Workshop: Energy Conservation and IAQ in Residences
Indoor Air 2011 – Austin, TX

Problem Statement

Historically, building codes were established to protect the health and safety of occupants. Today in the face of climate change and diminishing fuel resources, the public policy priority appears to be shifting from health to energy efficiency. In addition to adding insulation, a common intervention to enhance energy efficiency in homes is air sealing, since by reducing leakage of hot or cold outdoor air into a residence less energy is required to condition the space. However, reducing the outdoor air exchange rates causes the concentrations of air contaminants with indoor sources to increase, which can lead to adverse health effects for the occupants. During the energy crisis of the 1970s we learned that reducing outdoor air exchange rates in buildings can lead to significant health problems, especially given the vast array of chemicals now found in indoor environments. Saving energy in homes by reducing air infiltration is of particular concern in the homes of low-income households which generally have higher indoor emission rates of air contaminants such as those associated with mold, pests, and environmental tobacco smoke (ETS). These homes are often targeted for weatherization by government subsidized programs, of which the single biggest program is the federal Weatherization Assistance Program, which received over $5 billion in investments through the American Recovery and Reinvestment Act to jump start the energy efficiency retrofit sector and to provide relief to income households burdened by rising energy costs. There is a clear need for homes that are both energy efficient and healthy. To address this need, Indoor Air 2011, an international conference on indoor environmental science, convened a workshop to discuss the technical and policy/code aspects related to furthering the pursuit of healthy and energy efficient homes.

Workshop Objectives

The primary objectives of the workshop were to discuss the impact of energy conservation measures on IAQ and occupant health in residences, identify research needs, and develop policy and code recommendations promoting healthy and energy-efficient residences.

The workshop addressed six key questions:

1. What are the impacts upon IAQ and health, as homes are made more airtight?
2. What are the health related costs of reduced outdoor air ventilation?
3. How tight is too tight and how much outdoor air ventilation is needed?
4. What is the reduction in the envelope leakage associated with Weatherization Assistance Programs (WAPs)?
5. What are the options for providing ventilation and what are the installation/operation costs?

6. What are some things that can be done to further the pursuit of residences that are both energy efficient and healthy?

Workshop Presentations

The workshop convened on Monday, June 6, 2011 from 3:25pm to 5:30pm during the Indoor Air 2011 conference at the Austin, TX Convention Center. Bud Offermann, PE CIH facilitated the workshop, which included six panelists speaking to different aspects of air quality and energy conservation in residences. Roughly ninety participants from around the world participated in the workshop. Following the presentations by the panelists, they and the other attendees discussed the six key questions in more depth and identified some research and policy priorities.

The panelists included six leading experts in indoor air quality and energy conservation, focusing on different aspects of the challenge.

Bill Fisk, Staff Scientist and Department Head of the Indoor Environment Department at Lawrence Berkeley National Laboratory presented on the impacts upon indoor contaminant exposures and health as homes are made more airtight.

Jennifer Logue from Lawrence Berkeley National Laboratory then tied the indoor environmental quality changes to health related costs of reduced outdoor air ventilation using Disability Adjusted Life Years (DALYs).

Paul Francisco of the University of Illinois at Urbana-Champaign discussed the extent to which the Weatherization Assistance Program typically reduces building envelope air leakage.

Bud Offermann of Indoor Environmental Engineering then discussed available residential outdoor air mechanical ventilation systems and their associated installation/operation costs.

Laura Kolb of the Environmental Protection Agency then discussed the EPA’s new Healthy Indoor Environment Protocols for Home Energy Upgrades, a set of voluntary standards.

Paul Francisco spoke on behalf of Julie Hughes of the Department of Energy on the DOE’s Workforce Guidelines for Home Energy Upgrades.

Workshop Summary

1. What are the impacts upon IAQ and health, as homes are made more airtight?

Bill Fisk reviewed the various impacts on IAQ and health as homes are made more airtight, drawing on theory, modeling, and some limited field research for different scenarios. Fisk emphasized that most of our knowledge comes from a theoretical perspective and we need a great deal more field research on the effects of weatherization on IAQ.

Fisk also pointed out that tightened buildings can lead to both negative and positive IAQ impacts, depending upon whether the source of the indoor air contaminants are primarily indoors or are outdoors.

For air contaminants that are primarily emitted from indoor sources (e.g. formaldehyde and other volatile organic compounds), air sealing can lead to low outdoor air exchange rates with resulting elevated indoor air contaminant concentrations. For air contaminants that enter homes primarily from infiltration of outdoor air (e.g. ozone), air sealing can result in decreased concentrations.

For air contaminants that enter homes primarily from the ground (e.g. radon), air sealing can result in either increased of decreased concentrations depending upon the impact of the air sealing on the transport of the ground contaminants into the home.

For some air contaminants air sealing has relatively little impact on the indoor air concentrations, such as air contaminants with low vapor pressures (e.g. semi-volatile organic compounds, SVOCs, such as flame retardants and plasticizers) and large particles that settle out of the air rapidly (e.g. dust mite allergens and pollen grains).

Well-managed, mechanical outdoor air ventilation has been shown to significantly improve indoor air quality. A number of studies show that increased outdoor air ventilation rates are associated with decreased concentrations of formaldehyde, acetaldehyde, and other indoor air contaminants. In the California New Homes Study (CNHS) conducted 2006 and 2007 in 108 homes in California (Offermann, 2009) there were 26 homes with mechanical outdoor air ventilation systems and 82 homes without mechanical ventilation. Offermann found that formaldehyde and acetaldehyde concentrations correlated with the inverse of the outdoor air exchange rate, with lower concentrations in homes with higher outdoor air exchange rates.

While more studies based on modeling have been conducted, mass balance predictions often have to rely on assumptions that introduce significant uncertainties such as constant contaminant emission rates, zero surface deposition rates, and zero indoor chemical reaction rates. A study of manufactured homes reported a 38% reduction in the indoor concentrations of 24 VOCs with a 125% increase in outdoor air ventilation rates (Hodgson, Rudd, Beal, & Chandra, 2000)Assuming that the emission rates of these VOCs remained constant, a mass balance model predicts a 66% reduction in air contaminant concentrations. The emission rates of individual VOCs were observed to increase for some compounds at the increased ventilation rates and decrease for other compounds.

These studies notwithstanding, there have been few field studies demonstrating the impact on air sealing for energy-efficiency on indoor air quality.

Energy efficiency interventions can also have impacts unrelated to ventilation.

Many of the materials and processes involved in making homes more energy efficient may negatively impact indoor air quality. These new, potential toxic indoor sources include spray foam insulation, polystyrene, adhesives in structural insulated panels SIPs, and caulks used for sealing. Jack Spengler from Harvard University also emphasized the importance of considering the potential health effects of weatherization materials, including PCB used in caulk and other new contaminant sources that could be introduced. Previously, he urged the EPA to include these recommendations in their voluntary standards literature.

There are also some energy efficiency interventions that appear to have clear benefits for improved air quality as well. For instance, high-efficiency forced combustion furnaces eliminate the risk of exhausts flue back drafting. Similarly, installation of stoves without pilot lights saves energy and reduces emissions of NOx, ultrafine particles, and carbon monoxide.

While the addition of mechanical ventilation in tightened homes can mitigate the negative impact on IAQ, Fisk referred to research suggesting that we cannot at this time fully rely on mechanical ventilation to provide good indoor air quality. In the CNHS field study of ventilation and IAQ in new homes (Offermann, 2009)), researchers found that due to design and occupant control factors, the installed mechanical ventilation systems were often underperforming. Of the 17 mechanical ventilation systems with ducted outdoor air to the forced air heating/cooling system, 3 were disabled, 9 had flow rates/operation times less than those required to meet the California building code, and 4 homes had outdoor air exchange rates less than 0.12 air changes per hour (ach). Additionally, the residents did not significantly use mechanical spot ventilation in the kitchen or bathroom.

During the discussion, Peter Ashley from HUD's Office of Healthy Homes and Lead Hazard Control noted that these reservations about mechanical ventilation appear to challenge Joe Lstiburek's argument for tightening buildings as much as possible and providing controlled mechanical ventilation (presented during the plenary session that morning). Fisk agreed, noting that he would like to see data that these mechanical ventilation systems work in the long term before we massively put them in all of our building stock.

2. What are the health related costs of reduced outdoor air ventilation?

Current ventilation standards such as ASHRAE's 62.2 are aimed at controlling indoor air contaminant exposures through a calculation of ventilation based upon the combined requirements for emissions from the building materials (i.e. 1 cfm per 100 ft^2 floor area) and emissions from occupants (i.e. 7.5 cfm per number of bedrooms plus one). But there is no basis other than professional judgment for the 1 cfm per 100 ft^2 floor area requirement and the 7.5 cfm per number of bedrooms plus one requirement is loosely based upon the perceived acceptability of body odor). Indeed, there has been little research done to quantify the health related benefits of providing mechanical ventilation, or the health costs of reduced outdoor air ventilation. Since provision of mechanical outdoor air ventilation is not without cost, making the case for the investment would be easier with some sort of unifying metric of health or cost. Jennifer Logue presented on one such unifying metric, Disability Adjusted Life Years (DALYs) and stepped the workshop through the causal chain from concentrations → exposure → dose/body burden → adverse health effects → costs/harm. She also traced the role of different sciences in assessment of health impacts. This metric makes it possible to directly compare the costs of mechanical ventilation with the avoided health costs.

DALYs are the sum of Years of Life Lost (YLL) and Years Lived with Disability (YLD). Numerous studies on DALY damages consider survivability, how long one is sick, and how people perceive disability, resulting in projected values for DALYs on the order of $50,000 to $160,000.

Logue showed that $PM_{2.5}$ is considered the primary driver of health costs, with environmental tobacco smoke next, followed by formaldehyde and acrolein, all of which have higher DALYs burdens than carbon monoxide.

Logue used the DALY impact assessment methodology outlined by Huijbregts et al. (2005) and a literature review of disease incidence and damage factors to determine the annual health burden per 100,000 homes (Logue et. al., 2011) based on estimated annual exposure for different ventilation scenarios; infiltration only, unbalanced mechanical, and balanced mechanical. The pollutants considered were 14 VOCs identified in the CNHS (Offermann, 2009), and did not include $PM_{2.5}$, NO_2, acrolein, or mold or infectious disease.

Results suggest that adding unbalanced mechanical outdoor air ventilation yields an average cost per DALY avoided of $150,000 and adding balanced ventilation yields an average cost per DALY avoided of $240,000. Since these analyses only considered 14 VOCs, and these represent approximately just one third of the DALYs due to indoor exposures, considering these as well as other air contaminants such as $PM_{2.5}$, NO_2, and acrolein, the energy cost of mechanical outdoor air ventilation is on par with the expected benefits.

Logue's results suggest that the health benefits of adding mechanical ventilation often outweigh the costs of the systems, although there is a high level of uncertainty in the health cost estimate results. She also emphasized that the other benefit of ventilation is that you remove the things you don't really know about – it serves as a safety net for new pollutants.

In the discussion after Logue's presentation, Paula Schenk, representing the University of Connecticut health systems, noted that it would be good idea to add the costs of medical treatment into the assessment of health costs. Lost workdays and school days are another way to factor in the costs. Peter Ashley of HUD suggested that in accounting for health costs and benefits related to weatherization for low-income households, it would help to account for how energy savings from weatherization are reinvested in other health promotion activities.

3. How tight is too tight and how much outdoor air ventilation is needed ?

This is of course the $64 K question and has been debated much over the past 40 years. The answer inevitably is "well it depends". The required amount of outdoor air ventilation depends upon the emission rates of air contaminants from indoor sources, the concentrations of air contaminants in the outdoor air, and the susceptibility of the occupants.

Engineers routinely size heating and air conditioning equipment based on the anticipated thermal loads and desired indoor air temperature and humidity. Analogous to this, engineers should be able to size mechanical outdoor air delivery rates from air contaminant emission rates and the desired indoor exposures. However, there is very little information on the air contaminant emission rates in homes.

While ASHRAE and other organizations have historically offered a "one-size fits all" approach to recommending minimum outdoor air ventilation rates, the truth is "it depends". In the CNHS (Offermann, 2009), the results for the formaldehyde measurements suggest that a minimum ventilation rate of 0.5 air changes may be needed as opposed to the approximate 0.15 air changes per hour of mechanical ventilation that ASHRAE Standard 62.2 recommends. ASHRAE Standard 62.2 assumes that an outdoor air infiltration rate of 0.15 air changes per hour adds to the mechanical rate and results in a total outdoor air exchange rate of approximately 0.30 air changes per hour. However, it was noted in discussions on this topic that this assumed infiltration rate might be too high, especially for periods of time with low indoor-outdoor air temperature differences and low wind speeds, and also for homes with unbalanced mechanical outdoor air ventilation systems, which reduce the contribution of infiltrating air to the total outdoor air exchange rate.

Ideally we would have sensors that could measure "all" of the air contaminants of concern and could control the amount of outdoor air delivered to the home, but as Offermann pointed out, we are a long ways to having that "Star Trek Tricorder" that could provide such a comprehensive measurement of air contaminants.

As far as what may be an acceptable minimum residential outdoor air ventilation rate, there was no consensus on what that rate should be other than the ASHRAE 62.2 rates are more likely too low than too high.

4. What is the reduction in the envelope leakage associated with Weatherization Assistance Programs (WAPs)?

Paul Francisco discussed the envelope air leakage reductions that are typical with weatherization, especially through the DOE Weatherization Assistance Program's interventions, which targets homes of low-income families. Francisco emphasized that one of the most cost-effective and popular home energy-efficiency interventions has been air sealing. As a general rule, homes that are exceptionally leaky to begin with have the most dramatic percentage reductions in leakage rates, even though their ultimate leakage rate may very well be higher than a home that started off less leaky.

Francisco drew his observations from data from five different states. In a statewide survey of 1,792 weatherized homes in Ohio between 1995 and 1996, homes generally started off exceptionally leaky (with an average of 4,156 CFM_{50}) and had an average CFM_{50} reduction of 31.3%. Some homes had reductions of 45% but they were starting at extreme levels of leakiness. In a 2005 survey of 308 homes in New Hampshire the average CFM_{50} reduction was 33% and in a Illinois study of 36,558 homes weatherized from 2004 to 2010, the average CFM_{50} reduction was 21% with a median of 23%, a 75th percentile of 34% and a 90th percentile of 46%.

To take advantage of the maximum ventilation percentage reductions, Pennsylvania's utility programs actually target the highest users of energy, instead of low-income families, since these households are likely to bring the greatest energy savings. In this program, contractors using blower doors to guide their air sealing achieved a 42% reduction in the average CFM_{50} as compared to contractors that did not use blower doors and simply installed weather-stripping and caulk and achieved a 20% average reduction.

A 2006 Wisconsin survey found that even though single-family homes started off on average much leakier than mobile homes, the average leakage reduction for single-family homes was 25%, while mobile homes had a 38% leakage reduction on average.

Thus, the reduction in average envelope air leakage in the WAPs is 20-40% with some homes with reductions of as much as 50%.

Assuming that the air contaminant emission rates remain constant, and the occupants keep their windows and doors closed and rely only on envelope air leakage, a 50% reduction in the envelope air leakage results in a doubling of the indoor air contaminant concentrations with indoor sources.

For homes with significant indoor air contaminant emission rates, reducing envelope air leakage without the addition of mechanical outdoor air ventilation may potentially result in indoor air contaminant exposures that could result in adverse health impacts, especially in homes where windows are not opened for ventilation.

5. What are the options for providing ventilation and what are the installation/operation costs?

Bud Offermann discussed the different types of residential mechanical outdoor air systems and the associated costs to install and operate these systems as well as potential problems.

Residential mechanical outdoor air systems were classified as either unbalanced systems or balanced systems. Unbalanced systems include exhaust air systems (either single or multi-point) or outdoor air systems that deliver outdoor air typically to the home forced air heating/cooling system. Balanced systems are two fan systems that typically bring in outdoor air and exhaust indoor air through and air-to-air heat/energy exchanger. Heat exchangers only transfer sensible heat, while energy exchangers also transfer moisture between the outdoor air and exhaust air streams, which can be important in hot/humid climates.

Offermann compared the costs of three different residential mechanical ventilation systems; unbalanced exhaust air (e.g. a quiet continuous operating bathroom fan), unbalanced outdoor air ducted to the forced air heating/cooling system, and a balanced heat/energy recovery ventilator.

Depending upon the climate zone where the home is located, the total annual cost of ventilation, including capital and installation first costs, added heating/cooling costs, and the fan power costs, ranges from \$190-\$365 for the unbalanced exhaust air system, to \$280-\$430 for the unbalanced outdoor air system integrated with the forced air heating/cooling system, to \$385-\$435 for the balanced heat/energy recovery ventilator.

While unbalanced exhaust systems are the least costly system to install, the potential problems associated with these systems include:

- inability to filter outdoor air contaminants,
- potential for increasing the transport of ground based air contaminants (e.g. radon) into the home,
- inability to dehumidify the incoming outdoor air in hot/humid climates
- reduced addition of infiltration air, and
- increased potential for flue back drafting.

The potential problems associated with unbalanced outdoor air systems include:

- delivery of cold outdoor air to home, and
- reduced addition of infiltration air.

The potential problems associated with balanced heat/energy recovery ventilators do not have any of the problems associated with the unbalanced systems provided:

- the outdoor air is filtered where there are high outdoor air contaminant concentrations,
- in cold climates the system has defrost capability, and
- in hot/humid climates the outdoor air can be adequately dehumidified.

Offermann concludes that in the future, there will be an increased installation frequency of mechanical outdoor air systems in residences. Following the CNHS, California implemented in 2009 a requirement that all new single-family detached residences have a mechanical outdoor air system installed that meets the ASHRAE 62.2 ventilation requirements. In addition, his future outlook for residential mechanical outdoor air systems include:

- a trend towards balanced continuous systems with heat/energy recovery,
- improved outdoor air filtration,
- self-maintaining systems with alerts,
- dehumidification of humid outdoor air, and
- “vent-o-stats” for automatic control of outdoor air flow rates for maintaining acceptable IAQ.

John Woollett from Sweden emphasized the need for noise reduction in design of future systems, or else adoption will be limited. Woollett said this is especially important in residences because of the small duct sizes, where the force for the airflow through small ducts may generate too much noise and could disrupt sleep. He also said that we must also look at diffusers, since sometimes you’re dealing with high flow rates, others low, so we'll need to look at distribution issues, and how to have a good distribution system with low noise.

6. What are some things that can be done to further the pursuit of residences that are both energy efficient and healthy?

Laura Kolb from the US EPA provided an overview of the "Healthy Indoor Environment Protocols for Home Energy Upgrades", which is a voluntary guidance document for home energy retrofits available online (EPA, 2010)

Kolb stated that weatherization retrofits are most likely to negatively affect IAQ unless measures are taken to maintain good IAQ.

These protocols provide guidance for 28 specific environmental hazards plus ventilation. For each hazard there are recommended "minimum actions" and "expanded actions". The "minimum actions" were developed to help ensure that the home energy retrofits "Don't make it worse". The "expanded actions" were developed to help improve IAQ in home energy retrofits.

As an example, for radon the protocols recommend a "test-in/test-out" or "test-out" approach for achieving the goal of "don't make it worse" with a radon gas action level of 4 pCi/L the current EPA guideline.

Kolb concluded with six steps to good indoor air:

- educate occupants,
- keep it dry, clean and pest free,
- remove or control sources,
- provide local exhaust,
- provide dilution ventilation, and
- reduce unplanned airflows.

Paul Francisco spoke on behalf of Julie Hughes from the US DOE and provided an overview of the "Workforce Guidelines for Home Energy Upgrades," a voluntary guidance document for home energy retrofits that is still under development. These guidelines will be available online for a second round of public review in Spring 2012, at the Department of Energy's Energy Efficiency and Renewable Energy website, http://www1.eere.energy.gov/wip/retrofit_guidelines.html.

Francisco also spoke about the DOE WAP Health & Safety Guidelines that can be found on the Weatherization Assistance Program's Technical Assistance Center webpage, at http://www.waptac.org/data/files/website_docs/government/guidance/2011/wpn%2011-6.pdf.

These Health and Safety Guidelines focus on:

- combustion appliances (depressurization limits for exhaust air ventilation, removal of unvented space heaters used for primary heat, and CO alarms encouraged),
- outdoor air ventilation (requires ASHRAE 62.2),
- air sealing (to help mitigate moisture, radon, and air contaminants from attached garages), and
- lead paint assessment (EPA RRP required).

The following were cited as examples for "deferral" of weatherization work in WAPs:

- occupant prohibits removal of unvented gas appliance used as primary heat or not listed to ANSI Z21.11.2,
- mold and moisture conditions are beyond WAP's ability to address,
- formaldehyde, VOCs, etc. pose a risk and cannot be managed, and
- presence of other biological or unsanitary conditions.

During the discussion period, some attendees from Europe also noted that there are already some systems in Europe that help occupants more strategically manage ventilation to promote health and comfort with minimal energy output. The focus tends to be tightening homes, and then directing outdoor ventilation air to where it is most needed. Some of these systems work automatically with carbon dioxide sensors: if there is not enough outdoor air, the ventilation increases in that area.

Conclusions and Research Recommendations

Air sealing of residences to save energy can result in reduced outdoor air ventilation rates, which in turn can cause the concentrations of air contaminants with indoor sources to increase and result in adverse health impacts to the occupants.

In addition to the adverse impacts of reduced outdoor air ventilation, many of the materials and processes involved in making homes more energy efficient can potentially have adverse effects on IAQ (e.g. spray foam insulation, polystyrene, adhesives in structural insulated panels SIPs, and caulks used for sealing).

Analyses of the energy costs associated with mechanical outdoor air ventilation and the health related costs (i.e. DALYs) indicate that the health benefits from reduced exposure to indoor air contaminants are worth the costs of adding mechanical ventilation.

As far as what may be an acceptable minimum residential outdoor air ventilation rate, there was no consensus on what that rate should be other than the ASHRAE 62.2 rates are more likely too low than too high.

The reduction in the average envelope air leakage in the WAPs is 20-40% with some homes seeing reductions of as much as 50%. Assuming that the air contaminant emission rates remain constant, and the occupants keep their windows and doors closed and rely only on envelope air leakage, a 50% reduction in the envelope air leakage results in a doubling of the indoor air contaminant concentrations with indoor sources. For homes with significant indoor air contaminant emission rates, reducing envelope air leakage without addition of mechanical outdoor air ventilation may potentially result in indoor air contaminant exposures that may result in adverse health impacts.

Depending upon the climate zone where the home is located and the system type, the total annual cost of mechanical ventilation, including capital and installation first costs, added heating/cooling costs, and the fan power costs, ranges from $190-$435 per year.

The EPA "Healthy Indoor Environment Protocols for Home Energy Upgrades" and the DOE "Workforce Guidelines for Home Energy Upgrades", provide useful, although strictly voluntary, guidance on how to minimize negative impacts on IAQ that might result from the implementation of energy conservation measures in residences.

Some areas where research is needed are:

- better understanding of residential indoor air contaminants and health effects (acute and chronic effects) including infectious disease agents,
- the effects of air sealing on outdoor air ventilation rates and indoor air contaminant concentrations,
- the impact of ventilation on the air contaminant emission rates for indoor sources, as well as the penetration rates for outdoor pollutants such as ozone and particulate matter,
- the health costs related to exposure to indoor air contaminants (measured in terms of DALYs as well as incurred treatment costs and lost productivity),
- the reliability, performance, and costs of residential mechanical outdoor air systems, and
- development of affordable indoor contaminant monitoring systems, so that people can manage to optimize thermal comfort *and* health.

References

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