2	0.16	0.16	0.16	0.15	0.15	0.15
3	0.19	0.16	0.16	0.07	0.09	0.14
4	0.23	0.23	0.23	0.24	0.23	0.21
5	0.40	0.27	0.26	0.37	0.34	0.15

- Mixed cases have uniform rates
- Balanced cases have higher decay rates

Conclusions

- A calibrated model can be created that replicates results of tracer gas testing, given sufficient detail is known about the enclosure
- Visual agreement of the tracer gas decay curves can result in satisfactory results to statistical testing via ASTM D5157

Conclusions

- Agreement between modeled and measured data is high for well-mixed cases and lower for non-well-mixed cases.
- Agreement lowest at low or no ventilation flow rate.

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Questions?

2.18.7. 2009 ASHRAE Transactions 12, Paper #2 Presentation

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

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Joseph Lstiburek, Ph.D., P.Eng.
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Introduction

- ASHRAE Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings
  - Ventilation rate = 7.5 cfm/person + 0.01 cfm/ft^2 floor area
  - No differentiation between different types of systems known to have different performance

The Goal

- Can the standard account for the difference in performance between systems?
- A modification to the base ventilation rate based on what type of system is installed
- $Q_{fan} = C_S * Q_{vent}$

The Approach

- Establish a baseline system and determine the airflow ratio needed in order to achieve equivalent performance
- What is the baseline system?
- What is equivalent performance?

The Approach, II

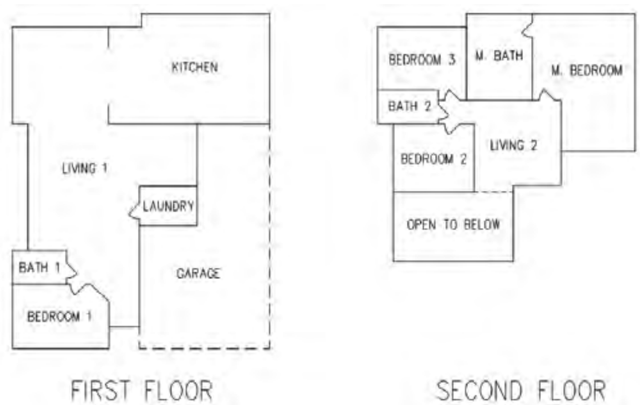
- Use computer model to compare different systems using occupant exposure as the comparison metric
- Work with the 62.2 committee to determine assumptions to make and systems to simulate

The Computer Model

- CONTAM was used as the modeling software
- Multi-zone airflow network modeling tool
- Exercised model over a range of parameters to cover a reasonable subset of new and existing houses

The House

- 2 story, 4 bedroom, 2600 ft^2 (240 m^2)



Assumptions

- 5 occupants on a daily occupancy schedule
- Bedroom doors closed at night
- Small interior temperature differences to drive airflow through open doorways

Contaminant Generation

- Unique contaminant generated in each zone and by each occupant
- Contaminant behaves as tracer gas: non-reacting, non-decaying, non-settling. Only removed by dilution with outdoor air.
- Outdoor air contaminant-free

Enclosure Leakage

- Total enclosure leakage varied to determine effect (1.5 to 20 ach @ 50 Pa)
- Leakage distribution over enclosure held constant
- Diffuse leakage approximated in walls and ceiling
- Attic and garage neglected as outdoors

Climates and Wind

- 9 climates modeled, from Florida to California to Minnesota
- Wind modeled from TMY2 data and standard shielding factors for suburban terrain

Central Air Handling System

- AHU size determined by design temperature of each climate using industry-standard procedures
- AHU runtime determined by linear interpolation of hourly outdoor temperature, design temperature, and balance point temperature

Minimum Runtime or Turnover

- Some ventilation systems included minimum runtime or turnover criteria for AHU
- Minimum runtime [min/hr]
- Minimum turnover of house (% of house volume of air passed through AHU each hour) [1/hr]

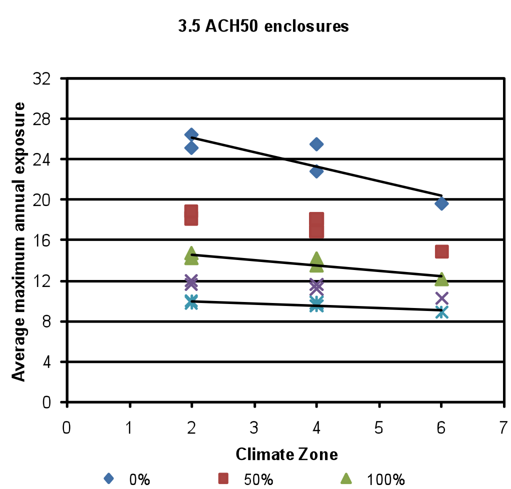
Post-Processing

- Occupants exposed to the contaminants in the zone according to their daily schedule
- Hourly exposures averaged over a time period to determine average exposure
- Generally focused on annual average exposure

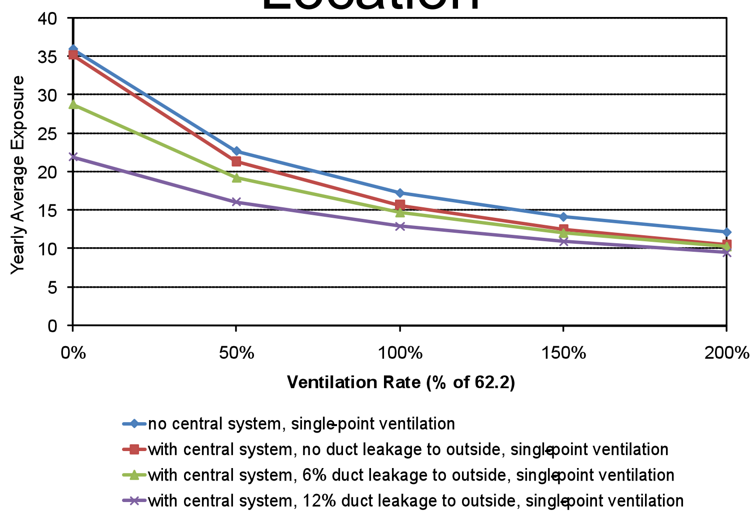
Initial Results

- Initial set of simulations performed to determine general effect of certain parameters

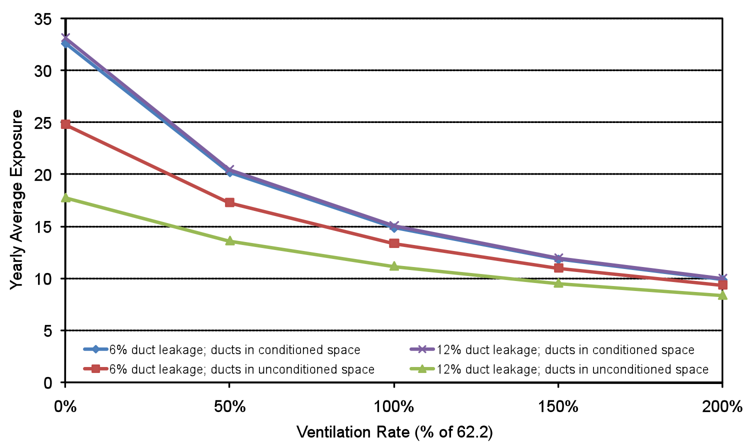
Effect of Climate



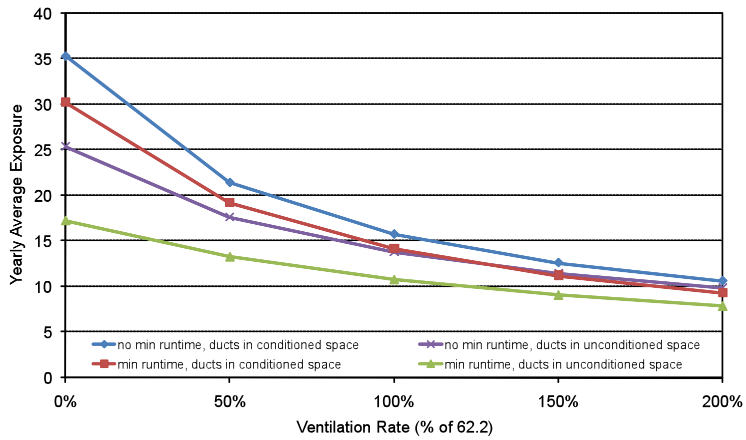
Effect of AHU Presence & Location



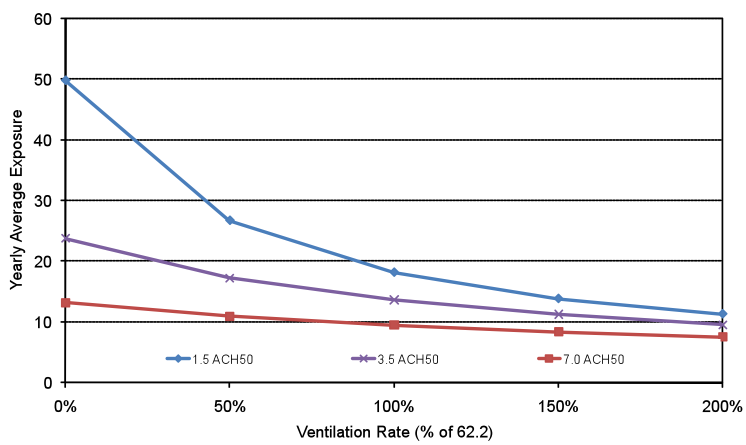
Effect of Duct Leakage and Location



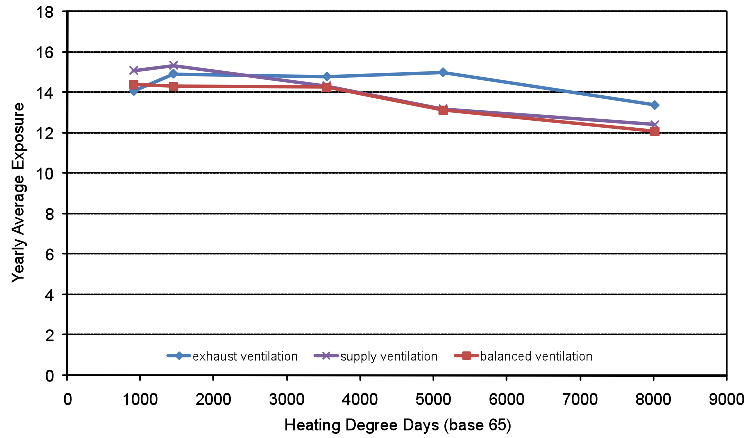
Effect of Duct Location and Minimum AHU Runtime



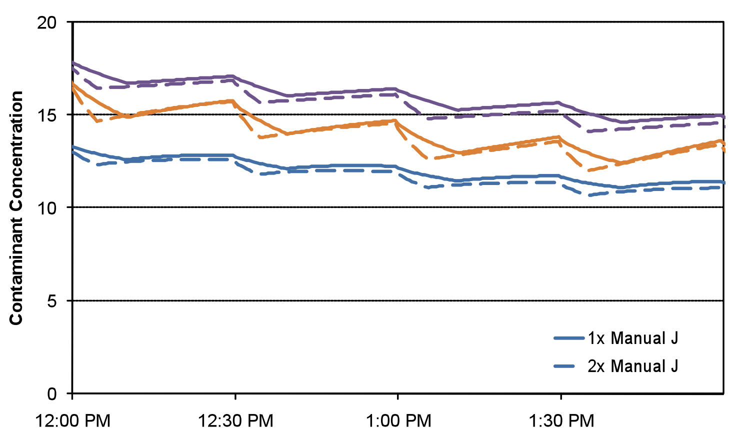
Effect of Enclosure Leakage



Effect of Ventilation Direction and Climate



Effect of AHU Sizing



Final Simulations

- Reference system chosen and reference exposure level established (occupant with highest exposure in each simulation)
- Other systems simulated and compared to reference exposure level
- Airflow ratio calculated to achieve equivalent exposure

Ventilation Systems

- 36 ventilation systems
  - Supply-only, exhaust-only, balanced
  - Single-point, ducted, central-fan integrated
  - With or without minimum turnover requirements

Exposure Scenarios

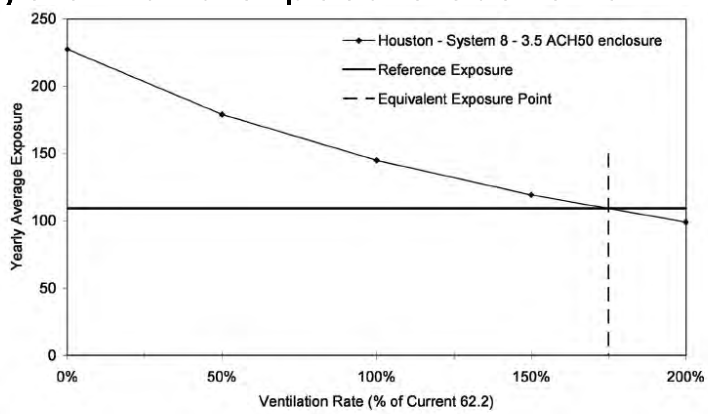
- Volume-weighted contaminant sources
- Contaminants from kitchens and bathrooms
- Occupant-generated contaminants

Reference Exposures

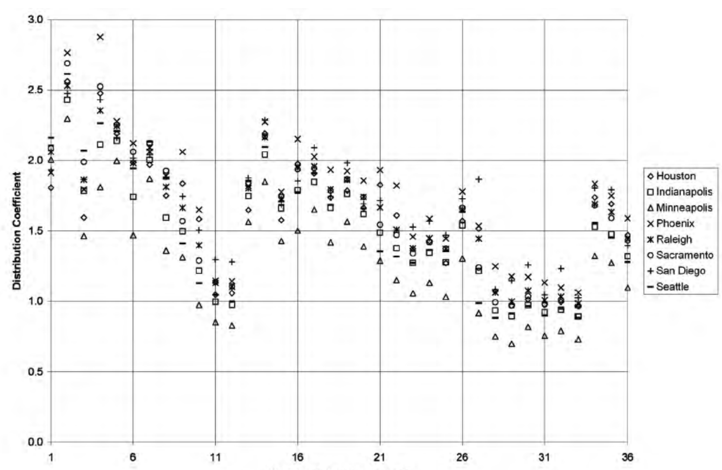
- Average of the reference system exposure from all climates
- Each exposure scenario has a different reference exposure

Airflow Ratio Calculation

- An airflow ratio is calculated for each system and exposure scenario



Airflow Ratio Results – Volume Weighted Sources



System Coefficients

- Similar systems perform similarly: single-point exhaust, multi-point supply, etc.
- Systems grouped by characteristic appropriate for a standard and the airflow ratios averaged to get a system coefficient

Conclusions

- A method for comparing different ventilation systems has been demonstrated
- System coefficients range from 1 to about 3 with the given reference system using volume-weighted contaminant sources

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Questions?