Indoor Air Quality and Ventilation in the NIST Net-Zero Energy Residential Test Facility

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In 2012, the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, completed construction of the Net-Zero Energy Residential Test Facility (NZERTF), a 250 m^2 (2700 ft^2) single family residence intended to serve as a laboratory for developing the measurement science needed to improve the building industry's ability to build and operate energy efficient housing. Previous articles in ***Energy Design Update*** (EDU) covered the overall performance of the facility during the first two one-year test periods, with a focus on the energy performance of specific equipment. As with all buildings, however, the facility's value is greatly reduced if it does not provide a healthy and comfortable indoor environment for the occupants. While the facility was unoccupied, a number of steps were taken to address indoor environmental quality. This installment will focus on the approaches taken to enhance indoor air quality (IAQ) in the facility and the measurements conducted to assess how those approaches worked in practice.

Airtightness and Ventilation Design

As with most energy efficient housing, the envelope was constructed to minimize unwanted infiltration. The envelope tightness was measured with whole-building pressurization tests at various stages of the construction process, with final measurements yielding an airtightness value of 223 L/s (473 cfm) at 50 Pa, or 0.6 h^{-1}. Based on the statistical analysis of the Lawrence Berkeley National Laboratory Residential Diagnostics Database (Chan et al., 2013), the NZERTF is tighter than well over 99 % of US homes. However, this level of airtightness necessitated a mechanical ventilation system to meet the outdoor air requirements in support of IAQ.

The system installed in the NZERTF is a balanced system with dedicated ductwork and a heat recovery ventilator sized to comply with ASHRAE Standard 62.2-2010, which corresponds to a minimum ventilation rate of 38 L/s (80 cfm) for this building. Indoor air is exhausted from the three bathrooms in the house, and outdoor air is supplied to the three bedrooms and the first floor living area.

Source Control

As a key step in promoting good IAQ, guidelines were developed for selecting the building materials to be used in the house to reduce volatile organic compound (VOC) emissions. These detailed specifications included limits on the VOC content of adhesives and sealants, requiring VOC emissions reports for insulation, and not allowing any added urea formaldehyde in the building materials. These guidelines are available in architectural specification language at the NZERTF website (*https://www.nist.gov/el/net-zero-energy-residential-test-facility*).

Results

- Ventilation System performance and energy impacts

The ventilation system had discrete fan settings controlling the amount of outdoor airflow that could be provided in the house. For the first year of operation, the team elected to run the system continuously, and a fan setting was selected that minimally exceeded the minimum ventilation rate required by Standard 62.2. This setting resulted in a ventilation rate of 48 L/s (100 cfm), which exceeded the 62.2 requirement by 25%. The average measured power consumption of the HRV fan was 60 W, and the average sensible effectiveness of the heat exchanger in the HRV was 0.72. This effectiveness approaches the rated value of 0.8 during the coldest times of the year when the temperature difference between the indoor air and outdoor air is greatest.

The fans on the HRV consumed 514 kWh over the course of the first test year, amounting to 4% of the energy consumption of the home. This energy consumption, however, is only part of the story, as any ventilation, intended or not, will have a major impact on the heating and cooling loads. To quantify this impact, detailed measurements of the sensible and latent load introduced into the house through the HRV and the efficiency of the heat pump enabled an estimate of the impact of ventilation throughout the year. Additionally, a hypothetical situation meeting the ASHRAE 62.2-2010 ventilation requirement by mechanically introducing the same quantity of outdoor air without heat recovery was analyzed computationally[1]. Figure 1 shows the sensible and latent heat introduced into the house by month with and without heat recovery. Months with predominantly cooling are boxed. Over the course of a year, continuous operation of the HRV resulted in an annual savings of 7% in heat pump energy use compared with the hypothetical case without heat recovery. The savings varied depending upon season, with the heat pump electrical use increasing by up to 5% in the cooling months and decreasing by up to 36% in the heating months compared with ventilation without heat recovery. The increase in cooling months occurred when the outdoor temperature was lower than the indoor temperature; in these instances, the ability of the HRV to operate under an economizer mode would have been beneficial. Another potential area for improvement is the fan motor in the HRV; use of a more efficient motor is feasible given current technology and could reduce the electrical requirements.

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[1] Lisa C. Ng and W. Vance Payne, “Energy Use Consequences of Ventilating a Net-Zero Energy House,” *Applied Thermal Engineering* 96 (March 5, 2016): 151–60, doi:10.1016/j.applthermaleng.2015.10.100.

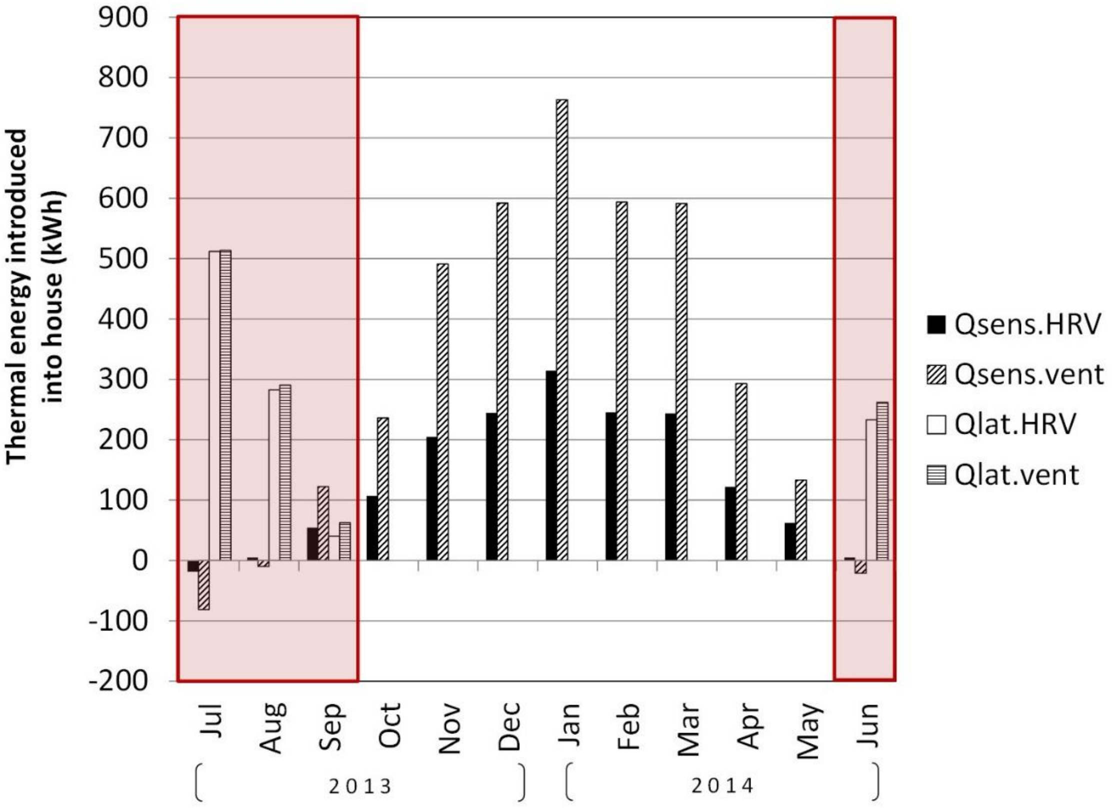

Figure 1. Change in heat pump energy consumption with and without heat recovery.

- Contaminant Monitoring

To assess the contaminant level in the home, indoor and outdoor concentrations of formaldehyde and 30 other VOCs were measured approximately monthly during the first year of operation. The monitoring was meant to assess the effectiveness of both the specifications on materials as well as the ventilation system[2]. To focus attention on the building materials, it was decided to leave the house unfurnished, as furnishings would also emit chemicals. During this year, interior temperatures remained fairly constant between the heating season setpoint of 21 °C (70 °F) and the cooling season setpoint of 24 °C (75 °F).

Measurements were taken on both floors of the interior and outside the house. Figure 2 shows differences between indoor and outdoor concentrations of a select group of VOCs over the course of the testing. Concentrations measured during the winter months tended to be lower than those measured in the summer months. Spikes in acetone concentrations observed in May 2014 were attributed to use of an adhesive in the basement of the facility for repair of a geothermal heat pump test apparatus. The average formaldehyde concentration over the sampling period was 7.7 $\mu g/m^3$. While finding comparable studies of emissions is challenging, it is estimated that implementation of the formaldehyde source

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[2] Dustin G. Poppendieck et al., “Long Term Air Quality Monitoring in a Net-Zero Energy Residence Designed with Low Emitting Interior Products,” *Building and Environment* 94, Part 1 (December 2015): 33–42, doi:10.1016/j.buildenv.2015.07.001.

control guidelines reduced formaldehyde emission factors to less than 12% of typical emission factors in conventional site-built and manufactured houses[3].

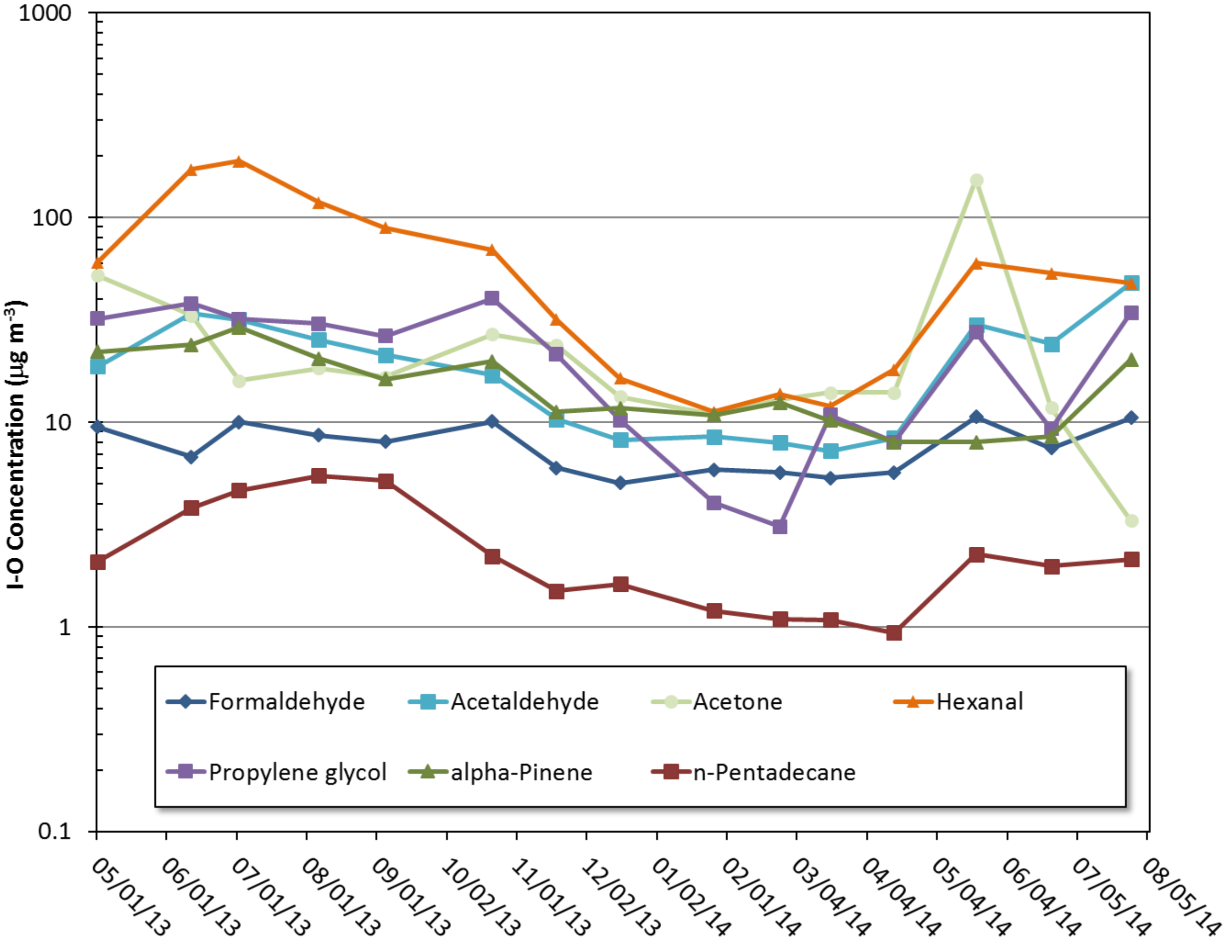

Figure 2. Indoor minus outdoor concentrations of selected VOC's over 15 sample periods at standard conditions.

Following the one-year test period, additional studies were carried out to assess the impact of changes to indoor temperature and ventilation rate settings on contaminant concentrations. Samples were taken with an elevated indoor temperature of 32 °C (90 °F) with the HRV on. A second set of samples was taken with the normal temperature setpoint (24 °C, 75 °F), but with the HRV turned off. Figure 3 shows the ratio of the concentrations of various VOC's during these evaluations to those with the temperature at setpoint (24 °C, 75 °F) and the HRV on. On average, the 8 °C increase in temperature resulted in a factor of 2.6 (Standard Deviation = 1.1) increase in steady state VOC concentration.

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[3] Tania Ullah et al., "Energy and Indoor Air Quality Benchmarking of the NIST Net-Zero Energy Residential Test Facility (NZERTF)," in *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings* (2016 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA: American Council for an Energy Efficient Economy, 2016), https://www.nist.gov/publications/energy-and-indoor-air-quality-benchmarking-nist-net-zero-energy-residential-test.

Because the air change rates were not consistent for the test case and the base case, however, a modeling adjustment suggests the temperature increase alone resulted in an average 3.8-fold increase in VOC emission rates. For a number of the VOCs, the impact of decreasing the outdoor air change rate when the HRV was off had a larger impact on indoor VOC concentrations than the increase in temperature. Some compounds saw increases up to nine times with the HRV turned off compared to the base case when the ventilation system operated. Further details on the study can be found in Poppendieck et al[4].

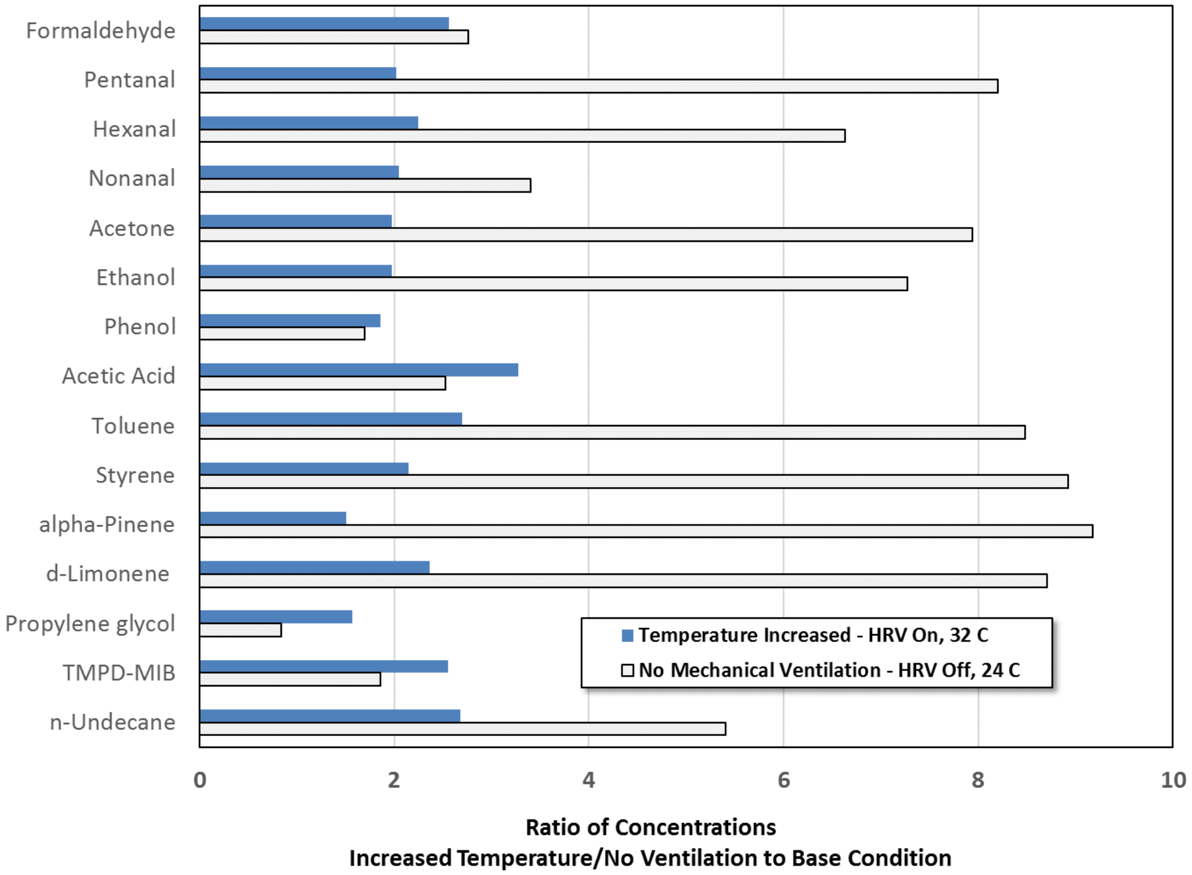

Figure 3. Ratios of I-O concentrations when indoor temperature was increased approximately 8°C compared to standard conditions. Ratios of calculated steady state VOC concentrations when HRV was turned off compared to standard conditions.

- Modeling

These studies brought into focus the tradeoffs between the energy consumption and contaminant levels associated with ventilation. To build upon these investigations, a computer model using the CONTAM software coupled with EnergyPlus was used to evaluate the IAQ and energy impacts

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[4] Ibid.

of different outdoor ventilation rates[5]. The two contaminants most closely studied were formaldehyde and acetaldehyde, as the former has been identified as a human carcinogen and the latter as a probable human carcinogen according to the International Agency for Research on Cancer.

The results show a dependence of average concentration on ventilation rates. The measured and simulated concentrations for the NZERTF were below those reported for other actual homes, but the modeling indicates that reduced ventilation rates could bring concentrations of formaldehyde and acetaldehyde above risk levels used by the EPA for chronic exposure to air toxics in outdoor air. Reducing indoor concentrations below the EPA risk level of 1 cancer in 1,000,000 people (0.08 $\mu g/m^3$) appears difficult to achieve; in fact, the measured outdoor concentrations were above this level. However, the concentrations could be brought below the 1 in 10,000 risk level for both formaldehyde and acetaldehyde with sufficient ventilation. While concentrations below the 1 in 10,000 risk levels were achieved for both acetaldehyde and formaldehyde at the ventilation rate used in the NZERTF, reducing the ventilation rate to the ASHRAE 62.2-2010 level would raise the formaldehyde concentration above the 1 in 10,000 risk level (8.0 $\mu g/m^3$). This reduction in ventilation is projected to lower energy consumption by 4%, but the findings show the increased health risk involved in doing so. To drop the concentrations of acetaldehyde below the EPA inhalation reference concentration risk level, which is a concentration below which there are deemed to be no deleterious noncancerous impacts, would require an increase in the NZERTF ventilation rate from 171 m^3/h to at least 280 m^3/h, a rate that would increase the energy consumption by 13 % and result in the house no longer achieving net-zero energy use for the year. The challenge of balancing the IAQ and energy impacts of ventilation are highlighted by this analysis.

Conclusion

Careful selection of products in the NZERTF was the first step towards the goal of healthy indoor air quality to go along with low energy consumption. Measurements of 30 compounds showed the benefits of these specifications, but some chemicals were present in concentrations that may be considered high. The importance of ventilation was demonstrated, both for its impact on the energy consumed by the heat pump and for its relationship to indoor concentrations. High performance homes must keep indoor air quality issues in mind when designing for low energy consumption, appreciating that solutions such as heat recovery ventilators can allow for adequate ventilation while reducing energy use for space conditioning.

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[5] Lisa Ng et al., “Evaluating IAQ and Energy Impacts of Ventilation in a Net-Zero Energy House Using a Coupled Model,” in *ASHRAE IAQ 2016 Defining Indoor Air Quality: Policy, Standards, and Best Practices* (ASHRAE IAQ 2016 Defining Indoor Air Quality: Policy, Standards, and Best Practices, Alexandria, VA: ASHRAE, 2016).