Topic C6: Low Energy Buildings

Long Term Air Quality Monitoring in a Net-Zero Energy Residential Test Facility Designed with Specifications for Low Emitting Interior Products

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SUMMARY: This study evaluated the effectiveness of a low-VOC (volatile organic compounds) specification designed to minimize occupant exposures to indoor air pollutants in a net-zero energy research house meeting the ASHRAE Standard 62.2 ventilation requirements. The results show that the use of medium density fiberboard and particleboard with no-added formaldehyde resins for cabinetry and other finished products effectively controlled the formaldehyde emissions and kept concentrations below levels in typical new homes. Monitoring of seasonal indoor VOC concentrations suggests that building envelope components may be an overlooked source for some VOCs, especially aldehydes and alkanes.

INTRODUCTION: As residences are built tighter and air change rates are lowered to reduce energy use for heating and cooling, the emission of gaseous pollutants from building materials and furnishings into indoor air becomes more of a concern in maintaining a healthy indoor environment. In 2012, the National Institute of Standards and Technology (NIST) built a Net-Zero Energy Residential Test Facility (NZERTF) to demonstrate that a typical home is able to achieve net-zero energy use over one year while meeting the needs of a family of four. The NZERTF is a two-story, detached home with a basement and an attic within the building thermal envelope. The house is similar in size and aesthetics to homes in the surrounding communities. To achieve the net-zero energy goals, several energy-efficient technologies are employed, including a highly insulated thermal envelope, a high efficiency heat pump, and renewable energy systems including a solar hot water system and a 10.2 kW photovoltaic system. To minimize infiltration, special attention was paid to the design and construction of the building envelope, resulting in a measured airtightness value of 0.60 h^{-1} at 50 Pa.

Two strategies were employed to minimize VOC concentrations in the house: 1) ventilation was provided continuously with a heat recovery ventilator, and 2) specifications were developed to require construction with low emitting building materials. To comply with the outdoor air requirements in ASHRAE Standard 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings (ASHRAE 2013), a stand-alone heat recovery ventilator was installed to supply 171 $m^3 h^{-1}$ of outdoor air (0.13 h^{-1}). The heat recovery ventilator consumes approximately 42 kWh/month, which is estimated to be 3 % to 6 % of the total annual energy consumed in the house. The thermal load of the ventilation air can be up to 25 % of the heating load in the winter.

Prior to construction of the NZERTF, specifications were developed for the selection of interior products with low emissions of hazardous and odorous VOCs. Reduction in sources of formaldehyde was emphasized. These specifications addressed adhesives and sealants; paints and coatings; interior woodwork, doors and closets; cabinetry; floor coverings; and insulation. Publicly available standards and regulations for VOC content and emissions were referenced as applicable. Material safety data sheets and other published information for products selected by the design team were reviewed for consistency with the specifications, and recommendations on these selections were provided as needed.

In order to reduce formaldehyde sources, the specifications required that materials had to meet the following requirements: paints, coatings, adhesives and sealants not contain chemicals of concern, including formaldehyde, as an ingredient; all composite woods including cabinetry, countertops, trim, and engineered flooring be constructed with no-added formaldehyde (NAF) cores and adhesives; cabinetry cases, drawers and interior components be constructed with NAF plywood; and insulation have NAF resins. It was recognized that the specified products likely emit VOCs other than formaldehyde. For example, wood and composite wood products are known sources of terpenes, aldehydes, acids and some alcohols. Paints and other finishes release TMPD-MIB (2,2,4-trimethyl-1,3-pentanediol monoisobutyrate) and glycols. Adhesives and caulks can be sources of alkane and possibly aromatic hydrocarbons.

The objective of this research was to document if the low-VOC specifications were successful at minimizing exposure to indoor pollutants in a net-zero energy building meeting the ASHRAE Standard 62.2 ventilation requirements..

METHODS: One year after the completion of NZERTF construction, indoor air was sampled approximately monthly for the next eight months. Concentrations of 32 target VOCs associated with paints, flooring, adhesives, insulation, and composite wood were monitored. During each sampling event, duplicate samples were collected in three locations: first floor, second floor, and outdoors. Outdoor concentrations were subtracted from the average of the indoor concentrations to determine the increased concentrations (herein referred to as I-O concentration) due to indoor emissions. VOCs were collected with sorption tubes (1 hour sample at 0.1 L min^{-1}) and analyzed using thermal desorption-GC/MS. Aldehydes were collected with DNPH cartridges (1 hour at 1 L min^{-1}) and the extracted derivatives analyzed using LC/UV. These sample tubes were shipped overnight to a laboratory for analysis.

RESULTS: The combined VOC concentration of the 32 measured chemicals (Table 1) fell from 876 $\mu g\ m^{-3}$ to 204 $\mu g\ m^{-3}$ over the eight months of monitoring. The average concentration of formaldehyde, which was targeted by the design specifications, was 6.5 ppb_v (max 8.2 ppb_v). This value is below the average of 32 ppb_v reported for 20 new homes of standard construction and the average of 17 ppb_v for 60 existing homes (Hodgson and Levin 2003). The average concentration of acetic acid was 17.8 ppb_v, which is below the average concentrations of 71 ppb_v for the 20 new homes and 24 ppb_v for 60 existing homes (*ibid*.).

Average concentrations of toluene, benzene, 2-butanone, tetrachloroethene, α-pinene, β-pinene, d-limonene, n-undecane, ethylene glycol, and TMPD-MIB were all at least a factor of five less than the corresponding concentrations reported for 20 new homes (Hodgson, Rudd et al. 2000). Average concentrations of butanal, pentanal, hexanal, styrene, 1,2,4-trimethylbenzne, benzaldehyde and ethylene glycol were all elevated compared to the 20 new homes (*ibid*.).

In general, aldehydes and ketones increased throughout the summer sampling events and decreased thereafter (Figure 1). Aromatic and alkane hydrocarbons followed a similar trend. In contrast, the concentrations of acids and alcohols were mostly constant through the summer and fall sampling events.

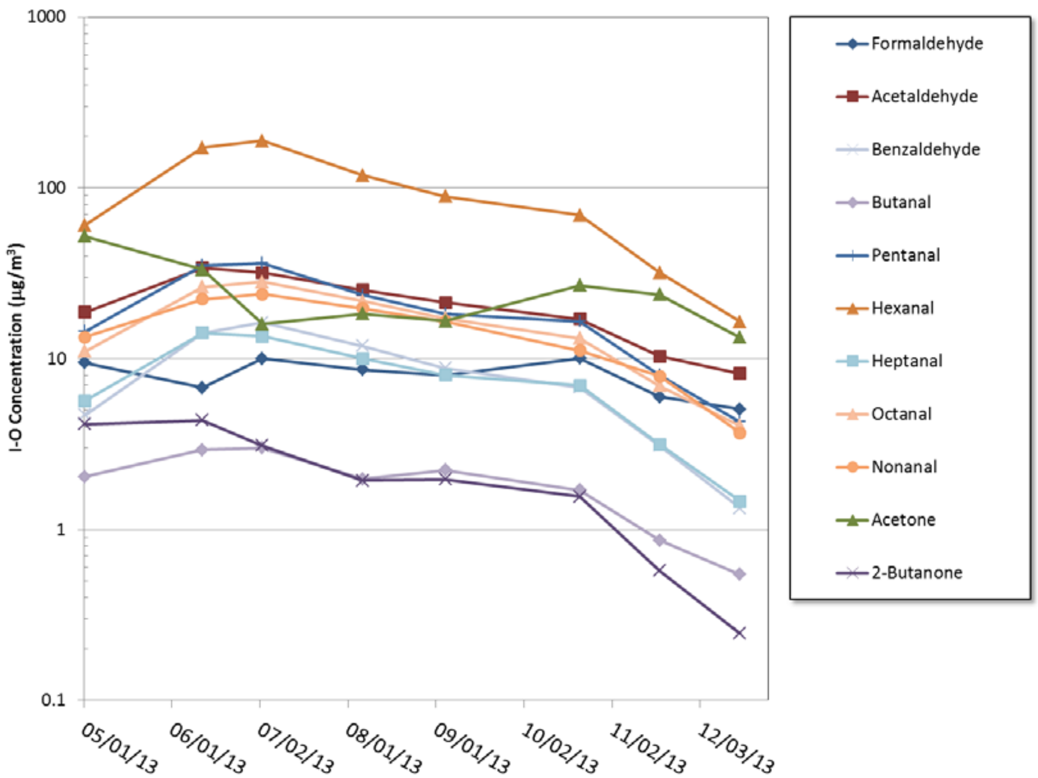

Figure 1: Indoor minus Outdoor (I-O) Concentrations of Aldehydes and Ketones over Eight Months.

Chemical vapor pressure is known to relate to temperature in an Arrhenius relationship and to concentration by the ideal gas law as follows:

$$C \propto P \propto e^{\left(\frac{\Delta H}{RT}\right)} \tag{2}$$

where P is the vapor pressure (Pa), T is the absolute temperature (K), R is the universal gas constant, and ΔH is the enthalpy of vaporization. Hence, if the concentration of the VOCs is purely controlled be evaporative primary emissions, a plot of $1/T$ versus the $\ln(C)$ should result in a linear relationship. Figure 2 illustrates this relationship with outdoor temperature for aldehydes and ketones.

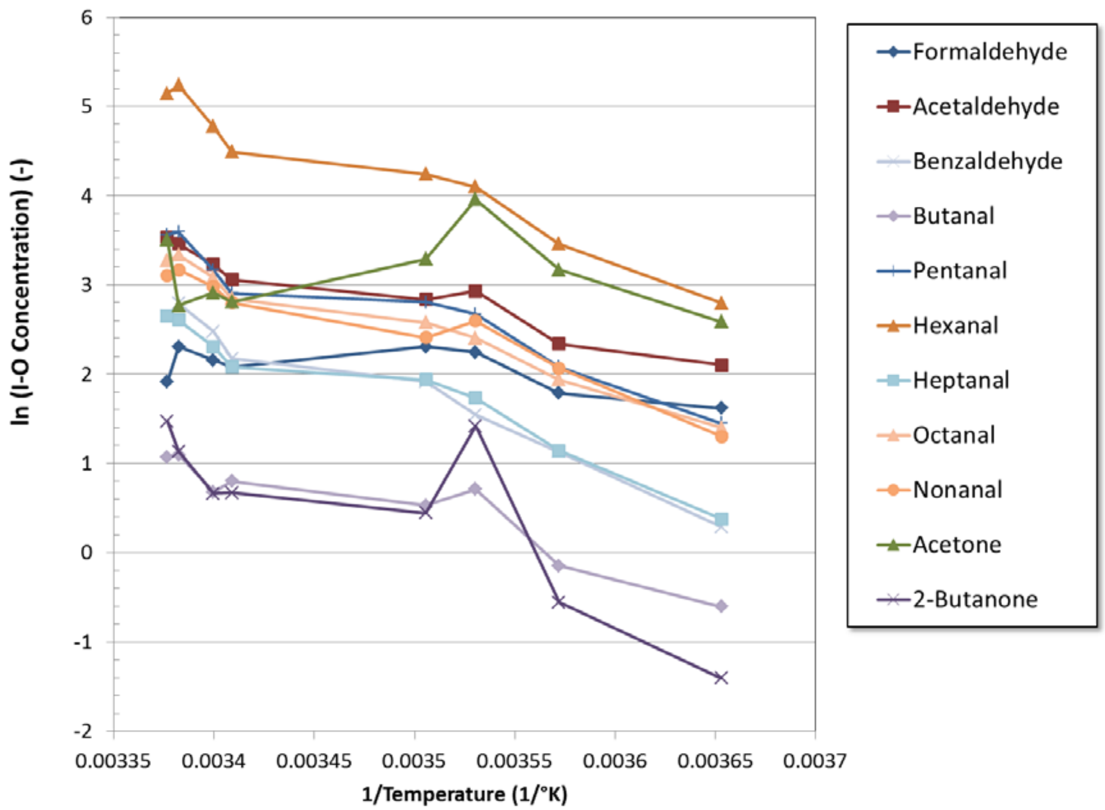

Figure 2: Arrhenius Relationships between I-O Concentration and Outdoor Temperature.

The R-squared values for a linear fit of concentration to the inverse of absolute outdoor temperature were greater than 0.8 for all the aldehydes except formaldehyde (Table 1). In addition, the aldehyde concentrations fell for the last three sampling periods (Figure 2), during which the outdoor ozone concentrations were 18±5.6 ppb_v, 33±1.6 ppb_v and 11±1.9 ppb_v, respectively (an average indoor-to-outdoor ozone concentration ratio of 0.32). The lack of correlation between aldehyde and ozone concentrations indicates that the aldehydes are not primarily the result of secondary chemical reactions. The natural log of the concentration of alkanes, toluene, β-pinene, hexanoic acid, and 1-butanol also had a high correlation (greater than 0.8) with the inverse outdoor absolute temperature. The observed relationships with outdoor conditions with nearly constant indoor temperatures, suggests that emissions of these chemicals may be related to the building envelope temperature.

Through six months (July-December) of monitored operation, the NZERTF produced more total energy through the roof-mounted 10.2 kW photovoltaic panels than it consumed. The heat recovery ventilator was operated continuously at approximately 0.13 h^{-1} during that time. To account for infiltration due to building envelope leakage, the house was modeled using the CONTAM multizone airflow model (Walton and Dols, 2005) using local weather data for the sampling periods. The calculated infiltration rates ranged from 0.01 h^{-1} to 0.05 h^{-1}. The average value of the total air change rate (λ, sum of the infiltration rate and the heat recovery ventilator airflow) for the 12 hours prior to air sample collection were used to calculate steady state emission rates (E_f, μg m^{-2} h^{-1}) using Equation 1:

$$E_f = \frac{\lambda V(C_{in} - C_{out})}{A_i} \qquad (1)$$

where V is house volume (m^3), C_{in} is average indoor concentration (μg m^{-3}), C_{out} is average outdoor concentration(μg m^{-3}), and A_i is area of the material of interest (m^2). Emission rates were calculated using the average concentration, the entire floor area, and total house volume (1,300 m^2 and 485 m^3, respectively). Average whole-house emission rates are shown in Table 1. Only acetic acid, 1-butanol, and ethylene glycol exceed previously reported values for new manufactured homes or site built homes. Formaldehyde emission rates were an order of magnitude lower than previously reported values.

Certain chemicals were likely emitted by only one type of product in the house. For example, the only known source of styrene was the extruded polystyrene insulation in the basement. Glycols and TMPD-MIB were likely emitted from painted surfaces. For these chemicals, the projected surface areas of the materials in the house were measured and used to calculate product specific emission factors (μg h^{-1} m^{-2}) as shown in Figure 3. For the other chemicals, their sources were inferred as discussed below and product specific emission factors were estimated.

For the chemicals shown in Figure 3, the average linear correlation coefficient (RSQ) of outdoor temperature to the emission factor was twice that for the indoor temperature. Hexanal, α-pinene and β-pinene are known to be emitted by wood products (flooring, cabinets, structural plywood, etc.). However, the outdoor temperature dependence of the emissions of these chemicals suggests that they originated from building products in the building envelope. The building envelope consists of cement board siding, extruded polyisocyanate board, a self-adhering bituminous air/vapor barrier, plywood sheathing, cellulose insulation and wallboard. Of these products, cellulose insulation and plywood are the most probable sources of these compounds. To distinguish between these sources, we examined the ratios of chemical concentrations. When the I-O concentrations of the aldehydes are normalized by the hexanal concentration, the ratios match concentrations from plywood chamber emission studies within 4 % with exceptions of acetaldehyde, benzaldehyde, and d-limonene. Given this “fingerprint” and the emission correlation to the outdoor temperature, it is likely the main source of hexanal, α-pinene and β-pinene emissions is the exterior plywood. Hence, the emission factors for these chemicals were calculated using the area of the plywood sheathing and are shown in Figure 3.

Table 1. Average whole-house emission rates normalized by floor area (Emission Factors) for NZERTF compared to California New Homes Study (CNHS) and studies of new, unoccupied manufactured and site-built homes. R-Squared (RSQ) values for correlations between I-O VOC concentrations and temperature.

		Emission Factor ($\mu g\ h^{-1}\ m^{-2}$)					
Compound	**Chem Class**	**NZERTF** [a]	**CNHS N=108** [b]	**Manuf Home N=1** [c]	**Manuf Home N=4** [d]	**Site-Built Home N=7** [e]	**Arrhenius RSQ**
Acetic Acid	Acid	19.8			8.5	23.2	0.56
Hexanoic acid	Acid	3.8			7.3	17.8	**0.83**
Ethanol	Alcohol	50.1					0.01
2-Propanol	Alcohol	5.9					0.05
1-Butanol	Alcohol	**4.3**			3.9	25.8	**0.89**
Phenol	Alcohol	**1.1**	0.8		1.8	3.8	0.70
Formaldehyde	Aldehyde	3.6	28.9	61.9	45	31	0.32
Acetaldehyde	Aldehyde	9.1	13.9	26.3	17	25	**0.92**
Butanal	Aldehyde	0.8					**0.84**
Pentanal	Aldehyde	8.4		50.0			**0.92**
Hexanal	Aldehyde	**39.6**	5.8	181	76.9	84.5	**0.94**
Heptanal	Aldehyde	3.4			7.7	7.2	**0.93**
Octanal	Aldehyde	6.9		29.4	14.1	1.6	**0.97**
Benzaldehyde	Aldehyde	3.6		9.1			**0.96**
Nonanal	Aldehyde	6.4		28.1	63.5	166	**0.93**
n-Undecane	Alkane	0.6			11.5	18.5	0.21
n-Pentadecane	Alkane	1.4					**0.85**
n-Hexadecane	Alkane	2.2					**0.91**
n-Heptadecane	Alkane	3.0					**0.91**
Toluene	Aromatic	0.7	5.5		309	94.8	**0.82**
Styrene	Aromatic	1.7	0.5		27.6	50.6	0.72
1,2,4-Trimethylbenzene	Aromatic	1.7	0.5				0.78
Cyclohexanone	Cyclic	0.1					0.15
TMPD-MIB	Ester	2.1			10.8	16.1	0.32
Propylene glycol	Glycol	12.0			105	123	0.53
Ethylene glycol	Glycol	12.0	10.3		4.1	8.3	0.65
Acetone	Ketone	11.7					0.00
2-Butanone	Ketone	1.0			21.5	19.1	0.17
Decamethylcyclopentasiloxane	Siloxane	2.7			14.7	13.4	0.18
α-Pinene	Terpene	8.6	7.6	156			0.58
β-Pinene	Terpene	3.6		50.6			**0.82**
d-Limonene	Terpene	1.0	6.8	27.5	9.6	2.1	0.43

[a]Average E_f measured over eight-month period. Bold highlight for value exceeding any reported value.

[b]Median E_f for 108 new, occupied, single-family homes. Calculated as products of volume specific E_f from Offermann and Hodgson (2011) and 2.63 m median ceiling height. Homes in this study had attached garages and were occupied during testing. (Offermann and Hodgson 2011)

[c]Aldehyde and terpene E_f in single, new manufactured home. Home was furnished (Hodgson, Beal et al. 2002).

[d]Geometric mean E_f in sample of four new, furnished manufactured homes. (Hodgson, Rudd et al. 2008).
[e]Geometric mean E_f in sample of seven new, unfurnished manufactured homes. (Hodgson, Rudd et al. 2008)

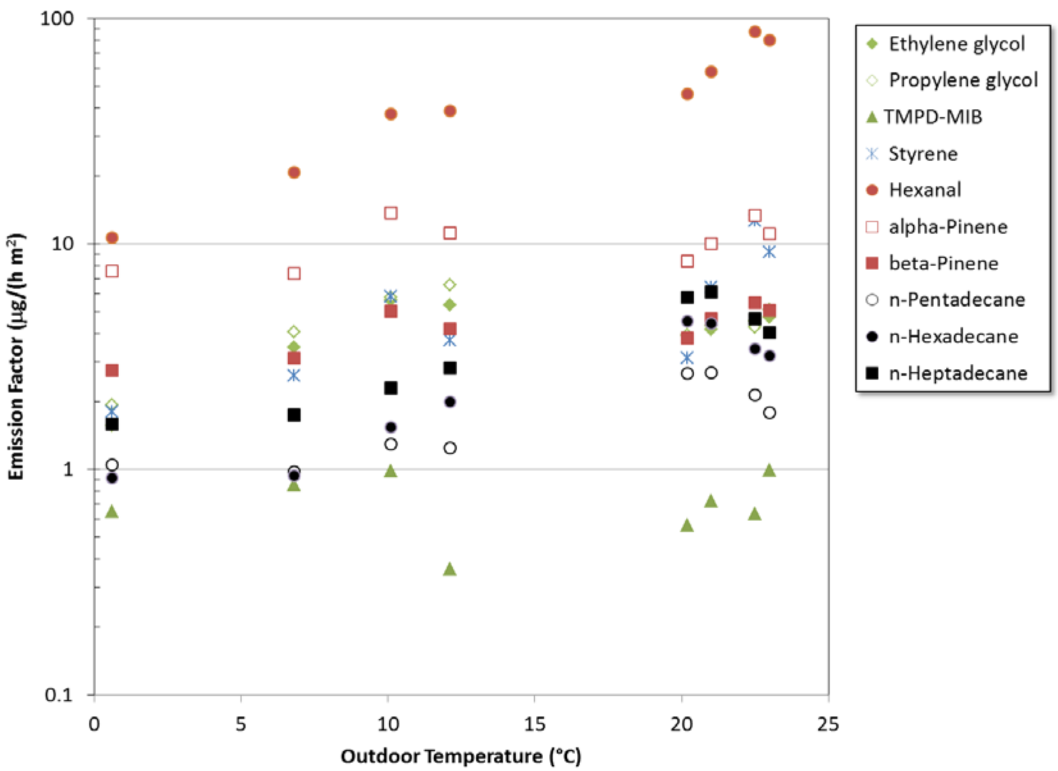

Figure 3: Relationships between Emission Factors and Outdoor Temperature (Green: Paint, Red: Building Envelope Plywood, Blue: Polystyrene Insulation; Black: Air and Vapor Barrier).

A sample of the air/vapor barrier emitted n-pentadecane, n-hexadecane, and n-heptadecane when placed for an hour in a 114-mL microchamber (40 °C at 100 mL min^{-1}, with sample collection and analysis by thermal desorption GC/MS). Hence, the product specific emission rate shown in Figure 3 for these chemicals is calculated using the area of the air/vapor barrier.

CONCLUSIONS: The results show that specification of low emitting interior products in the construction of Net-Zero energy homes with ventilation per ASHRAE Standard 62.2 can result in indoor residences with lower VOC concentrations and VOC emission rates than typical new homes. Specifically, this research demonstrated for the NZERTF:

- The measures taken to reduce medium density fiberboard and particleboard in the cabinetry and other finished products appear to have effectively controlled the formaldehyde concentrations.
- Interior finish and building envelope-related VOC sources are persistent but generally decrease with time.

- Structural composite woods and air barrier materials may be an important source of some VOCs, especially aldehydes and alkane hydrocarbons. If this is the case, their contribution to formaldehyde concentration is low in this house.
- Evidence suggests that aldehydes are due to primary sources and not secondary reactions.

Indoor air sampling at the NZERTF will continue through summer of 2014.

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