SYSTEMS ENGINEERING APPROACH TO DEVELOPMENT OF ADVANCED RESIDENTIAL BUILDINGS

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

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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

Presenter bio: 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.

Presentation Title: *Performance Requirements for Residential Ventilation Systems*

Presentation Summary:

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.

Appendix A1: January 2007 Expert Meeting 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**
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

- 9:35 to 9:45 (10 min) Break/refreshments
- 9:45 to 10:15, (30 min) Ren Anderson, "Performance Requirements for Residential Ventilation Systems"
- 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.

Lstiburek, J. Townsend, A., Rudd, A., 2006. “Evaluation of unique systems issues and research needs for multifamily housing.” Final report submitted to USDOE, December.

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.

Appendix A2: June 2007 Expert Meeting Agenda

USDOE Building America Sponsored Expert Meeting on Ventilation Air Distribution

21 June 2007
Long Beach

bsc

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
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