Measured Formaldehyde in High Performance Homes with Outdoor Air Intakes – Paper Presented at the Indoor Air Quality Association Annual Meeting, 2/23/2009, Fort Worth Texas.

Melissa Malkin-Weber*, Jonathan Coulter, Tracy Dixon, Benjamin Hannas, Shaun Hassel, and Jamie Kingston.

Advanced Energy, Raleigh, North Carolina

*Corresponding author mweber@advancedenergy.org

Introduction

Formaldehyde has multiple indoor sources, is a probable human carcinogen, and is associated with short term effects including respiratory irritation and eye irritation (Institute of Medicine 2000). Causal links to asthma and allergy have not been definitively established, but reviews of published research suggest an association between formaldehyde exposure and respiratory symptoms including wheezing (Mendell 2007). The general public has become more widely concerned about indoor formaldehyde since reports of acute symptoms among those living in trailers and mobile homes after Hurricane Katrina in 2005, but the need for effective ventilation is not uniformly appreciated throughout the building industry.

Methods to reduce formaldehyde exposures in homes have focused on 1) diluting formaldehyde with outdoor air and 2) reducing formaldehyde sources in the building. Formaldehyde is present in many building products and consumer products in varying concentrations. Sources include pressed wood products that use urea-formaldehyde resins, urea-formaldehyde foam insulation, fabric finishes, paper products, cosmetics and detergents (Institute of Medicine 2000, Hodson 2002, Kelly 1999). Formaldehyde may also be generated through combustion such as heaters or furnaces. Further, chemical reactions between the terpenes in common household products and ozone (outdoor or from air cleaners) produce formaldehyde and other byproducts (Destaillats 2007). Energy efficiency interventions that tighten homes and reduce infiltration of outdoor air have been shown to increase formaldehyde levels in the home (Grimsrud, 1987).

This paper examines a ventilation strategy used in high performance homes programs to dilute pollutants in indoor air. The ventilation strategy was tested in conjunction with elements designed to reduce other asthma triggers, particularly dust mites and mold. Unlike other environmental asthma prescriptions, this healthy homes intervention package does not rely on homeowner behavior such as weekly vacuuming or laundering linens. The goal was to create specifications and construction processes that would lead to a home that performs effectively while experiencing the typical wide range of homeowner behaviors.

Methods

The study was conducted in central North Carolina (mixed-humid climate zone) during 2003-2006. The study examined a total of 36 homes built by Habitat for Humanity Affiliates, including 20 intervention and 16 non-intervention homes.

Non-intervention homes were not altered from their original building-code compliant construction.

Intervention Package Based on High-Performance Homes Standards

The intervention package was based on high-performance home standards used in successful regional and national programs. The programs include both specifications and a quality assurance process. This program goes beyond local building codes to upgrade and provide quality control in the areas of ventilation, moisture control, energy efficiency, durability and safety. To ensure all standards were met, each home received a minimum of three quality control visits. The three quality control visits occurred after the framing, insulation and pre-occupancy stages. The programs include a two-year guarantee for the amount of energy the home will use for heating and cooling. The guarantee is based on energy use predicted by a software model. Additional details on these standards and process can be found on the *System**Vision*** web site at www.systemvision.org. The same standards are used in the national *Environments for Living* program in which over 150,000 homes have been built across the United States.

Ventilation Strategy in the Intervention Package

The ventilation strategy used by the high performance homes programs aims to offset the reduced infiltration of outdoor air through the envelope and ducts by providing outdoor air to dilute pollutants generated indoors. The study intervention package did not specify any source control of formaldehyde or other volatile organic compounds. The builders used carpets and cabinetry that were part of their typical construction specifications. Likewise, study participants were not asked to make any changes to their behaviors or to the products they brought into the homes.

The ventilation components of the intervention package consist of an outdoor air intake and spot exhaust in the kitchen and bathrooms.

The outdoor air intake consisted of a six-inch flex duct connected to a vent at the foundation at one end, and to the return air plenum at the other end. A six-inch manual balancing damper was installed in the flex duct near the outside intake, the damper was adjusted using an Exhaust Fan Flow Meter (the Energy Conservatory) and a digital manometer while the air handler was operating. A fiberglass mesh filter was installed at the intake in order to exclude insects and large particles.

The outdoor air was controlled with an AirCycler timer (Lipidex Corporation, Marshfield MA). The timer turns on the air handler for twenty minutes out of every hour when the thermostat is not calling for heating or cooling. This brings in a consistent amount of outdoor air, even when the homeowner does not use their heating or cooling system during mild-weather times of the year.

The amount of outdoor air introduced was equivalent to 10 cubic feet per minute (CFM) in each bedroom plus 10 CFM. Thus, a 3 bedroom house received added mechanical ventilation of 40

CFM (10 CFM x 3 + 10 CFM). The level of outdoor air provided meets ASHRAE Standard 62.2 on an intermittent basis. In mixed-humid climates such as the study location, there is concern that providing continuous untempered ventilation will introduce more moisture load than the heating, ventilation and air conditioning (HVAC) system can wring out of the air, thereby generating moisture-related problems in the home.

Spot exhaust fans were required in the kitchen and bathrooms. Fans were installed with insulated metal or flexible ducts and all connections were sealed with mastic. Each bathroom fan exhausts at least 50 CFM directly to the outdoors. The kitchen fan was hard-ducted to the outdoors with a back-draft damper installed and exhausts a minimum of 100 CFM. The exhaust ratings conform to ASHRAE Standard 62.2.

The kitchen and bath exhaust fans and the outdoor air ventilation system were performance-tested with an exhaust flow pan meter to ensure the flows of these items met program standards. The exhaust fan was turned on, the flow pan was placed over the fan and a tight seal was created. When needed, tape was used to create an air-tight seal to get accurate ventilation numbers. In order to test the outdoor air ventilation, the HVAC system was turned on and the exhaust flow pan meter was placed over the outdoor air intake on the exterior of the homes to obtain a reading. If the outdoor air flow was outside of requirements, the manual damper was adjusted until the required air flow was achieved.

The air-tightness standards created by *System***Vision** were designed to reduce air entering homes through unplanned holes. All large holes and penetrations (such as p-traps, chases, vents, etc.) into the air barrier were sealed. The bottom plate of the wall assembly was either caulked or set on Sill Seal (Sandell Manufacturing Company, Schenectady NY) in order to reduce air leakage into the homes. The air-tightness of the homes was verified to be no more than 0.35 CFM at 50 Pascals of pressure per square foot of building surface area.

The intervention and non-intervention homes were similar in size, but had different home performance characteristics. The non-intervention homes had more leaks in the building envelope and ducts. They had less effective spot ventilation. None of the non-intervention homes had spot ventilation in the kitchen—all had recirculating fans, which force odors and moisture from cooking back into the kitchen by means of a fan located in the vent hood. In contrast, all of the kitchen exhaust fans in the intervention homes were vented to the outside by running a duct from the vent hood to the exterior of the home. Table 1 displays a comparison of the intervention (I) and non-intervention (N) homes over several categories. The recirculating fans are shown with a value of 0 CFM because they did not vent to the outside.

Table 1. Summary of home performance characteristics.

Average home performance values by intervention				
Data type	Units	Intervention	Non-intervention	% Diff (I from N)
Duct leakage	CFM25	34 (3%)[1]	122 (10.4%)[1]	72% tighter
Home leakage	CFM50	862 (0.25)[2]	1142 (0.31)[2]	25% tighter
Kitchen exhaust	CFM	106	0	n/a
Bath 1 exhaust	CFM	58	38	53% higher
Bath 2 exhaust	CFM	56	37	52% higher
Floor area	square ft	1143	1192	4% smaller
Envelope area	square ft	3466	3619	4% smaller
[1] Percentage in parentheses represents CFM25 total duct leakage per square foot floor area. For comparison, note that the Energy Star program requires 6% duct leakage to outdoors.				
[2] Number in parentheses represents CFM50 home leakage per square foot envelope area				

Using the measured air tightness of the home we calculated air changes per hour the intervention homes experienced compared to the leaky non-intervention homes using a common calculation based on the air flow across the blower door at 50 pascals (Meier, 1994). The air changes per hour calculated in this manner are a rough estimate of actual air changes (Gao, 2007). On average, the intervention homes are calculated to have about 25% fewer air changes per hour than the non-intervention group as shown in Table 2.

Table 2. Calculated ventilation rates at 50 Pascals.

Snapshot of Ventilation Rates (Air Changes Per Hour) *excluding* impact of air cycler and ventilation fans		
Group	Average ACH at 50 Pa (measured)	Average ACH Natural (calculated)
Intervention	5.7	0.3
Non-Intervention	7.2	0.4

Other High-Performance Elements of the Program Package

The *System***Vision** standard requires combustion appliances to be sealed combustion, power vented or installed outside the living space. In this study, only one home had a gas combustion appliance and a carbon monoxide detector was installed for that homeowner.

The installed HVAC units were within a half-ton of the ACCA Manual J calculated size. Refrigerant charge was installed according to the manufacturer's instructions. An outdoor thermostat controlling the strip heat was installed so the strip heat is locked out until outdoor temperatures fall below 40 degrees Fahrenheit.

All joints in the air distribution system were sealed with duct mastic, fiberglass mesh and mechanical fasteners. Total duct leakage, measured in CFM, at 25 Pascals of pressure was verified to be less than or equal to three percent of the floor area. For example, a home with 1,000 square feet of conditioned space was required to achieve less than or equal to 30 CFM25 of duct leakage. Bedroom doors were undercut and ductwork was designed to ensure that all zones had pressures between –3 and +3 Pascals when referenced to outside. In order for the airflow to be within 10 % of the designed airflow in each room, all the runs in the air distribution system had manual dampers installed and adjusted.

Additional Elements in the Intervention Package

The intervention package tested in this study added elements to enhance possible respiratory health benefits. Elements included filtration installed in-line with the duct work and additional moisture management, from a closed crawl space installed using a protocol previously demonstrated to manage moisture and reduce energy use (Dastur, 2005; Malkin-Weber et al. 2007).

An Aprilaire media filter (Research Products Corporation) with a Minimum Efficiency Reporting Value (MERV) of 10 was installed at the air handler. Once the outdoor air is pulled into the return air plenum it mixes with house air and is drawn through a six inch pleated media filter before it enters the air handler and is conditioned for distribution to the living space and closed crawl space.

At the time of construction in 2003 and 2004, upgrades for the intervention home cost $6,145 extra compared with the code built home. Over the years, the contractor and supply infrastructure for installing closed crawl spaces has greatly improved in North Carolina so the cost for installing a closed crawl space has decreased. Simultaneously, costs for *System***Vision** upgrades have increased. The intervention upgrades have decreased overall to $4,540 in 2007 – a reduction of $1,605 in four years.

Environmental Parameters Measured

A seven-day formaldehyde sample was taken in the living space of each home during a 40-day period beginning August 2005. This period fell during the humid season. Due to construction delays, the intervention homes were built later than the non-intervention homes. At the time of sampling, the median age of the intervention homes was 10 months and all had been occupied for at least 5 months. The median age of non-intervention homes was 20 months.

UMEx 100 Passive Samplers (3M) were used. The samplers have a level of detection of 0.03 ug (2 ppb). The samplers were stored in a freezer at Advanced Energy until needed. Samplers were deployed in the central hall of the homes suspended by a string measuring approximately 12 inches.

The date, location and time the samplers were turned on was recorded on the back of each sampler and on the accompanying aluminum pouch. After seven days, the samplers were retrieved. Again, the date and time the samplers were turned off was recorded. The samplers were immediately placed in an ice cooler and later sent to be processed at a local laboratory.

Each badge contained an exposed (sample) and unexposed (blank) side. The membrane from each side of each badge was removed and placed into 3 mL of acetonitrile. Analysis was conducted by injection of 25 µL of the extract onto a gradient HPLC system (Waters Alliance 2695) fitted with a Deltabond Res AK column (4.6 mm x 25 cm, Keystone) and a UV absorbance detector set at 365 nm. The initial solvent composition was 45:55 acetonitrile:water and was programmed to 75:25 acetonitrile:water. The flow rate was 1 mL/min.

Calibration was accomplished using solutions prepared from a purchased formaldehyde DNPH solution (500 µg/mL as formaldehyde, Ceriallant) in acetonitrile. A total of 6 points was used in the curve and masses ranging from 0.313 to 31.4 ng/25µL were introduced onto the column. Data were acquired using an Atlas 2000R2 Chromatography Data System (Thermo Informatics, Version 4.30). Formaldehyde masses in each sample were determined by subtracting the mass of the formaldehyde derivative in the blank from the formaldehyde mass in the sample. The concentrations of formaldehyde were then calculated using the sampling (exposure) time, the sampling rate supplied by the manufacturer (20.4 mL/min for a 7 day sample), and the mass of formaldehyde derivative in the total volume of extract.

Analytical precision was characterized by analyzing 3 samples in duplicate. Percent differences among the duplicate injections ranged from less than 1% to 4.2%. Both of these method performance criteria were considered acceptable.

Concentrations ranged from 24 to 150 µg/m3. Many of the sample extracts required dilution and re-analysis to bring the peak areas within the range of the calibration. The capacity of the membranes is stated by the manufacturer to be 29 µg formaldehyde/sample. For a 7 day sample, this would correspond to an air concentration of 141µg/m3. Only sample number 6 exceeded that formaldehyde mass. However, it should be noted that the presence of large amounts of other carbonyls that react with the DNPH reagent would be anticipated to decrease the total capacity for formaldehyde; this was not evaluated.

Results

No significant difference was found between formaldehyde levels in the intervention and non-intervention groups. Formaldehyde values averaged 0.067 ± 0.025 parts per million (ppm) inside the homes, as summarized in Table 3.

Table 3. Average Formaldehyde Levels Found in Homes by Group

Average formaldehyde levels				
Status	Weight [µg/m^3]	St Dev* [µg/m^3]	Weight [ppm]	St De [ppm
Intervention	85	27	0.069	0.02
Non-Intervention	79	31	0.064	0.025
All	82	29	0.067	0.025

*Standard Deviation

Levels in individual homes varied between 0.02 ppm and 0.122 ppm, as shown in Figure 1 below.

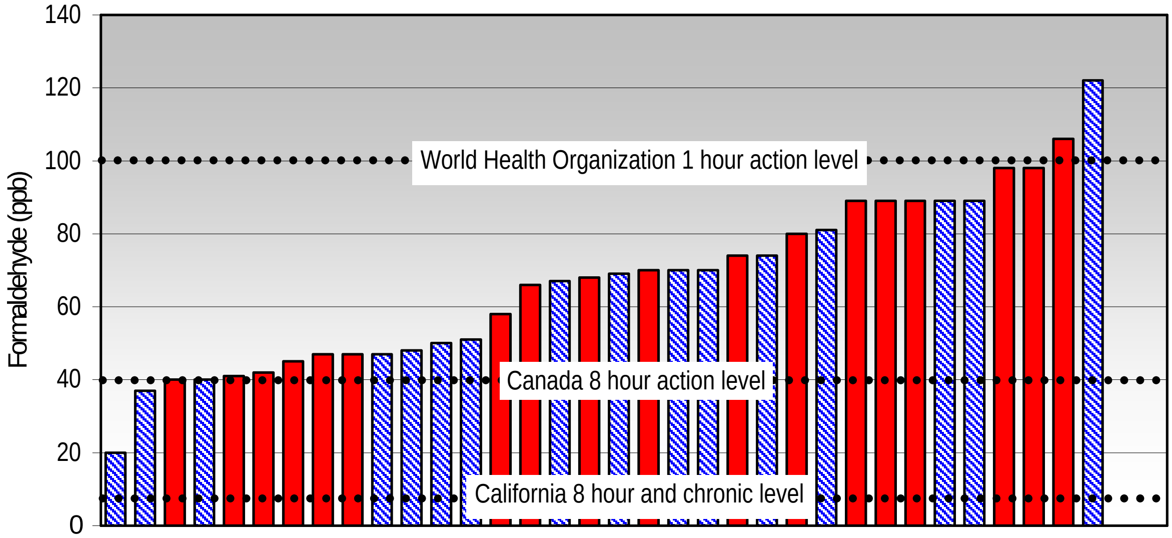

Figure 1. Formaldehyde levels in each home. Solid bars represents the intervention (I) homes and bars with diagonal lines represent the non-intervention (NI) homes.

Guidelines for non-occupational levels of formaldehyde vary. Health Canada and the World Health Organization recommend a 100 ppb action level (WHO 1989, Health Canada 2006). Health Canada also recommends a 40ppb eight-hour residential exposure limit. California recommends an eight-hour and chronic Reference Exposure Level guideline of 7 ppb (State of California Office of Environmental Health Hazard Assessment (OEHHA)). The 7 ppb level is lower than what is often present in ambient outdoor air (CDC 2008).

Discussion

Two important conclusions come from the study results: first is that the high performance homes program succeeded in its mandate to “do no harm” while improving the energy efficiency performance of the homes. Second, the levels of formaldehyde found in the homes are not reassuring compared to published guidelines.

The formaldehyde measurements in this set of houses demonstrate that the construction standards for a tight envelope and tight ductwork did not create higher levels of formaldehyde in these homes compared to homes with unplanned ventilation (duct and envelope leakage). The ventilation package seems to have compensated for reducing the infiltration of outdoor air through the ductwork and building envelope.

However, the high performance homes program did not deliver measurably lower levels of formaldehyde in indoor air compared to the non-intervention group. Thus, the program can not claim to improve formaldehyde in indoor air compared to other leaky houses. A study by the authors currently underway tests whether a similar ventilation package provides lower formaldehyde levels compared to houses with minimal duct and envelope leakage, but without planned ventilation.

The results of this study speak directly to the central issue in an ongoing discussion within the building science community: how best to control and dilute indoor pollutants while managing indoor moisture levels in humid and mixed-humid climates. Continuous ventilation would likely improve formaldehyde results as shown in a recent study by Offerman et al. However, continuous ventilation without an energy recovery ventilator or dehumidifier will most likely introduce excessive moisture and increase energy costs. The tradeoff between moisture and dilution in humid climates poses a dilemma for affordable housing programs in particular. The initial and operational costs associated with energy recovery ventilators have yet to be justified to builders and homeowners on a very tight budget

Given the risks to health, comfort, durability and affordability posed by moisture introduced through extensive dilution in a mixed-humid climate, it is clear that prevention of emissions must also play a role in indoor air quality. Some reductions in indoor formaldehyde levels are expected when the U.S. Environmental Protection Agency completes its rulemaking process to regulate formaldehyde emissions from wood products. However, wood products are not the only source of formaldehyde, and formaldehyde is just one of many volatile organic compounds in the indoor air. Therefore, effective dilution strategies must be developed. It may be that we need to re-think the way we design and install our heating, cooling, and ventilation systems to put a greater, or even central, emphasis upon ventilation rather than characterizing it as an optional addition or pricey upgrade. Following such an approach would address moisture concerns more effectively and better manage the costs of installing and operating the system.

References

Health Canada. Residential Indoor Air Quality Guideline: Formaldehyde. Ottawa, Ontario, April 2006.

Centers for Disease Control and Prevention (CDC). Final report on formaldehyde levels in FEMA-supplied travel trailers, park models, and mobile homes July 2, 2008

Davis B, Dastur C. Moisture performance of closed crawl spaces and their impact on home cooling and heating energy in the southeastern United States. U.S. Department of Energy Oak Ridge National Laboratory and ASHRAE Performance of the Exterior Envelopes of Whole Buildings IX International Conference 2004. Clearwater Beach, Florida.

Destaillats H. Indoor chemistry of ozone with household product constituents. ASHRAE IAQ 2007 Conference. Baltimore, Maryland.

Grimsrud DT, Turk BH, Prill RJ, Harrison J, Revzan KL. Effects of house weatherization on indoor air quality. lndoor Air '87: Proceedings of the 4th International Conference on lndoor Air Quality and Climate, Berlin (West). August 1987.

Guo L, and Lewis JO. Carbon dioxide concentration and its application on estimating the air change rate in typical Irish houses. International Journal of Ventilation 2007; Vol 6, No 3.

Hodgson AT, Beal D. Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house. E.O. Lawrence Berkeley National Laboratory 2002. Contract2002. Contract number DE-AC03-76SF00098. Available at http://eande.lbl.gov/ied/viaq/.

Kelly TJ, Smith DL. Satola J. Emission rates of formaldehyde from materials and consumer products found in California Homes. Environmental Science and Technology 1999; 33: 81-88.

Loh, MM, Levy JI, Spengler JD, Houseman EA, Bennett DH. Ranking cancer risks of organic hazardous air pollutants in the united states. Environmental Health Perspectives 2007; Vol 115, Num 8.

Malkin-Weber M, Coulter J, Hannas B, Dixon T. High performance intervention houses in north carolina – an attempt to control indoor relative humidity at 50% year round. Indoor Air 2008, Copenhagen, Denmark. http://www.indoorair2008.org/.

Meier, A. Infiltration: just ACH50 divided by 20? Home Energy, 1994

Mendell, MJ. Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: a review. Indoor Air 2007; 17: 259–277

Office of Environmental Health Hazard. Assessment Technical Support Document For the Derivation of Noncancer Reference Exposure Levels, Appendix D.1 Individual Acute, 8-Hour, and Chronic Reference Exposure Level Summaries. Oakland: California 2008

Offerman F, Brennan S, Roberson J, Springer D Woo T. Window Usage, Ventilation, and Formaldehyde Concentrations in New California Homes: Summer Field Sessions. ASHRAE IAQ 2007 Conference, Baltimore, Maryland.

WHO - World Health Organization. Environmental health criteria for formaldehyde. 1989. Geneva, Switzerland: World Health Organization; Volume 89