Equinox House is a net zero building that still keeps comfort and IAQ at acceptable levels.

Comfort Conditioning & Indoor Air Quality

By Ty Newell, Member ASHRAE; and **Ben Newell,** Associate Member ASHRAE

While Ty and Deb Newell were in Las Vegas for the ASHRAE Winter Conference, Equinox House was switched "off." Everything except the refrigerator and a data acquisition system were turned off. Piping would freeze in most homes in central Illinois without power during January, but not in Equinox House. Vacating the house provided an opportunity to examine some important aspects of the house. Without fresh air ventilation, would volatile organic compounds (VOCs) increase or decrease? How would humidity and carbon dioxide levels change?

Any house can achieve net zero energy by simply disconnecting from the utility. The real goal, however, is to maintain comfort and indoor air quality at acceptable levels while being able to use the modern conveniences of daily living. Comfort conditioning and indoor air quality are two areas in which many ASHRAE members are intimately involved through their research, standards committee work, and professional practice. As in our previous discussions, we are indebted to our ASHRAE colleagues for their contributions that have been essential for providing us with the tools and experience needed to assess these aspects of Equinox House.

Figures 1 and *2* show the predicted range of average daily latent and sensible conditioning capacities required for maintaining a house with conventional construction and Equinox House at 21°C (70°F) and 50% relative humidity.

The conventional constructed house shown in *Figure 1* is based on an actual house in our subdivision that was discussed in our October 2010 article. The conventional house has a UA that is three times that of Equinox House, and air infiltration that is 50 L/s (105 cfm) with no energy recovery compared to the average fresh air ventilation rate of 35 L/s (75 cfm) with 70% sensible energy recovery in Equinox House.

Each data point in *Figures 1* and *2* represents a day of actual weather data for Urbana, Ill., from 2002. During the winter, sensible heating capacity is significantly lower in Equinox House with the most extreme weather only requiring the equivalent of two hairdryers to maintain comfortable temperatures. During the

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summer, Equinox House conditioning capacities are similarly reduced, however the hot humid summers in central Illinois result in Equinox House having a high latent load relative to its sensible load. Managing the latent load is one of the challenges in super-insulated, super-sealed homes. Notice that a significant number of days exist during the "swing" seasons (fall and spring) for both homes in which heating and dehumidification are required. A basement dehumidifier or the equivalent can be used to convert the latent heat of condensation into sensible heat.

Figure 3 shows the location of the comfort conditioning system, located in a utility chase (attic) that is within the conditioned envelope of Equinox House. The comfort conditioning system installed in Equinox House is a small, air source heat pump that is incorporated into the fresh air ventilation system. The heat pump can exchange energy between the incoming fresh air and the outgoing exhaust air when it is beneficial to do so.

Two 1,500 W electric heaters are used for supplementing the air source heat pump during times with low ambient air temperatures. The air source heat pump consists of a variable speed compressor. The nominal heating and cooling capacity of the unit is 2,000 W (6,900 Btu/h) with a compressor power of 400 W. In addition to the house conditioning system, as discussed in the April 2011 article on appliances, the heat pump water heater contributes approximately 2.5 kWh per day per person of cooling and dehumidification and the ventless heat pump dryer adds approximately 2.5 kWh per laundry load to the house. Cooking energy, lighting, refrigerator and other electrical appliances of lesser importance also contribute heating loads.

Figure 4 shows the ventilation ductwork connected to the fresh air, exhaust air, supply air, and return air duct systems. The balanced ventilation system consists of two "duct" fans with a flow of 100 L/s (210 cfm) that provides fresh air to the house for one hour out of every three hours. The fans require 70 W each, with the energy from one fan added to the supply airstream and the energy from the other fan exhausted to the outside. The additional two hours of the duty cycle can be used for house conditioning when required, with the ventilation system in a "recirculation" mode rather than fresh air mode. When outside air is "nicer" than inside air, the system operates in "free" conditioning mode, leaving the heat pump off while bringing in fresh air to condition the house; equivalent to opening the windows in the house. The two additional hours also allow for increased fresh air ventilation during periods of high occupancy levels.

The ventilation system is designed such that fresh air is supplied to the "living" areas of the house (living room and bedrooms), and return air to be exhausted from the house is pulled from the kitchen, laundry room and bathrooms. In this manner, the house is "purged" by the airflow. The ventilation system is designed such that wireless sensors in the bathroom light circuits change the ventilation system to fresh air mode when bathrooms are occupied.

Figure 5 shows temperature collected at three interior locations (living room, master bedroom and utility attic space) and outdoor ambient reported by a local weather service from

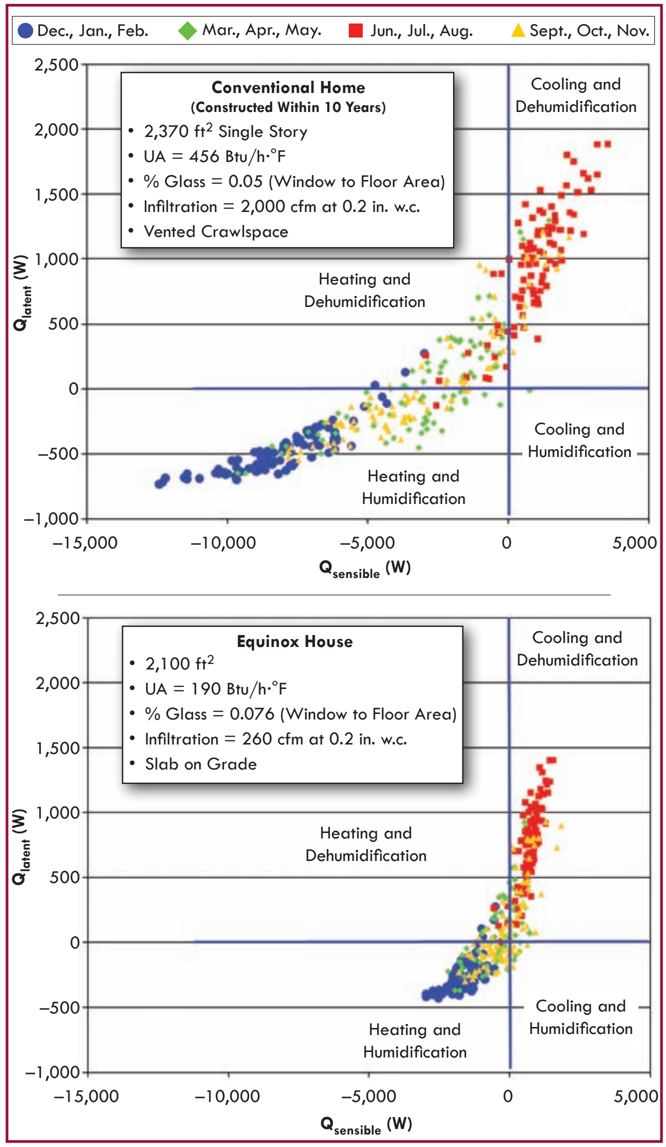

Figure 1 (top): Conventional house daily average latent and sensible conditioning capacity requirements to maintain comfort conditions. **Figure 2 (bottom):** Equinox House daily average latent and sensible conditioning capacity requirements to maintain comfort conditions.

January to early March 2011. At the end of January is the time period when Equinox House was unoccupied during the ASHRAE Winter Conference. For three days, the interior temperature declined. Comfort conditioning systems were activated after three days to observe the dynamics of moving the house back to comfort conditions. The temperatures shown for the master bedroom, living room and attic areas are quite close in temperature without any discernable temperature variations as one moves throughout the house. The average temperature level in the house has been maintained in the 19°C to 20°C (66°F to 68°F) range.

Figure 6 shows the humidity ratio for the same time period in Equinox House. The associated relative humidity level is in the

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range of 40% to 60% during this time period. The humidity spikes observed in the master bedroom area each day are from shower moisture. The humidity sensor is located approximately 2 m (6.5 ft) from the bathroom door, which is generally left open during showers. The open bathroom design has no shower enclosure or shower curtains (one can "tour" these areas with the 3-D model located on our website: http://newellinstruments.com). The ventilation system has proven very effective at purging moisture out of the bathroom, and at least since last November, no residual moisture has been observed in the master bathroom a few hours after use. During the vacancy at the end of January, a drop in interior humidity was recorded.

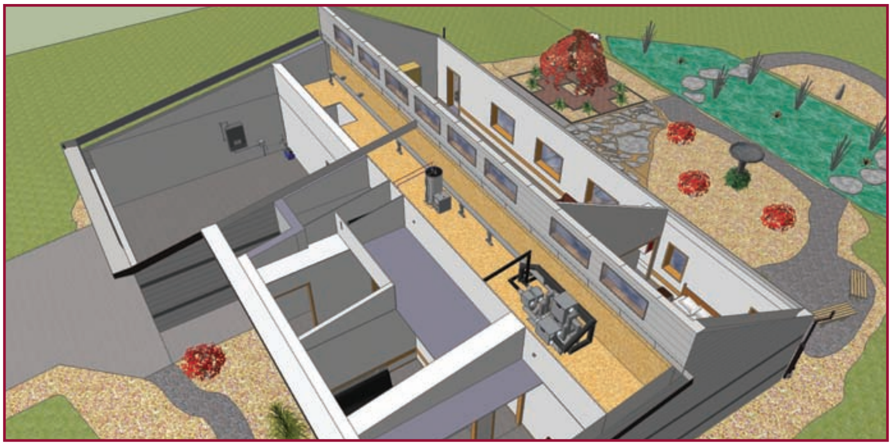

Figure 3: View of utility chase (attic) where the heat pump, fresh air ventilation system and the heat pump water heater are located.

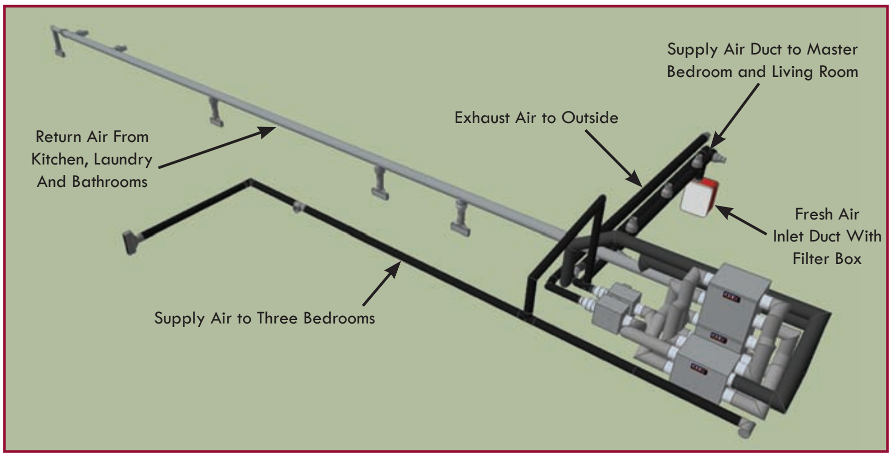

Figure 4: View of ventilation ductwork showing the fresh air filter box, exhaust air duct, ventilation supply air to living room and bedrooms, and return air from kitchen, laundry and bathrooms.

The basis for choosing interior ambient conditions is based on whether Deb Newell, Ty's spouse and Ben's mother, is comfortable. Her vote is the only vote that counts for comfort. During the winter, typical dress and metabolic activity are in the 1 to 2 clo and 1 to 2 met range (see Chapter 9 of *ASHRAE Handbook—Fundamentals*; 1 to 2 clo represents long sleeve shirts, sweater, pants while 1 to 2 met represents relaxed and sitting to a cooking level of activities). As described in previous columns, the level of wall and roof insulation in Equinox and modest window area results in radiant surfaces being very close to ambient air temperature. Air velocities throughout the house are undetectable, and humidity is generally in the 40% to 60% range.

Healthy indoor climates should keep odors minimized and carbon dioxide maintained at reasonable levels as specified by ASHRAE Standard 62.2 for residential ventilation. *Figure 7* presents data from a carbon dioxide (CO_2) sensor and a volatile organic compound (VOC) sensor we have located in the main living room of Equinox House. The VOC sensor saturates above 2,000 ppm and has a base level of approximately 390 ppm, which represents a nominal outdoor air background level of VOCs. The "ppm" unit used for the VOC sensor are scaled to represent the amount of CO_2 that would be associated with the VOCs produced from a human rather than being actual VOC parts per million. Other VOC producing events, such as from cooking, candles, perfumes, cleaning chemicals, flooring materials, and building materials add to the VOC level, causing it to exceed the actual CO_2 level from human respiration.

VOCs are quite interesting as they represent a family of compounds whose health effects are difficult to define. Are VOCs generated from cooking good or bad for you? Are the aromatic compounds from an herbal tea good or bad? In our case, we are interested in understanding how periods of human activity correlate with CO_2 levels and VOC (odor) levels to implement a demand controlled ventilation algorithm. Although very unscientific, we regularly ask visitors whether they are able to detect any odors, and to date the consensus is that there are no odors. We should also note that Deb Newell is a prolific cook whose range of cooking activities generate an unbelievable amount of wonderful odors. The odors are no longer detectable the following day by visitors (including some char producing cooking adventures).

Figure 8 presents transient data over an 11-hour period just after Deb and Ty left for the ASHRAE conference (6 p.m., Jan. 28, 2011). The house was shut down, the fresh air ventilation dampers were placed in a closed position, and the house was able to coast for three days. The data in *Figure 8* spans the nighttime when the impact of solar radiation was absent. The logarithmic variation of the temperature, humidity ratio, CO_2 and VOC sensors are shown in *Figure 8,* in a manner discussed in our February 2011 column on thermal mass. The time constants of the four quantities, shown in *Figure 8,* vary from each other

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in interesting manners. The temperature variation, as previously discussed, indicates the amount of mass participating in energy storage in the house. The results in *Figure 8* are similar to the time constant data previously discussed from October 2010 data, with a time constant of 118 hours for the January 2011 data.

The carbon dioxide transient variation in *Figure 8* is perhaps the most straightforward to characterize of the other three factors. As a relatively "inert" gas, and assuming that there are negligible sources and sinks of CO_2, its level changes by interaction with the surrounding outside ambient CO_2. A simple model, analogous to that used for the temperature time response model is:

$$\ln\left(\frac{CO_2 - CO_{2a}}{CO_{2i} - CO_{2a}}\right) = -(\text{ach})t$$

where

ach = air changes per hour

t = time of test with zero time at the test beginning

CO_2 = inside house ambient carbon dioxide

CO_{2i} = inside house ambient carbon dioxide at beginning of test (time = 0)

CO_{2a} = outside average ambient carbon dioxide (~390 ppm)

The time constant for CO_2 is found to be 22 hours, and the reciprocal of this is the normal atmospheric ach value (ach = 0.045). The house interior volume is 790 m^3 (28,000 ft^3), which results in an estimated house infiltration level of 10 L/s (21 cfm) during this time period.

The variation of humidity ratio during the vacancy period results in a time constant of 61 hours. If moisture transport was due purely to the water in the air, we would find that time constant for humidity transport would be the same as that determined for CO_2. The 61-hour humidity ratio time constant found from the *Figure 8* data is roughly (very roughly) equivalent to the ratio of the moisture mass capacitance of the house per infiltration air mass flow. The moisture mass capacitance of the house (again, very roughly) is the sum of the air mass and an apparent building moisture absorption mass. Using the air infiltration level determined from the CO_2 analysis and the humidity ratio time constant, we find

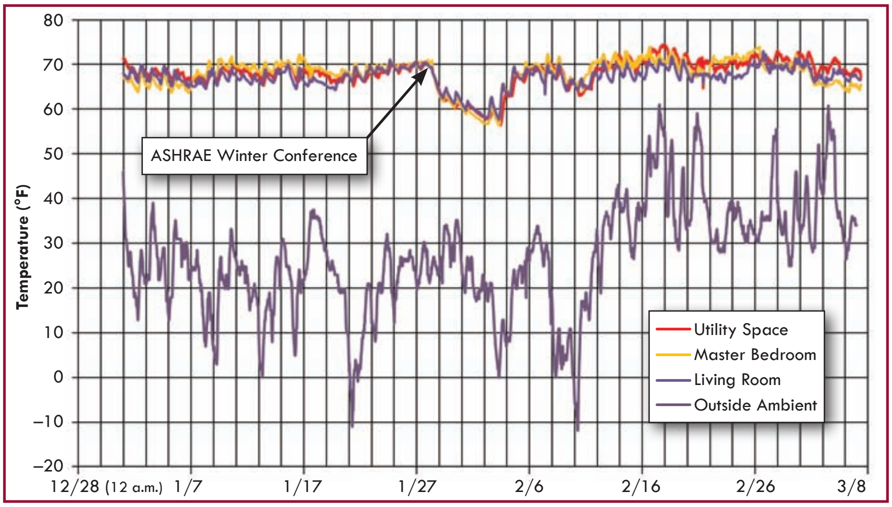

Figure 5: Interior ambient and exterior ambient temperatures in Equinox House from January 2011 to early March 2011.

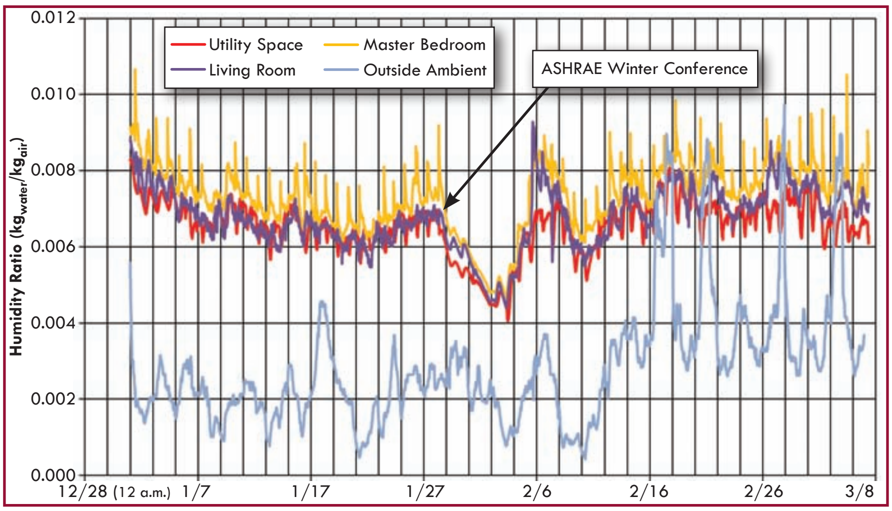

Figure 6: Interior ambient and exterior ambient humidity ratios for Equinox House from January 2011 to early March 2011.

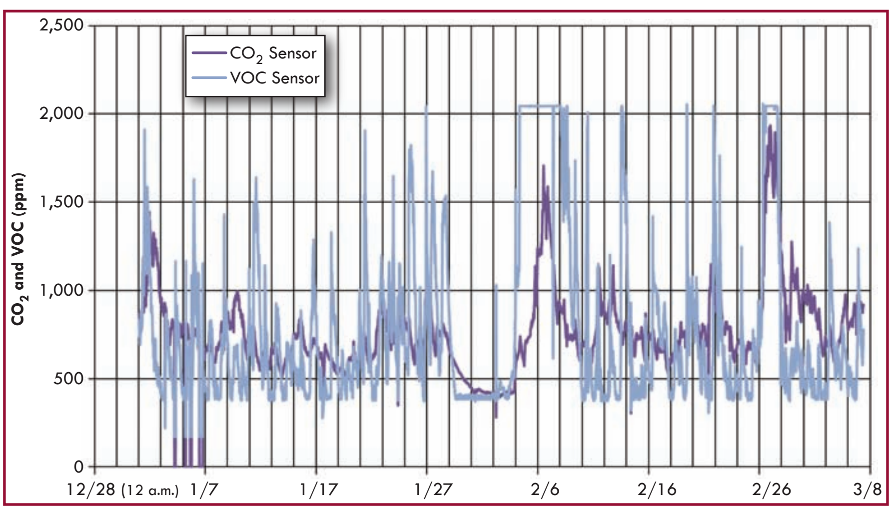

Figure 7: Interior carbon dioxide and volatile organic compound levels for Equinox House from January 2011 to early March 2011.

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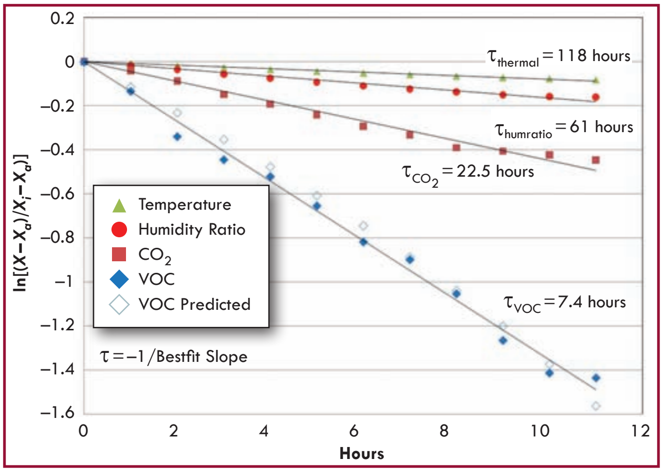

Figure 8: Time constant decays of temperature, humidity ratio, carbon dioxide and volatile organic compound levels during the 2011 ASHRAE Winter Conference.

the moisture mass capacitance to be 2640 kg (580 lb_m) of air mass. For example, a humidity ratio change of 0.001 in the house represents a change of 26.4kg (58 lb_m) of water from the house interior. The house air mass portion of this moisture mass capacitance based on the house volume and nominal air density is 950 kg (2090 lb_m), indicating that building interior and furnishings water absorption capability contributes 1685 kg (3,707 lb_m) of apparent air mass to the house. Notice that in *Figure 6*, the humidity ratio changes with changes in interior ambient temperature, indicating some water absorption/desorption sensitivity to temperature level.

VOCs, in relation to CO_2, decay quite rapidly. Whereas water vapor decays more slowly, indicating additional storage or generation of moisture, the VOC trend indicates some type of VOC "sink." The VOC sink most likely is a reactive decay of the VOCs and possibly some adsorption/absorption of the components. The 7.4 hour VOC time constant is quite fast compared to the dissipation of CO_2. This trend indicates that the occupants are the primary source of all VOCs measured by the sensor, and that when humans are not present, there does not seem to be any significant generation sources of VOCs. Assuming a reactive decay of VOCs coupled with infiltration transport of VOCs to the ambient, a simple model describing this process can be derived as:

$$Cv - Cv_a = Cv_i - Cv_a \left[\left(1 - \frac{1}{1 - \frac{ach}{k}} \right) \exp(-ach \times t) \right.$$
$$\left. \left(\frac{1}{1 - \frac{ach}{k}} \right) \exp - (-k \times t) \right]$$

where

ach = air changes per hour
k = reaction decay rate per hour
t = time of test with zero time at the test beginning
Cv = inside house ambient VOC
Cv_i = inside house ambient VOC at beginning of test (~1,400 ppm at t = 0)
Cv_a = outside average ambient VOC (~390 ppm)

Assuming the ach is the same as that determined for CO_2 (1/22 h), the reaction decay rate, k, is found to be 1/14 h. A plot of the VOC model is shown in *Figure 8* that combines the effects of VOC infiltration dissipation and reaction decay. A lot of assumptions have been made by lumping all of the VOC components into such a simple model; however, regardless of the correctness of its physics, the model seems to capture the dynamics of the process that are of most interest to us for control algorithm development.

Equinox House has proven very comfortable during one of the most bitterly cold and snowy winters we have experienced in a long time. In addition, we are very pleased with both our measured and perceived levels of indoor air quality. Only a small portion of our data has been displayed in this column. For readers interested in examining more data, our website (http://newellinstruments.com/equinox) has all of our data posted, including interior and ambient temperatures, humidity, electrical energy use, solar energy production, CO_2, VOC, radon, rainwater collection, precipitation, and rainwater use.

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