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Content submitted to and published by:
Air Media Magazine, Winter (2016)

U.S. Department of Commerce
Wilbur Ross, Secretary of Commerce

National Institute of Standards and Technology
Walter Copan, Director

National Institute of Standards and Technology • U.S. Department of Commerce

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ABSTRACT

The Net Zero Energy Residential Test Facility (NZERTF) was constructed at the National Institute of Standards and Technology (NIST) to support the development and adoption of cost-effective net zero energy designs and technologies. The 250 m^2 two-story, unoccupied NZERTF, built in 2012, had the following design goals: meeting the comfort and functional needs of the occupants; siting to maximize renewable energy potential; establishing an airtight and highly insulated building enclosure designed for water and moisture control; providing controlled mechanical ventilation; and installing highly efficient mechanical equipment, lighting and appliances. The NZERTF achieved its goal of generating more energy than it consumed during its first year of simulated occupancy by a single family, despite a severe winter. The airtightness goal was achieved through detailed envelope design, careful construction, and during- and post-construction commissioning. The NZERTF is one of the tightest residential buildings in North America with a whole building pressurization test result of roughly 0.6 h^{-1} at 50 Pa. The ventilation goals were met with a heat recovery ventilator sized to comply with ASHRAE Standard 62.2-2010, which corresponds to roughly 40 L/s or 0.1 h^{-1} for this building. Low indoor contaminant levels were achieved through the careful selection of building materials. This paper describes the design and construction methods used to achieve such a tight building as well as the performance measurements made to verify that the building achieved its ventilation and indoor air quality (IAQ) goals.

INTRODUCTION

Buildings consumed 41 % of all energy used in the United States in 2010, with residential buildings and commercial buildings accounting for 22 % and 19 %, respectively (DOE 2011). In addition to consuming more energy than the transportation or industrial sectors, buildings represent the fastest growing sector of energy usage. Thus, many buildings have been designed, constructed and monitored throughout the world to demonstrate the feasibility of achieving net-zero energy. Parker (2009) presents a history of low energy homes, including annual performance data from a dozen very low energy homes in North America. While most studies of net zero energy buildings report data on energy usage, very few of them focus on ventilation and IAQ in terms of either design or performance.

Residential buildings in the U.S. and other countries have historically been ventilated by infiltration, supplemented by window openings and local exhaust ventilation. As energy efficiency has become a priority, buildings have been built to be more airtight and mechanical ventilation has been increasingly employed to meet building ventilation requirements. The U.S. was slower in making these changes compared to some countries, particularly the Nordic countries in Europe, but U.S. homes are getting tighter (Chan et al. 2013) and mechanical ventilation is becoming more common (Persily 2015). Envelope leakage or infiltration is not a good way to ventilate a building as the rate and air distribution is not controlled, the entering air cannot be filtered for outdoor contaminants or dehumidified, and the rates tend to be highest during more severe weather when the energy penalty is greatest. Mechanical ventilation allows the rates to be controlled and the incoming air to be treated, as well as providing the opportunity for heat recovery. In general, mechanical ventilation will provide better performance when combined with a tight envelope, or in the words of Arne Elmroth "Build tight, ventilate right" (Elmorth 1980). The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 62.2 contains minimum ventilation rates to achieve "acceptable" IAQ based on the floor area and number of bedrooms (ASHRAE 2010; ASHRAE 2013a).

The NIST Net Zero Energy Residential Test Facility (NZERTF) was built on the campus of the National Institute of Standards and Technology to demonstrate low energy residential technologies with the goal of net zero energy use on an annual basis. As described below, this facility is unique in the attention given to ventilation and IAQ. This paper describes the design and construction methods used in the NZERTF to achieve a very tight building with reliable mechanical ventilation, as well as the results of selected performance measurements in the building. Measures taken to address IAQ are also described, along with selected measurements of indoor chemical concentrations.

1 DESIGN AND CONSTRUCTION OF THE NZERTF

The NZERTF is a 250 m^2 two-story, unoccupied house located in Gaithersburg, Maryland with an unfinished basement and an attic, both within the conditioned space. The building envelope was constructed using advanced framing techniques (i.e., wood studs of greater depth than typical of U.S. construction, allowing for more insulation to be installed) with a continuous fully-adhered membrane air and moisture barrier sealed down to the foundation wall (Figure 1). The nominal R-value of the exterior wall assembly is 7.9 $m^2 \cdot K/W$ (R-45 $h \cdot ft^2 \cdot °F/Btu$). The roof insulation is part of the roof structure, with a nominal R-value of 12.7 $m^2 \cdot K/W$ (R-72 $h \cdot ft^2 \cdot °F/Btu$). These two values exceed the current code requirements in the state of Maryland of 2.3 $m^2 \cdot K/W$ (R-13 $h \cdot ft^2 \cdot °F/Btu$) and of 6.7 $m^2 \cdot K/W$ (R-38 $h \cdot ft^2 \cdot °F/Btu$) respectively. A 10.2 kW photovoltaic system is located on the main roof, and four solar thermal collectors are located on the roof of the front porch to contribute to the domestic hot water requirements. More details on the building design and construction can be found in Pettit et al. (2014). Internal loads, energy and water usage of a virtual family of two adults and two children were simulated according to daily schedules (Omar and Bushby 2013). Sensible heat from the occupants is simulated throughout the house, while the occupant latent loads are released in the kitchen. Energy performance results for the first year of operation of the house, which demonstrated that the facility achieved better than net zero energy, are found in Fanney et al. (2015).

While the NZERTF was designed with several heating, ventilating, and air conditioning (HVAC) options for future research purposes, only a two-speed air-to-air heat pump with a dedicated dehumidification function has been used to date. Outdoor air ventilation is provided continuously by a heat recovery ventilator (HRV) with dedicated ductwork. It supplies air to the living room on the first floor and the three bedrooms on the second floor. The air returned to the HRV is drawn from a bathroom on the first floor and two bathrooms on the second floor. It is sized to comply with ASHRAE 62.2-2010 (ASHRAE 2010) which corresponds to an outdoor air ventilation rate of roughly 40 L/s. Based on the available HRV fan settings, the actual ventilation supplied to the house was 56 L/s, as measured by duct traverse. It is interesting to compare the ventilation rate based on Standard 62.2 with the requirements based on other standards. For example, the historical ventilation requirement for residences in Standard 62, which last appeared in 62.1-2001, was 0.35 h^{-1}, which corresponds to 123 L/s in this house. A recent review of residential ventilation requirements in Europe showed that several countries require 0.5 h^{-1}, which equals 176 L/s for the NZERTF (Dimitroulopoulou 2012). It is also worth noting that a literature review of ventilation rates and health found that air change rates about 0.5 h^{-1} have been associated with reduced risk of allergic symptoms in children in Nordic climates as compared with lower ventilation rates (Sundell et al. 2011).

The NZERTF building systems are equipped with particulate filters but do not employ any gaseous air cleaning. The air distribution system of the heat pump used for heating and cooling employs a MERV 8 filter that is replaced approximately every 30 days; ASHRAE Standard 62.2 requires MERV 6. The heat recovery ventilator has washable filters in the incoming outdoor airstream and the return airstream from the building, which are rated at MERV 9 and are replaced every month.

Figure 1. Construction of NZERTF showing the air barrier (top) and completed structure (bottom).

Indoor air quality (IAQ)-based guidelines were developed for this project to support the design goal of providing good IAQ in this low-energy residence, in particular to guide the selection of interior finishes, insulation and other indoor building materials. The guidelines were mostly prescriptive, requiring use of certain products and the avoidance of others, with the objective of reducing common sources of volatile organic compounds (VOC) that affect health and comfort. Emphasis was placed on reducing sources of formaldehyde emissions based on its known health impacts (IARC 2012). Reduced emissions of VOCs in solvents were addressed by incorporating maximum VOC content requirements for wet-applied products. Guidelines were also included for adhesives and sealants, paints and coatings, built-in cabinetry, woodwork, doors, countertops, floor coverings, and insulation. Note that the house contains no furniture, which can be an important source of VOC emissions. The NZERTF IAQ guidelines have been updated and formalized into a detailed architectural specification intended for use in new residential construction and major renovations. This specification is written in a manner so that it can be applied to any project and is available in Bernheim et al. (2014).

2 PERFORMANCE MEASUREMENTS

While the NZERTF was carefully designed and construction, its actual performance in terms of infiltration, ventilation and IAQ were verified via the measurements described below.

2.1 Envelope Airtightness

Five blower-door tests were performed at the NZERTF to confirm that the envelope airtightness met the design targets (Figure 2). The first three tests (without windows, pre-drywall, and substantial completion) were conducted by third-party testing companies (Pettit, Gates et al. 2014). The final tests (#4 and #5) were performed by NIST after the house was completed, according to the methods in ASTM E779-10 (ASTM 2010). These results have an uncertainty of about 10 %. Test #4 was performed with the kitchen and dryer vents sealed and yielded an airflow rate of 195 L/s at 50 Pa, which corresponds to 0.55 h^{-1}. Test #5 was performed with those vents unsealed, yielding 223 L/s at 50 Pa or 0.63 h^{-1}. This airtightness value is compared with several guidelines in Table 1 and is tighter than the requirements in LEED and ENERGY STAR and slightly leakier than the Passiv Haus requirement. Based on statistical analysis of Lawrence Berkeley National Laboratory Residential Diagnostics Database (ResDB) by Chan et al. (2013), the NZERTF is tighter than well over 99 % of U.S. homes.

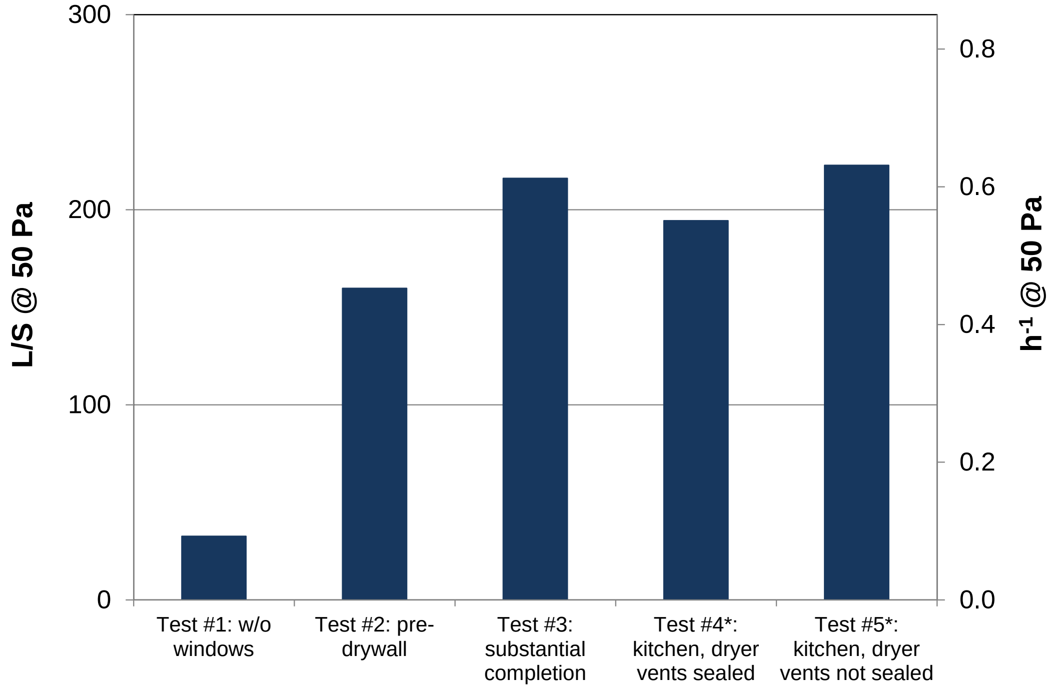

Figure 2. Blower door test results at various stages of construction. (* indicates the tests performed by NIST)

Table 1. Summary of NZERTF airtightness and relevant guidelines for airtightness

Guideline/Standard	Target Airtightness (L/s at 50 Pa)
NZERTF Design	381
Passiv House (PHI 2015)	212
LEED BD+C: Homes v4 (for 2 points) (USGBC 2014)	706
DOE Challenge Home (DOE 2013)	953
ENERGY STAR v3.1 (rev. 06) (EPA 2015)	1059
ICC 700 National Green Building Standard (testing option) (NAHB/ICC 2012)	2648

2.2 Infiltration

The total outdoor air change of the NZERTF was measured on several occasions using tracer gas decay (ASTM 2011) with the HRV on continuously and with it off. During these measurements, the heat pump and its air distribution fan were controlled by the thermostat. Measurements were made in July 2014, August 2014 and January 2015. For the summer measurements, with an average indoor temperature of 27 °C, an average outdoor temperature of 23.0 °C and an average wind speed of 1.6 m/s, the average outdoor air change rate with the HRV on was 0.17 h^{-1} and 0.02 h^{-1} with the HRV off. In the winter, with an average indoor temperature of 21 °C, an average outdoor temperature of -2.9 °C and an average wind speed of 2.9 m/s, the average outdoor air change rate with the HRV on was 0.19 h^{-1} and 0.06 h^{-1} with the HRV off.

2.3 Ventilation

As noted earlier, the HRV in the NZERTF was sized to comply with ASHRAE Standard 62.2-2010 (ASHRAE 2010), which corresponds to roughly 40 L/s or 0.1 h^{-1} for this building. The airflow through the HRV was measured periodically using a hot wire anemometer (accuracy ±3 % or 0.015 m/s), yielding an average flow of 56 L/s. The airflow of the HRV supplies and returns were measured using a balometer, with a stated uncertainty from the manufacturer of ±3 % plus 2.5 L/s. Table 2 summarizes these measurements, along with the exhaust airflows associated with the kitchen exhaust and the clothes dryer, also measured with a balometer. The sums of the HRV supply and return vents match within their measurement accuracy but are below the values measured at the unit itself, which is likely a reflection of the measurement uncertainties of the flows, particularly for the balometer measurements at the individual vents, as well as the existence of duct leakage. It is worth noting that the measured envelope infiltration rates, even in this extremely tight house, are on the order of 15 % to 40 % of the HRV ventilation rate based on the outdoor air requirements in ASHRAE Standard 62.2.

Table 2: Measured System Airflow Rates

Heat Recovery Ventilator	Supply	Return
1st Floor	15	19
2nd Floor	30	27
SUM	45 (0.13 h^{-1})	46 (0.13 h^{-1})
Ducts at HRV unit	56 (0.16 h^{-1})	54 (0.15 h^{-1})
Local exhaust		
Kitchen hood	49	
Clothes dryer	47	

* All flows in L/s except where otherwise indicated.

During the periodic HRV airflow measurements, the airflow rates were sometimes found to be significantly reduced over time. One such reduction occurred in the spring when the outdoor pollen levels were particularly high. After cleaning the HRV filters, the airflow rates returned to the levels that were measured more typically. Also, the filters were found to clog very quickly after humidifiers were installed in the building to simulate occupant-generated moisture. Once the cause of filter clogging was understood to be water-borne minerals released from the humidifiers, deionizers were installed in the water supply line to effectively eliminate this problem.

2.4 IAQ and Thermal Comfort

A key design goal in designing the NZERTF was to make sure that low energy use did not come at the cost of indoor environmental quality. As noted above, special care was taken in selecting building materials with low contaminant emissions. In addition, the heating and cooling systems were carefully designed to provide for thermal comfort. In order to ensure that these design intentions were achieved, conditions in the house were monitored for a year.

Thermal comfort measurements included dry-bulb temperature and relative humidity in each room, as well as the operative temperature, which captures radiant heat transfer from interior surfaces to occupants. Figure 3 is a photo of these sensors deployed in the center of a room, with a close-up of the probe used to measure the operative temperature (a ping-pong ball painted gray with a thermocouple placed in its center). The results of these measurements were used to calculate the thermal sensation parameters contained in ASHRAE Standard 55, specifically the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) (ASHRAE 2013b). As defined in Standard 55, the PMV is “an index that predicts the mean value of the thermal sensation votes (self-reported perceptions) of a large group of persons” on a scale from –3 to +3 corresponding to “cold,” “cool,” “slightly cool,” “neutral,” “slightly warm,” “warm,” and “hot.” The PPD is “an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.” It should be noted that the baseline PPD, as defined by ASHRAE, is 5 %. Thus, even if all occupants are thermally neutral (PMV=0.0), 5 % of the occupants will be dissatisfied.

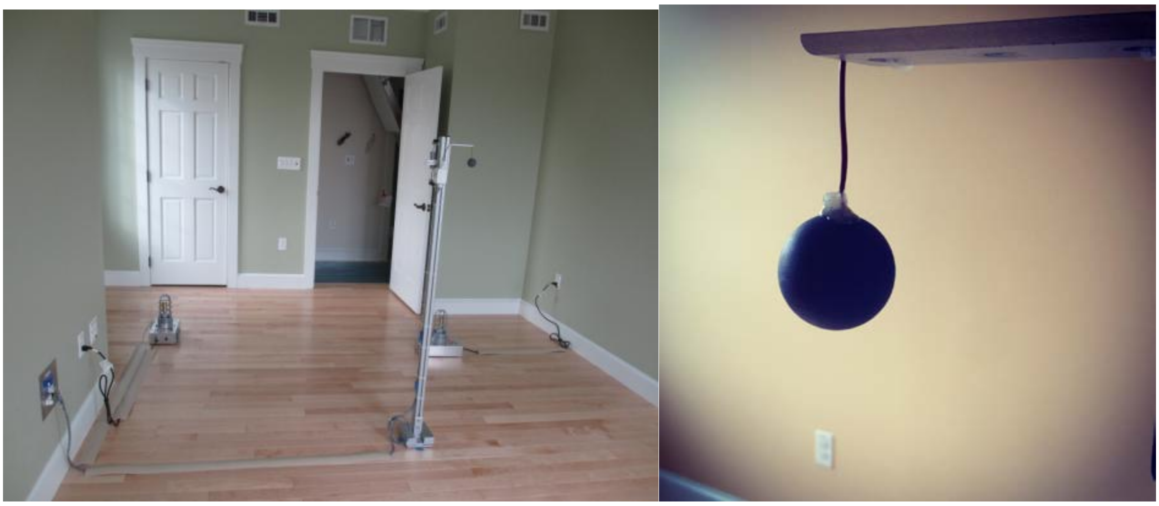

Figure 3. Thermal comfort sensors in room of the NZERTF (operative temperature probe on the right)

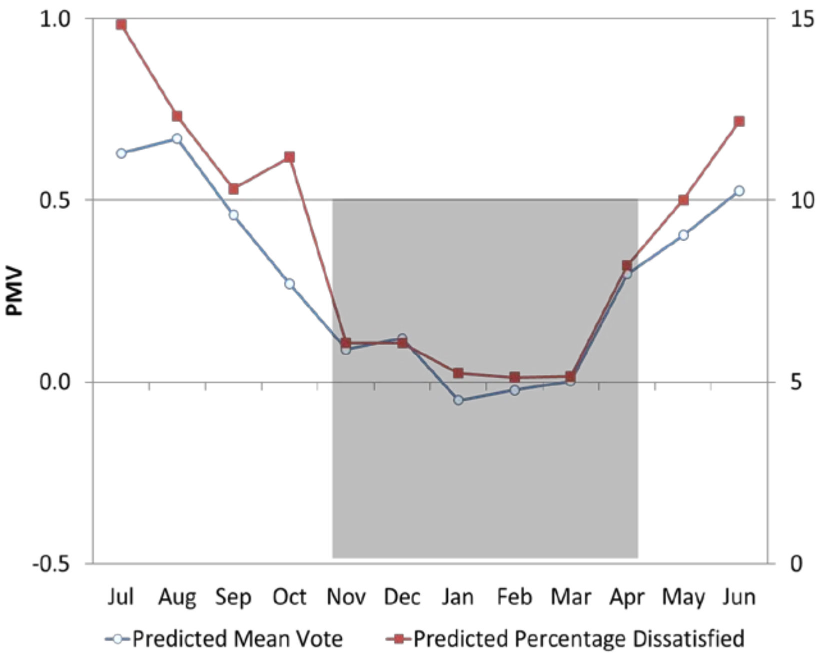

Figure 4. Monthly average thermal comfort parameters. Grey box indicates “comfortable” zone (values of PMV between -0.5 and +0.5 and values of PPD below 10 %) as defined by ASHRAE 55.

Figure 4 is a plot of the monthly average PMV and PPD values for the house, with the shaded area indicating values of PMV between -0.5 and +0.5 and values of PPD below 10 %. All of the monthly average PPD values are less than 15 %, which is consistent with the definition of “acceptable thermal environments” in Standard 55, i.e., less than 20 % of occupants finding the thermal conditions unacceptable.

Indoor concentrations of VOCs (volatile organic compounds) were measured approximately every month in the NZERTF during the first year of operation. Detailed descriptions of the measurements and results are presented in Poppendieck et al. (2015). Concentrations of formaldehyde, acetaldehyde, hexanal, propylene glycol, acetone and α-pinene are plotted versus time in Figure 5. The temporal data reveal two general trends. Concentrations of some VOCs were higher during the first summer of sampling than during the second summer, indicating that building product and material emissions decreased with time. Additionally, concentrations of many VOCs increased throughout the warmer summer sampling events and decreased during cooler winter sampling events, presumably due to the effects of temperature on emission rates.

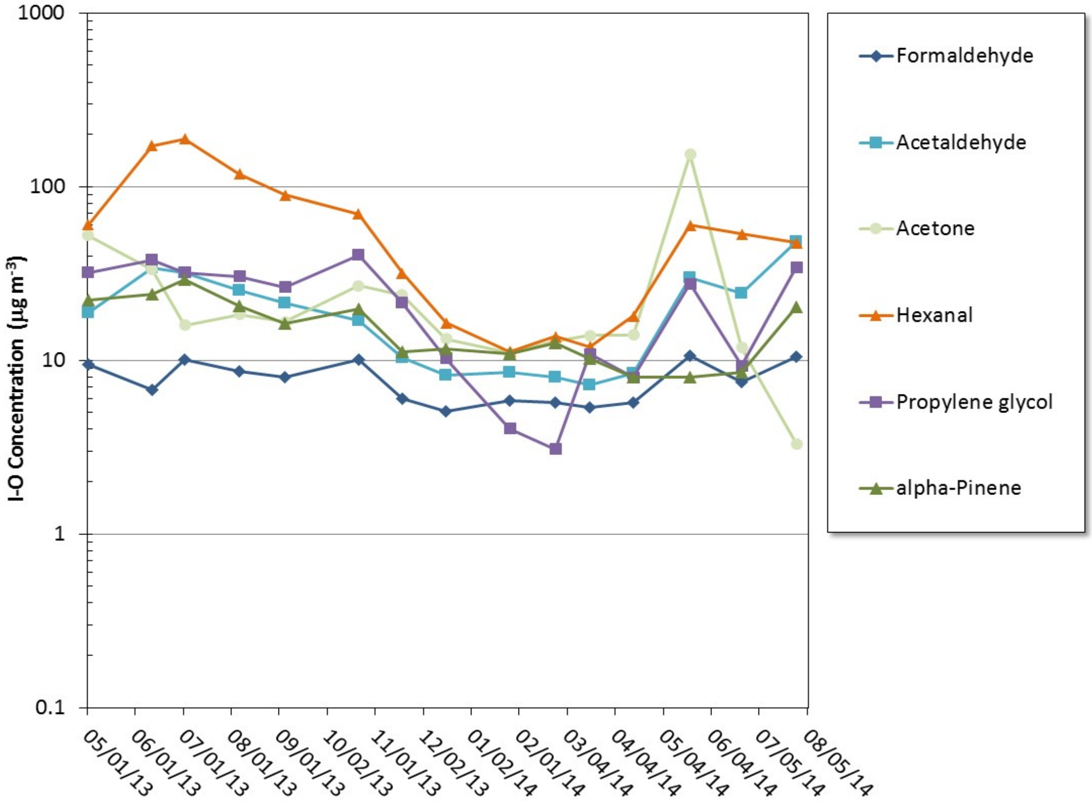

Figure 5. Indoor minus outdoor concentrations of selected VOCs over 15 sample periods

Table 3 compares the measurements in the NZERTF to those made in several other residential IAQ studies. This table presents emission factors, which are the rates at which each listed VOC is emitted per unit floor area. VOC emission rates were calculated separately for Phase 1 of monitoring (8 months, June through December, 2013) and for Phase 2 (7 months, January through July, 2014). The results show that for many VOCs, the emission factors decreased from Phase 1 to Phase 2. The results for the California New Home Study (CNHS) were obtained in houses built to the 2005 California energy code and were occupied at the time of the study (Offermann and Hodgson 2011). None were reported to be designed specifically for low VOC emissions. A study of new, unoccupied site-built and manufactured houses conducted in the late 1990’s reported floor area-specific emission rates for 28 VOCs, and the results are presented in the last two columns of Table 3 (Hodgson et al. 2000).

Table 3: Average VOC emission factors for NZERTF with values reported by other studies.

	Floor Area Emission factor ($\mu g\ h^{-1}\ m^{-2}$)				
Compound	Phase 1 (8 mon) average	Phase 2 (7 mon) average	CNHS[1] n = 108	Site-Built[2] n = 7	Manufactured[2] n = 4
Acetic Acid	39	21		95	310
Formaldehyde	7.1	6.2	29	31	45
Acetaldehyde	18	7.4	14	25	17
Hexanal	79	14	5.8	84	77
Toluene	1.4	33	3.4	26	3.9
TMPD-MIB	4.0	4.9		64	24
Ethylene glycol	24	4.3	10	170	64
α-Pinene	17	11.6	7.6	120	100
d-Limonene	2.0	1.1	6.8	23	19

3 CONCLUSIONS

Infiltration and ventilation of residences has been studied for decades, with trends towards the mantra of "build tight, ventilate right." The design and construction of the NZERTF was consistent with that philosophy, resulting in a very tight envelope and controlled mechanical ventilation. Even in this tight house, the remaining infiltration is nontrivial compared with the intentional ventilation rate supplied in accordance with industry standards. As a result of careful material selection, the formaldehyde levels measured in the NZERTF over the course of eight months were on average 80 % less than the average measured in other new homes and 60 % less than the average measured in existing homes. Levels of acetic acid, toluene, and other VOCs were also lower on average than in new and existing homes.

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