10 zone CERV2 with Wireless Distributed IAQ Sensors and Actuators Preparing to Ship

PREVENTILATION – Part 1

Smart Ventilation

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FOREWORD

Preventilation. Try Web searching “preventilation”. Few web matches are likely to turn up. To us, it is a fascinating term we invented to describe new possibilities for beneficially managing our indoor environment. Preventilation sounds oddly familiar, and yet unfamiliar. Build Equinox is making preventilation a reality. Preventilation improves our health and well-being. The power of “Big Data”, “AI” (Artificial Intelligence), and ever-increasing improvements in technology for seamless monitoring and controlling the indoor environment are all important pieces of our preventilation concept.

We emphasize two aspects of “preventilation”:

1) **PRE**ventilation anticipates the need for ventilation before undesirable thresholds of poor air quality and energy usage occur
2) **PREVENT**ilation is a prescient ability, a meta-based awareness of the interaction of seemingly unrelated factors that impact our health and feeling of well-being

Smart ventilation and smart air distribution are two essential features of preventilation. As expressed by Florence Nightingale more than 150 years ago, without proper ventilation, all else is for naught.

Our Part 1 - Preventilation report concentrates on smart ventilation, describing how automated sensing and control of residential indoor air quality improves both air quality and energy efficiency beyond that of today’s ventilation systems. Part 2 – Preventilation focuses on smart air distribution and the concept of “ventilation efficiency”, the fraction of fresh air that benefits a home’s occupants.

Join us on this journey to improve the health and well-being of yourself and those around you!

Executive Summary

The primary features of this report are:

1) Air quality in a leaky house blows with the wind. When wind speeds are low, air quality is poor, and when wind speed is high, average air quality improves but may still be poor.
    a. The example home (10ACH50, 2700ft^2, 4 bedrooms, 5 occupants) has an infiltration electrical energy usage of 2230kWh for the Jan 2010 Urbana Illinois simulation month.
2) A high efficiency HRV (90%) in a US average constructed home (4 bedroom, 2700ft^2, average US occupancy of 2.5) with ASHRAE 62.2-2016 ventilation standards (120cfm air flow), during cold winter conditions (2010 January Urbana IL weather) requires:
    a. 893kWh for electrical energy for a 3ACH50 home
    b. 428kWh for electrical energy for a 0.6ACH50 home
3) CERV2 smart ventilation adjusts fresh air ventilation outperforms constant flow systems with high efficiency HRV while automatically managing excellent air quality.
    a. A well-sealed, CERV2 smart ventilated US average home with 3ACH50 requires 646kWh, or 28% less energy usage than constant ventilation with high efficiency HRV home
    b. A highly sealed, CERV2 smart ventilated US average with 0.6ACH50 requires 269kWh, or 42% less energy usage than constant ventilation with high efficiency HRV home
4) CERV2 smart ventilation systems adjust ventilation as occupancy needs change. For the highly sealed (0.6ACH50) average US house discussed above with an occupancy of 1.25 (2.5 occupants outside of the home 12 hours per day) during the 2010 January Urbana IL month:
    a. An HRV ventilated home requires 471kWh
    b. A CERV2 smart ventilation system reduces ventilation energy requirements to 228kWh, or less than half of the energy used by the HRV home
5) A small, high performance home (0.6ACH50, 2 bedrooms, 1000ft^2) with 4 occupants will have poor indoor air quality when using ASHRAE 62.2-2016 ventilation levels and good air quality with CERV2 smart ventilation.
    a. Air quality in a small home with 4 occupants will have average carbon dioxide of 1300ppm with more than 25% of the general populace dissatisfied with the air quality. The home would use 201kWh of electrical energy related to infiltration and ventilation
    b. Air quality in a CERV2 smart ventilated, small home with 4 occupants automatically maintains carbon dioxide levels at 1000ppm while using 321kWh for the 2010 January Urbana IL weather month.
    c. Increased energy usage of the smart ventilation system in relation to the HRV system equates to 12cents per occupant per day and is compensated by improved health
6) CERV2's heat pump-based smart ventilation system generally provides positive heat contribution to homes during cold months while high efficiency HRVs (90%) require significant make up energy for ventilation

Introduction

Our goal at Build Equinox is a truly healthy home. We want all homes to have excellent air quality regardless of the occupants, occupant activities, home construction characteristics, home furnishings, and climate. In order to have a healthy home, a smart ventilation system that actively manages air quality is required. We have left home air quality to happenstance for too long, and we have paid the price with poor health.

The year after our first generation CERV smart ventilation unit was released in 2013 to the market[1], Lawrence Berkeley National Laboratory (LBNL) issued a report (1) declaring homes without smart ventilation are dumb. The problem with a dumb house is that it is inefficient while degrading the health, impairing the cognition, and disturbing the sleep of its occupants. Even a broken clock is correct two times every day while a stupid home may never have proper ventilation. Both yesteryear's leaky homes and today's code-built homes meeting ASHRAE 62.2-2016 ventilation standards often have poor air quality or excessive ventilation energy usage, or both. It may seem odd that a home can have excess ventilation *and* poor air quality, but unfortunately it is a frequent occurrence.

LBNL has released two more recent reports (2,3) with extensive reviews of field data and computational studies that further define the importance of smart ventilation systems. Annual ventilation energy savings of 40 to 60% are common with smart ventilation systems in comparison to constant flow ventilation. The reports also stress the importance of smart air distribution in which fresh air is efficiently distributed to where it is needed most within a home. Field study results demonstrate that a home's occupants may be living in poor air quality even though an adequate amount of fresh air flows into the house (4,5).

Smart ventilation is essential for maintaining a healthy indoor environment in an energy efficient manner. The reasons why smart ventilation and smart air distribution are more effective and efficient requires complex analyses of the integrated house system. Fortunately, we can understand the results of these analyses without having to work through analysis details. The common sense answer before wading into the results is that a smart home delivers fresh air when and where the occupants need it, and minimizes ventilation when it is not required nor beneficial.

This report discusses smart ventilation systems for residences in comparison to leaky home ventilation and constant air flow ventilation strategies. Preventilation – Part 2 describes the importance of "smart air distribution". A smart home must have both smart ventilation and smart air distribution in order to provide its occupants with a healthy indoor environment. The combination of smart ventilation and smart air distribution form the foundation for Build Equinox's "preventilation" philosophy. Our preventilation philosophy places occupant health and well-being above all else in building design.

[1] The first CERV unit was installed in our zero-plus Equinox House in 2011. Live operation of the Equinox House CERV can be viewed at BuildEquinox.com, along with 4 years of archived data (CERVs came online in 2014).

Human Fresh Air Needs and Ventilation Standards

We need fresh air in buildings to stay healthy, to sleep effectively, and to be productive (6-14). We need a lot of fresh air; more than 2 tons of fresh air per person per day (40cfm per person) should be delivered to every building. And when we are not in a building, we don't need to deliver fresh air at such a rate. Infiltration air enters a home through construction flaws, door openings, flue vents, kitchen hoods, clothes dryer vents, plumbing vents, ventilation systems, pet doors, and other ways. Reducing uncontrolled, unfiltered air flow paths and maximizing the controlled passage of filtered fresh air through an active ventilation system is desirable for energy efficiency and for delivering fresh air when and where it is needed.

Figure 1 shows strong correlation between rising indoor air pollutant concentrations (indoor generated particulates and VOCs) and increased asthma over the past century. House leakage information coupled with asthma health information are incorporated into Figure 1 (13, 14, 16, 19, 21, 22). Although correlation does not mean causation, it is quite clear that reduced leakage characteristics of conventional homes without active ventilation have significantly increased indoor air pollutant concentrations.

Today's indoor pollutants are different than yesteryear's pollutants, too. Household products, food containers, cleansers, toys, furnishings, etc were generally made from natural products and "simple" materials such as glass, paper, metal, wood and leather. Today's manmade materials are a soup of polymers, toxic metals, fire retardants, pesticides, herbicides, and many other synthetic chemicals. Some of these materials have hormone characteristics that may directly disrupt our bodies as well as other living systems when released into the environment. We have been conducting a real time experiment with our health, and Figure 1 is an indication that something in modern living may be negatively impacting our well-being.

Carbon dioxide concentration has also increased in our home indoor environment due to better sealed house envelopes and the increase of outdoor carbon dioxide. Figure 2 shows the increase of outdoor carbon dioxide relative to indoor carbon dioxide over the past century. One downside of increasing outdoor carbon dioxide, among many, is the need to further increase fresh air ventilation in our homes. From Figure 2, it is apparent that we will not be able to return to indoor carbon dioxide concentration levels prior to 1950 until outdoor concentrations drop below 400ppm. In urban environments, outdoor carbon dioxide concentrations may be 100ppm or more above those in rural areas.

Figure 3 plots the trend of home carbon dioxide concentration level against fresh air flow rate per person. Appendix A describes human carbon dioxide generation rates. Human carbon dioxide production varies by more than a factor of 10 based on age, size, gender and activity (15). An individual's activity, from sleeping to exercising, will vary their carbon dioxide output by a factor of 8. That is, a home with one active person can have the same fresh air requirements as a house with 8 sedentary occupants!

Carbon dioxide, coupled with VOCs (Volatile Organic Compounds) our bodies produce, is a toxic combination of pollutants that impairs our cognitive capabilities in several ways including information processing, information organization, productivity, creativity, and decision making (6, 7). Carbon dioxide is also an indicator of the buildup of contagions (10), particulates, and VOCs. An old rule-of-thumb design guideline uses 20cfm of fresh air per occupant for building ventilation. The old rule-of-thumb is based on human odor perception in which 20% of the general populace expresses dissatisfaction with air quality (16, 17). Most humans cannot smell bad air quality, and 20cfm per occupant is not good air quality even though 80% of the populace won't complain.

We know ventilation air flow impacts our health. Milton and co-workers (8) at the Harvard School of Public Health found that increasing ventilation rates from 20cfm to 40cfm per employee is as effective as the flu vaccine in reducing short term absenteeism (35% reduction). Increased fresh air dilutes the amount of air you breathed that has previously been breathed by someone else, which lowers the probability of contracting an airborne illness. The $50/employee per year cost of increased ventilation (a 2.5 cents per hour pay raise per employee) is easily paid for by a reduction in illness cost ($400/year per employee). Fisk, et al (12) found that adding an economizer to a building while increasing ventilation rates could save both energy and reduce illness costs. Fisk determined that health savings were 5 times greater than energy savings. Improving our health is more valuable than saving energy.

MacNaughton, et al (10) estimated improved cognition and productivity due to increased fresh air ventilation is worth $6500/year per employee in relation to a $50/year per employee cost for increased ventilation energy in harsh climates <u>without</u> adding any HVAC system energy conserving features. Smart business owners who look beyond energy should readily spend 2.5 cents per hour per employee for a combined annual return of $6900 per person! These air quality improvements are just as important in our homes, whether they are old, leaky homes or today's well-sealed, high performance homes. As we will discuss later, it is a myth that leaky homes have good air quality.

The ASHRAE 62.2-2016 ventilation standard for residences has "modernized" the old rule of thumb with a ventilation schedule based on a combination of assumed pollutant emissions from household furnishings and occupant pollutant generation. Table 1 shows ASHRAE 62.2-2016 residential ventilation requirements in terms of number of bedrooms and floor area. The problem with Table 1 is that it assumes one size fits all, but it does not! The ASHRAE 62.2 committee readily admits that the standard is not designed to be an air quality standard. Why should a home with a pollutant spewing gas stove (18) have the same ventilation standard as homes with an electric range? Why should a house with wall-to-wall carpeting, formaldehyde-laden composite materials, and other poor furnishing selections (16) have the same ventilation standard as a home based on Frank Lloyd Wright's "organic design" that emphasizes simple materials such as wood, metal, glass, stone, and concrete?

Figure 4 is a ventilation map of air flow per person based on the Table 1 ventilation schedule with an occupancy based on 1 more occupant than the number of bedrooms (ASHRAE 62.2 assumed occupancy). ASHRAE 62.2-2016 standard's prescribed ventilation air flow varies from 10cfm per occupant to more than 80cfm per occupant. The average home currently constructed in the US is 2700ft^2 with four bedrooms and an average occupancy of 2.5 (20). Table 1 requires 120cfm of ventilation, or 48cfm per person based on average occupancy. If the occupants are only home for 12 hours per day (average occupancy of 1.25 people), the average ventilation rate per person is 96cfm per person. If the home is sold to someone with 6 family members, ventilation is 20cfm per person. The standard's wild ventilation variation causes significant differences in air quality, occupant health, and energy usage per occupant. Smart ventilation adjusts ventilation automatically to a home's fresh air needs. Thermostats were developed more than a century ago (Figure 5), significantly improving comfort and energy efficiency. With today's modern air quality sensors and smart building ventilation systems, we can similarly improve our health and ventilation energy efficiency.

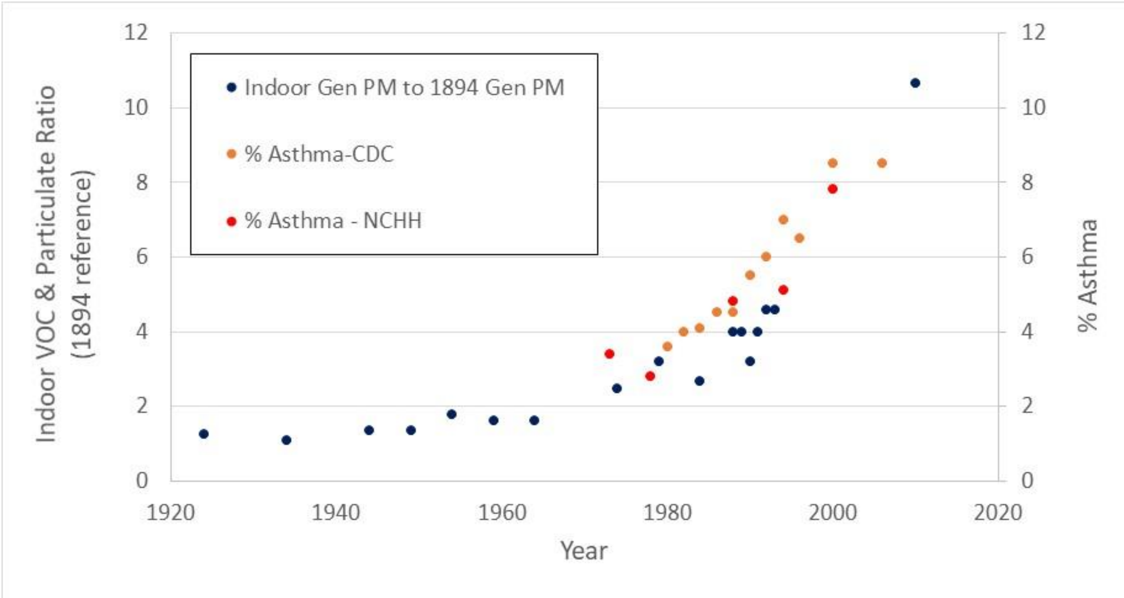

Figure 1 Increase in indoor pollutant concentration and asthma relative to an 1894 home.

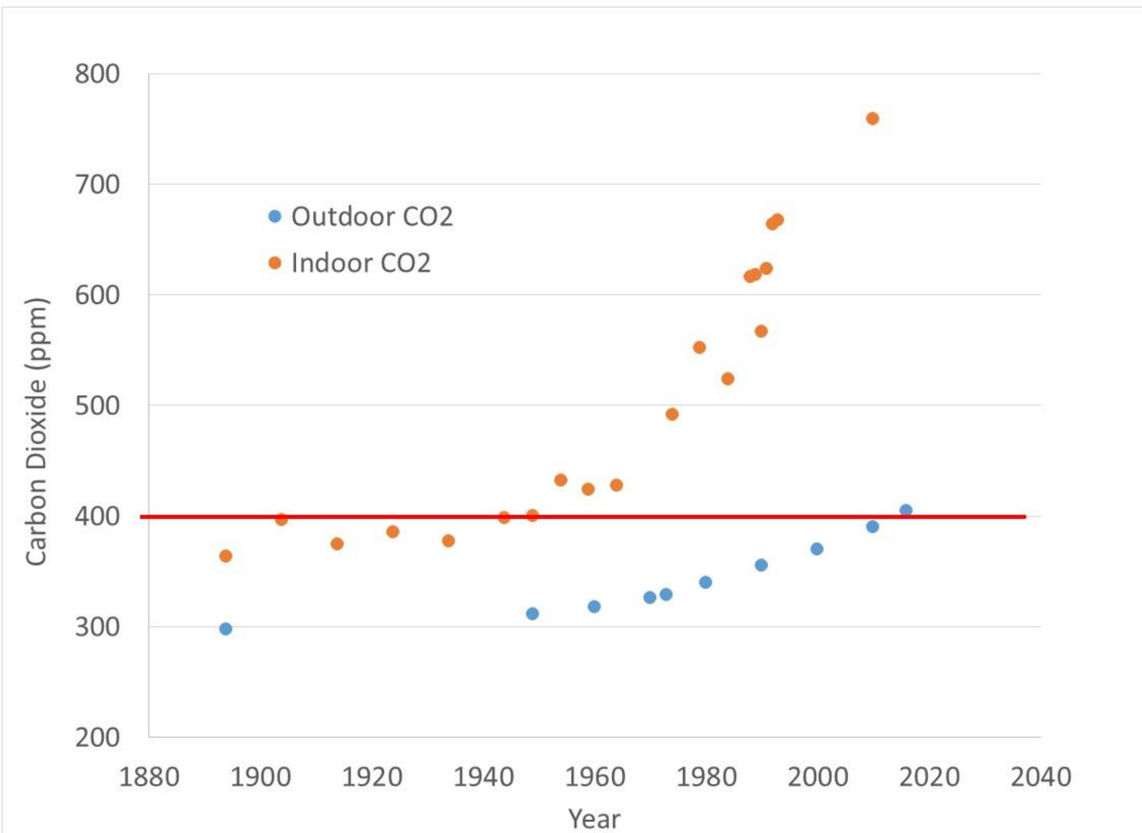

Figure 2 Indoor and outdoor carbon dioxide concentrations since 1890.

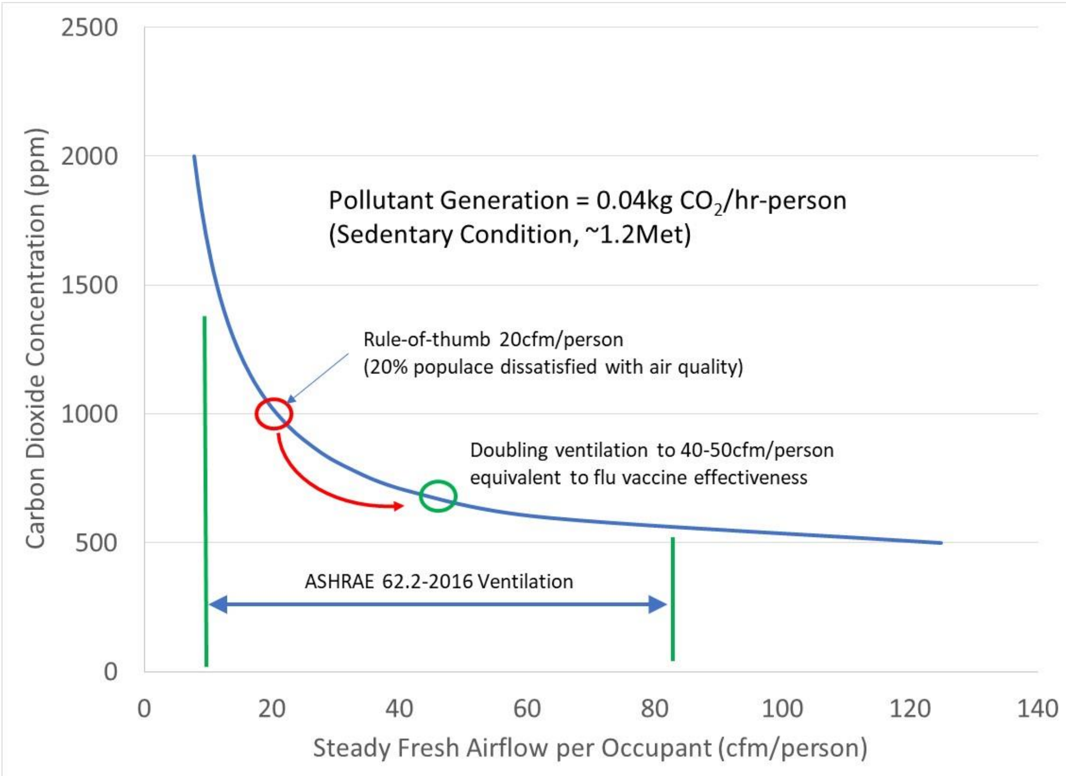

Figure 3 Steady pollutant concentration level versus air flow rate per occupant in a building. Outside carbon dioxide concentration assumed at 400ppm.

Table 1 ASHRAE 62.2-2016 Ventilation air flow table (cfm) based on house floor area and number of bedrooms.

	Bedrooms				
Area(ft^2)	1	2	3	4	5
500	30	37.5	45	52.5	60
1000	45	52.5	60	67.5	75
1500	60	67.5	75	82.5	90
2000	75	82.5	90	97.5	105
2500	90	97.5	105	112.5	120
3000	105	112.5	120	127.5	135
3500	120	127.5	135	142.5	150
4000	135	142.5	150	157.5	165
4500	150	157.5	165	172.5	180
5000	165	172.5	180	187.5	195

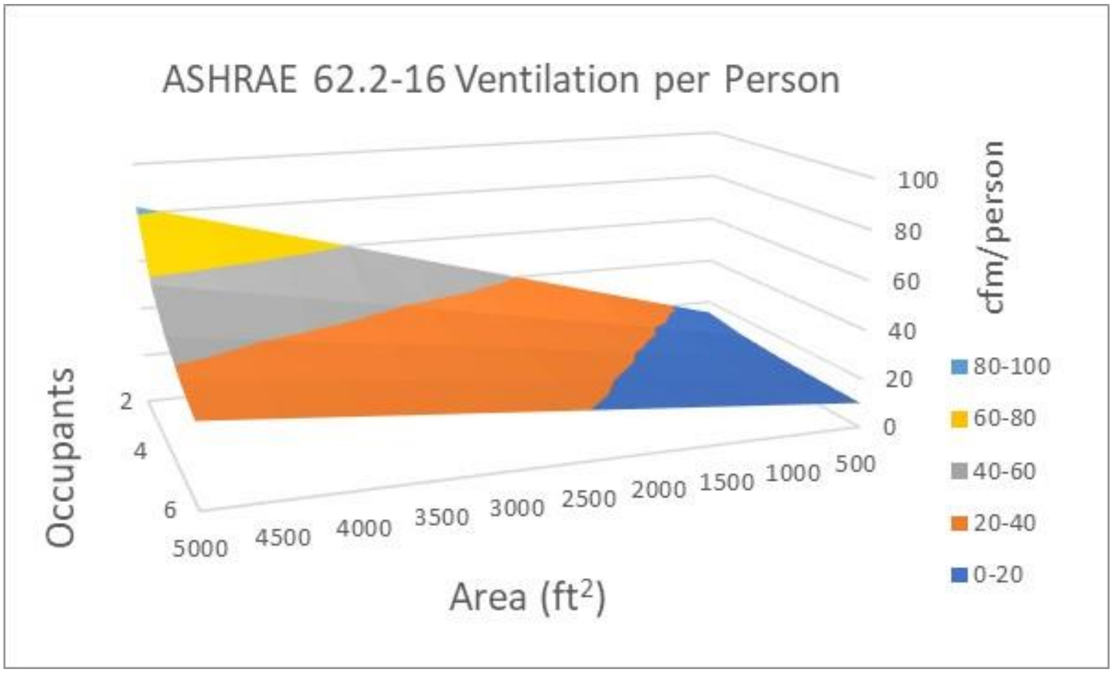

Figure 4 ASHRAE 62.2-2016 ventilation per person based on 1-plus occupant than number of bedrooms and house floor area.

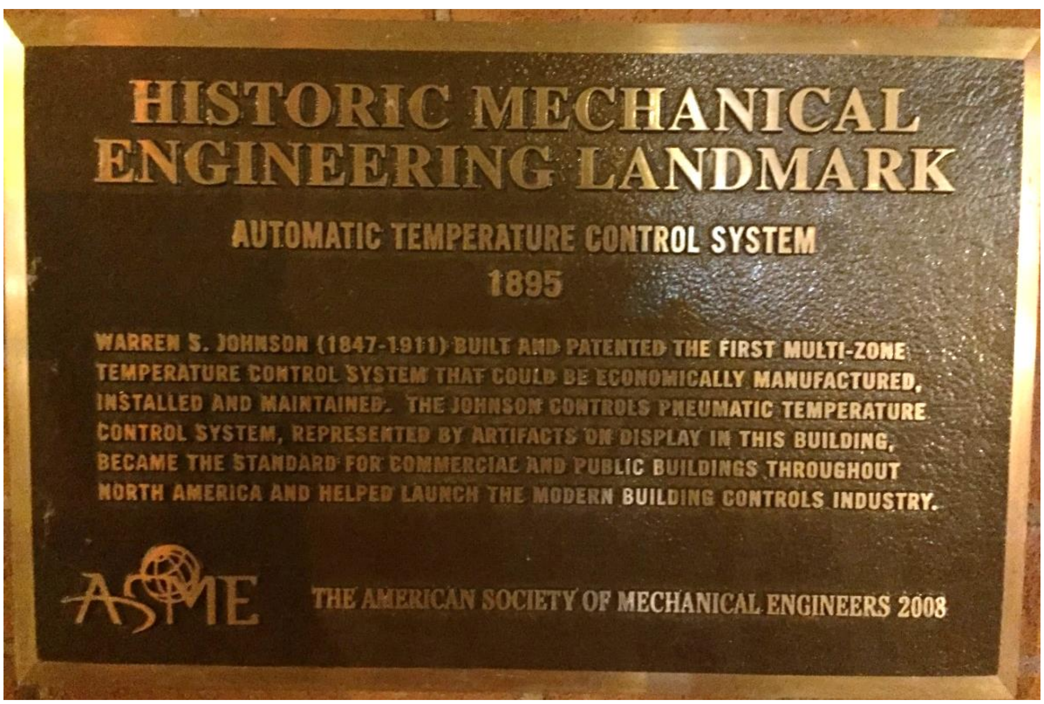

Figure 5 This plaque on the Johnson Controls headquarters in Milwaukee commemorates automatic building temperature control, developed more than a century ago. It's time to use smart ventilation in homes to improve our health and energy efficiency.

Build Equinox IAQ Metrics

Build Equinox introduced air quality metrics that form a basis for determining air quality impact on human health (23). Three sets of air quality metrics have been defined for describing current air quality conditions, cumulative pollutant effects, and basic air quality levels. The air quality metrics are incorporated into the CERV-ICE (CERV-Intelligently Controlled Environment) online website app with a goal of providing CERV community members with information regarding their home's environmental quality. Realtime CERV data, IAQ analytics, and archived house data (since 2014) for Equinox House can be viewed from the Build Equinox website.

Cumulative pollutant exposure is important for assessing longterm health effects. We are at the very beginning of cumulative pollutant monitoring, which will help improve our individual health as well as contribute to improved health of others. As we accumulate data from building environment sensors and personal data monitors, we will be able to piece together those effects that impact us in positive and negative manners.

Build Equinox cumulative indoor air quality metric is based on a "pollutant exposure unit" integrated over time. Figure 6 shows our definition of a pollutant exposure unit. We assume that indoor carbon dioxide concentrations less than 700ppm do not accrue significant detrimental pollutant exposure. Pollutant levels above 700ppm concentrations are considered significant. The pollutant exposure index is normalized relative to 1000ppm. Normalizing with 1000ppm has the additional vantage of being similar to Fanger's "olf" (olfactory unit) which is the sensation produced by the smell of a human in a room with 20cfm of fresh air flowing through the room (16). A level of 1 olf is the level in which 20% of the general populace is dissatisfied with the air quality. Therefore, 1000ppm carbon dioxide concentration for 24 hours results in 24 pollutant-hours of exposure. Perhaps a pollutant-hour of exposure should be called an "olf-hour"?

A number of European nations have also developed cumulative indoor air quality metrics (2) based on carbon dioxide that are "ppm-hours". These units are unwieldy in terms of typical numbers (eg, 100,000 ppm-hours) and not easily understood in relation to 1 pollutant-hour being a reference to a human exposed to their own pollutant output at common ventilation conditions.

Carbon dioxide and VOCs impact our health in some combined manner. Additionally, particulates of varying size and composition, as well as biological materials (molds, pollens, bacteria, endotoxins, dander, dust mite excrement, etc). Our pollutant exposure index has been formulated on a flexible basis to accommodate inclusion of other factors into a single index. At present, we include total VOCs in which VOCs are scaled in a manner correlated to a human's carbon dioxide output. That is, the total VOC output of a typical human is scaled such that a room with 1000ppm of carbon dioxide concentration has an equivalent total VOC concentration of 1000ppm, assuming no other source of VOCs beyond that of human generation.

We do not know how VOCs should be weighted relative to carbon dioxide in terms of health impact. Not all VOCs are bad. Inhaled medications are an example of good VOCs. For the time being, we combine total VOCs with carbon dioxide using vector addition (square root of the sum of the squares of carbon dioxide and total VOC pollution exposure units) without any weighting to either component. Additional health impacting pollutants such as particulates can be added in a similar manner as well as weighting adjustments as we learn more about health factors. Therefore, spending 24 hours in a room with 1000ppm of carbon dioxide and 1000ppm of total VOCs (in equivalent carbon dioxide units) would result in an accumulation of 24 CO_2 pollutant-hours, 24 total VOC pollutant-hours, and 34 combined pollutant-hours of exposure.

Figure 7 and 8 show daily pollutant-hour exposures for a group of conventional (non-ventilated) and CERV smart ventilated homes, respectively. The 14 conventional homes in Figure 7 were monitored for approximately 2 weeks at various times of the year over a range of geographical locations spread across the US. The 10 CERV smart ventilated homes were also spread across the lower 48 of the US. The CERV's online monitoring capability allows data to be selected from any time of year. The CERV data selected for the 10 homes in Figure 8 is from January 2016, which represents a time when most homes would be sealed from the outside weather.

Daily, combined pollutant-hour exposures for each house are shown in Figures 7 and 8. The conventional homes are all "leaky", that is, they are all conventionally built prior to 2010 without any efforts to seal beyond that of conventional practice at the time of construction. Although blower door performance is not known for any of the conventional homes, air exchange rates greater than 6ACH50 are likely. Comparing Figure 7 and 8 data trends indicate that conventional homes often exceed 24 pollutant-hours of exposure per day, while CERV smart ventilated homes rarely exceed 24 pollutant-hours of exposure per day. Note that January 1 and 8 of 2016 were Fridays, and that some smart ventilated homes exceeded 24 pollutant-hours per day during those vacation holidays when parties and house guests were likely to have added to pollutant loadings.

Figures 9 and 10 are radial plots of pollutant exposure hours for the homes depicted in Figures 7 and 8. The radial plots are constructed such that the contribution of total VOCs and carbon dioxide contributions to overall pollutant-hour exposure can be viewed. The inner green region of the pollutant exposure radial plot is Build Equinox's recommended region. The yellow banded intermediate region is the area covered by ASHRAE 62.2-2016 ventilation schedule. The red region beyond the yellow should be avoided. Conventional homes are often operating with poor levels of air quality. In fact, almost all of the conventional homes had days of poor air quality, while almost all days of the smart ventilated homes were within the green region.

Figure 9 for conventional homes is weighted toward carbon dioxide as the predominate pollutant while Figure 10 for the smart ventilated homes is weighted toward VOCs. The smart ventilated homes in this data set are electric homes while an unknown number of the conventional homes (most likely 50%) have gas cooking ranges. Our internal studies have shown that a gas range produces carbon dioxide at a greater rate than total VOCs from gas combustion products and cooking odors. This does not suggest that pollutants are less significant. In fact, gas ranges add carbon monoxide, nitrogen oxides, and sulfur compound pollutants.

We do not always have access to detailed pollutant data, but instead only know average ventilation air flow rates. The air exchange rate per person for a building can be used to characterize the fraction of time that one spends at different carbon dioxide concentration levels in a building, as shown in Figure 11. For example, at 20cfm per person, 50% of the time is spent in less than 1000ppm and the other 50% is spent within 1000 to 2000ppm. Very little time occurs with carbon dioxide concentration above 2000ppm. At 10cfm, relatively little time has less than 1000ppm, 70% of the time the indoor environment is between 1000 and 2000ppm, and 30% of the time has carbon dioxide concentrations greater than 2000ppm. As ventilation levels reach 40cfm per person, 90% of the time is spent in a room with less than 1000ppm of carbon dioxide and 10% with carbon dioxide between 1000 and 2000ppm.

The data in Figure 11 is from 50 sets of field data from 20 different buildings (18 residential, one public library, and one business). Multiple data sets from some of the buildings were collected during time periods with differing ventilation levels and/or occupancy levels. Data was collected in 1 to 5 minute intervals over a time period of a few days to two weeks with carbon dioxide and total VOC levels "binned" in <1000ppm, 1000ppm to 2000ppm, and >2000ppm levels. Total VOCs, which used "equivalent" carbon dioxide concentration units (human VOC output registering on the total VOC sensor correlated to human carbon dioxide output), were less predictable in terms of the fraction of time spent within the defined pollutant concentration bins, presumably because of a greater range of VOC producing sources in the living environment. Appendix B includes the time fraction models developed for carbon dioxide.

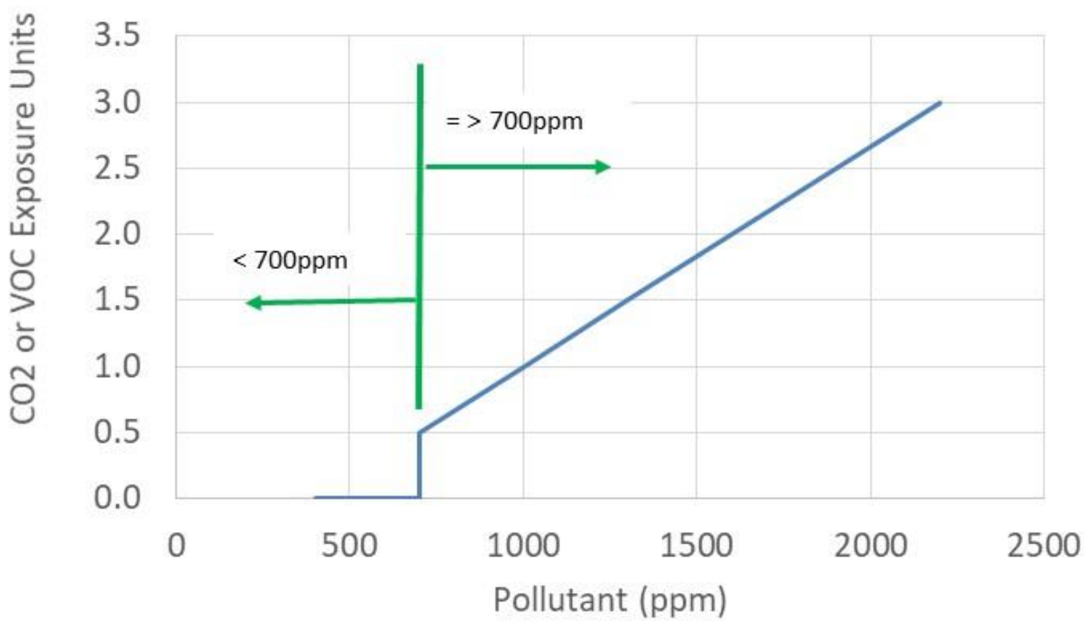

Figure 6 Building Equinox cumulative pollutant exposure unit definition.

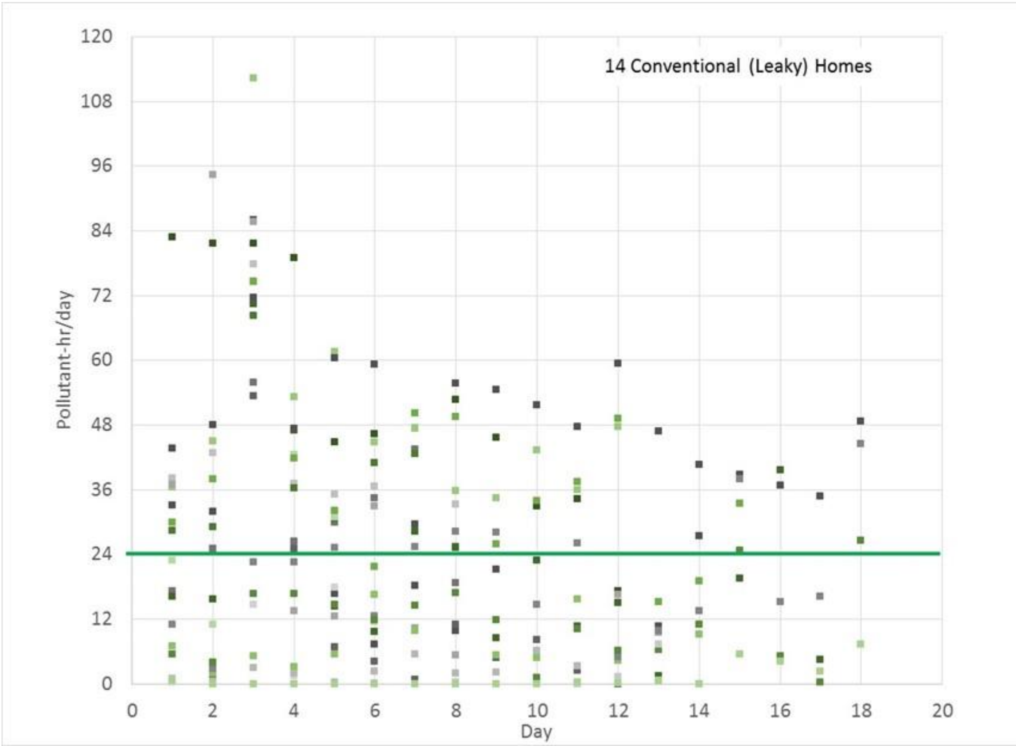

Figure 7 Daily combined carbon dioxide and total VOC pollutant-hours of exposure for 14 conventional (non-ventilated) homes over approximately 2 weeks.

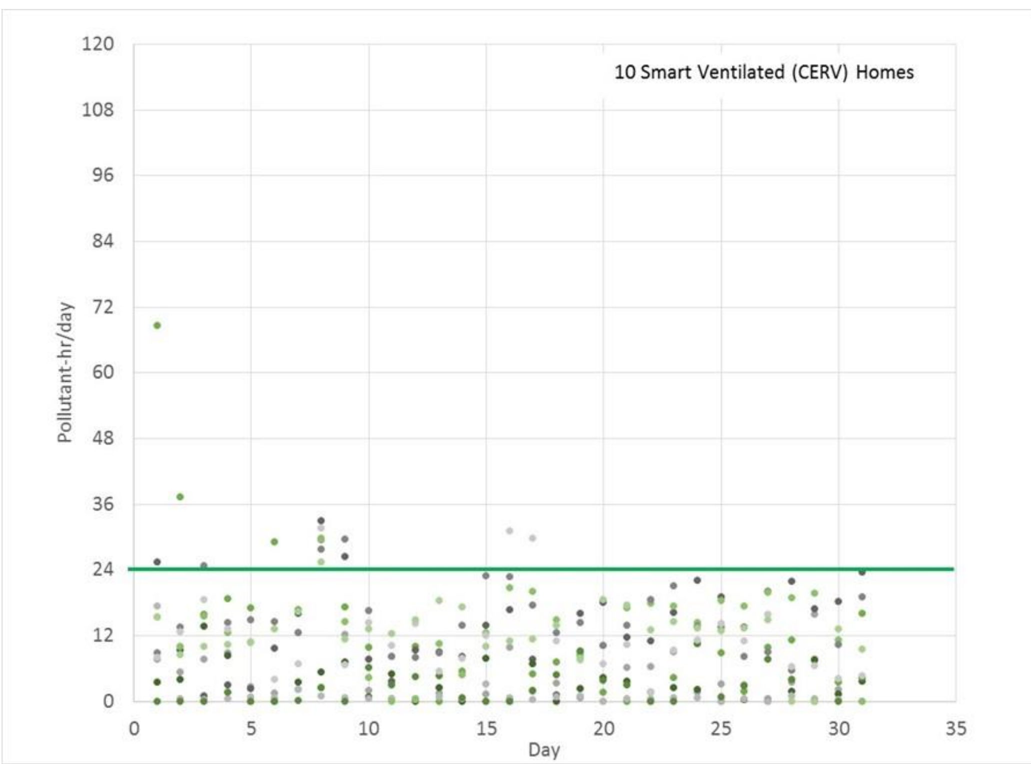

Figure 8 10 CERV smart ventilated home combined carbon dioxide and total VOC pollutant hours for January, 2016 (note January 1 and 8 are Saturdays).

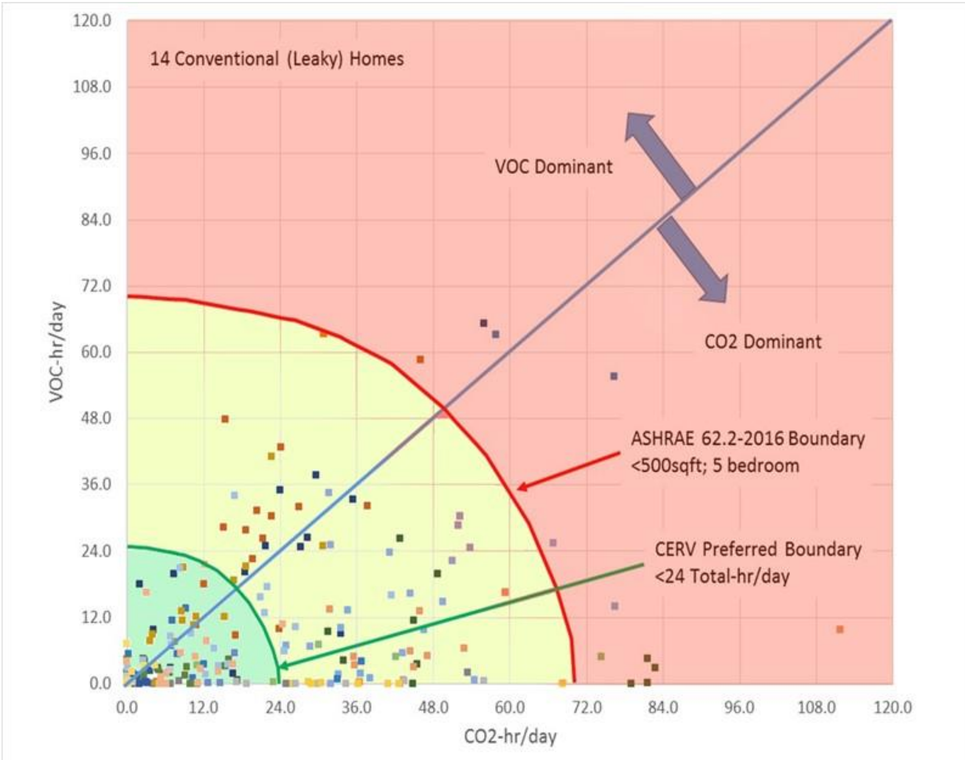

Figure 9 Radial plot showing carbon dioxide and total VOC pollutant-hours for Figure 6 data.

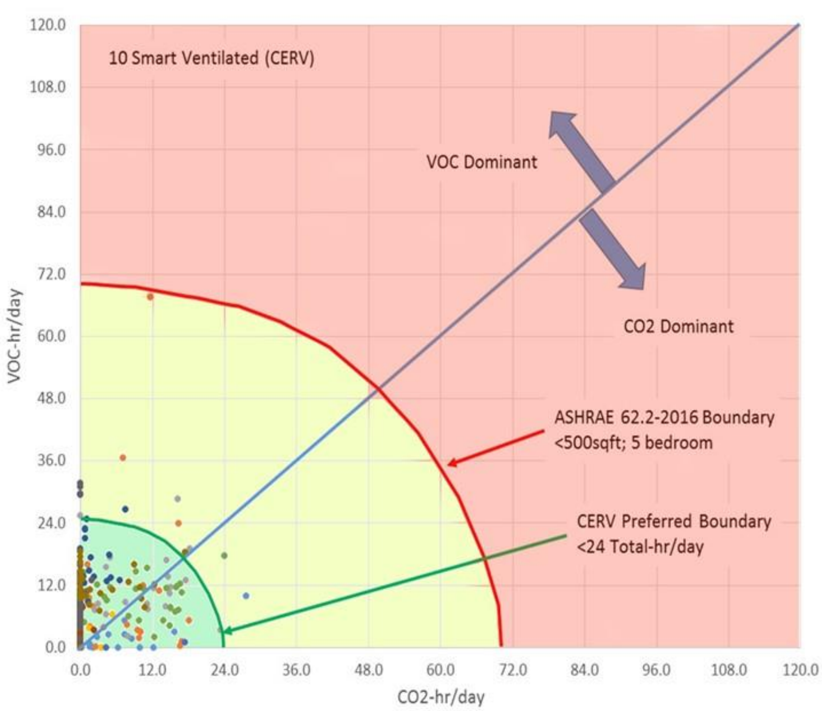

Figure 10 Radial plot of daily combined pollutant-hours for January 2016 for CERV smart ventilated homes shown in Figure 7.

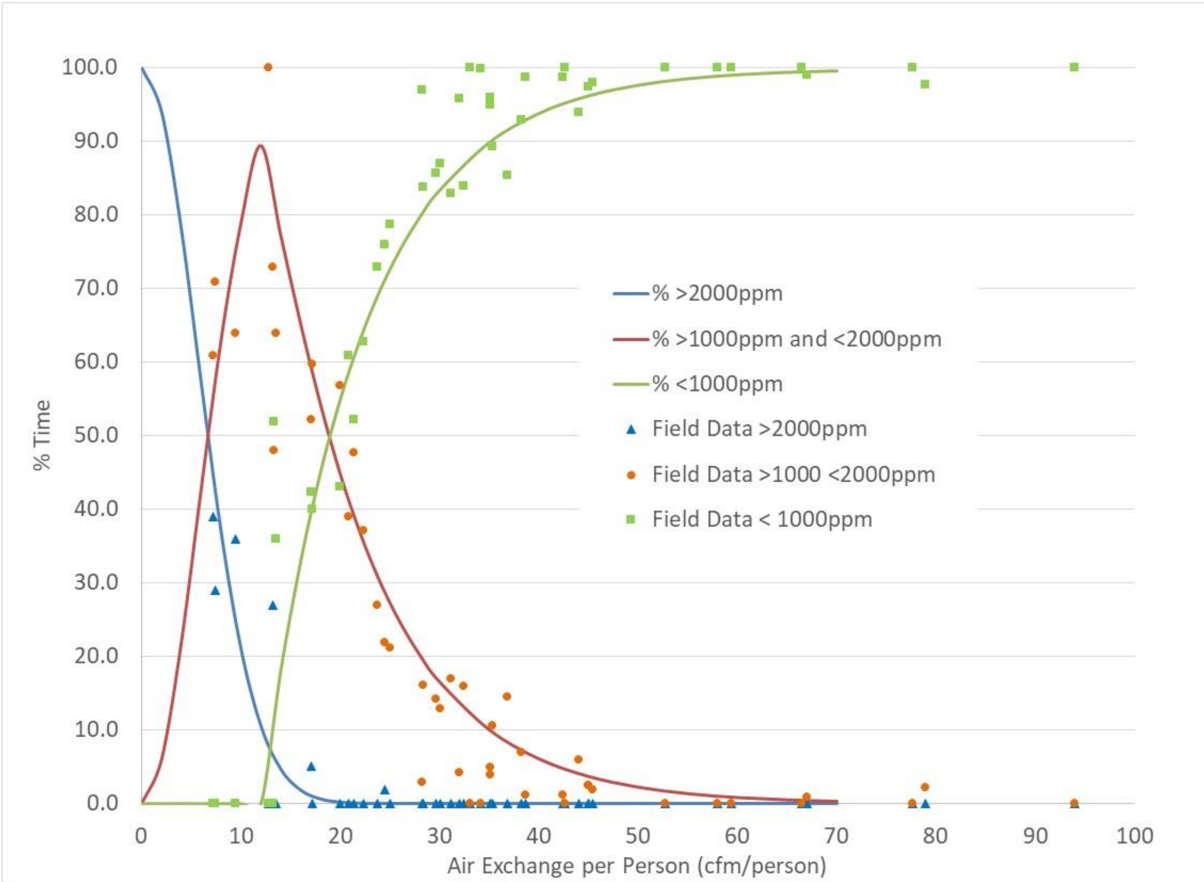

Figure 11 Fractional time characteristics of homes based on ventilation air flow rates.

Leaky Homes

We examine the air quality of a "leaky" home in this section. Making general statements is often a mistake, however, our experience indicates that almost everyone who lives in a "leaky" home thinks they have good air quality. A few people living in leaky homes with respiratory sensitivities know their air quality is poor as they continuously battle airborne allergens and molds leaking into their home. Figures 7 and 9 show that leaky, unventilated homes are homes with poor indoor air quality. But why?

My Grandmother's farm house in Michigan was as leaky as a home could be, but she knew the value of fresh air and always opened windows in every bedroom every night. She grew up in the "open-air" era of the early 20th century before the advent of modern antibiotics and vaccines, and she knew the ravages of polio, tuberculosis, rheumatic fever, and many other diseases. Modern medicines have reduced these horrible afflictions and dulled our alarm when we hear of sporadic contagion outbreaks. Weakened potency of our drug arsenal to fight increasingly drug resistant germs is a warning that we must use other means to protect our health, and fresh air is one of our most important weapons.

Today's home builders regularly construct homes with "blower door" leakage levels below 6ACH (air changes per hour) at 50Pa (equal to 0.2"H_2O pressure). Progressive communities that implement the latest International Residential Code (IRC) standards are requiring house leakage to be less than 3ACH at 50Pa pressure. And those progressive builders constructing homes to even more stringent standards are achieving leakage levels less than 0.6ACH at 50Pa. We will examine the impact of today's low leakage homes when we compare smart ventilated homes with code-based ventilated homes.

We consider a "leaky" 2700ft^2, 4 bedroom home with 5 occupants and an air exchange rate of 10ACH50. Infiltration is the only source of ventilation air. Our Ductology Part 2 (App G) report provides background information for relating blower door infiltration tests to actual infiltration driven by wind and thermal (buoyancy) effects. We assume wind-only driven infiltration for our leaky example house as it is the most dominant factor and illustrates the trends in air quality (21).

Hourly weather from January 2010, Urbana Illinois is the basis for infiltration air flow. Pollutant concentration variations and energy usage are predicted using 5 minute computational intervals. We use a real month's weather data rather than "TMY" (Typical Meteorological Year) weather because it is real. Figure 12 is a plot of hourly temperatures and wind speed for the month. Urbana's 2010 January was two degrees colder than the long term average (20F average versus the long term average of 22F), with periods of bitter cold and not-so-cold weather. Note that there is very little correlation between wind speed and ambient temperature. That is, high and low wind speeds occur randomly in relation to time periods with high and low ambient temperatures.

Figure 13 shows the variation of infiltration air flow with wind speed for the leaky home. Note that infiltration is related to the square of wind speed as wind-imposed pressure variations around the home's exterior cause air to be driven into and out of the home. Wind speeds greater than 20 mph cause very high infiltration rates that exceed 800cfm, while infiltration rates drop rapidly at low wind speeds.

Figure 14 presents indoor carbon dioxide variations for the month, coincident with wind speed variations. As one would expect, house carbon dioxide concentrations are low when wind speed is high, and concentration levels are high with low wind speed. The changes are quite rapid as wind speed changes.

Figure 14 shows 5 days with undesirably high pollutant concentrations during windless days. Is 5 days of poor air quality acceptable? January is a windy month. How many days with poor air quality occur during less windy times of year? A home should not be at the mercy of the wind and have any days of poor air quality. Electricity for comfort conditioning (see Figure 14) to make up for the infiltration heat load is predicted to be 2226kWh for the month, or roughly $250 of the home's January utility bill is due to infiltration. We assumed Mitsubishi's efficient HyperHeat minisplit heat pump to convert comfort conditioning heat to electric energy.

A leaky home is a home with periods of poor air quality and excessive energy use. Before leaving this section, an additional comment regarding the distribution of ventilation is important. Figure 14 seemingly shows that 26 days of the month have reasonably good air quality levels. Our modeling assumes a "well-mixed" house volume in which infiltration air is mixed throughout the house volume. In reality, where one lives in a house and where the leakage air flows are often different. That is, one's bedroom may be well-sealed and highly polluted at night even though the wind is whistling through the rest of the house. Additionally, other sources of pollutants, such as emissions from gas cooking (which we strongly discourage) locally raise pollutant concentrations to unhealthy levels that are not properly addressed without active ventilation.

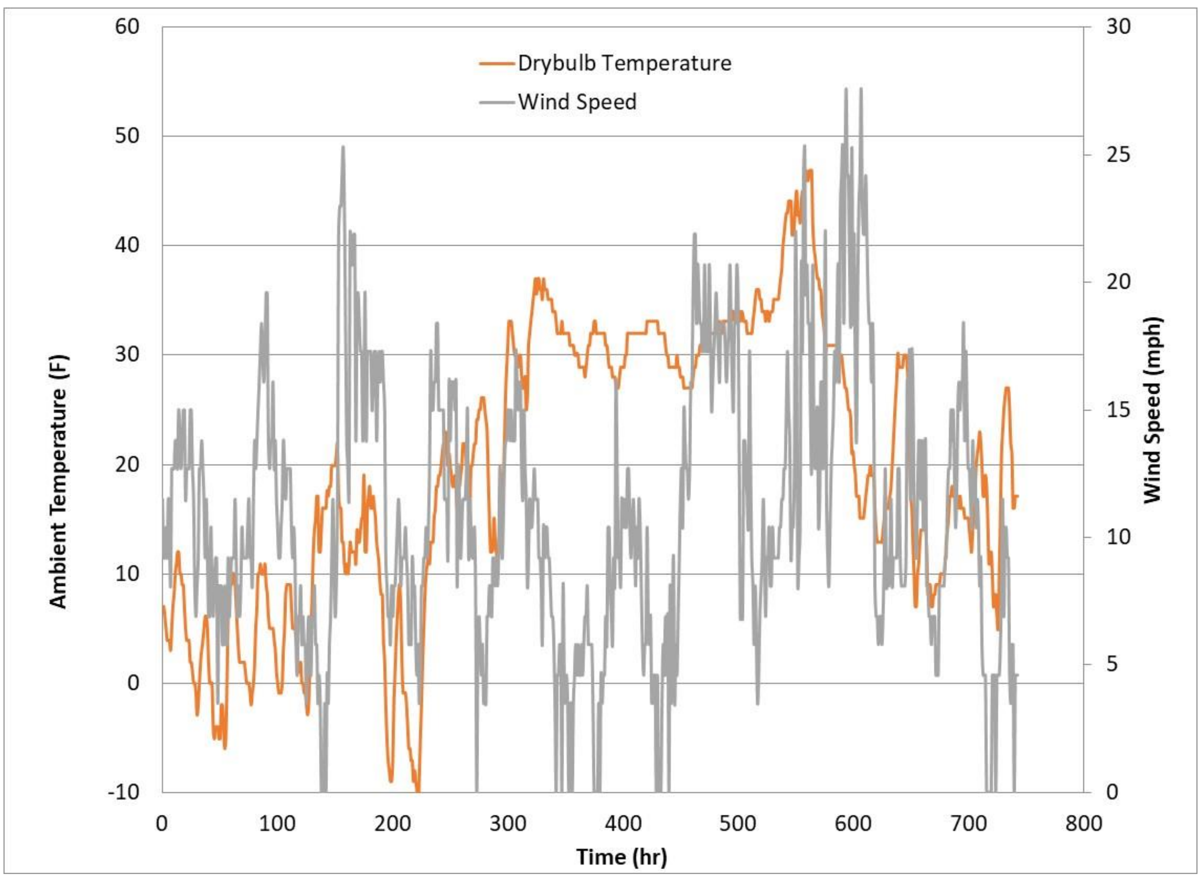

Figure 12 January 2010 hourly temperature and wind speed for Urbana Illinois.

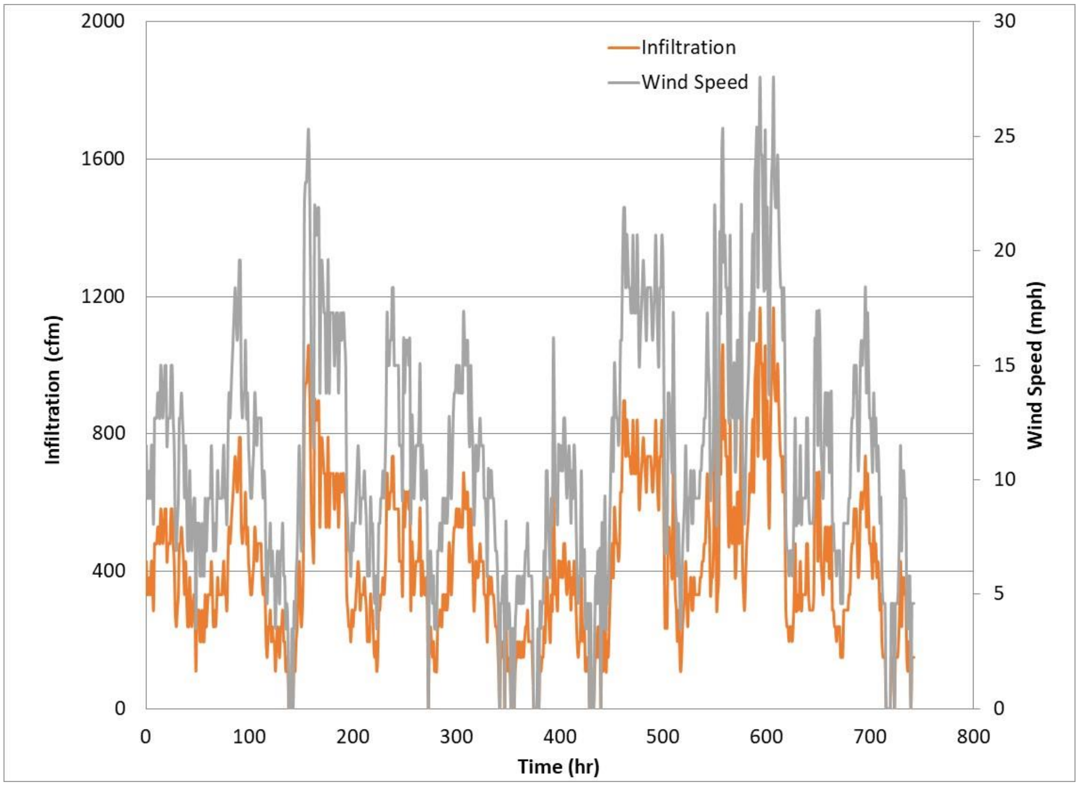

Figure 13 Hourly wind speed and infiltration air flow for a 2700ft² home with blower door 10ACH at 50Pa using Urbana Illinois January 2010 weather.

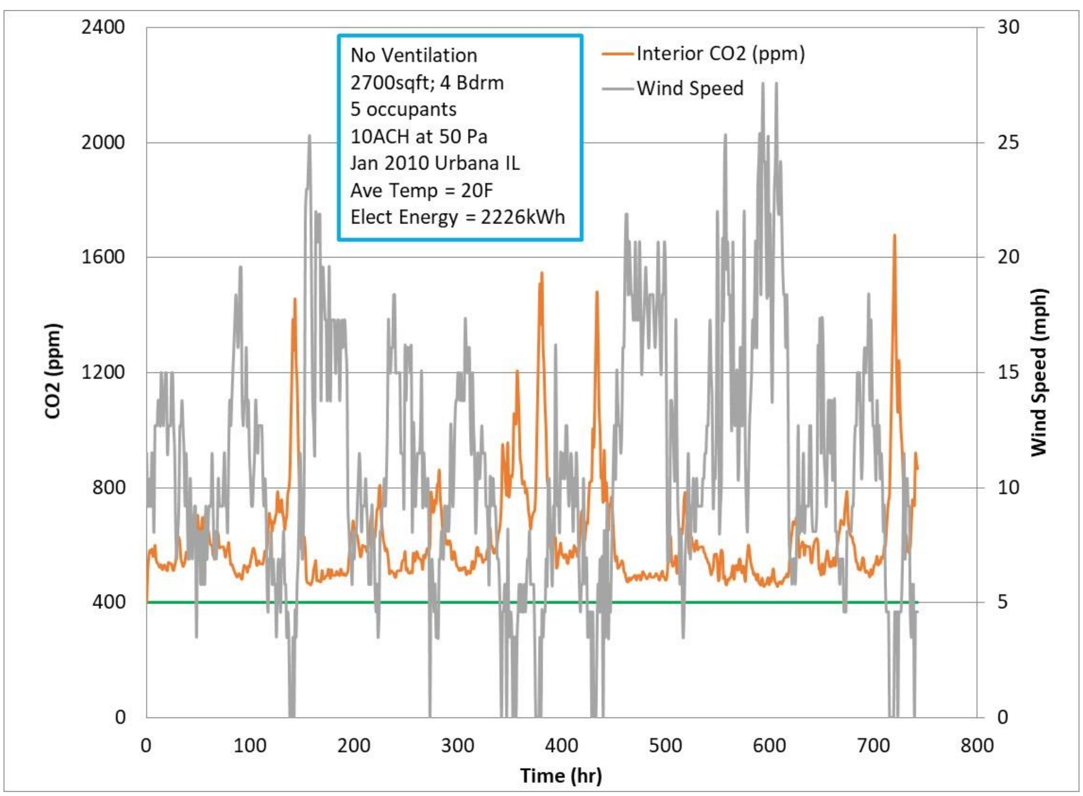

Figure 14 Indoor carbon dioxide concentration variations for a leaky home with January 2010 Urbana Illinois weather.

Smart Home Ventilation Characteristics

Figure 3 presents the steady ventilation air flow rate needed to maintain a building at a desired pollutant concentration based on an occupant's metabolic pollutant emission rate at sendentary conditions (see Appendix A). For example, if one would like to maintain a room with an occupant at a carbon dioxide concentration of 800ppm, 30cfm of fresh air flow is required. If the room was initially at a higher pollutant concentration (eg, someone uses an ill-advised gas stove that increases room pollution), 30cfm of air flow will require a long time to return the room to back to 800ppm (theoretically, an infinite amount of time as the room creeps closer and closer to the desired concentration level). Bringing in fresh air at an elevated flow rate returns the room to the desired air quality level faster. This is analogous to the reason why we design comfort conditioning systems with "excess" capacity in order to move from one level of comfort to another in a reasonable period of time as well as add extra horsepower to our vehicles in order to accelerate to a desired speed within a timeframe that minimizes irritation to other drivers.

Assume we have a room with a volume of $10,000ft^3$ (eg, a $1200ft^2$ home with 8ft ceiling height) with one person in it. If we would like to reduce an elevated pollutant concentration level to 800ppm using the 30cfm, approximately 5 to 6 hours is required to reduce the elevated pollutant level 2/3's of the way to 800ppm. For example, if the room's pollutant level had increased to 1700ppm (900ppm above the desired 800ppm level), 5 to 6 hours of ventilation would lower the room to 1100ppm (300ppm above 800ppm). Another 10 to 12 hours of ventilation is required in order to decrease the elevated pollutant level to within 95% of the target concentration level.

A smart ventilation system using an elevated ventilation air flow rate reduces pollution levels faster. When a target concentration level is reached (the "setpoint" concentration level), the smart ventilation system switches to another mode of operation. For example, a CERV2 operating at 200cfm will clear the polluted air from the building within an hour. After reaching the desired setpoint concentration level, the CERV2 switches into one of its recirculation modes (recirculation heating/recirculation cooling/recirculation).

Recirculation is an important means for utilizing fresh air that has been "stored" in unoccupied areas of a home. Recirculation is also a means for filtering particulates and absorbing pollutants (eg, with carbon impregnated filters) from a home's interior. Most particulates in today's well sealed homes are generated within the home and recirculation filtering is an effective means to remove particulates. It is a myth that a well-sealed home has no dust!

A home with steady pollutant generation should have alternating periods of fresh air ventilation and recirculation. During harsh climate conditions (cold weather or hot/humid weather), minimizing the fraction of time spent in fresh air ventilation mode reduces energy usage. Without recirculation, air in unoccupied regions is unused and either increased vent time is required to reduce pollutants in occupied areas or unsatisfactory air quality (or both) occur.

Figure 15 is a plot showing the fraction of time in fresh air ventilation mode for a home with a volume of $10,000ft^3$ and a smart ventilation system operating at 200cfm. The fresh air ventilation time fraction is plotted versus occupancy with one occupant assumed to produce 0.04kg/hour of carbon dioxide (see Appendix A).

Today's average home with an occupancy of 2.5 people requires 30% fresh air ventilation time, assuming continuous occupancy. If the occupants are home for 12 hours per day, fresh air ventilation would only be required for 15% of the day. Also plotted on Figure 15 are the times for fresh air venting and recirculation periods. For example, a home with 4 to 5 occupants would ventilate 50% of the time with 20 minutes in fresh air ventilation and 20 minutes in recirculation.

A large building increases in pollutant concentration more slowly than a smaller volume building with the same pollutant generation (occupancy) level. A smart ventilation system alternating between fresh air ventilation periods and recirculation periods will spend the same fraction of time in ventilation and recirculation modes in a large building as it does in a small building! The time length of a ventilation period and a recirculation period are longer in a large building in comparison to a small building, but the fraction of time spent in fresh air ventilation is exactly the same. This is very important because it means that the ventilation efficiency of large and small buildings are the same.

Figure 16 illustrates large building and small building ventilation characteristics. Two homes, one with 20,000ft^3 volume and the other with 10,000ft^3 volume, are ventilated with 200cfm of air flow. Both homes have 2 occupants. The smart ventilation air quality setpoint is 1000ppm. A control deadband of 100ppm switches the ventilation system from fresh air mode to recirculation mode when indoor carbon dioxide levels decrease to 900ppm. When carbon dioxide concentration increases above 1000ppm, fresh air ventilation mode is activated. As seen in Figure 8, the length of time spent in fresh air ventilation and recirculation modes is greater for the larger home, but the increase of time is proportional to that of the smaller home, resulting in the same fraction of time in ventilation mode.

Figure 17 is a plot of 34 "Vermod" CERV smart ventilated homes showing the average carbon dioxide and total VOC concentration levels versus the CERV pollution threshold setpoint. The data is the average of a 5 month period (January through May 2017). The home occupants select pollutant threshold levels, with most choosing a 1000ppm (one setpoint is used for both carbon dioxide and total VOC with equivalent carbon dioxide concentration units). One home occupant selected a very low setpoint of 600ppm, which the CERV maintained. One other home showed average VOCs to exceed the CERV setpoint of 1000ppm. From Figure 17, the associated carbon dioxide level is less than 800ppm, which indicates an additional source of VOCs that exceeds human generated VOCs. Vapping, smoking, cooking, gluing model airplanes, or some other activity are common causes of excessive VOC pollution.

Figure 18 plots average VOC versus carbon dioxide concentration for the 34 homes. Two-thirds of the homes are dominated by VOC pollutants, while a third of the homes have VOC pollutant levels similar to carbon dioxide pollutant levels. Significant reductions in fresh air ventilation might be gained with improved home occupant awareness of VOC pollutant source reduction.

Figures 19, 20, and 21 show different ventilation characteristics over the course of a year for one of the Vermod homes included in the Figure 17/18 data. Figure 19 shows the fraction of time during each month that the CERV spent in one of 9 operation modes. Over the course of the year, the fraction of time spent in one mode or the other changes significantly. With the CERV's indoor and outdoor temperature and humidity sensors, the CERV knows when it is "nicer" outside than inside. During Vermont's relatively cool spring, summer and fall, the CERV spends significant time in either "Vent Cool" or "Free Vent" modes.

Free venting is a condition in which fresh air is supplied and indoor exhausted without any conditioning or energy exchange between incoming and outgoing air streams. It is the equivalent of automatically opening windows when it is nice outside, except that the incoming fresh air is filtered. Vent Cool mode is a mode in which the home needs active cooling to maintain comfort. The CERV has determined that outside air is more energy efficient to cool than indoor air, resulting in very high levels of fresh air flow to the house. During October, the CERV automatically switches to heating modes, contributing some of its heating capacity to that of the home's bulk heating system (1 ton Mitsubishi Hyper Heat).

Figures 20 and 21 show the average daily amount of fresh air delivered to the home for each month (2000 pounds per day = 20cfm of continuous air flow). The home has a single occupant who works, equivalent to 0.5 occupants. During the spring months, as much as 5 to 6 tons of fresh air are brought into the house! Figure 21 indicates that carbon dioxide concentrations during the spring are very low due to the high fresh air ventilation levels, however total VOC concentration levels are high. Vegetation ("pine scented" forests) is a significant source of VOC emissions, which is a complication along with other outdoor sources of VOCs (forest fires, homes with wood stove emissions) to consider in managing indoor air quality (22).

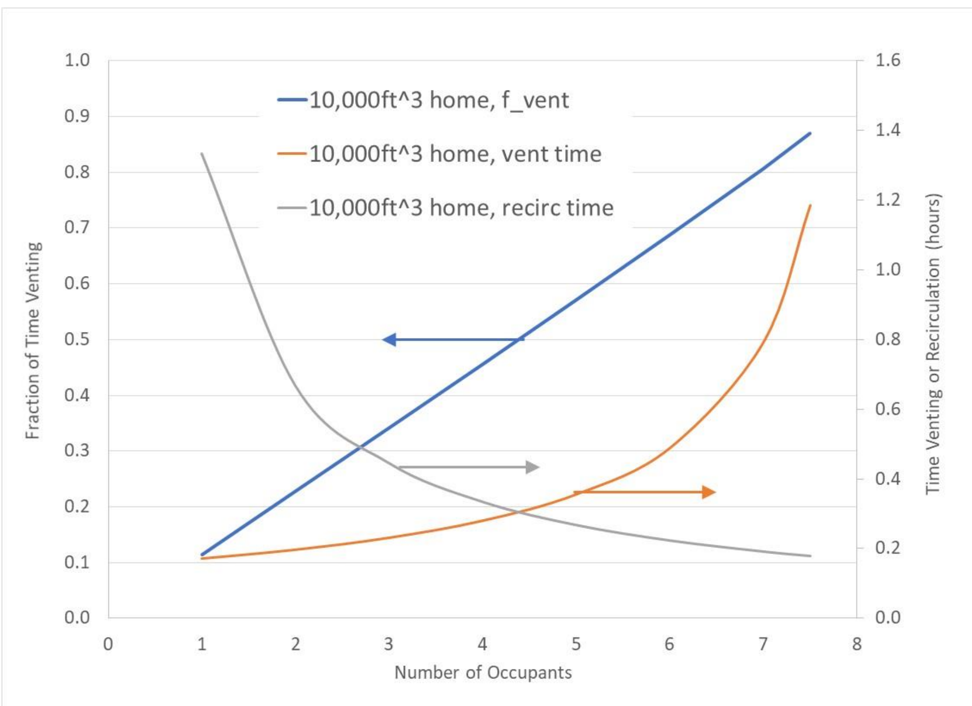

Figure 15 Fraction of time in ventilation mode and amount of time in ventilation and recirculation relative to house occupancy. The home is assumed to have perfectly mixed air with ventilation air flow of 200cfm and a carbon dioxide concentration of 1000ppm. Each occupant is assumed to produce 0.04kg-pollutant per hour, or roughly the amount of human pollutant output at average metabolic (1.2 Met) activity.

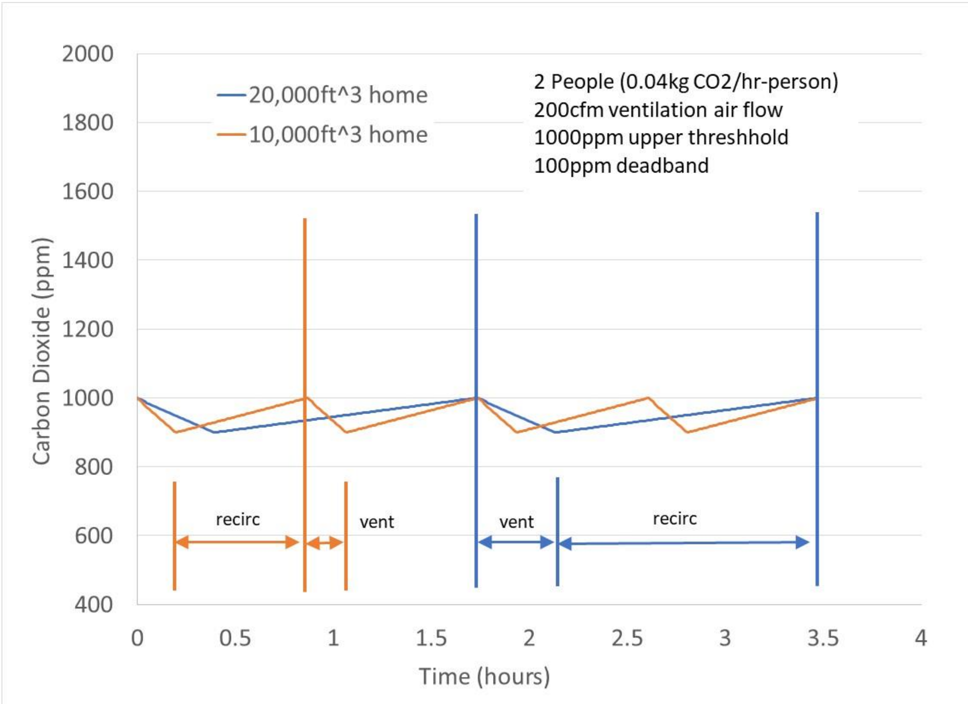

Figure 16 Indoor pollutant variation during fresh air ventilation and recirculation time periods for two homes with the same occupancy (2 occupants) and different indoor volumes (10,000ft^3 and 20,000ft^3). Upper CO_2 pollutant control setpoint is 1000ppm with a deaband of 100ppm.

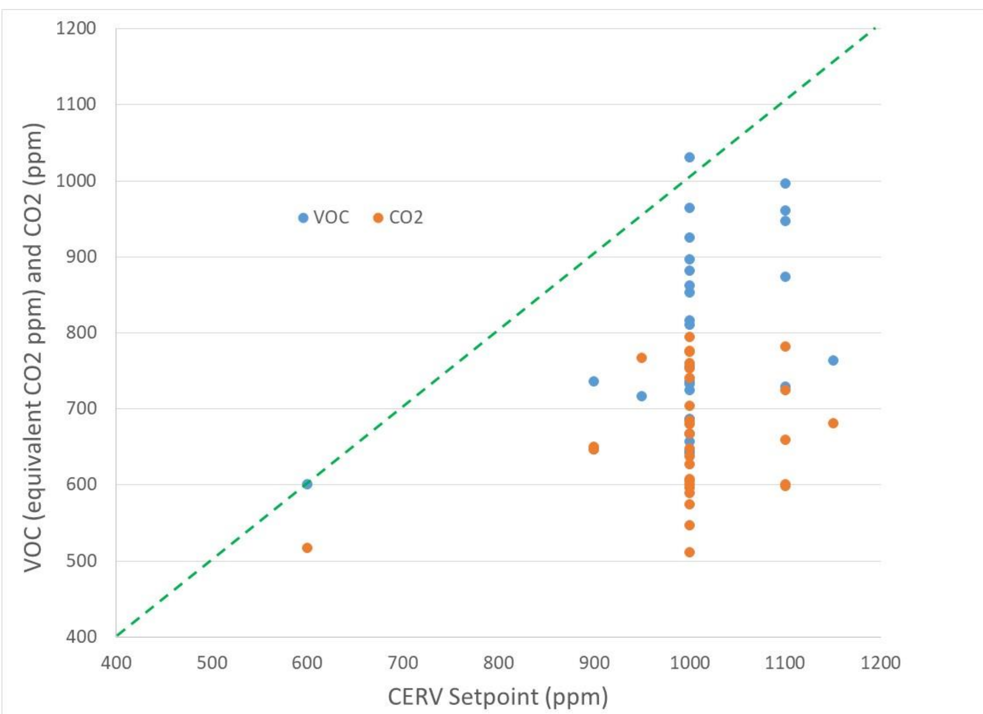

Figure 17 Average indoor carbon dioxide and total VOC concentration levels versus CERV pollutant threshold setting for 34 Vermod homes for January through May, 2017.

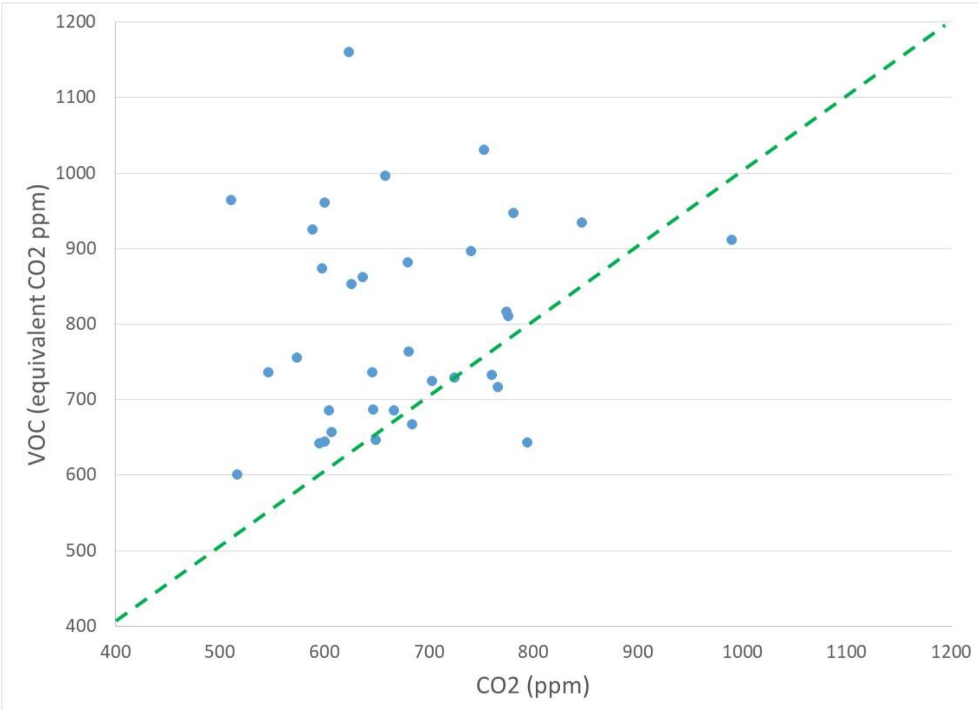

Figure 18 Total VOC versus carbon dioxide averages for 34 Vermod homes from January through May 2017.

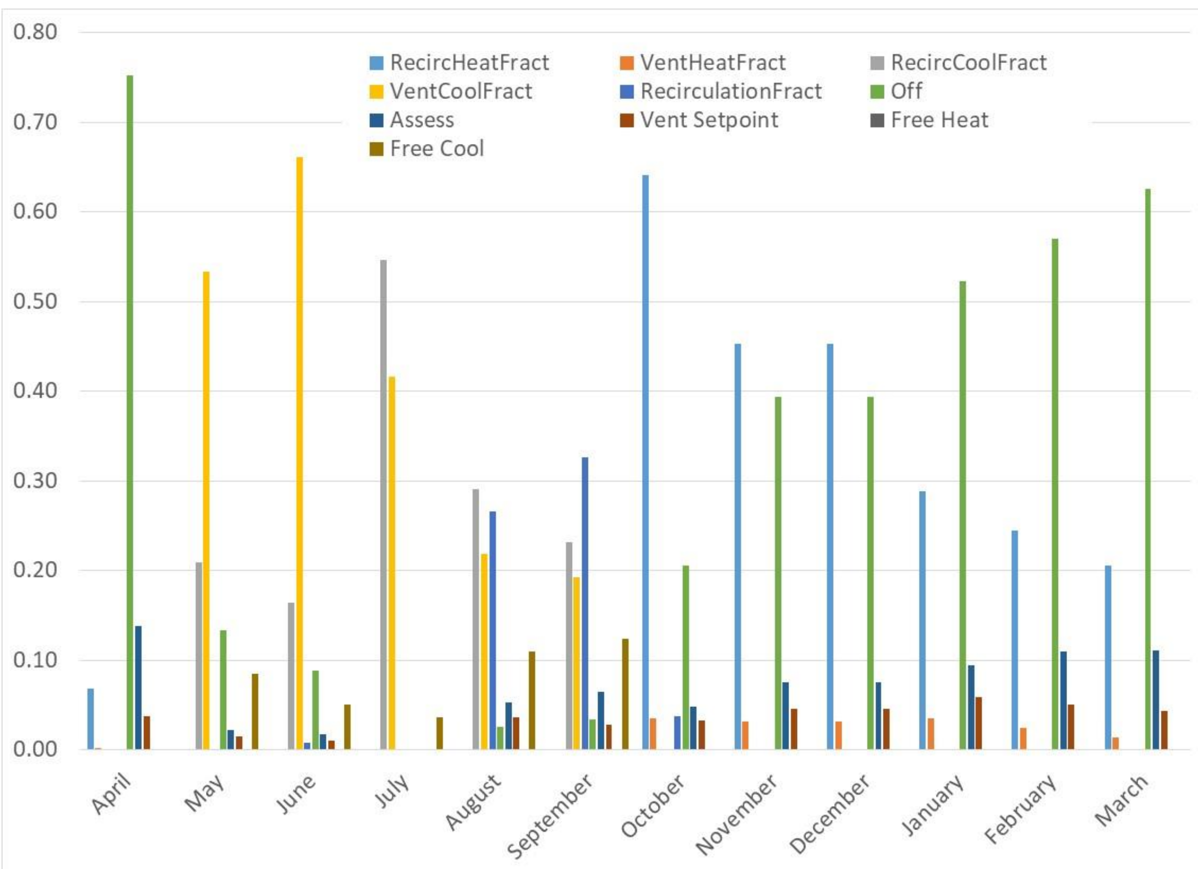

Figure 19 CERV operation mode time fractions for each month for a home in Vermont.

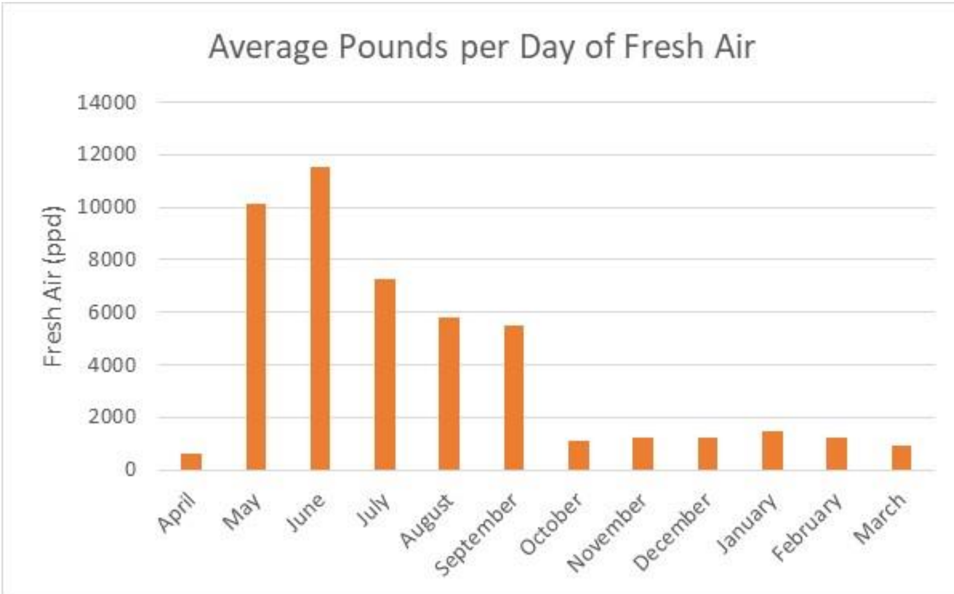

Figure 20 Average daily fresh air delivery (pounds per day) to a home in Vermont for each month of the year (note: 2000pounds per day = 20cfm air flow rate)

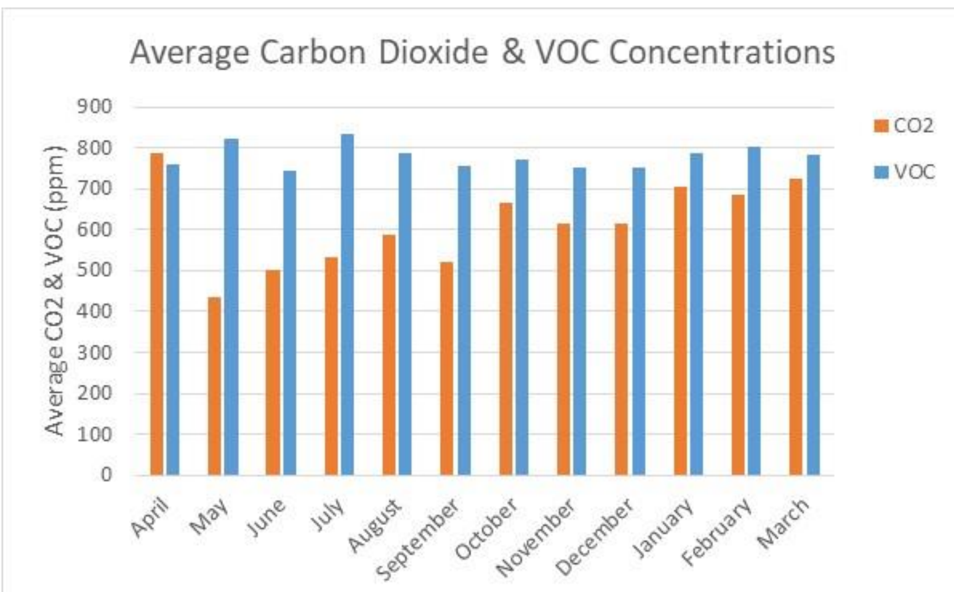

Figure 21 Average daily carbon dioxide and total VOC (equivalent carbon dioxide units) for a Vermod home for each month of the year.

Indoor Air Quality and Energy Usage Assumptions for Smart Ventilated and Constant Ventilated Homes

Comparing the operation of a smart ventilation system with a conventional steady flow ventilation system is difficult. Air quality variations are very dynamic, and the associated energy flows (thermal and electrical) for a constant flow HRV system and a heat pump smart ventilation system are different. We are limiting our comparison to a cold January so that we can examine air quality and energy in under challenging conditions. Smart ventilation systems perform well all year in all climate zones, so the trends discussed are similar but with lower energy impact. During swing seasons when one would like to open windows, a smart ventilation system should bring in a maximum amount of fresh air. In some locations, such as Denver, “swing season” lasts 7 months!

We will use the same January 2010 Urbana Illinois hourly weather data (see Figure 12) for our comparisons. Five minute computation steps are used for accurately resolving concentration variations. The HRV ventilated houses are assumed to follow ASHRAE 62.2-2016 ventilation. An HRV efficiency of 90% is assumed with no latent energy exchange assumed. The CERV2 smart ventilated homes are fresh air ventilated when indoor carbon dioxide reaches 1000ppm, and continue in fresh air ventilation mode until indoor carbon dioxide is reduced to 900ppm (100ppm control deadband). The smart ventilated homes operate in “recirculation heating” mode when fresh air is not required. The CERV2’s carbon dioxide setting is selected as the level resulting from 20cfm per person with average activity (see Figure 3). At this level of operation, homes would be maintained at 24 carbon dioxide pollutant -hours per day of exposure (the green-yellow boundary of Figure 11).

CERV2 heating and cooling characteristics are described in Appendices C and D. The heating and cooling capacity charts, coupled with electrical power (compressor and fans) allow others to model CERV2 performance over a broad range of ambient conditions. CERV2 fan performance characteristics are described in Appendix E. Fan power for HRV and CERV2 operation are not included. Fan power should be negligible for each system with good duct design practices. We recommend keeping all duct velocities between 300 and 400 fpm (feet per minute), which keeps combined supply and exhaust fan power below 30Watts for 200cfm. Poor duct design can result in more than 200Watts of fan power. Our reports on optimal duct design and duct performance tests contain more detail.

We consider 4 homes to illustrate the impact of home construction (leakiness), occupancy, and home size.

A) 2700ft^2 home, 3ACH50 leakage, 4 bedrooms, 2.5 occupants
B) 2700ft^2 home, 0.6ACH50 leakage, 4 bedrooms, 2.5 occupants
C) 2700ft^2 home, 0.6ACH leakage, 4 bedrooms, 1.25 occupants
D) 1000ft^2 home, 0.6ACH50, 2 bedrooms, 4 occupants

Homes A, B, and C represent today’s average home with 2700ft^2 and 4 bedrooms. Homes A and B have today’s average occupancy (2.5 people) with home A at IRC infiltration level (3ACH50) and home B sealed to high performance level. Home C is the same as home B with half the occupancy (essentially the same occupancy, but occupants are assumed away from home for 12 hours per day). Home D represents a smaller, two bedroom home with an occupancy of 4, similar to Vermod homes (26), which are very well insulated and sealed. Figure 17 data shows indoor air quality for 34 Vermod homes with CERV smart ventilation systems.

The HRV homes have 6 thermal energy terms related to home ventilation energy performance. The thermal energy terms are:

1) Infiltration energy; energy required to heat infiltrated air to room temperature (70F)
2) Ventilation energy; energy required to heat ventilation air from outdoor temperature to room temperature
3) HRV recovered energy; energy recovered by the HRV. The HRV recovers 90% of energy required to heat ventilation air to room temperature for ambient temperatures 20F and greater. An electric frost prevention preheater warms outdoor air to 20F whenever outdoor temperature is below 20F.
4) Defrost heat addition; outside ventilation air is heated to 20F when outdoor temperature is below 20F with an electric preheater
5) Heat pump thermal energy; the net deficit heat due to infiltration and ventilation is compensated with heat from an air source heat pump. The net deficit is the difference between the infiltration and ventilation thermal energy sum minus the sum of energy recovered and frost prevention preheat.
6) Heat addition equivalence term; the last thermal energy term is the excess heat produced by the smart ventilation system's heat pump. Because the CERV2 generally produces a net positive addition of heat to a home during winter conditions, this amount of heat is added to the HRV home for equivalence.

The CERV2 smart ventilated homes have 6 thermal energy terms, too:

1) Infiltration energy; energy required to heat infiltrated air to room temperature (70F)
2) Ventilation energy; energy required to heat ventilation air from outdoor temperature to room temperature
3) Recirculation heat addition; energy added to the home by the CERV2 heat pump during recirculation mode
4) Ventilation heat addition; energy added to the home by the CERV2 heat pump during ventilation mode
5) Heat pump thermal energy; additional heat added by house heat pump during time periods (5 minute computational periods) when the net energy balance of CERV2 heat pump addition is less than heat addition required for infiltration and ventilation
6) Total heat; a CERV2 generally produces net positive energy to a home. The CERV2's additional energy contribution is used in HRV analysis to provide an equivalent energy comparison basis

Both HRV and CERV2 ventilated homes are assumed to be heated by a high performance, low temperature air source heat pump. Mitsubishi Hyper Heat heat pump performance characteristics are assumed for the modeling. Heating deficits due to infiltration and ventilation for 5 minute time intervals integrated over an hour are calculated and heat pump performance based on current temperature conditions are used to determine heat pump efficiency for electric energy usage.

Energy values would change with other heating systems. Electric resistance heating, which we discourage due to its inherent inefficiency, would result in even poorer HRV system performance relative to a CERV2 heat pump system. Other high performance heat pump systems, such as geothermal or ducted heat pumps would be similar to the results presented in this report.

Electrical energy usage is a home's utility bill. The HRV constant ventilation home has 3 electrical energy terms:

1) Heat pump electrical energy; the electrical energy required to make up the heating deficit of infiltration and HRV heating loads
2) Defrost electrical energy; electrical energy required by the frost prevention heater to warm outside air to 20F when outside is colder than 20F
3) Heat pump electrical energy to match smart ventilation surplus heating; the electrical energy for the house heat pump to provide a total heat equivalent to the smart ventilation system's net positive heat contribution

The CERV2 smart ventilation system's electrical energy usage is comprised of 3 terms.

1) CERV2 recirculation mode electrical energy; the CERV2's electrical energy in heating recirculation mode, based on its heat pump performance at varying outdoor temperatures (see Appendix C) is integrated over 5 minute computation periods
2) CERV2 ventilation mode electrical energy; the CERV2's electrical energy in ventilation heating mode (see Appendix C) is integrated over 5 minute computation periods
3) Heat pump electrical energy; any hour of the month in which the sum of CERV2 recirculation and ventilation heating is less than the infiltration and ventilation heating load is assumed to be made up by the house heat pump

Comparison of Constant Flow Ventilation and Smart Ventilation Air Quality

We compare air quality in the four homes (A, B, C, D) described in the previous in Figures 22-29.

Home A is an average size home (2700ft^2) with average US occupancy (2.5 occupants) with 3ACH50 infiltration characteristics. Figure 22 shows home A carbon dioxide concentration during January 2010 Urbana Illinois weather with an HRV continuously operating at ASHRAE 62.2-2016 ventilation (119cfm). On average, “bulk” air quality is excellent with carbon dioxide concentration well below 1000ppm, however local air quality within the home may be poor. Variations of carbon dioxide are due to wind variations, however, unlike the leaky home with 10ACH50, ASHRAE 62.2 ventilation levels continue to provide sufficient air flow to maintain good average air quality. Total electrical energy for Home A is 893kWh, which is substantially lower than the 2226kWh of electrical energy usage in the leaky home.

Carbon dioxide concentration in Home A with CERV2 smart ventilation system is shown in Figure 23. During high wind periods, infiltration supplies sufficient air to keep carbon dioxide concentration below 1000ppm. During low wind speed conditions, the CERV2 operated in ventilation mode. For most of the month, the CERV2 operated in recirculation heating mode. As previously discussed, recirculation mode is very important for filtering particulates out of the house environment. Monthly electrical energy usage is 646kWh, or roughly $30-$40 lower utility cost than Home A with an HRV.

Figures 24 and 25 compare carbon dioxide concentrations for Home B (well-sealed 0.6ACH50, 2700ft^2, 2.5 occupants) with an HRV continuous flow and CERV2 smart ventilation systems. HRV Home B has slightly higher carbon dioxide levels than HRV Home A with very good bulk average carbon dioxide concentration. HRV Home B has less concentration fluctuations than HRV Home A because the increase infiltration sealing reduces the impact of wind driven air flow into the house. Reducing the home’s infiltration from 3ACH50 to 0.6ACH50 resulted in reducing ventilation related electric energy by more than half (428kWh for HRV Home B versus 893kWh for HRV Home A).

Figure 25 shows the CERV2 smart ventilated Home B operating near the carbon dioxide concentration threshold of 1000ppm. The ventilation system alternates between fresh air mode and recirculation mode. Ventilation related electrical energy is reduced from 646kWh for Home A to 269kWh for the better sealed Home B. In comparison to the HRV Home B, a CERV2 smart ventilated home would have a utility cost of approximately $30 versus approximately $50 for the HRV Home B.

A home’s occupants do not generally occupy a home continuously as assumed for Homes A and B. Home C with 1.25 occupants is representative of a home with 2.5 occupants who are absent for 12 hours per day. Figure 26 shows HRV Home C with lower average carbon dioxide concentration than HRV Home B because of the lower occupancy with the same infiltration and ventilation air flows. HRV Home C ventilation energy (471kWh) is essentially the same as Home B electrical energy (428kWh) because the infiltration and ventilation air flows are unchanged between the two cases. The difference in energy is due to the equivalent heating energy added to the two home cases to make each equivalent to the CERV2 Home B and Home C cases. These energy amounts will be discussed in the following section.

Figure 27 for the CERV2 smart ventilated Home C has some carbon dioxide variations due to high wind periods that add sufficient fresh air to the home for the relatively low occupancy level. During low wind speed periods, the CERV2 operates in fresh air mode to maintain good air quality. Note that Home C has reduced energy usage to 228kWh for the month. That is, ventilation energy usage in a smart ventilated home varies with occupancy and occupant activities. When pollutant generation is low, ventilation related energy will be low. The HRV system could be manually adjusted by occupants, but reality shows that humans are not reliable for modulating systems and automation is reliable.

The current model results assume steady carbon dioxide gas production (that is, steady occupancy and activity, see Appendix A) in order to compare ventilation systems without the complications of an occupancy schedule and occupant activity (eg, sleeping, exercising, etc) schedule. In general, more realistic occupancy schedules favor smart ventilation systems even more. That is, 8 occupants in a home for 3 hours release the same amount of pollutants as 1 occupant in a home for 24 hours. With a smart ventilation system, sufficient fresh air is automatically delivered during the 3 hour period. Continuous flow ventilation systems do not deliver sufficient air during the short, high occupancy period. Likewise, the smart ventilation system reduces ventilation air flow when unoccupied while the constant flow system delivers excessive, unneeded ventilation air.

Home D comparison is for a smaller (1000ft^2), two bedroom, well-sealed (0.6ACH50) home with 4 occupants. Figure 28 for HRV Home D, even though operating with ASHRAE 62.2-2016 ventilation of 52cfm, has an excessively high average carbon dioxide concentration of 1300ppm. As discussed previously with Figure 11, HRV Home D would rarely have carbon dioxide less than 1000ppm. More than 20% of the general populace would not like the air quality in this home, flu and colds would be transmitted efficiently among the home's occupants, and carbon dioxide and VOC levels will impair cognition and disrupt sleep. Ventilation energy usage is a low 201kWh ($25 utility cost), however health costs and productivity costs are much greater than the perceived energy savings associated with insufficient ventilation.

Figure 29 shows the CERV2 Home D to use 321kWh of energy while maintaining an average carbon dioxide concentration of 1000ppm. The smart ventilated home is continuously switching between fresh air venting and recirculation modes to maintain the 1000ppm IAQ setpoint. The smart ventilation system uses more electrical energy than the HRV system because of the higher fresh air flow. From Figure 15, we can determine that the smart ventilation system is operating in fresh air mode 45% of the time for an average fresh air ventilation flow rate of 90cfm (0.45 x 200cfm), in comparison to the HRV's ASHRAE 62.2 ventilation air flow rate of 52cfm. The utility cost difference is $15, or $4 per house occupant for the month (about 12 cents per day per occupant for improved ventilation).

HRV Homes A, B, and C all appear to have more than adequate fresh air flow, however, this may not be the case in reality. If the HRV homes have no means for recirculation or zone flow control, occupied spaces may be polluted while unoccupied spaces are overventilated. A 4 bedroom, 2700ft^2 home most likely has at least 6 occupancy regions (4 bedrooms, family room, kitchen/dining). Dividing the 119cfm ASHRAE 62.2 ventilation air flow among 6 or more spaces indicates that some rooms have less than 20cfm of fresh air flow. If the home's occupants are all in one room, less than 8cfm of fresh air per room occupant will result in poor air quality in that space. Our second report air distribution system design to avoid inefficient use of fresh air and to automatically maintain good air quality wherever in homes.

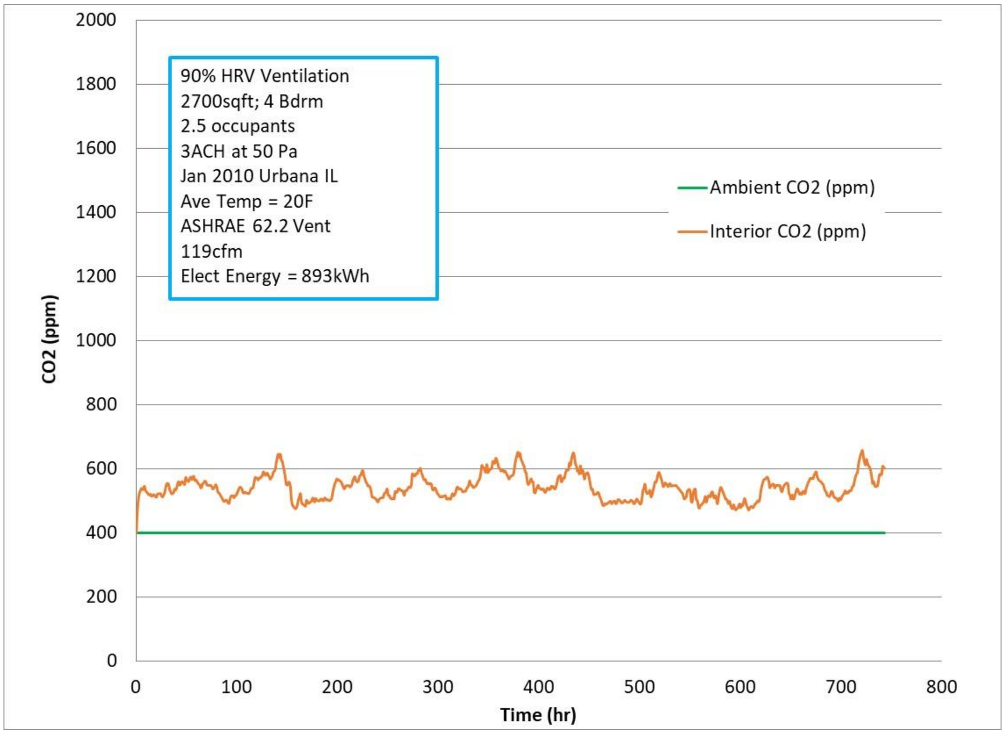

Figure 22 Carbon dioxide concentration in an average house(2700sqft) with average occupancy (2.5) and infiltration of 3ACH50 for Urbana in January 2010 with a 90%HRV

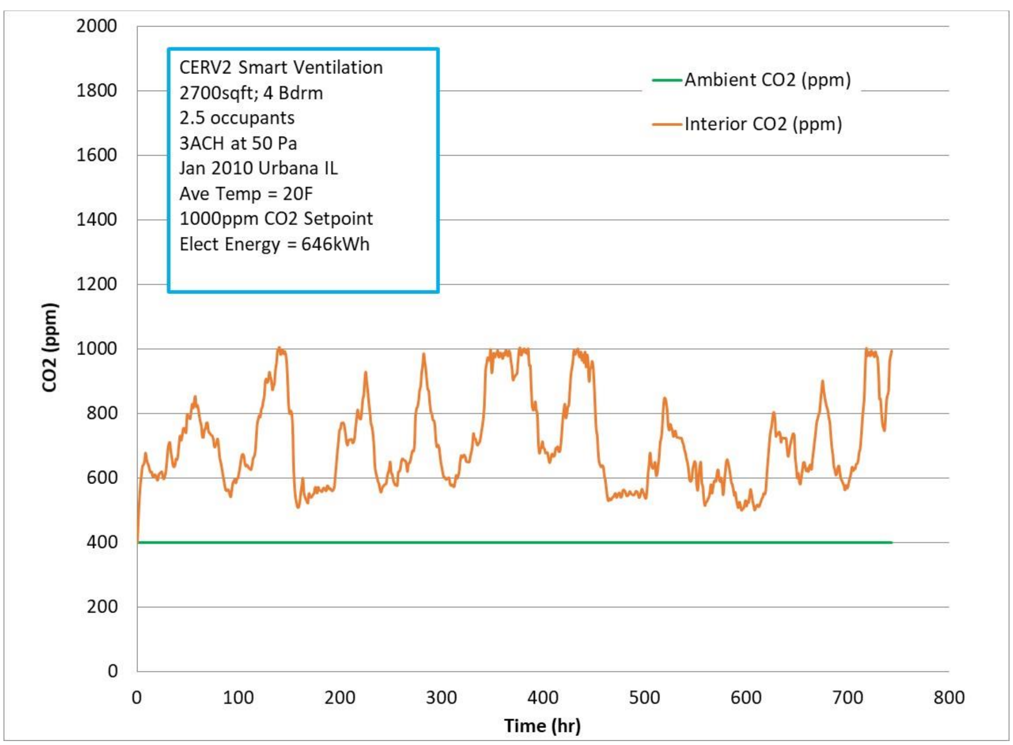

Figure 23 Carbon dioxide concentration in an average house(2700sqft) with average occupancy (2.5) and infiltration of 3ACH50 for Urbana in January 2010 with CERV2 smart ventilation.

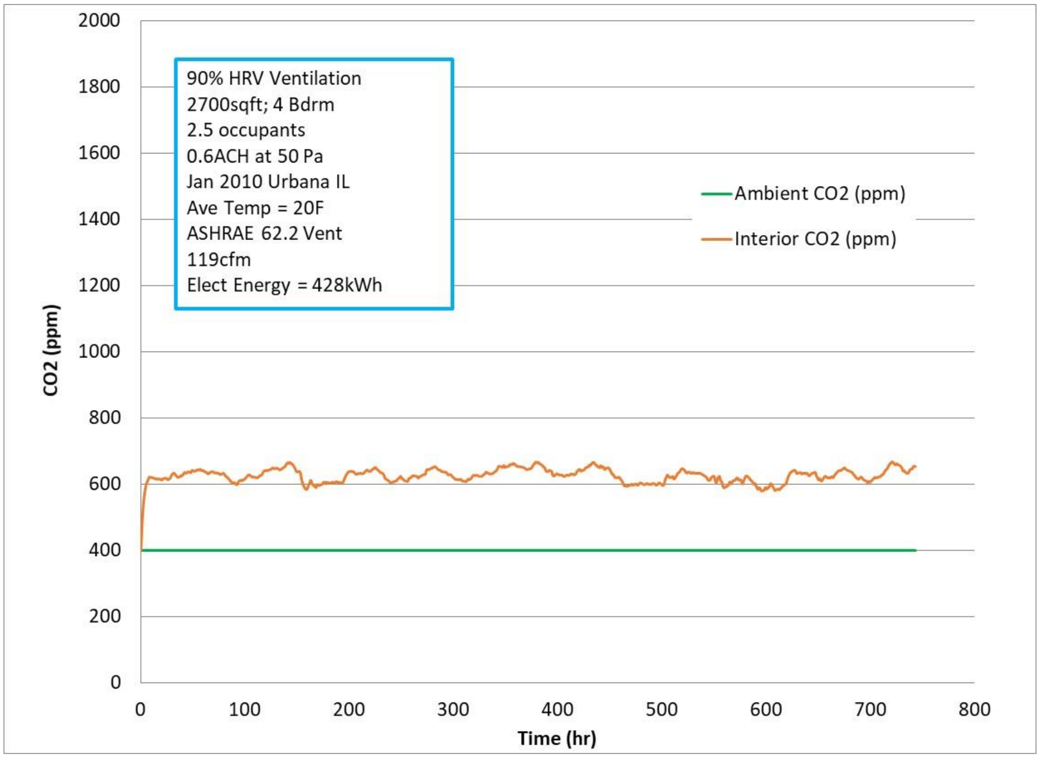

Figure 24 Carbon dioxide concentration in an average house(2700sqft) with average occupancy(2.5) and infiltration of 0.6ACH50 for Urbana in January 2010 with a 90%HRV

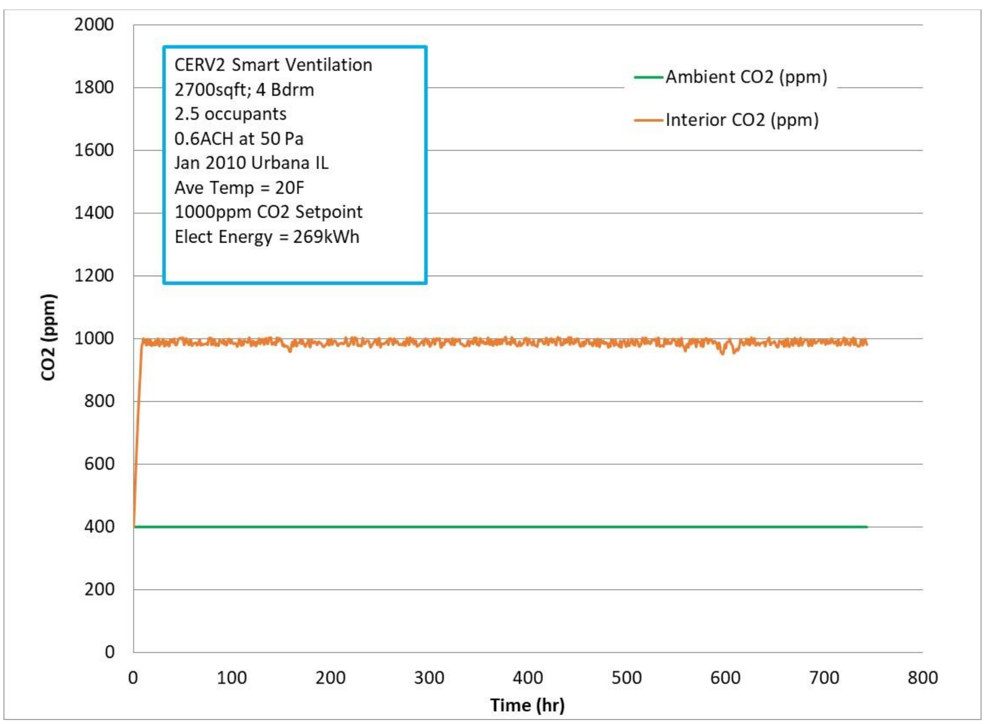

Figure 25 Carbon dioxide concentration in an average house(2700sqft) with average occupancy (2.5) and infiltration of 0.6ACH50 for Urbana in January 2010 with CERV2 smart ventilation.

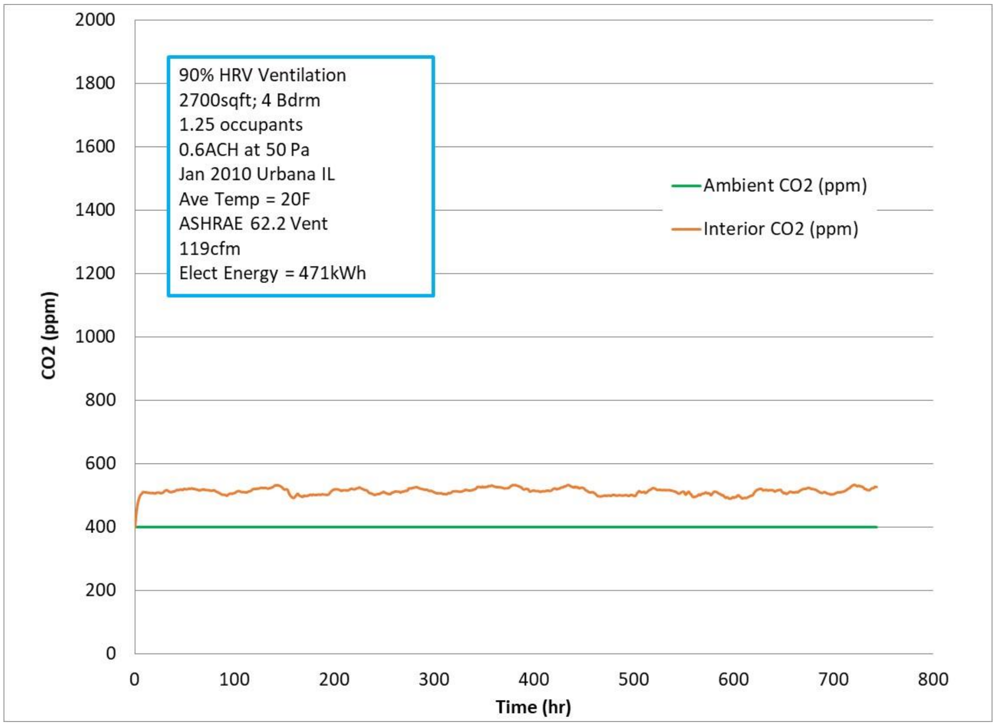

Figure 26 Carbon dioxide concentration in an average house(2700sqft) with an occupancy of 1.25 and infiltration of 0.6ACH50 for Urbana in January 2010 with a 90%HRV

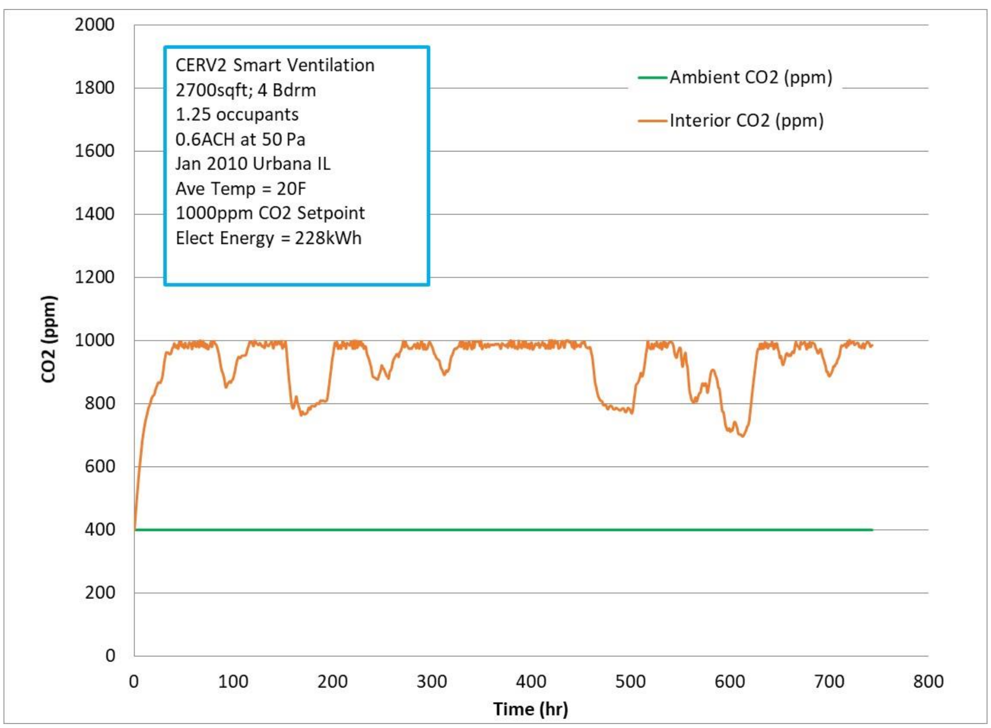

Figure 27 Carbon dioxide concentration in an average house(2700sqft) with an occupancy of 1.25 and infiltration of 0.6ACH50 for Urbana in January 2010 with CERV2 smart ventilation

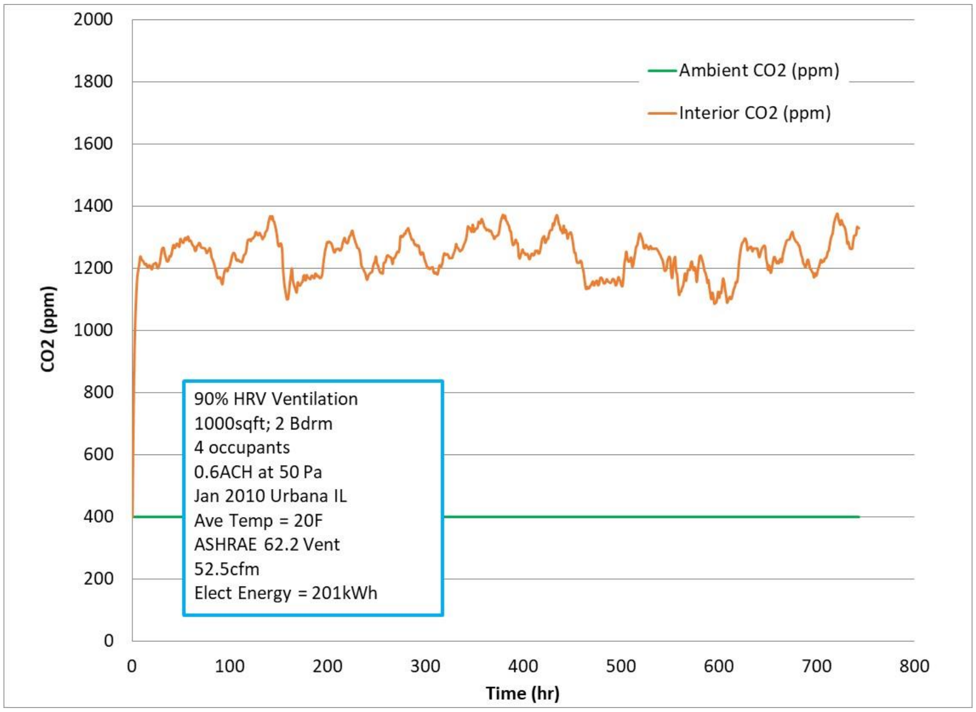

Figure 28 Carbon dioxide concentration in a small house(1000sqft) with an occupancy of 4 and infiltration of 0.6ACH50 for Urbana in January 2010 with a 90% HRV

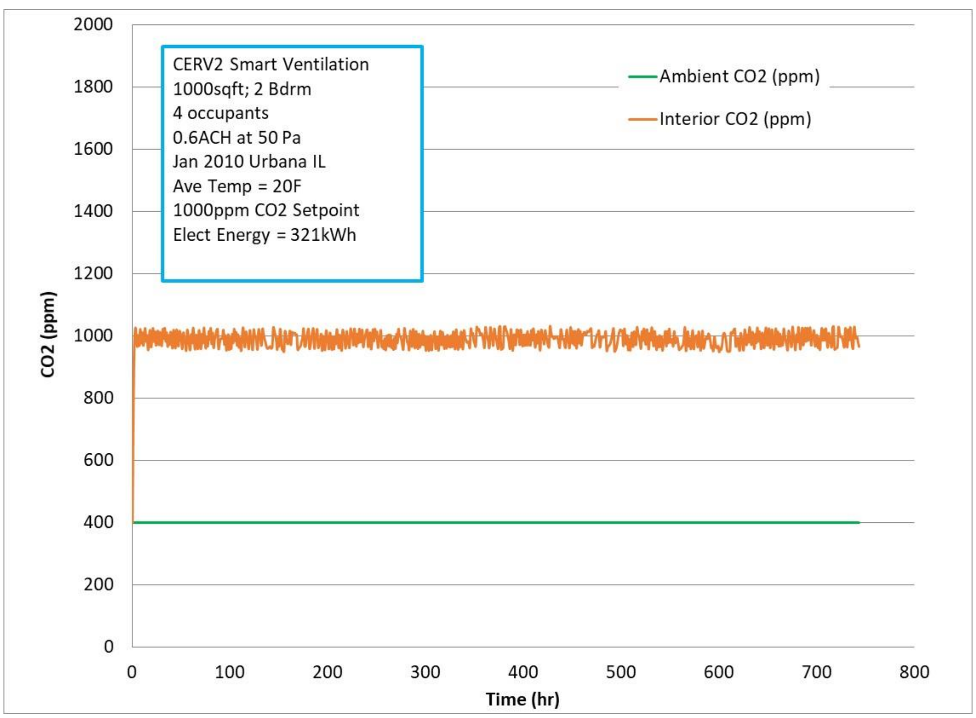

Figure 29 Carbon dioxide concentration in a small house(1000sqft) with an occupancy of 4 and infiltration of 0.6ACH50 for Urbana in January 2010 with CERV2 smart ventilation

Comparison of Constant Flow Ventilation and Smart Ventilation Energy

We discuss details of thermal energy and electrical energy associated with HRV constant flow ventilation and smart ventilation systems for Homes A, B, C, and D in this section. The total electrical energy usages presented in the previous section were significantly lower for smart ventilated homes A, B, and C in comparison to HRV homes. HRV Home D (4 occupants with 2 bedrooms) "saves" energy but has poor air quality in comparison to a smart ventilated home. Home D occupants ultimately pay a higher price from poor health.

Figures 30 and 31 present thermal energy results for HRV homes and smart ventilation homes, respectively. Home A, with 3ACH50, has a significant ventilation contribution due to wind driven infiltration. Figures 30 and 31 show both the HRV and smart ventilated homes have a thermal energy load of nearly 1500kWh for heating infiltration air to room temperature (70F) during the month. The HRV Home A also has a heat load of 1400kWh for thermal energy required to heat ventilation air to room temperature. The HRV recovers 90% of the ventilation energy needs to bring 20F and higher outdoor air temperatures to room temperature (approximately 1200kWh). The HRV is assumed to require frost prevention electrical heating of 155kWh in order to bring outdoor air temperature up to 20F for ambient temperature below 20F. The house heat pump delivers an amount of thermal energy equivalent to the sum of the infiltration and net ventilation energy needs. The last thermal energy term is an amount of heat from the house heat pump that is equivalent to the excess heat delivered by a CERV2 smart ventilation system during the month.

Figure 30 shows significant energy reduction with infiltration improved from 3ACH50 to 0.6ACH50. A home sealed to 3ACH50 is a very well-sealed home relative to homes commonly constructed today and in the past. A "leaky" home with 10ACH50, typical of homes built within the past 10 to 20 years, has 3 times more infiltration energy load (23) than 3ACH50 home, however, the average home size was smaller.

Field tests (24) have indicated that new home infiltration increases by 20% over time, however, more studies should be conducted to determine seasonal as well as aging impacts. HRV homes B and C, which vary only by occupancy (2.5 versus 1.25 occupants) have the same thermal energy loads. HRV Home C has a slightly larger thermal energy term related to the smart home's increased net heat gain due to lowered ventilation energy needs in the smart ventilated home at the lower occupancy.

HRV Home D in Figure 30 has very low thermal energy needs. The smaller home with low infiltration (0.6ACH50) has very low infiltration heating load coupled with low ventilation energy due to insufficient fresh air flow.

Smart ventilated Home A has very low fresh air ventilation thermal energy (Figure 31) because almost all fresh air is supplied by infiltration. The CERV2 primarily operated in recirculation mode, supplying nearly 600kWh of thermal energy while the house heat pump delivered 900kWh. The total of the CERV2 and house heat pump is equivalent to the infiltration heat load. Very little excess CERV2 energy occurs because of Home A's high infiltration heat load.

The CERV2 supplies thermal energy in the highly sealed smart ventilated Home B greater than the sum of infiltration and ventilation air heating energy requirements. A small amount of house heat pump thermal energy is required during some of the extremely cold periods in the January weather. An “excess” of thermal energy (net balance of thermal energy terms) of 200kWh for Home B occurs, which is added to HRV Home B to make the thermal energy balance equivalent.

Smart ventilated Home C is identical to Home B but with reduced occupancy. Because the smart ventilated home senses reduced fresh air ventilation needs, the CERV2 spends more time in recirculation mode, resulting in an increased amount of excess thermal energy production above that needed for heating infiltration and fresh air ventilation.

The smaller, high occupancy smart ventilated Home D needs very little infiltration heat, but high ventilation heat needs. The CERV2’s net heat addition during recirculation and ventilation modes, plus some house heat pump energy added during extreme cold periods has a small amount of excess thermal energy for the month.

Conversion of the thermal energy terms into electrical energy is shown in Figures 32 and 33. In Figure 32, the HRV HP electrical energy is the house heat pump’s electrical energy requirements for supplying heat for the infiltration heating load and the net HRV heat load. The electric heater for HRV frost prevention has a 1:1 conversion of electrical energy to thermal energy. Note that the amount of defrost heat is significant, but not dominant in relation to electrical energy associated with infiltration and ventilation. The excess heat term for the HRV homes for equivalence to the smart home’s heat is converted to electrical energy by using the coefficient of performance (COP) for a 1 ton Mitsubishi Hyper Heat heat pump with the outdoor ambient temperature. The total electric energy is also shown in the legends for Figures 22, 24, 26, and 28.

Figure 33 shows the electric energy terms for the CERV2 ventilation system in Homes A, B, C, and D. The CERV2’s heat pump performance is determined from information in Appendix C for recirculation and fresh air ventilation modes. The house heat pump electric energy assumes a Mitsubishi Hyper Heat performance as used for the HRV ventilated homes. The total electrical energy for each home is the same as the amount shown in Figures 23, 25, 27 and 29.

Both HRV and smart ventilated homes are much more energy efficient than yesterday’s “leaky” homes. Smart ventilated homes have the advantages of ventilating a proper amount that often results in less energy coupled with active air quality management.

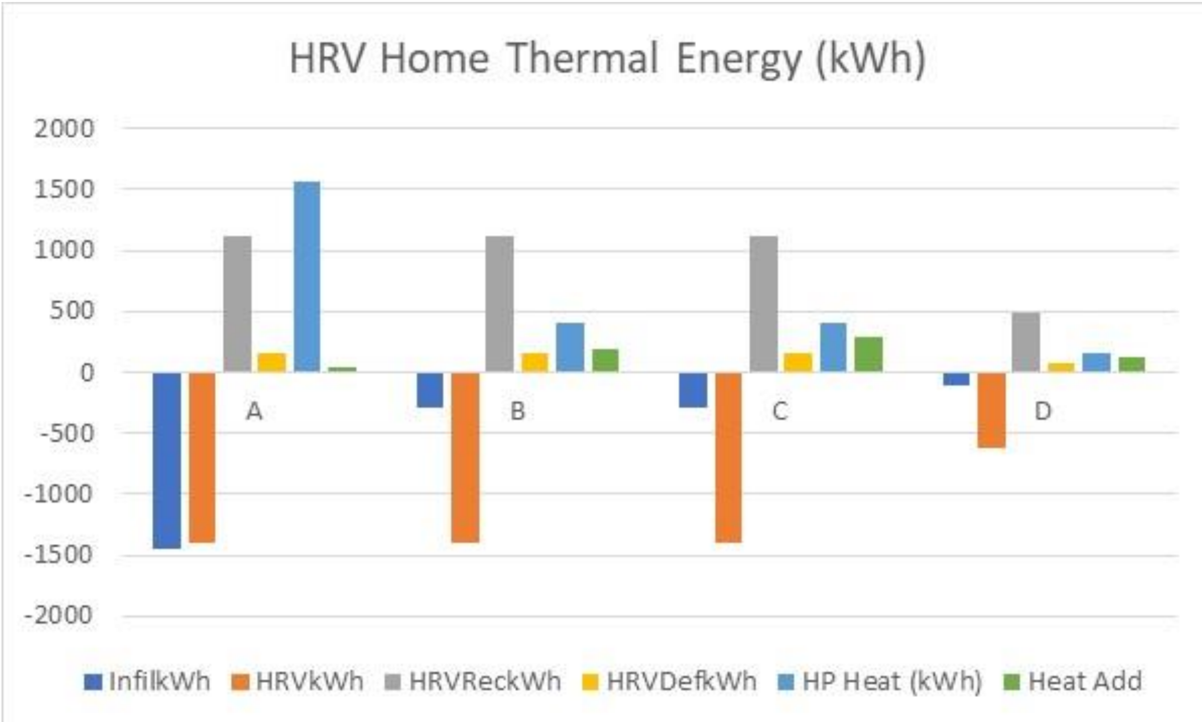

Figure 30 Thermal energy for ventilation in HRV constant air flow homes

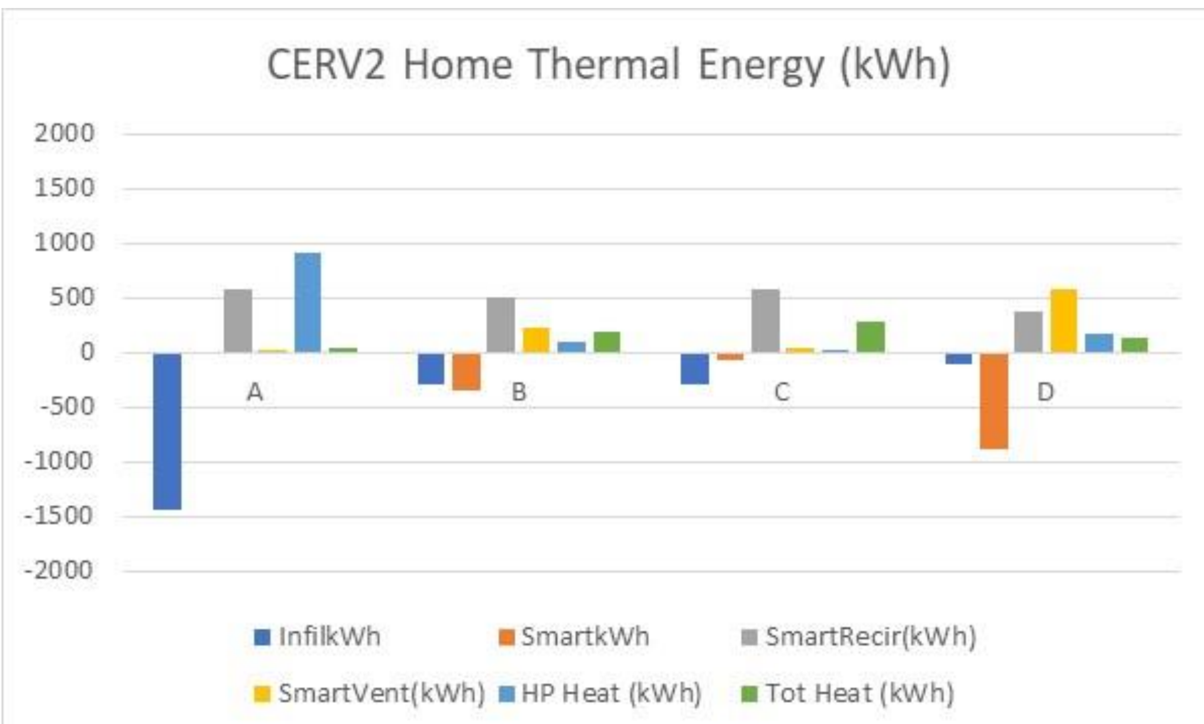

Figure 31 Thermal energy for smart ventilated homes

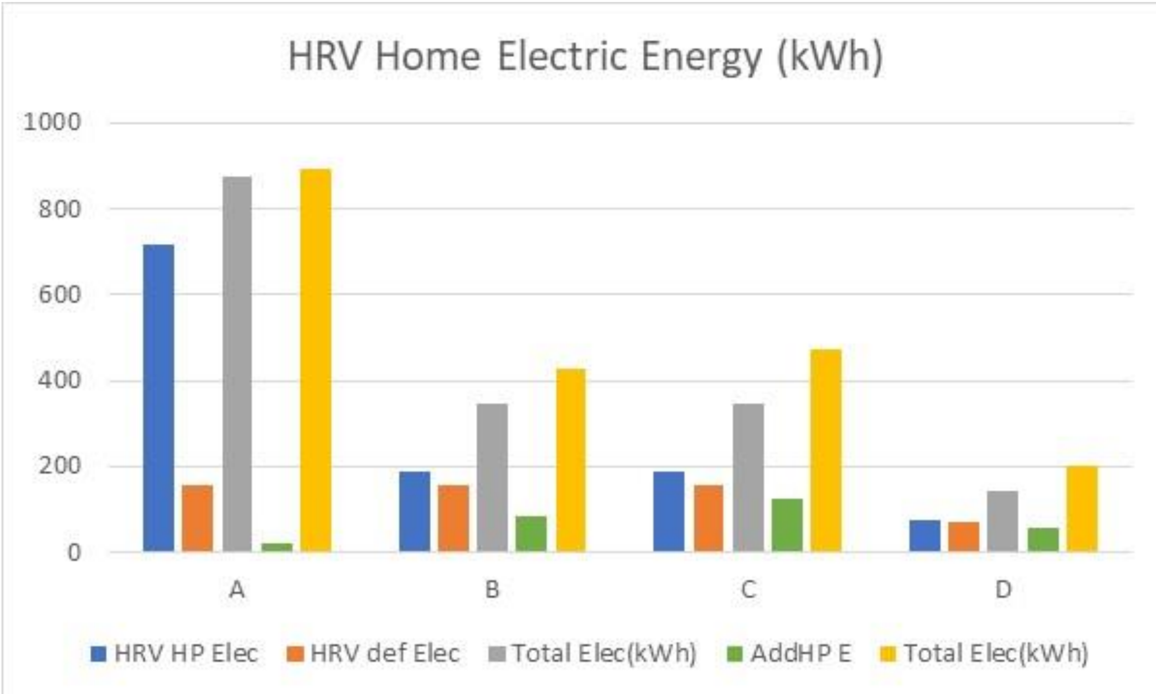

Figure 32 Electrical energy for HRV constant ventilation homes

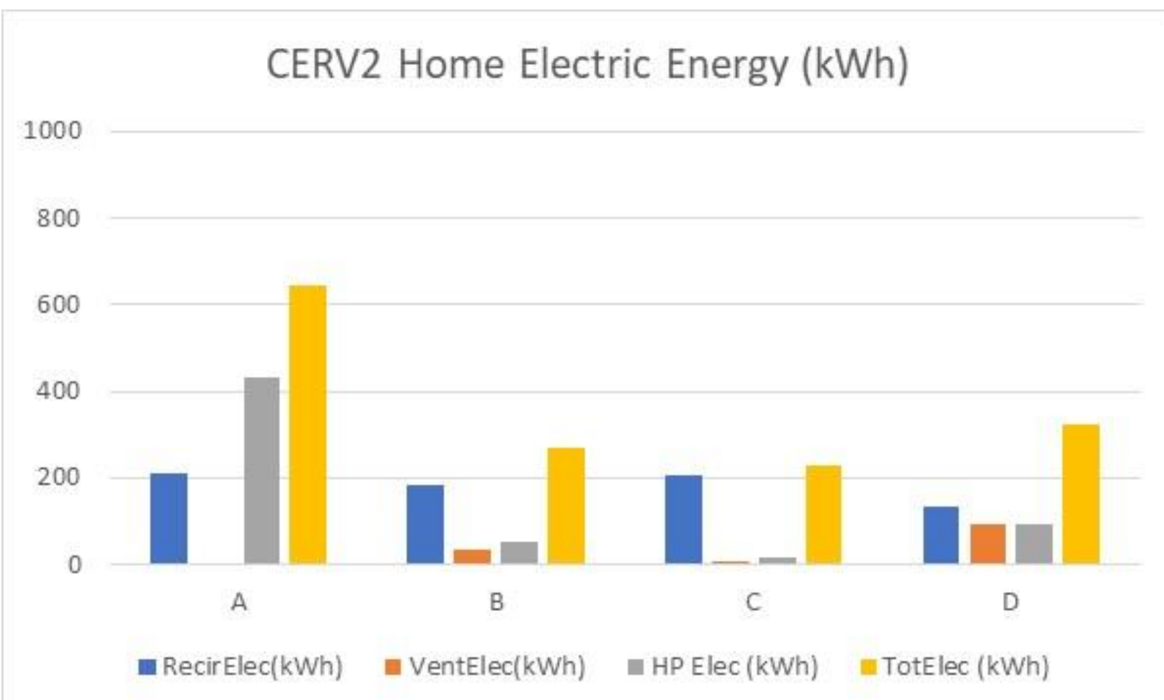

Figure 33 Electrical energy for smart ventilated homes

Summary

We have discussed characteristics of smart ventilation systems in terms of basic indoor air quality (carbon dioxide concentration) and ventilation energy. On average, today's homes ventilated according to commonly accepted building ventilation standards are overventilated, with excess ventilation energy usage. Some homes, such as smaller homes with high occupancy, are underventilated resulting in poor air quality. A smart ventilation system automatically manages air quality needs in an energy efficient manner.

Ventilation energy usage for a well-sealed smart ventilated home varied between 200 and 300kWh per month for homes with 1.25 to 4 occupants during a cold month with an average temperature of 20F, for a daily ventilation related energy usage of 6 to 10kWh per day. Our study of 13 Vermod homes (26) shows an average daily energy usage of 30kWh per day for a Vermod home with an occupancy of 4. A Vermod home with an occupancy of 4 uses 10kWh per day for occupant activities (cooking, lights, television, etc) and 4kWh per day for heat pump water heating (which adds similar amount of electric energy for adding heat to the home for the water heater's cooling effect). Ventilation comfort conditioning (heat pump) electric energy for a Vermod home with CERV smart ventilation is approximately 16kWh per day, for a total of 30kWh per day during a cold month.

Figure 34, showing daily energy usage for 13 identical, high performance Vermod homes, indicates the broad range of electrical energy usage. At an outdoor temperature of 20F, the average Vermod home electrical energy usage is 25 to 30kWh per day based on ZEROs energy simulation results. In reality, the homes vary from 15 to 70kWh, indicating the significant impact of a home's occupants and their behaviors in a high performance home. Even so, the average performance of Vermod homes is 20% lower than the most stringent of home energy performance criteria (PHIUS and PHI).

Figure 34 also includes average daily energy usage from 5 "conventional", modern (built since 2000), all electric homes located in Urbana Illinois. The conventional homes are ventilated by infiltration, with characteristics similar to the leaky home shown in Figure 14 with a daily infiltration energy load of 70kWh per day, or double the total load of the average Vermod home total electrical energy usage! The total daily electrical energy usage for the conventional homes with an outside temperature of 20F ranges between 120 and 180kWh per day!

As we make energy performance comparisons in high performance homes, it is important to keep in mind how conventionally constructed homes perform. Although smart ventilated homes are often more energy efficient than constant flow ventilation systems, the energy differences are small in relation to most homes being built today. The choice between smart ventilation and constant flow ventilation is not one based on energy, but rather the ability to automatically maintain a healthy indoor air environment as its occupancy and occupant activities change. Health related benefits of smart ventilation homes significantly exceed energy cost differences between smart ventilation and not-so-smart ventilated homes.

We examined gross differences in indoor air quality and energy usage between smart ventilated homes and constant ventilation system homes in this report. Equally important is the distribution of fresh air within a home. If fresh air does not benefit a home's occupants, it is a waste. Our second report focuses on effective distribution of ventilation air.

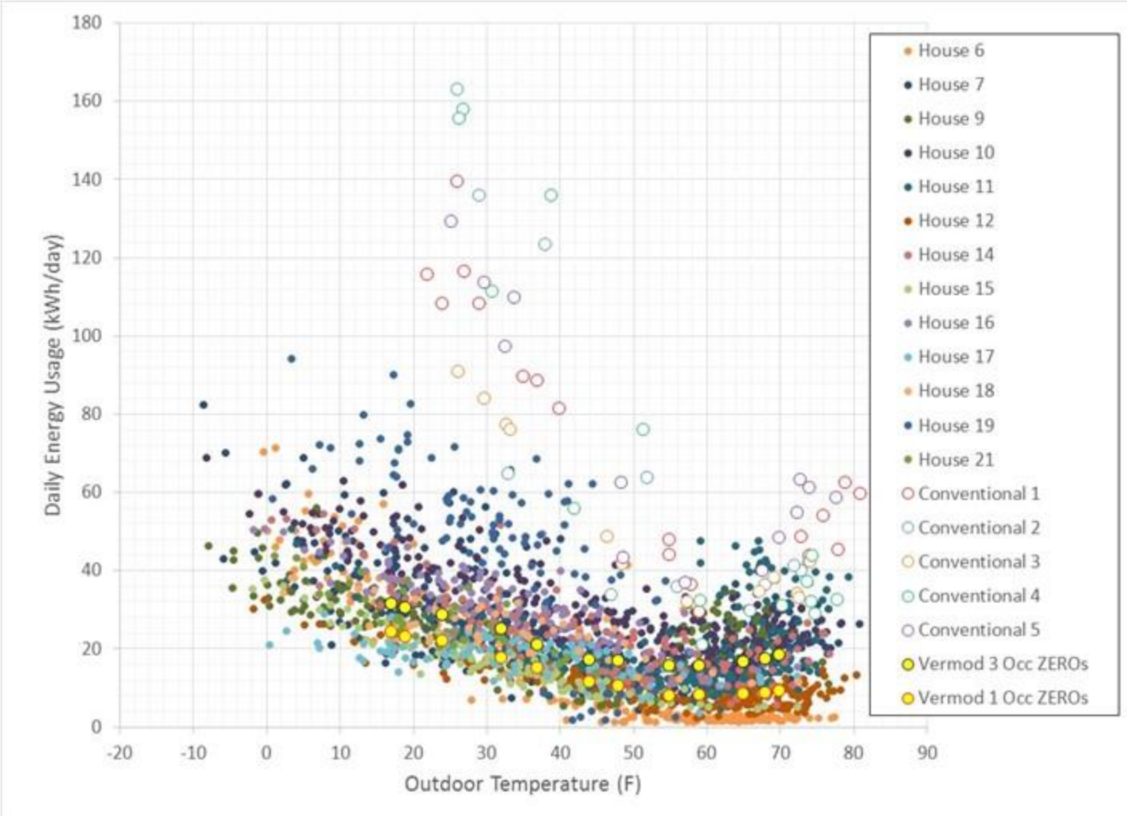

Figure 34 Daily energy usage for 13 "identical" Vermod high performance homes with CERV smart ventilation systems

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Appendix A – Human Pollutant Generation

We define the "effective" carbon dioxide concentration as a combination of the average human (female and male) carbon dioxide output combined with human expelled VOCs. Figures below provide a description of female and male carbon dioxide output based on body mass and metabolic activity.

In addition to human carbon dioxide output, we offgas various chemical compounds in our respiration and exuded through our skin. At a high enough concentration level, human VOCs become offensive odors. The 20cfm per person ventilation rule-of-thumb was developed in the 1930's by Harvard researchers who found that a recently showered human wearing clean clothing and performing office work level activity (sedentary) offended 20% of the general population.

A human subject was placed in a sealed room with a control flow of fresh air through the room. Experiment participants were recruited who smelled the air exhausted from the room. Only recently have we learned that carbon dioxide at these ventilation levels (~1000ppm) impair cognition. We have known that VOCs, such as emitted by offgassing from furnishings (carpeting, paints, polymers of various sorts), cleansers, adhesives, cosmetics, and many other sources also impair cognition and productivity as well as detrimentally impacting on our health.

A 30 to 40 year old female weighing 165 pounds (74.5kg) at sedentary conditions (1.2 Met) produces 0.0035liters per second of carbon dioxide. A 30 to 40 year old male weighing 191 pounds (87kg) at sedentary conditions produces 0.0046liters per second, or 0.0046liters per second of carbon dioxide. The average female and male carbon dioxide output is 0.00405liters per second, or 0.0275kg/hour.

We do not know the specific impact of differ VOCs, as well as the combined effects of carbon dioxide and VOCs on our health and cognition, but we do know both affect us and the combination of both affect us. In order to account for an "average" VOC impact, we assume a unit of human VOC output correlated to human carbon dioxide output as an additional effect to the pollution loading affecting building occupants. That is, an average human (female and male average) at sedentary conditions outputs a VOC loading equivalent to 0.0275kg/hour of carbon dioxide.

We assume the combination of carbon dioxide and VOC loading to be a vector addition rather than a direct sum, although we have no basis at this time for a rational method for combining the effects. Future research on carbon dioxide combined with common VOCs will help guide the best method for determining how health is impaired and cognition degraded. Based on a vector addition of effects, we find an effective average human carbon dioxide production rate of:

$$\text{Carbon dioxide generation (kg/hour)} = (0.0275^2 + 0.0275^2)^{1/2} = 0.04\text{kg/hour}$$

The analyses conducted in this report use a reference average human carbon dioxide generation rate of 0.04kg/hour. Note that very small increases in metabolic activity (walking, cooking, etc) will result in human carbon dioxide outputs exceeding this assumed value. In fact, a human's carbon dioxide output can vary by almost a factor of 10 from sleep to vigorous exercise. Therefore, the air quality in a home with 4 sedentary occupants can be the same as a home with one very active occupant.

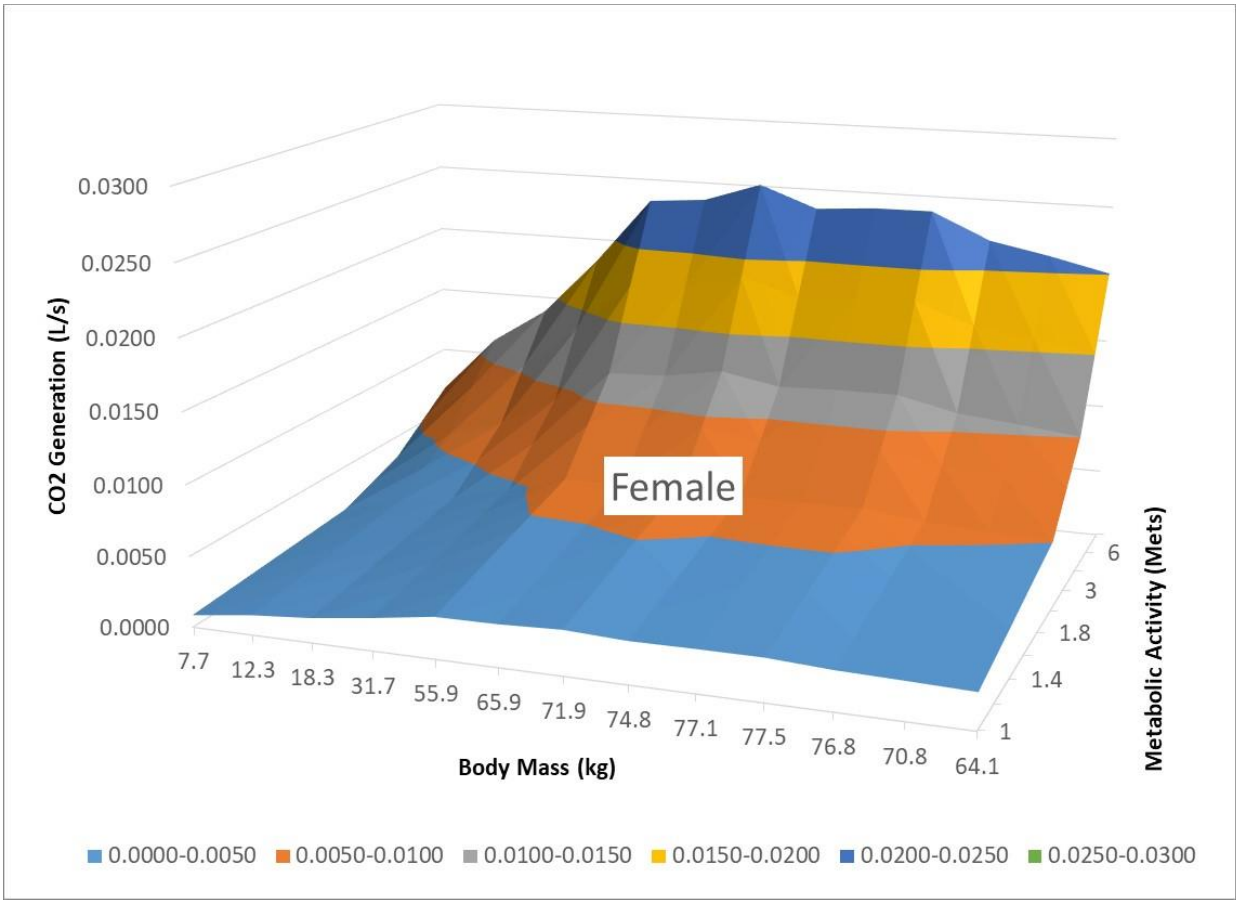


Figure 35 Female carbon dioxide output based on body mass and metabolic activity.

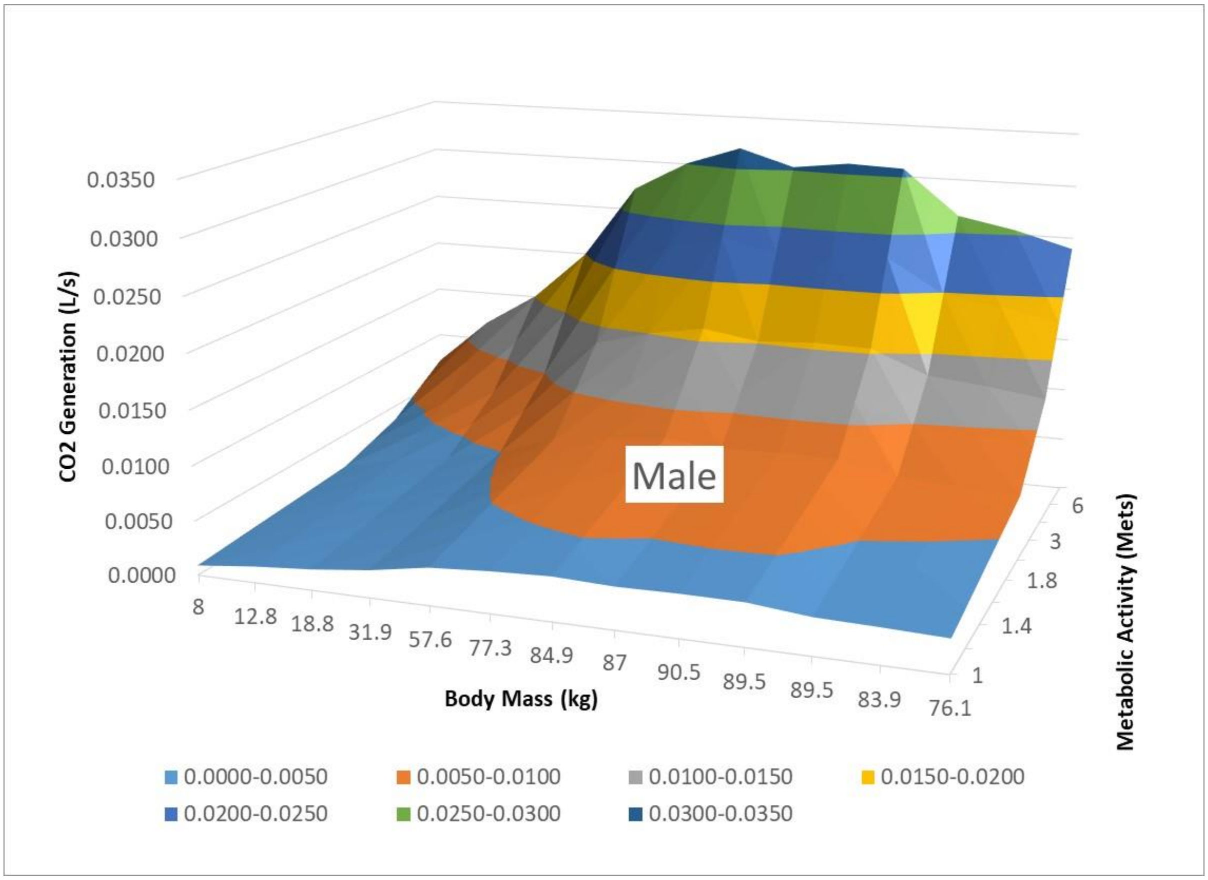


Figure 36 Male carbon dioxide output based on body mass and metabolic activity.

Appendix B – Build Equinox Air Quality Metrics

Fractional time models have been developed from a series of buildings (18 homes, a public library and a business). Data was collected at 1 to 5 minute intervals over a period of a few days to two weeks. Fifty data sets were binned into <1000ppm, 1000 to 2000ppm, and greater than 2000ppm levels for carbon dioxide and total VOCs (using equivalent carbon dioxide units in which 1000ppm total VOC is the VOC sensor output when human respiration results in 1000ppm carbon dioxide concentration. Carbon dioxide time fraction models plotted on Figure Bx are:

Average CO2<1000ppm	%Time = 100*(1-exp(-(cfm-12)/10)) for airflow >=12 cfm/person
1000ppm<Ave CO2<2000ppm	%Time = 100% - %Time(<1000ppm) - %Time(>2000ppm)
Average CO2>2000ppm	%Time = 100*(exp(-cfm/8)^2)

Total VOCs do not correlate into time fractions as well as carbon dioxide, as shown in Figure Bx2. Carbon dioxide is relatively unreactive and non-absorptive into house furnishing materials. Therefore, as carbon dioxide is released, dilution is the only path for its reduction. VOCs, unlike carbon dioxide, have multiple ways to be generated, reacted, absorbed, desorbed, and reformulated. The data is much more scattered with a shift to higher airflows, indicating the additional ways in which some homes evolve total VOCs beyond those generated by the occupants' metabolism.

The time fraction plots provide a conceptual framework for understanding how air flow rates shift one from a relatively healthy environment (<1000ppm) to an unhealthy environment (>2000ppm). In addition, the time fractions can be used to estimate accumulated pollutant exposure. For example, with an airflow of 20cfm per person, approximately half of the time is spent in healthy (<1000ppm) and the other half in transition (>1000ppm and <2000ppm). We do not know if the accumulated time average is made of 999ppm and 1001ppm versus 500ppm and 1500ppm concentrations, for example, but we can determine the range of accumulated pollutant exposure with this information and the air quality metrics previously discussed.

If the actual binned data consisted of 999ppm and 1001ppm levels (essentially, no deviation from 1000ppm), the occupants would be exposed to 24 carbon dioxide pollutant hours per day, which is the Build Equinox's upper recommended limit for indoor pollutant exposure. If one assumes that the equivalent total VOC loading is similar to carbon dioxide loading (but could be much greater depending on occupant behavior and building furnishings), then a total pollutant exposure of 34 pollutant hours per day (vector sum of 24 CO_2 pollutant hours per day plus 24 tVOC pollutant hours per day).

Assuming the binned data consisted largely of indoor air at 500ppm and 1500ppm (perhaps the occupants are outside the home for 12 hours per day), the carbon dioxide pollutant hours per day to be 18 carbon dioxide pollutant hours per day (1.5 pollutant units times 12 hours plus 0 pollutant units times 12 hours). Including total VOCs with the same distribution level, we find 25 total pollutant hours per day. Therefore, the estimated range of accumulated pollutant exposure is estimated to be 25 to 34 total pollutant hours per day. Note that ASHRAE 62.2 2016 ventilation tables result in accumulated daily pollutant hours between 24 and 72.

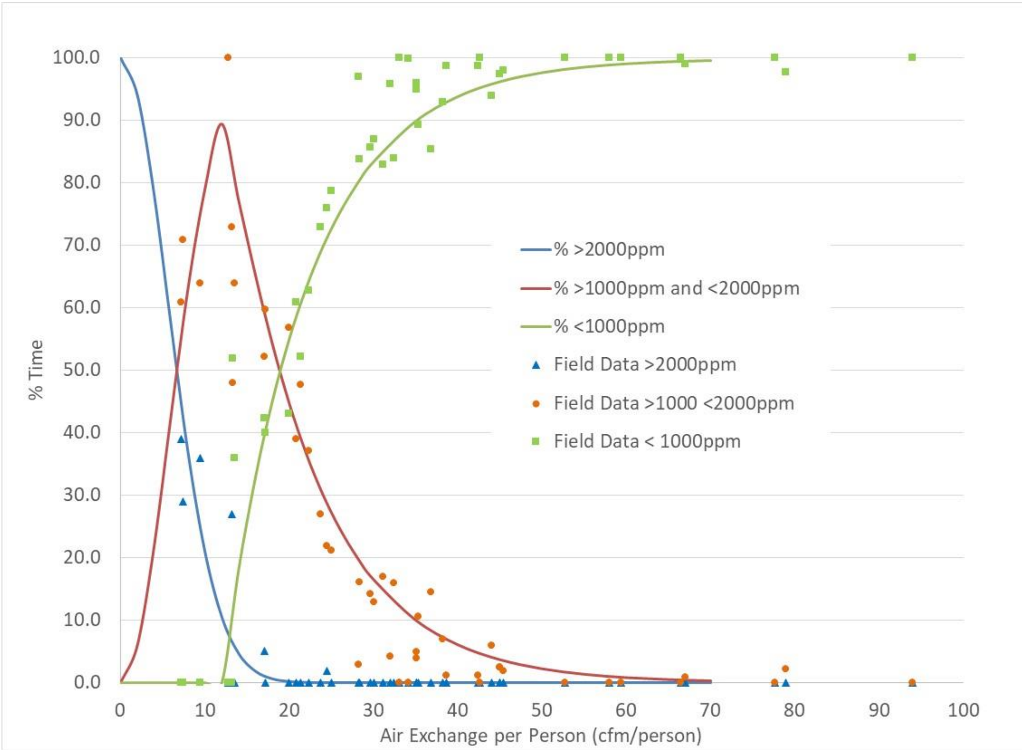


Figure Bx Variation of fraction of time spent in carbon dioxide concentration levels less than 1000ppm, between 1000ppm and 2000ppm, and greater than 2000ppm.

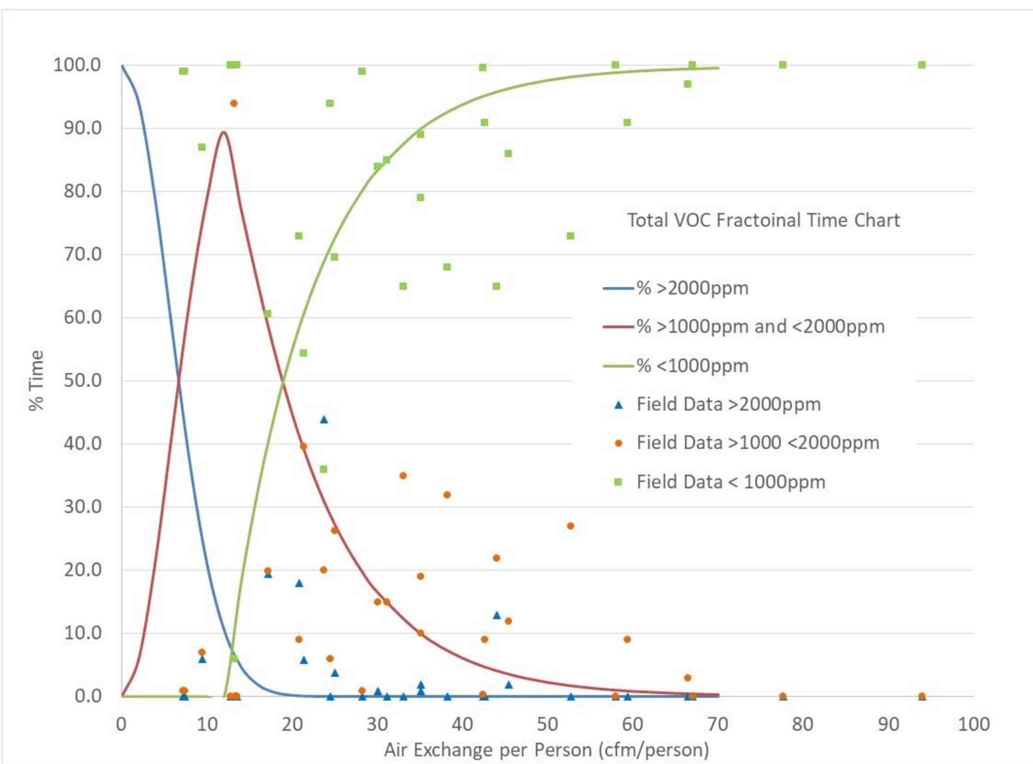


Figure Bx2 Variation of fraction of time spent in total VOC concentration levels, based on equivalent carbon dioxide unit, less than 1000ppm, between 1000ppm and 2000ppm, and greater than 2000ppm.

Appendix C CERV2 Heating Performance

The following figures describe CERV2 heating characteristics during recirculation heating and ventilation (fresh air) heating mode periods. The plots unify the recirculation and ventilation (fresh air) operations by plotting as a function of air stream temperature difference between the air entering the evaporator (cooling coil) and air entering the condenser (heating coil).

1) During ventilation (fresh air) heating, the temperature difference is positive as indoor air enters the evaporator for cooling and exhaust, and outdoor air enters the condenser for heating
2) During recirculation heating, the temperature difference is negative as outdoor air enters the evaporator for cooling and indoor air enters the condenser for heating

Under normal conditions, the CERV2 operates in recirculation heating with periodic switching into ventilation mode as dictated automatically by the CERV2's IAQ (CO_2 and total VOCs). For example, with an outdoor temperature of 32F, and indoor temperature of 72F, and 75% recirculation/25% ventilation modes, the CERV2 would be operating at temperature differences of -40F (recirculation) for 75% of the time and +40F (ventilation) for 25% of the time. The following charts allow the CERV2's integrated heating and power usage to be determined.

List of CERV2 Figures

Figure 1 Base Heat output

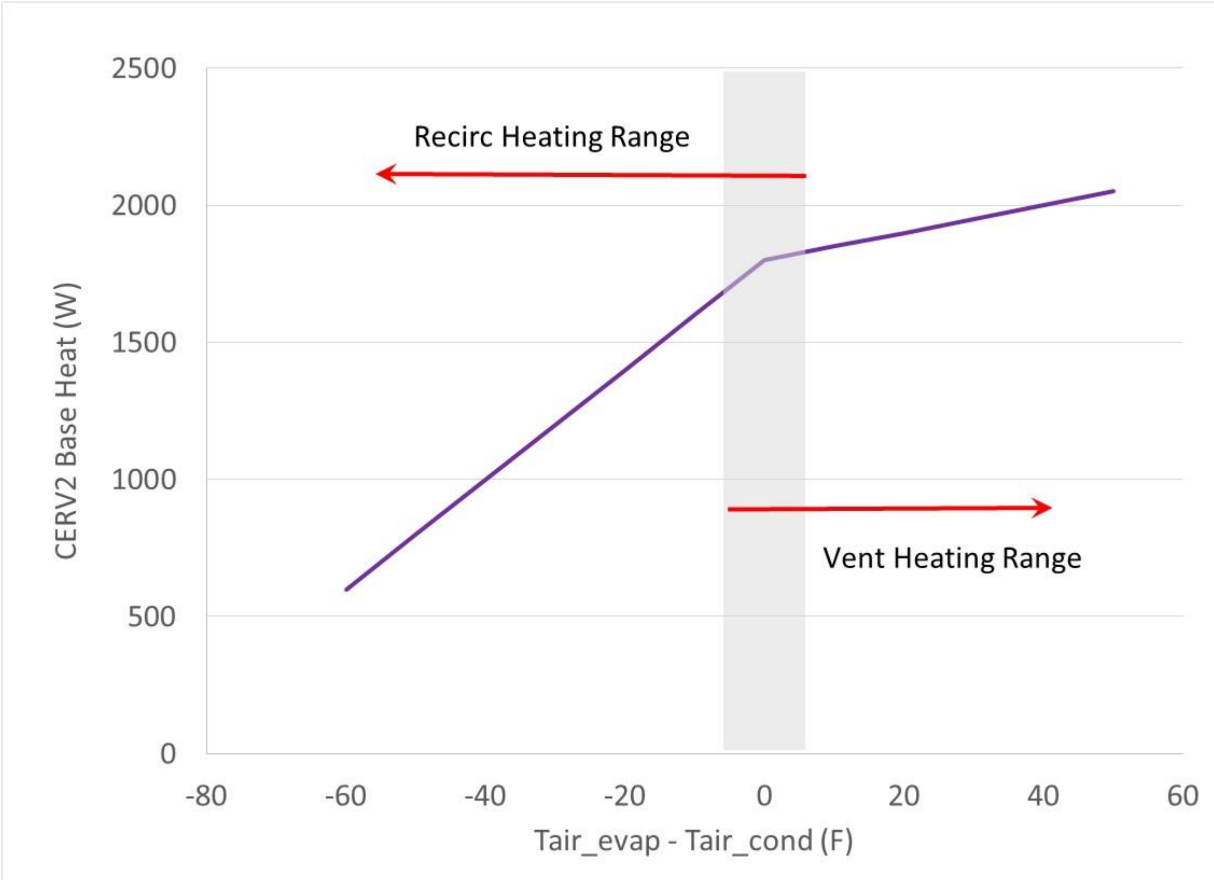


Figure 2 Total Heat output (includes power of the indoor fan with Base Heat)

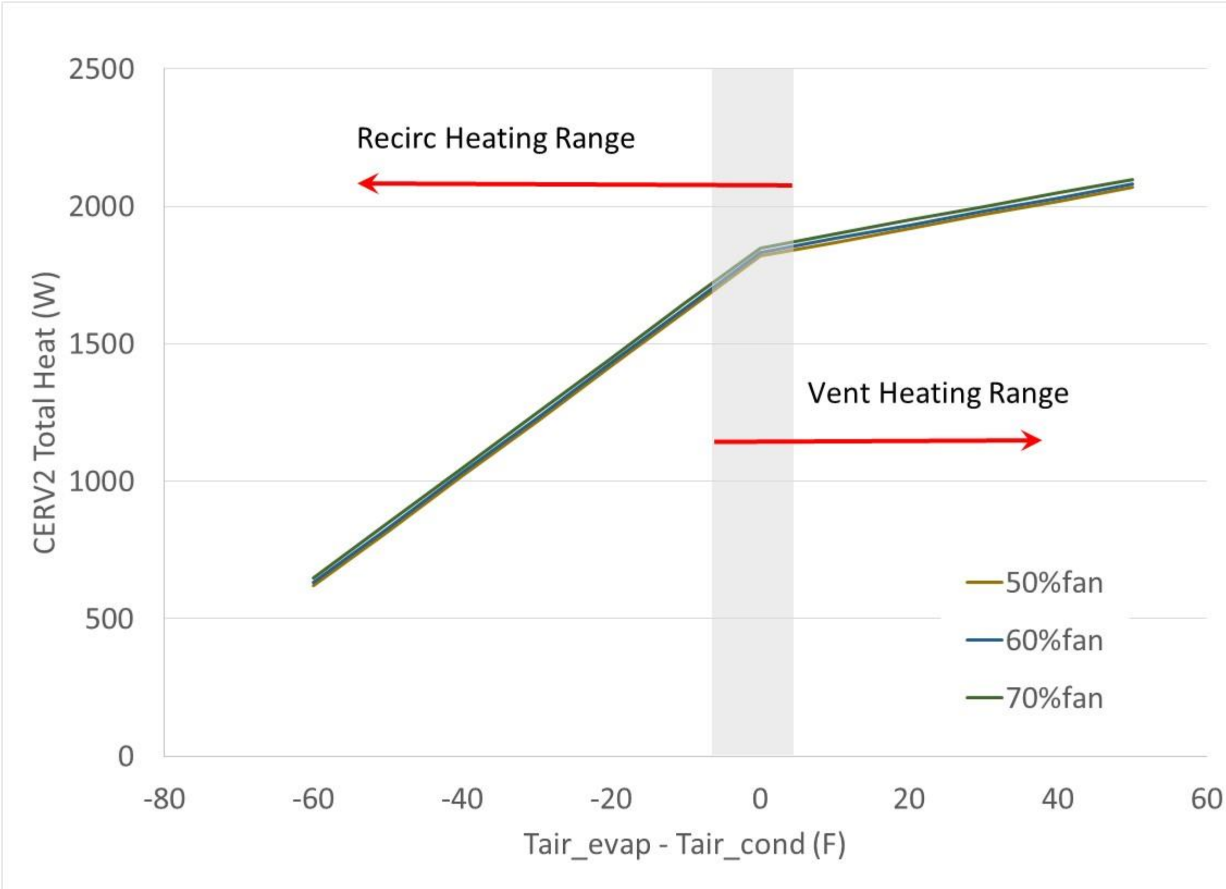


Figure 3 Compressor and controls power

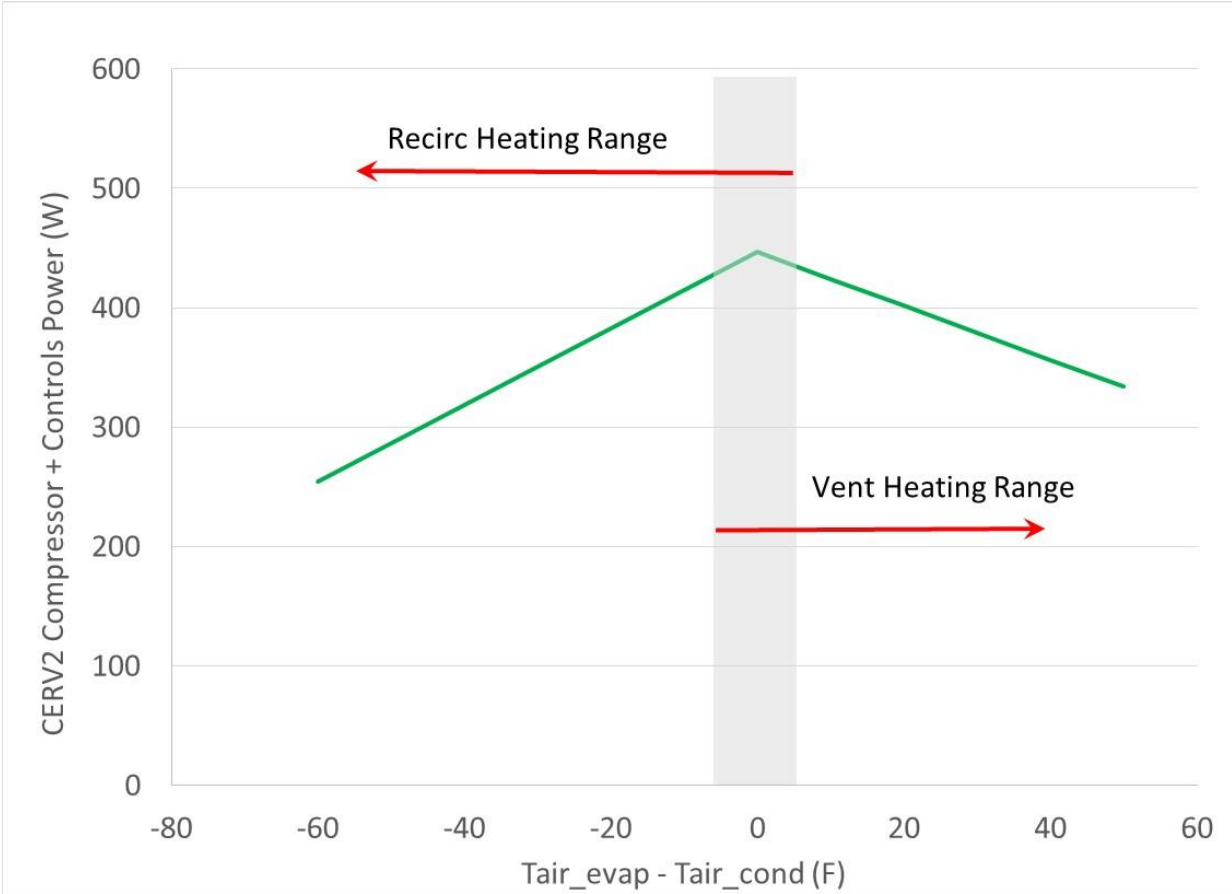


Figure 4 Total CERV2 power (compressor + controls + 2 fans)

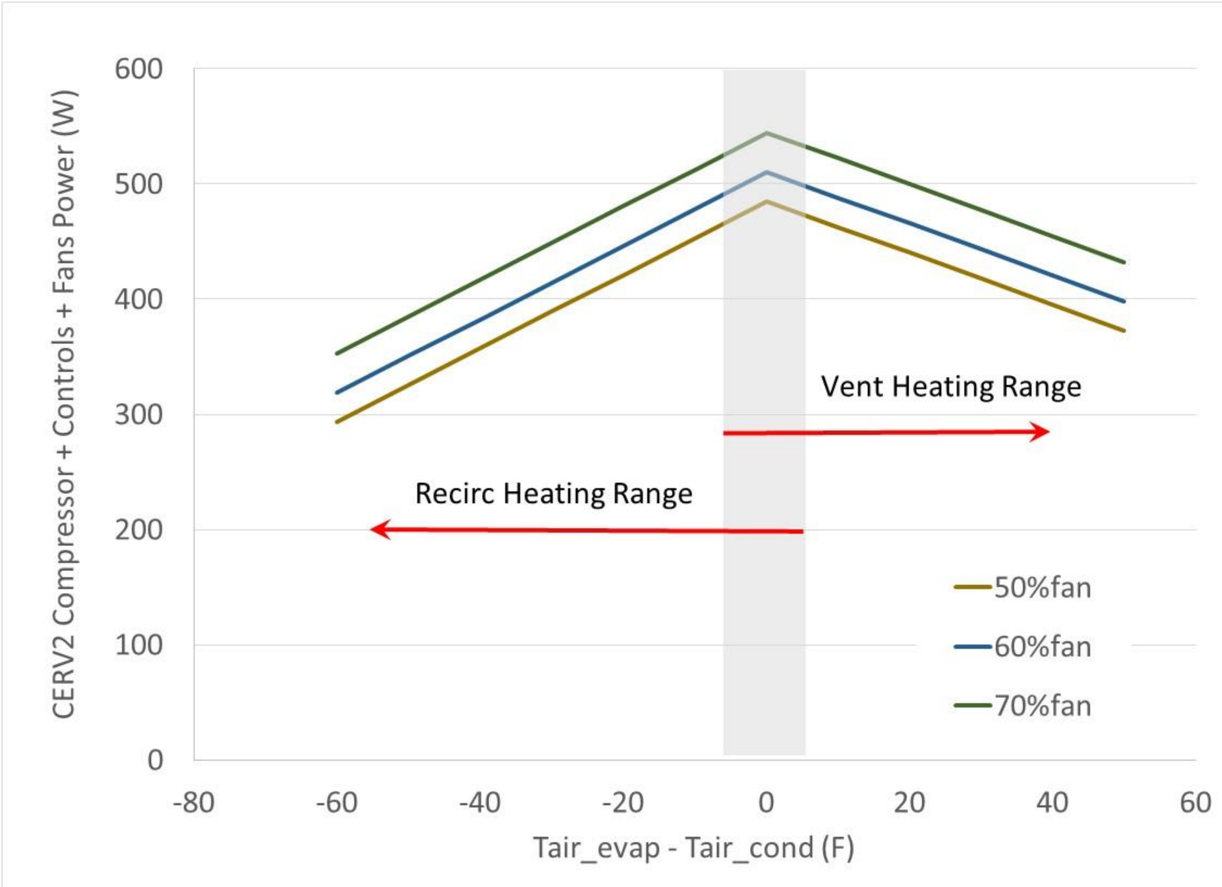


Figure 5 Base COP (coefficient of performance, Base Heat Output/Compressor + Controls Power)

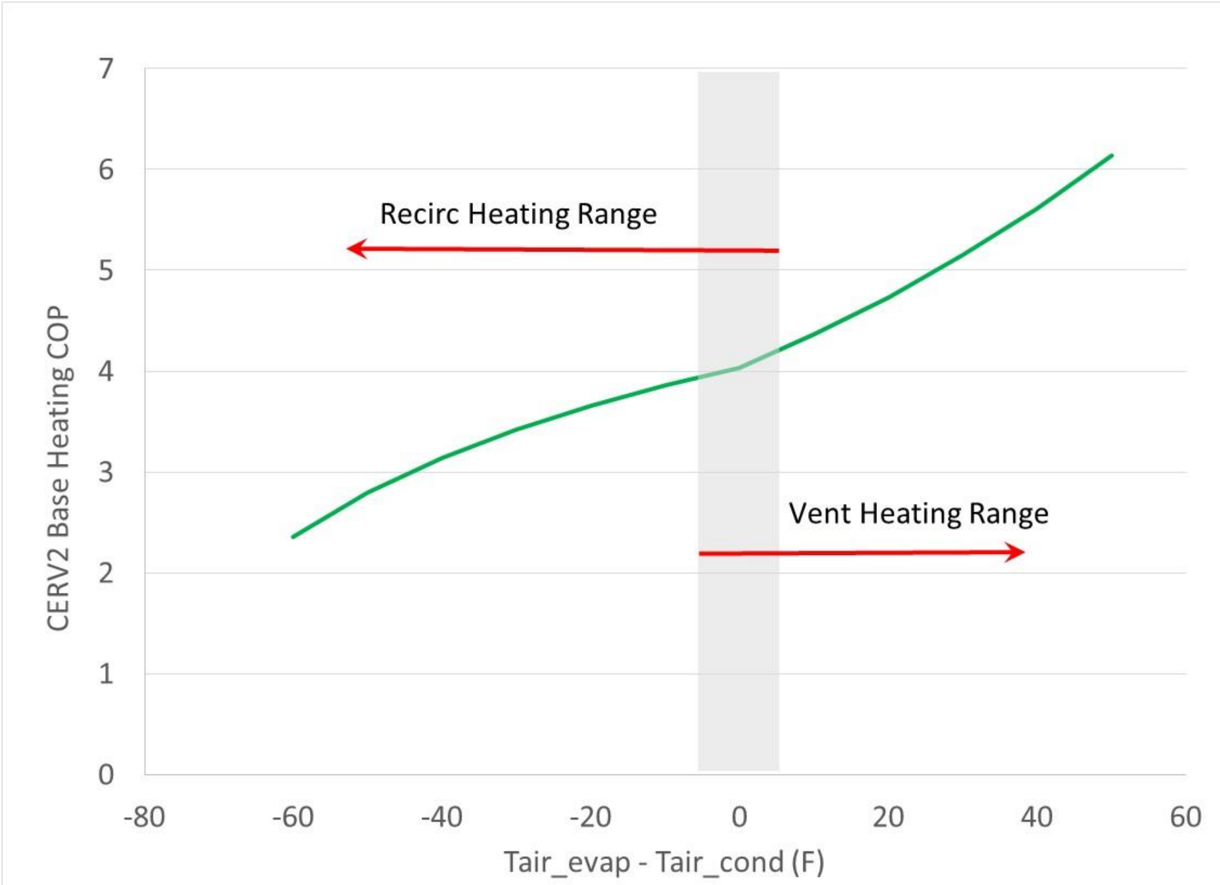
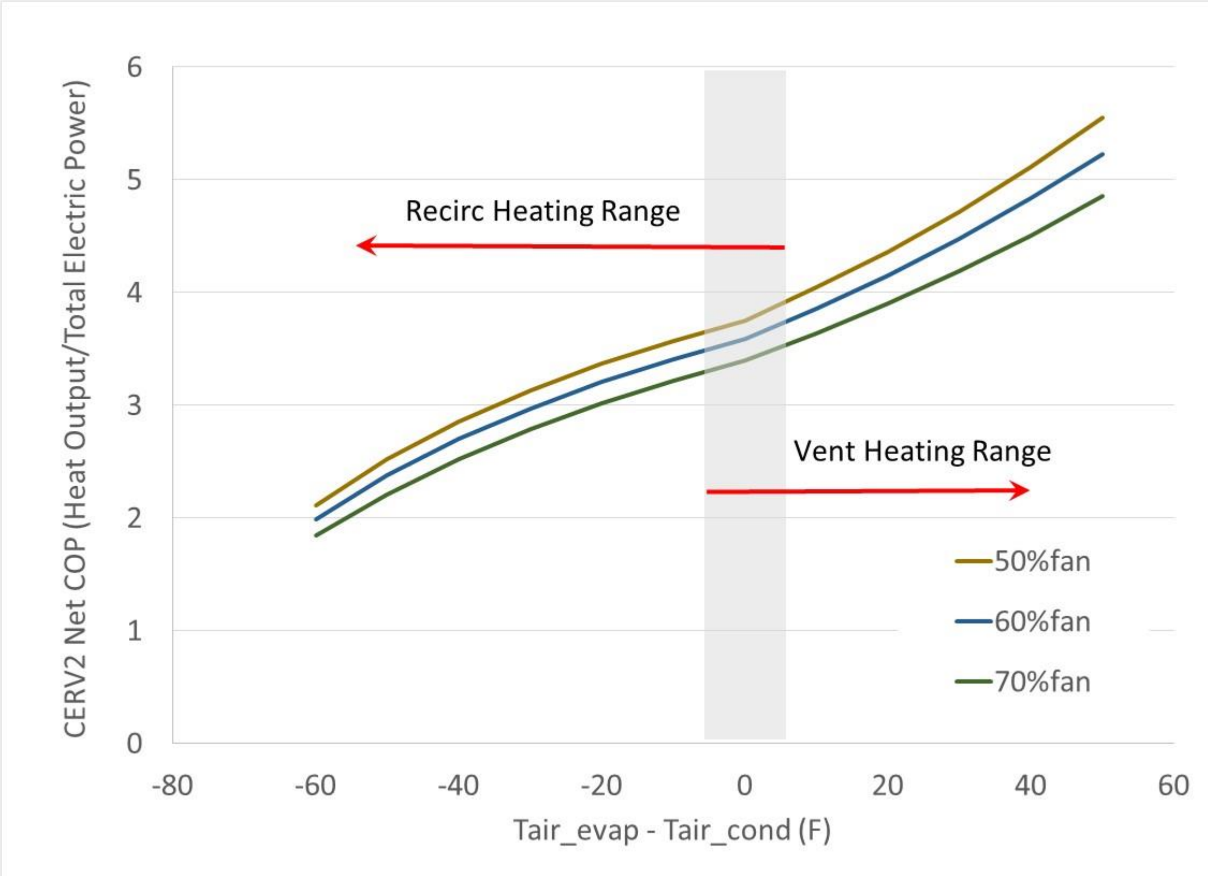


Figure 6 Net COP (coefficient of performance, Total Heat Output/Compressor + Controls + 2Fans Power)



Appendix D CERV2 Cooling Characteristics

The following figures describe CERV2 cooling characteristics during recirculation cooling and ventilation (fresh air) cooling mode periods. The plots unify the recirculation and ventilation (fresh air) operations by plotting as a function of air stream temperature difference between the air entering the evaporator (cooling coil) and air entering the condenser (heating coil).

3) During ventilation (fresh air) cooling, the temperature difference is positive as indoor air enters the condenser for heating and exhaust, and outdoor air enters the evaporator for cooling
4) During recirculation cooling, the temperature difference is negative as indoor air enters the evaporator for cooling and outdoor air enters the condenser for heating

Under normal conditions during warm weather, the CERV2 operates in recirculation cooling with periodic switching into ventilation mode as dictated automatically by the CERV2's IAQ (CO_2 and total VOCs). For example, with an outdoor temperature of 92F, and indoor temperature of 72F, and 75% recirculation/25% ventilation modes, the CERV2 would be operating at temperature differences of -20F (recirculation) for 75% of the time and +20F (ventilation) for 25% of the time.

The CERV2's latent conditioning capacity is related to the humidity ratio of the air entering evaporator. Dehumidification up to 20 liters per day (500-600W latent cooling) are achieved as humidity ratios exceed 0.02kg_{water}/kg_{air}. For example, at 92F and 60%RH (humidity ratio of 0. 02kg_{water}/kg_{air} with an indoor temperature of 72F, during ventilation cooling, the CERV2 would provide 1600W total cooling with 520W latent and 1080W sensible. 18Liters per day of moisture would be removed from the outdoor air stream under these conditions.

The following charts allow the CERV2's integrated cooling, dehumidification, and power usage to be determined.

List of CERV2 Figures

8) Figure 1 Base Cool output
9) Figure 2 Total Cool output (reduces cooling output due to fan power)
10) Figure 3 Latent Cooling Capacity
11) Figure 4 Dehumidification Capacity
12) Figure 5 Compressor and controls power
13) Figure 6 Total CERV2 power (compressor + controls + 2 fans)
14) Figure 7 Base COP (coefficient of performance, Base Cooling Output/Compressor + Controls Power)
15) Figure 8 Net COP (coefficient of performance, Cooling Output/Compressor + Controls + 2Fans Power)

Figure 1 Base Cool output

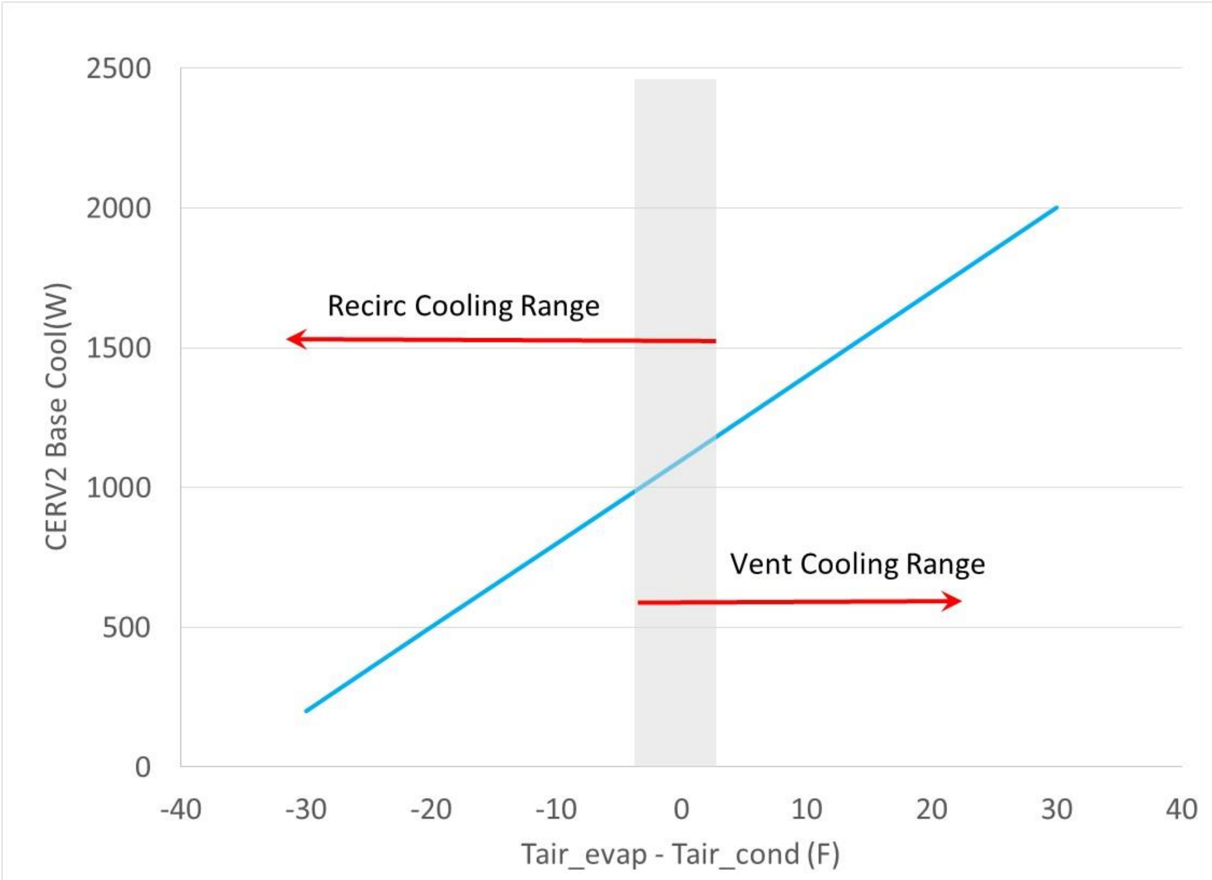


Figure 2 Total Cool output (reduces cooling output due to fan power)

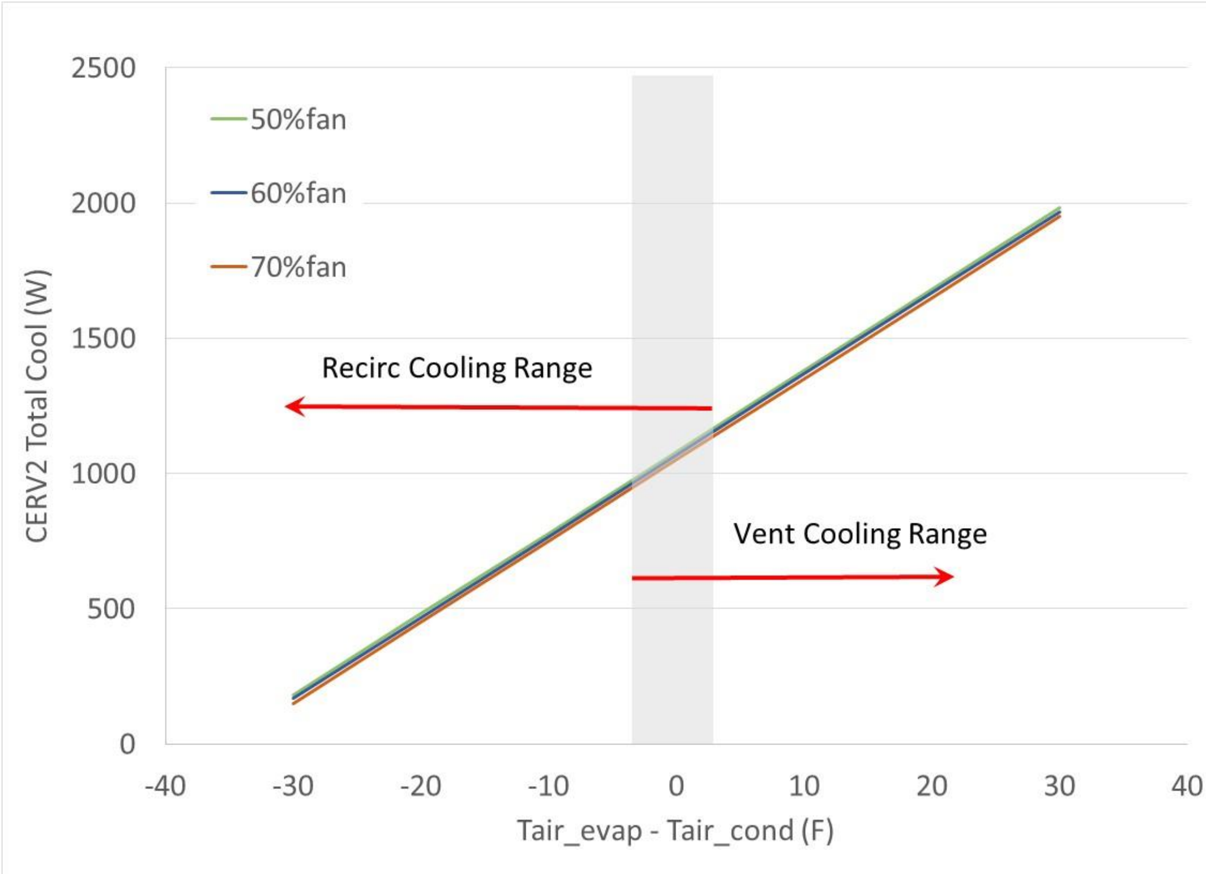


Figure 3 Latent Cooling Capacity

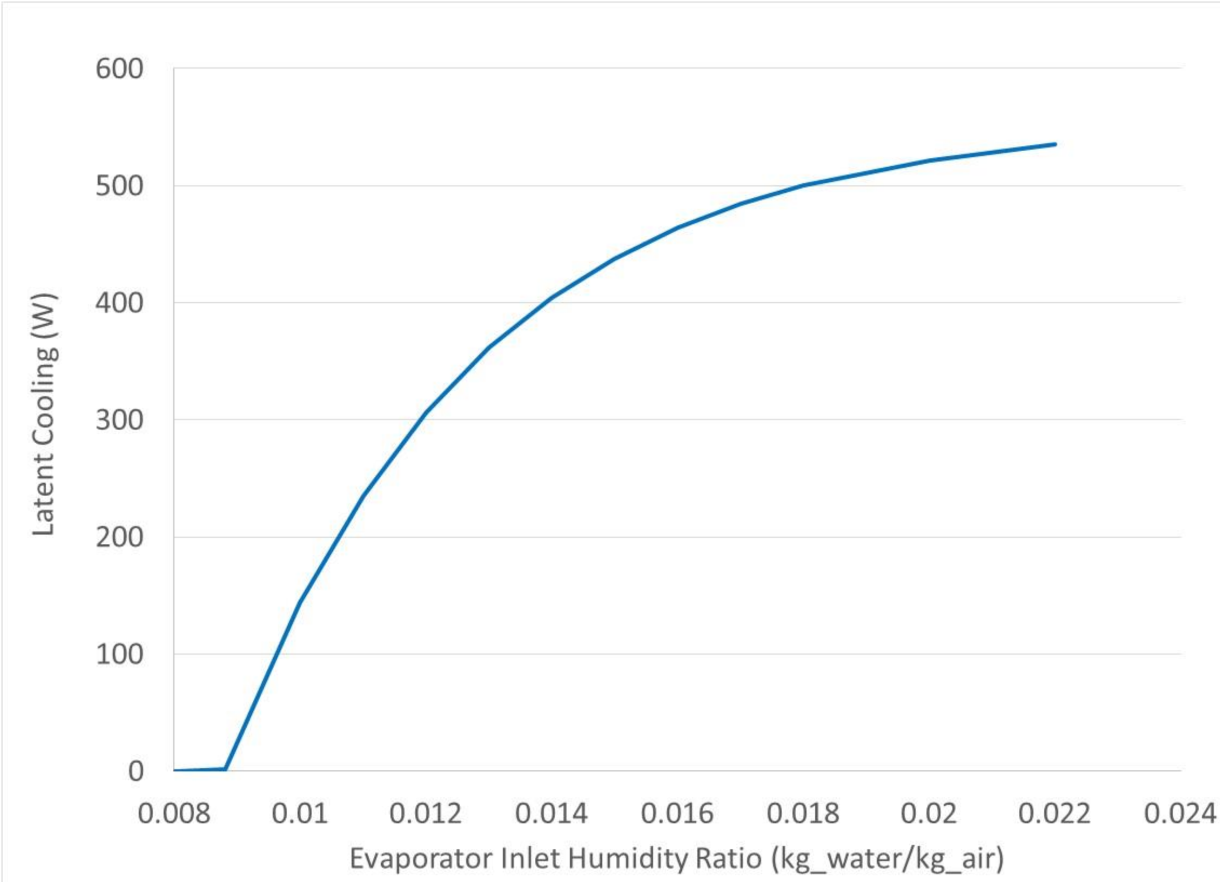


Figure 4 Dehumidification Capacity

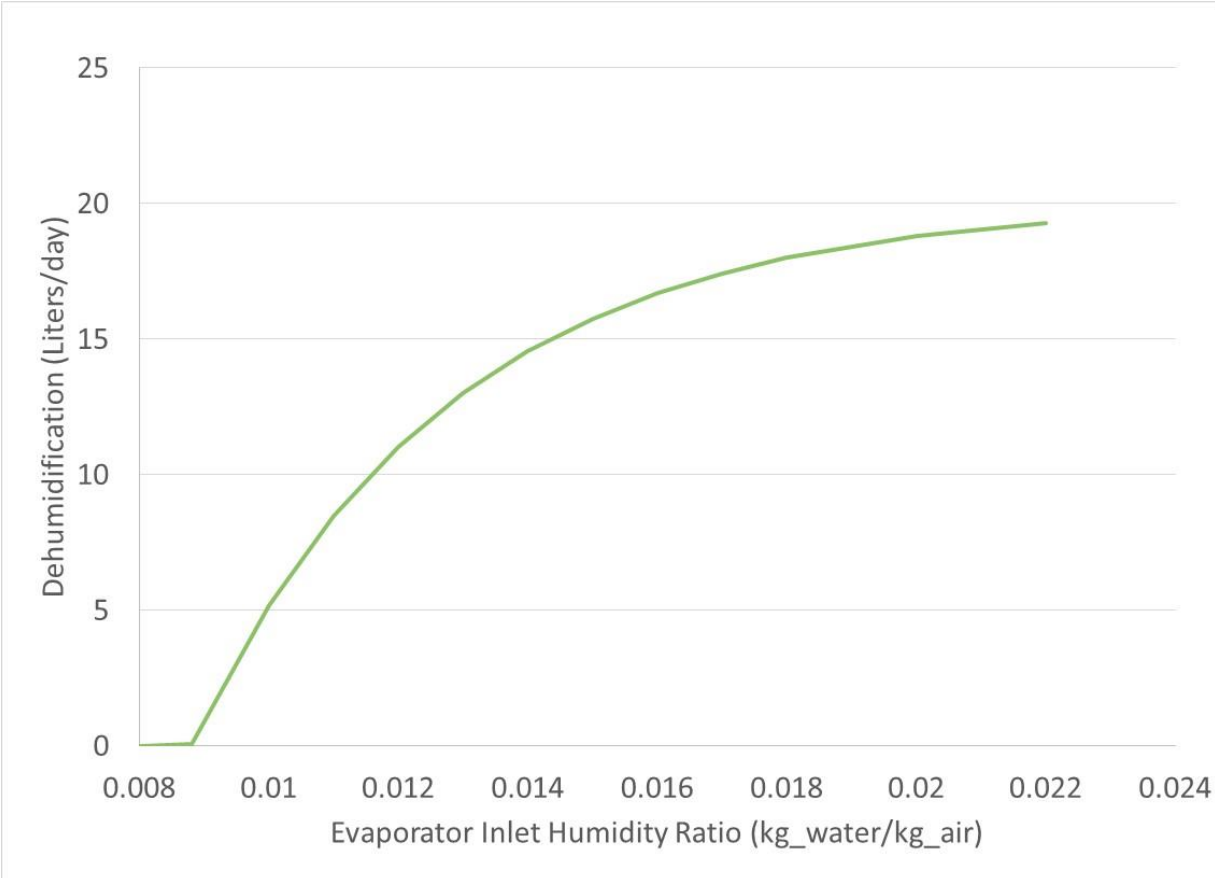


Figure 5 Compressor and controls power

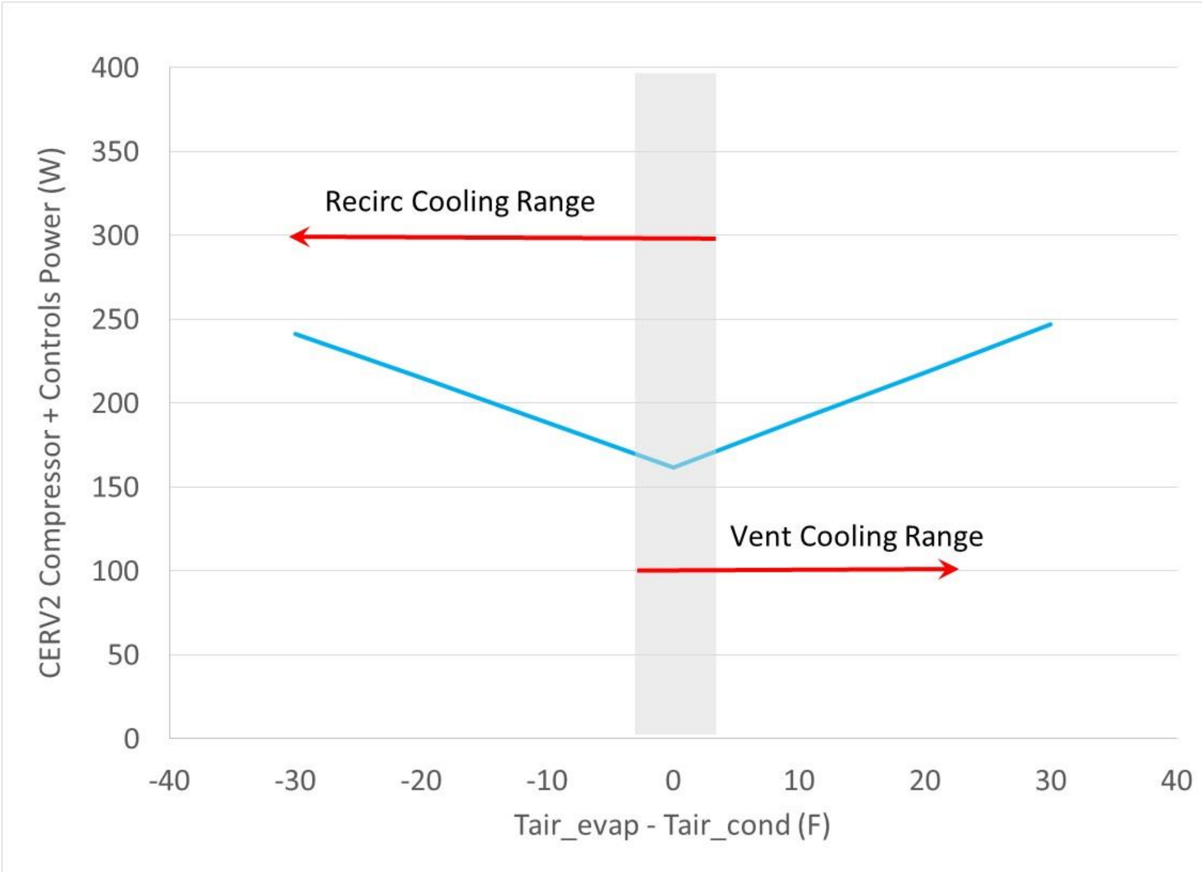


Figure 6 Total CERV2 power (compressor + controls + 2 fans)

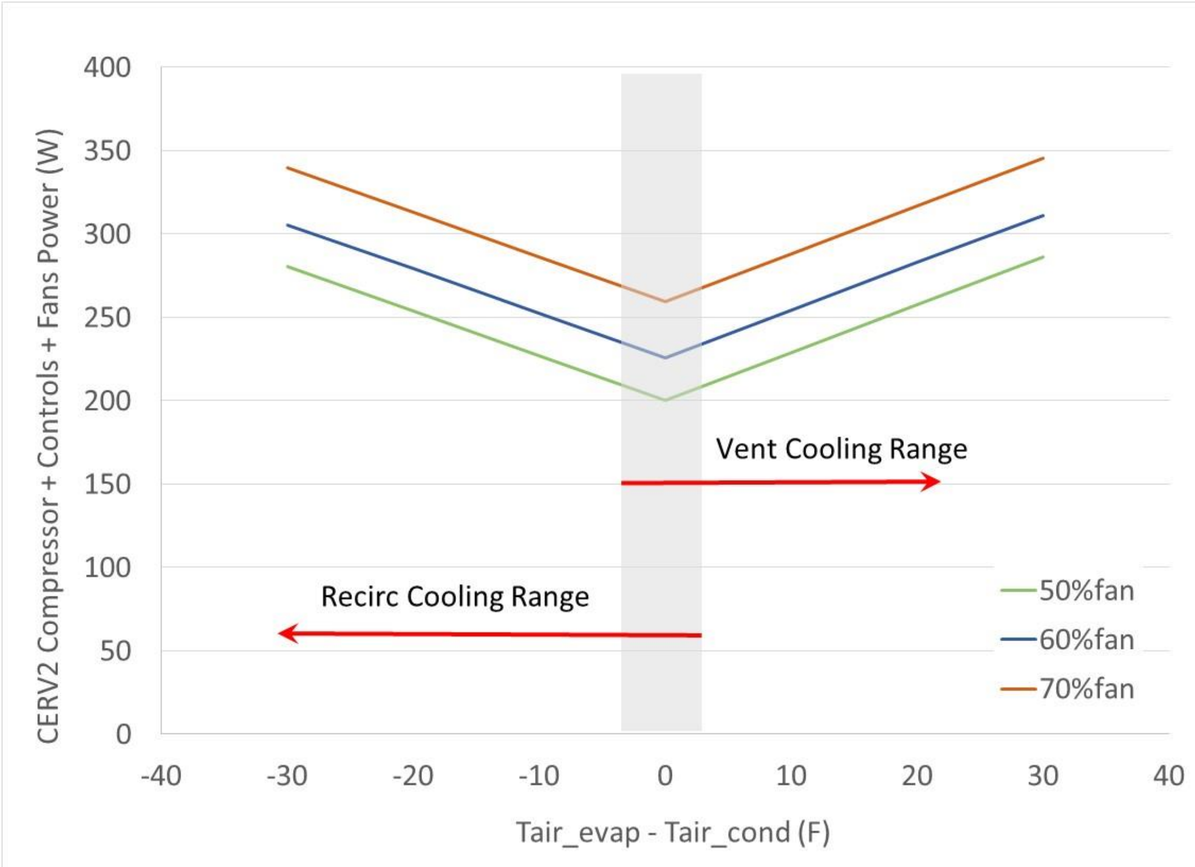


Figure 7 Base COP (coefficient of performance, Base Heat Output/Compressor + Controls Power)

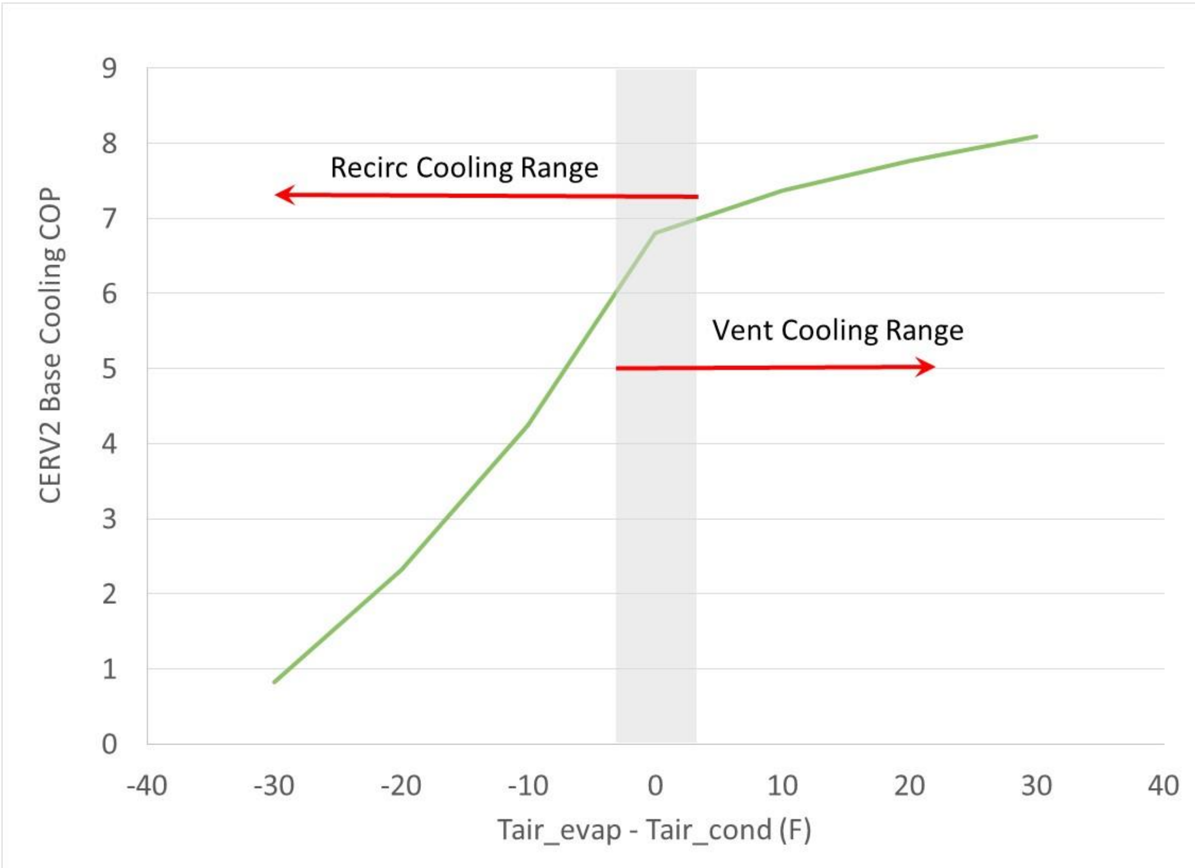
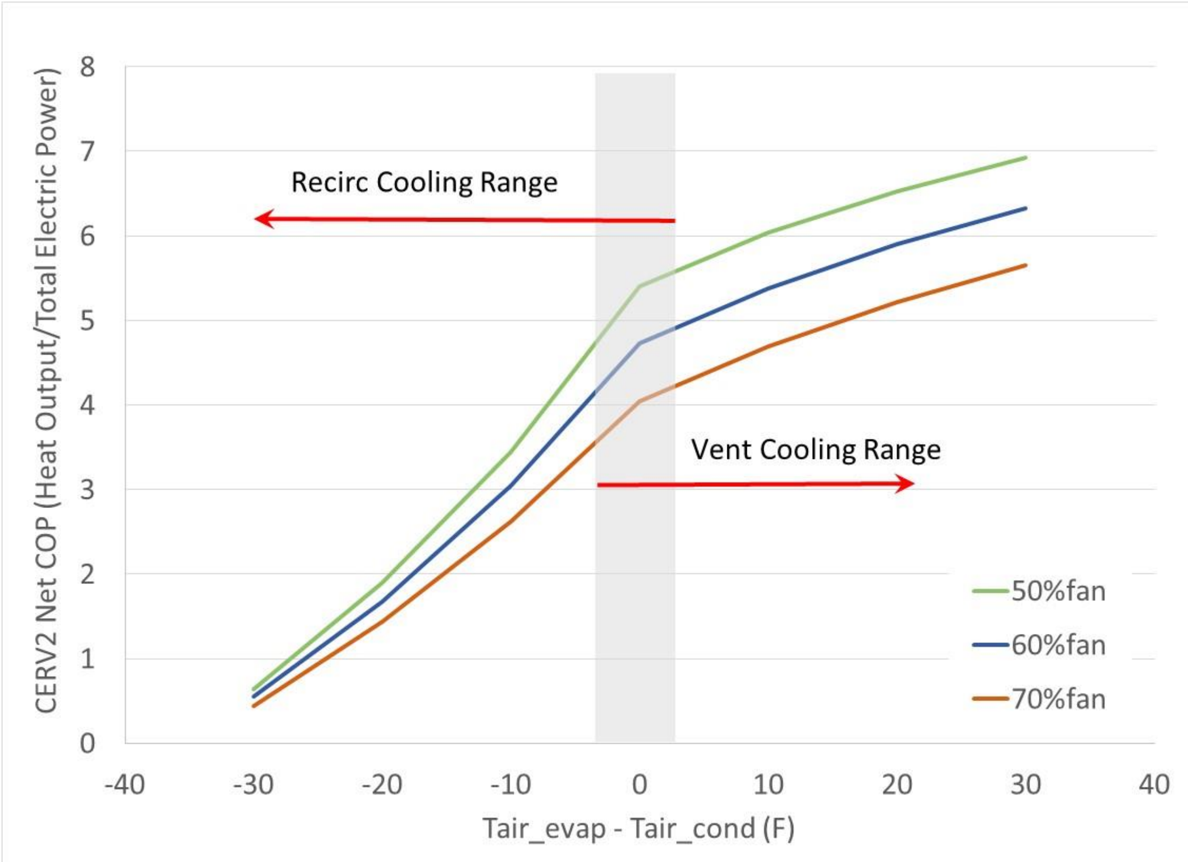


Figure 8 Net COP (coefficient of performance, Cooling Output/Compressor + Controls + 2Fans Power)



Appendix E CERV2 Airflow Characteristics

Duct design is critical for efficient ventilation system operation. Improper duct design increases fan power costs, increases duct noise generation, and reduces CERV2 system efficiency. Build Equinox's Ductology reports (Part 1 and Part 2) provide guidelines for economically optimized residential ventilation system duct design and duct system performance metrics. Conducting duct system performance tests for air flow efficiency and air flow leakage are important and recommended before ductwork is hidden behind walls and ceilings.

Build Equinox recommends designing duct systems with a minimum "C" value (duct system air flow coefficient) of 500, and ideally, 1000 or greater for economically optimized ventilation. Additionally, Build Equinox recommends operating the CERV2 with air flow in the 150 to 200cfm range for effective pollutant removal and particulate filtration. Build Equinox publications and newsletter articles provide background on optimized duct design and how the CERV2 smart ventilation system maintains excellent indoor air quality.

CERV2 fan power is primarily related to fan speed. The "ecm" (electronically commutated motor) fans efficiently supply and exhaust air from a home. A duct network with a C value of 1000 can provide 150cfm of CERV2 air flow with a 50% fan speed setting. At 50% fan speed, each prioAir 8 fan requires 20Watts of electrical power for an air-flow-to-power ratio of 7.5.

The following figures describe CERV2 air flow characteristics with Fantech prioAir 8 ecm fans.

List of CERV2 air flow Figures

Figure 1 CERV2 air flow characteristics based on duct system and prioAir 8 fan speed

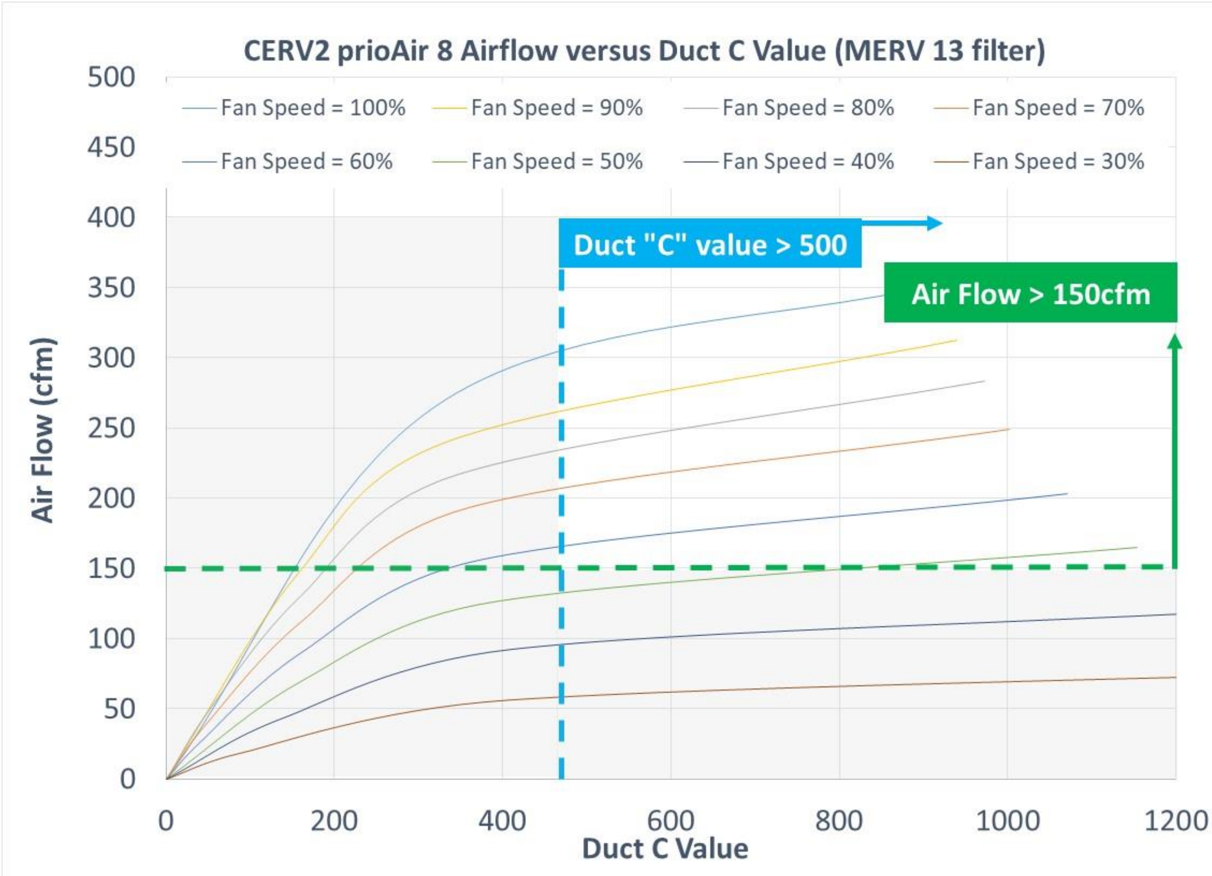


Figure 2 Fantech prioAir 8 (8 inch inlet/outlet) power versus fan speed curve