A Report on Moisture Control in Homes

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FOREWORD

At Build Equinox, we have always included moisture management as a primary aspect of CERV2 smart ventilation design. Our free-to-use ZEROs (Zero Energy Residential Optimization software) model is one of the few residential programs that can predict dehumidification and humidification in residences. Health, comfort and energy impacts of humidity are important!

Moisture is complex and has many facets, however it is an old, old problem that experienced HVACR engineers know how to address. This report series discusses sources of moisture in homes (Part 1), climate effects (Part 2), moisture management methods (Part 3), and overall house modeling of moisture and energy (Part 4). More and more regions around the world are experiencing increased temperature and humidity and the need for active comfort conditioning is expanding.

Build Equinox conducts residential research encompassing health, well-being, comfort, sustainable living, and energy efficiency topics. We hope sharing our knowledge will be a benefit to our growing CERV community. It is time to move beyond energy, designing homes with exceptional indoor environments that improve our health, comfort and well-being!

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Introduction

Figure 1 This proud, old building in Brooklyn (1013 Grand St) has the distinction of being the first air conditioned building in the world. Willis Carrier designed the air conditioning system in 1906. The AC system was needed for humidity control, not cooling! The Sackett-Wilhelms Lithography company had been unable to operate printing machines during NYC's humid summers.

The first building air conditioning system (see Figure 1) was designed for moisture management, not cooling. A young engineer named Willis Carrier designed his novel air conditioning system to reduce building humidity, allowing a printing business to operate during New York City's muggy summers. Many people are surprised to learn that Carrier dehumidified the air by spraying water into it! How can you dehumidify air by spraying water? The answer is a good understanding of thermodynamics.

Carrier's next project was on Wall St where investors knew that improved comfort would increase employee productivity, and that increased human productivity meant increased profits. Human productivity is significantly impacted by air quality and comfort, and human productivity is 100 times more valuable than the energy required to maintain a healthy, comfortable indoor environment [1,2].

Amherst Massachusetts might not come to mind as a hot, humid location, but on August 2, 2018, the breakfast café shown in Figure 2 photos was sweating inside and outside. The outside surface of the windows was below the outdoor "dewpoint" and covered with condensate. Cold, uninsulated supply ducts were covered with condensate, dripping on customers throughout the store. Moisture problems create unhealthy and uncomfortable conditions as well as degradation of building materials. 25% of homes with visible mold also report someone in the household with environmental illness.

In this report series we discuss moisture and how to properly design a home to manage moisture. Part 1 examines moisture generation by home occupants and transport of moisture through a home by air infiltration and ventilation. Part 2 discusses climate impact on a home's moisture management requirements. We focus on seasonal climate variations in the "lower 48" United States, but note that our ZEROs residential simulation software can model homes around the world. Part 3 introduces dehumidification and humidification processes, and associated energy requirements. Finally, Part 4 uses our ZEROs simulation model to conveniently predict home energy performance based on combined effects of home occupant activities, construction characteristics, climate, ventilation and comfort conditioning system.

Figure 2 Sweating inside and outside, drips from the ductwork fall on customers in an Amherst Massachusetts coffee shop while outside windows are dripping wet on a humid morning.

Moisture Generation and Moisture Transport in Homes

Humans are heaters and humidifiers. And, our activities generate heat and often moisture (eg, showering, cooking, aquariums, plants). If we are sealed in a perfectly insulated box, we would need to cool and dehumidify the inside environment to stay comfortable. Our goal in this section is to develop estimates of the moisture released by house occupants from their metabolism and activities. We also examine the amount of moisture transported into and out of a house by infiltration and ventilation. The sum of moisture generation and moisture transport determines whether dehumidification or humidification is needed for maintaining a desired level of comfort.

"Moisture" is a fuzzy term. In this report, moisture is used to describe water that becomes vapor inside a home's ambient air. The moisture may be released as either liquid water or water vapor. For example, moisture from respiration or cooking is added as a vapor to indoor air. Water absorbed in towels and wash cloths is liquid that is subsequently vaporized into indoor air.

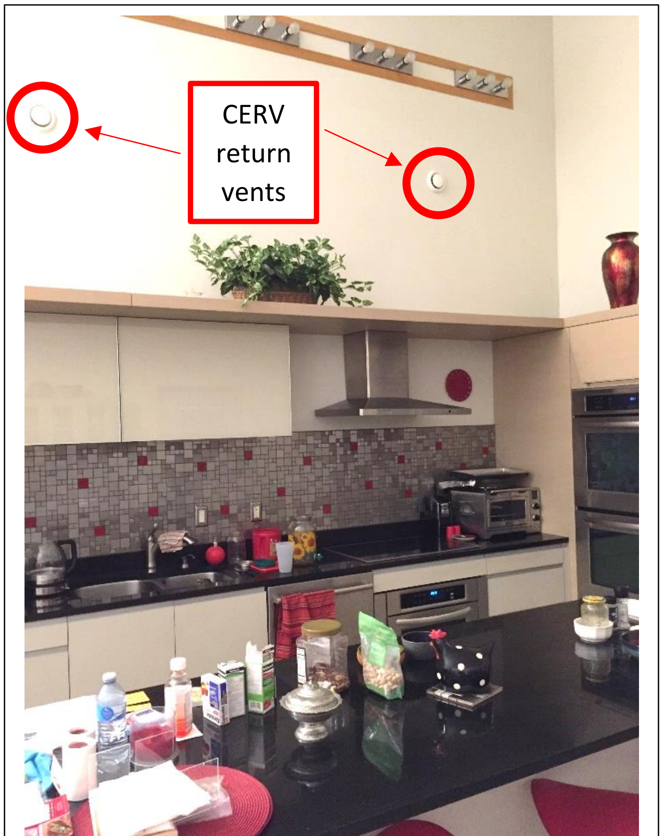

Figure 3 The kitchen in Equinox House uses a recirculating kitchen hood to remove particulates away from cooks while two CERV return vents exhaust kitchen air. Smart ventilation minimizes adsorption of cooking odors into building materials and furnishings, reducing home odors. This kitchen is heavily used. After 9 years of cooking activities, the kitchen has no cooking deposits, surface discolorations, or odors.

Note: Live data and over 5 years of continuous indoor IAQ and comfort data for Equinox House can be viewed online at BuildEquinox.com under the "Take Control" section.

1) Human moisture – Adults breathe approximately 7 to 10 liters of air per minute during typical activity levels. Increased physical activity increases breathing rates to as much as 60 liters per minute. The air that we exhale is nearly "saturated" with water vapor. Assuming an indoor relative humidity level of 50% at room temperature conditions (70F), approximately 0.5kg per day (about 1 pound per day) of water vapor is exhaled from our breathing. During

high levels of physical exertion, perspiration releases a significant amount of water that may be vaporized, however, we will neglect this source for this estimate.

2) Cooking (electric) – Water vaporized by cooking depends on the type of cooking and amount of moisture involved. Some simple kitchen experiments such as boiling water for tea and making oatmeal indicates about 1/3 of the electric energy for cooking vaporizes water. Our Vermod study of 13 homes determined an expression for cooking energy (stove/oven/microwave total) based on the number of occupants. Assuming 1/3 of cooking energy vaporizes water, we find:
    a. Cooking Water Vaporized (kg/day) = (0.12kg/day-Occupant) * #Occ + 0.12kg/day
    b. Note: 1 kg water = 1 Liter of liquid water
    c. A home with 3 occupants generates 0.48kg of water vapor per day based on the above relation, about the same amount as one person's daily vapor release from respiration
    d. The above comments refer to electric cooking methods (electric resistance, induction, microwave). We strongly recommend against gas cooking even though many gas chefs feel the quality of their cooking suffers if they switch to electric cooking. We know many gas chefs who have successfully made the transition to electric cooking with no degradation of their cooking skills. The combustion exhaust from a 5000Btu/h gas stovetop burner used 1 hour per day adds 0.2kg of water vapor and 0.25kg of carbon dioxide to indoor air which is the hourly equivalent of the moisture from 10 people and the CO_2 of 7 people breathing. The additional CO_2 must be ventilated out of the house, causing an additional load on the house. Gas cooking releases other pollutants including unburned hydrocarbons, carbon monoxide, nitrogen oxides, and sulfur compounds. Every energy need in a home is more efficiently met with electricity while combustion-based energy supplies only a few household needs (heating and cooking). If one is serious about having a healthy home, eliminating gas and other fossil combustion is a priority. All-electric homes are good for the pocketbook, too. Electric homes eliminate the costs associated with installation of gas service, flue vents (and their associated energy penalty), and an annoying monthly service fee for the privilege of having gas service. For our area, the gas service fee is $22 per month, a savings that is enough to pay for a 2 to 3 kW solar PV array (no tax credits assumed) that provides 8000 miles per year of combustion-free EV driving!
    e. Figure 3 shows the 9 year old kitchen in Equinox House with its CERV smart ventilation automatically maintaining excellent IAQ.

3) Washing/showering – All water absorbed in a washcloth, towel, and water deposited on the walls and floor of a shower stall or wash basin is vaporized into the surrounding air. Turning on a bathroom ventilation fan for 15 or 20 minutes only removes the moisture already vaporized into the air. Sporadic bathroom ventilation fan operation does not dry towels, washcloths, or water clinging to wet surfaces. In humid climates or rainy weather, it is likely that infiltration air that replaces bathroom exhaust fan air has added more moisture to a house than exhausted! Bathroom moisture is best managed by a smart ventilation system that continuously moves air throughout a house while minimizing the amount of outside air needed to maintain excellent indoor air quality.

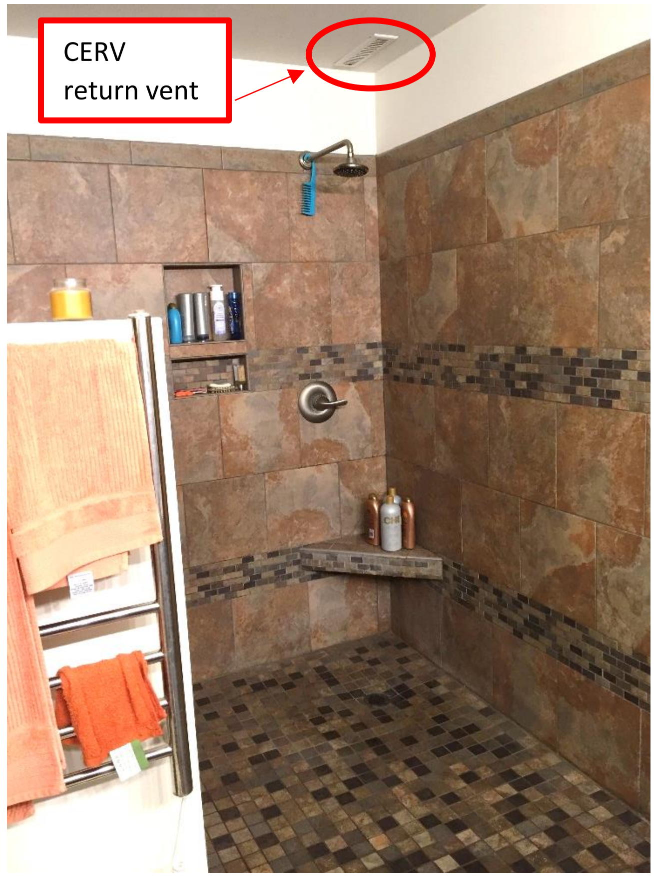

Figure 4 Master bathroom in Equinox House. CERV exhaust vent is located above shower area. Continuous flow of fresh air and recirculated air fully dries bathrooms and keeps air quality excellent. Note: after 9 years of occupation, absolutely no sign of any moisture damage, mold or mildew.

   a. Our research data shows that a 0.68kg dry weight bath towel contains approximately 0.075kg of water after drying a showered human. A 0.066kg dry weight, squeezed washcloth also holds a 0.075kg of water (unsqueezed washcloths can hold more than double that amount). Everyone who showers may not use a washcloth, many people use washcloths without showering, and not everyone showers daily so the variation in any household among occupants can be large.
   b. We find that wet walls in a shower stall hold 0.00275kg/ft^2 of water droplets and wet floors hold 0.008kg/ft^2 of water film. The actual amount of water is very dependent on the wall and floor surfaces ("wetting" versus "non-wetting" surface finishes), drainage angle of the floor, and whether or not someone has squeegeed the surfaces. The above data assumes no wiping of the residual water from walls and floor. A shower area with 40ft^2 of wall and 25ft^2 of floor

holds 0.11kg and 0.2kg, respectively, for a total of 0.31kg of water. If multiple occupant showers are taken successively before walls and floor can dry out, the amount of residual water on walls and floor per shower will be less per shower than that of a single shower. If one assumes that each successive shower contributes half of the wall and floor water amounts, the amount of shower water that is vaporized would be:

i. Shower Water (kg/day) = [0.00275kg/ft^2-wall * Wall Area (ft^2) + 0.008kg/ft^2-floor * Floor Area] x (1+Occ)/2
ii. A home with 3 people would have an average daily wet surface moisture amount of 0.61kg of water vaporized into the house
iii. An 8'x8'x8' bathroom with saturated air (100% relative humidity) holds approximately 0.2kg water vapor mass more than 70F, 50% relative humidity air. Approximately 20 minutes of ventilation (2 bathroom volumes) at 50cfm would return a 100% relative humidity bathroom to house humidity levels (but not dry towels, washcloths, walls and floor).

4) Clothes Drying – the most energy efficient manner that doesn't impact house moisture is a clothesline. Time constraints, home association rules and personal preference often dictate the use of a clothes dryer. Recently, "heat pump" clothes dryers (HPCD) have moved into the North American market. Conventional "vented" clothes dryers and HPCDs impact house moisture differently. We discuss both types of clothes dryers below in addition to "drying closets".
    a. Conventional clothes dryers do not directly add moisture to a home, but have a significant indirect effect related to elevated infiltration caused by the clothes dryer's exhaust air flow. Our laboratory measurements as well as those reported in research literature indicate vented clothes dryers operate with 100 to 200cfm of air flow. When outdoor moisture levels are higher than indoor, indoor humidity will be increased, and when outdoor moisture is lower than indoor, vented clothes dryers reduce indoor humidity. Although there are some time periods when moisture content of the infiltrated air is beneficial, usually, the impact is negative. That is, during cold winter periods when moisture levels are low, vented clothes dryers contribute to uncomfortably dry indoor conditions. Similarly, during warm and humid summers, vented clothes dryers contribute to undesirable increases of indoor humidity. We will further address the impact of vented clothes dryers when we consider climate because the impact is directly related to outdoor conditions.

b. HPCDs recirculate air within the clothes dryer which eliminates infiltration (and the cost of installing a dryer vent). HPCDs require less than 50% of the energy to dry clothes as vented clothes dryers. Ideally, all moisture is condensed and drained. Moisture is condensed from the warm humid air by the heat pump's cooling coil (evaporator) before being reheated and returned for further clothes drying. A 3kg, medium load of clothes will have 1kg of water remaining when washed in a modern, high spin speed clothes washer. By collecting the water condensate from a HPCD, we have found that 20% (0.2kg of water per medium dryer load) of the water weight escapes as water vapor into the surrounding room.

Figure 5 The laundry room in Equinox House features a HPCD and high spin speed washing machine. The laundry room is also used as a drying closet with a CERV return vent located above clothes drying on hangers. Note: after 9 years of occupation, absolutely no sign of any moisture damage, mold or mildew.

c. Note that today's high spin speed clothes dryers are very effective at wringing out water (1kg water retention in 3kg of clothes). By comparison, a manually squeezed wet washcloth retains 0.075kg of water (0.066kg dry weight washcloth). Liquid water removed from clothing increases clothes drying efficiency as well as reduces clothes dryer operation time.

d. Indoor clothes drying – Air drying clothing is often preferred for more delicate fabrics. A laundry room with smart ventilation that continuously moves air through the room, such as shown in Figure 5 for Equinox House, can be used as a drying closet without moisture problems. In Equinox House, approximately 2 loads of laundry are washed per week. A rough estimate would be that a quarter of the laundry (1 load out of four) are partially dried (50% drying), resulting in closet drying of 0.5kg moisture every two weeks.

5) Other Moisture Sources – anything wet that dries inside a home is adding vapor and increasing indoor humidity. When humidity is lower than desired, the additional moisture is a benefit, and when humidity is high it is a detriment

   a. Plants – Varying amounts of moisture will be added to a home by plants with the amount of transpired water released by plants depending on their type and size. Examples of plants that require significant moisture are prayer plants, philodendron, ferns, and dracaena. Snake plants, cacti, jade plants, and other succulents do not release water at a high rate. The 50 plants of assorted varieties and size in Equinox House (see Figure 6) are given 6 liters of water per week. During winter, an additional liter is poured, while a liter less is added during humid summer periods. Assuming a mix of plant types, 0.175kg per 10 plants per day would be reasonable to assume for water vaporization. Note that plants are excellent for adding sanitized moisture into the air, avoiding the health problems of "cold" humidifiers (endotoxins) and the energy and maintenance expense of steam humidification.

Figure 6 Some of the 50 plants in Equinox House that receive 6 liters of water per week.

   b. Aquariums – a 10 gallon aquarium with a 2liter per minute air pump would add 0.028kg of water vapor per day (1 ounce), assuming that the air bubbles are saturated with water vapor. A 100 gallon aquarium would add 10 times that amount, assuming a proportional scaling.
   c. Refrigerators – all of that desiccated food in your refrigerator is moisture released to the indoors. How much? It depends on the food, food packaging, and refrigerator settings. You can perform your own experiment by weighing

some produce before and after placing in the refrigerator for a known period of time (~1 week should be sufficient). In addition, water vapor from the indoor ambient is condensed and frozen on the refrigerator cooling coils. This moisture and the moisture evaporated from food is melted during defrost periods. The defrost water drains into a pan located underneath the refrigerator where the refrigerator's condenser fan evaporates the water into the indoor ambient air.

d. Exercise – Increased physical activity increases breathing rates to 60 liters per minute. Assuming exhaled air is saturated as before, an hour of high physical exertion would add 0.125kg of water. In addition, perspiration increases significantly to aid in the body's heat rejection needs. Perspiration rates can reach 2 to 4kg per hour! (Wikipedia) Note that sweat soaked clothing and towels that are washed do not add to house moisture levels, while clothing that is allowed to dry indoors before washing does add moisture to the house ambient.
e. Humidifiers – we will address humidifiers in Part 3 when we discuss different methods for changing indoor humidity levels. This report mostly focuses on reducing humidity rather than increasing it. We will discuss humidifiers in terms of energy impact and some do's and don'ts of humidification (do humidify with plants!)
f. Anything wet – arts and crafts activities (finger painting, water colors, papier-mâché, etc), mopping floors, dishwater pan, pet water dishes, and so on. For most homes, these are not significant on a daily basis, but noted here for awareness of wet things in general.

The information above allows estimation of daily water vapor added to a home's interior. Table 1 estimates daily water vapor addition of 1, 2, and 4 occupants who occupy a home 24 hours per day. Any of these amounts can be adjusted accordingly. For example, a house in which its two occupants are out of the house for 12 hours per day would have half of the occupant moisture levels shown. High occupancy times (holidays) and high activity level periods (exercise) may not add significantly to the average daily moisture load, however, moisture handling capacity should consider these times in addition to climatic "design day" conditions.

Stored Moisture

House construction materials and furnishings of a house absorb a lot of moisture. Moisture storage data from the 2100ft^2, ranch-style Equinox House shows that a reduction of indoor air moisture content 0.001kg of water per kg of indoor air requires removal of 26kg (58 pounds) of water. Approximately 1/3 of the moisture is water vapor "stored" in the indoor air while 2/3's of the moisture is absorbed in the house furnishings and building materials. Decreasing the indoor relative humidity by 5% at comfort conditions (~70F, 60% relative humidity) requires removal of 69kg (145 pounds) of water!

Changing the humidity level in a home takes some time for moisture to overcome the resistance of water movement through building materials (concrete, wallboard, wood, textiles, etc). One can reduce the ambient air humidity level in a reasonable amount of time, however the humidity will "rebound" as water continues to be transferred out of absorbed materials. Continued dehumidification is required in order to remove the 46kg (94 pounds) of absorbed moisture, which may require a few days.

A home's "moisture mass" is similar to "thermal mass", as described in our ASHRAE Journal paper on air quality and comfort characteristics in high performance homes. The moisture mass characterizes the time required to change humidity level. Equinox House, for example, has a moisture mass "time constant" of 62 hours. The time constant characterizes the time required to change the house moisture content by approximately 2/3s (more accurately, 63.2%) toward a new equilibrium level. Therefore, a home with similar moisture mass time constant would require a few days to reach a new humidity setting.

Coupled with the storage of moisture in a building's mass is moisture transport *through* building materials. The same vapor pressure driving water into and out of building materials also drives a net flow of moisture through building materials. Liesen's (11) detailed analyses of moisture movement and storage in common building wall and roof construction materials indicates the net movement of moisture through building materials is small compared to the transport of moisture by infiltration and ventilation. Understanding the movement of moisture within building materials is extremely important in order to avoid conditions causing moisture condensation and mold growth within building assemblies. For our purposes, gross movement of moisture with infiltration and ventilation air flows will be assumed to transport water into and out of a home.

Table 1 Water vapor addition to a home for 1, 2, and 4 occupants.

Average Daily House Water Vapor Addition (kg)			
# of Occupants	1	2	4
Occupant Moisture*	0.50	1.00	2.00
Elec Cooking Moisture**	0.24	0.36	0.60
Towel/Washcloth	0.15	0.30	0.60
Shower Surfaces***	0.31	0.47	0.78
HP Clothes Dryer	0.03	0.06	0.11
10 Plants	0.18	0.18	0.18
Total Daily Moisture (kg)	**1.40**	**2.36**	**4.26**
* 0.5 per Occupant, 24hr occupation			
** 1/3 cooking energy vaporizes water			
*** 40sqft wet shower wall and 25sqft wet shower floor			

Psychrometric Chart and Comfort Conditions

Figure 7 is a psychrometric ("psychro" = cold; "metric" = measurement) chart showing where most people feel comfortable in terms of temperature and humidity. The psychrometric chart cleverly "linearizes" latent (moisture) and sensible (temperature) effects into a convenient format that allows HVACR (Heating, Ventilation, Air Conditioning and Refrigeration) designers to graphically model complex air conditioning processes.

Most people "feel" comfortable in the 68F to 74F range, however, individual preference, clothing, activity level, surrounding surface temperatures, air velocity, and eating spicy food are among factors that impact one's feeling of comfort. "Relative" humidity levels below 65% are generally considered comfortable. Relative humidity is the fraction of water vapor in air relative to the maximum amount of water vapor that can exist in air at that temperature. For

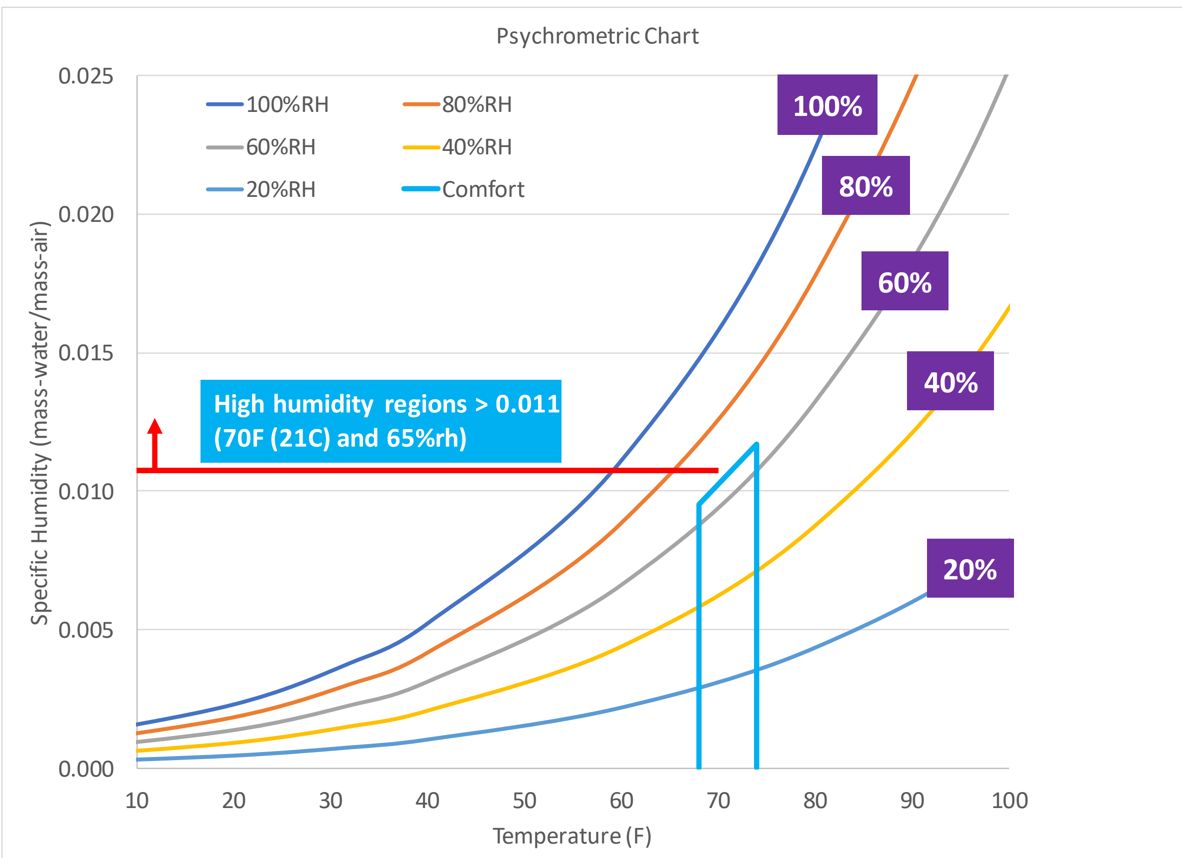

Figure 7 A psychrometric chart, first developed by Willis Carrier….yes, the same Carrier that designed the first air conditioned building….conveniently organizes temperature and moisture (in terms of specific humidity, the mass ratio of water vapor to air). When outdoor conditions are above 0.011 specific humidity, dehumidification will be required to stay comfortable.

example, Figure 7 shows that 70F air at 65% relative humidity has a "humidity ratio" of 0.011 water mass to air mass. Adding water until the air is "saturated" at the same temperature (70F) increases the relative humidity to 100% with a water to air mass ratio (humidity ratio) of 0.017

(that is, 0.011/0.65), which can be determined graphically by moving vertically at 70F to the 100% relative humidity line.

The red line drawn in Figure 7 indicates outdoor conditions that require dehumidification to maintain comfort. Locations in which outdoor conditions are below the red line may require dehumidification if indoor sources of moisture (eg, cooking, showering, breathing, plants, aquariums, etc) are significant. Climatic regions that frequently exceed the red line moisture level should have adequate dehumidification capability to avoid discomfort and moisture condensation issues.

We will apply the psychrometric chart in Part 2 for several regions around the US to gain perspective moisture trends related to climate. Some regions, such as central Illinois where Build Equinox is located, have significantly lower "average" humidity levels in comparison locations such as New Orleans that are known for their heat and humidity. Although Urbana Illinois and Amherst Massachusetts do not have as much of an overall moisture load as New Orleans, high moisture conditions frequently occur and must be managed to avoid the conditions shown in Figure 2.

The amount of water vapor in air is quite small. As shown in Figure 7, a mass of air at 70F and 60% relative humidity is only 1% water. A 5% change of relative humidity is only a 10% change of water mass (1.1% water mass to air mass). The energy content of water as it is vaporized and condensed from air is very important even though its mass fraction is small. For example, vaporizing 1kg of water per day requires nearly 250kWh of energy annually, or enough to drive 1000miles in an EV. Table 1 shows that a home's occupants release more than this amount each day. Remember, being small does not mean being insignificant!

Infiltration Moisture Transport

The amount of water transported into or out of a house with infiltration is primarily dependent on the "leakiness" of a home, wind speed, and temperature difference between inside and outside conditions. Other factors such as opening a door or windows also affect infiltration.

Analyzing a home's moisture (latent) load throughout a year is best accomplished with a computer simulation model, such as our ZEROs (Zero Energy Residential Optimization software). We will use ZEROs to examine overall house moisture loading in Part 4. At this point, we examine the significance of moisture transport into and out of a home on a simple basis in order to gain perspective relative to the moisture generation factors previously discussed (human respiration, cooking, etc).

Figure 8 is a plot showing infiltration air flow rates for a relatively "leaky" home (6 Air Changes per House at 50Pa) versus a well-sealed home (0.6 ACH at 50Pa) at different wind speeds. A 2000sqft home with 8ft tall ceilings with an internal volume of 16,000ft^3 is assumed for Figure 8. Infiltration air flow due to wind speed variations are discussed in Appendix G of our

Ductology – Part 2 report [6]. Today's conventional homebuilders typically produce 6ACH homes. Many homebuilders can build homes with 3ACH at 50Pa leakage with improved construction methods. Progressive homebuilders who work to reduce infiltration with leakage testing and sealing techniques can reach 0.6ACH (aka "Passive House" level). Infiltration air flow at a given wind speed is 10 times greater in a 6ACH home as it is in a 0.6ACH home.

Humidity ratio differences between outside and inside air results in a net transport of moisture into or out of a house. Figure 9 shows a relatively small change of +/-0.001 water-mass to air-mass ratio (that is, 0.1% water to air ratio difference) on a psychrometric chart at 70F and 60%rh. At room temperature conditions, a 0.1% difference between indoor and outdoor specific humidity is equivalent to a +/-5% relative humidity difference.

The infiltration air flow for a 6ACH at 50Pa home with a relatively mild 7mph wind speed is 100cfm. A 0.001 specific humidity difference between inside and outside air moves nearly 5kg per day of water into or out of a home. A 0.005 specific humidity difference, equivalent to 25 to 30% relative humidity difference between indoor and outdoor conditions at 70F, would transport 25kg per day of moisture, or 25 liters of liquid water per day!

The addition or subtraction of moisture from a house by infiltration can be either desirable or undesirable. During cold winter conditions, humidity ratio differences of 0.005 and greater are common. For a leaky home, 25liters of water must be added to the indoor air to keep indoor humidity constant at a comfortable humidity (40 to 60% relative humidity at 70F). From Table 1, home occupant respiration and activities would add 1 to 5 kg per day depending on number of occupants and their behaviors. Vaporizing an additional 20 liters of water per day requires approximately 12kWh of electrical energy, which could either be direct electric heating of water to vaporize it, or 4kWh of electrical energy if water vaporization heating is accomplished with a heat pump (assuming a COP, or Coefficient of Performance, of 3). An electric vehicle can drive 40 miles with 12kWh of energy!

A highly sealed home manages moisture more efficiently. Figure 8 shows a 0.6ACH at 50Pa (Passive House sealed) home to have 1/10 of the infiltration air flow as the 6ACH home. Therefore, a 7mph windspeed has only 10cfm of air flow, with only 0.5kg of water transport with a 0.001 specific humidity difference between indoor and outdoor conditions. A relatively large 0.005 specific humidity difference as is common in winter months, only removes 2.5kg of water, which is similar to the moisture generation level of a home's occupants. Homes sealed to Passive House levels often maintain 40% to 50% relative humidity during winter without active humidification. Humidifiers are notorious for promoting environmental illnesses. For example, homes with cold mist humidifiers have been found to have extremely high levels of endotoxins. Eliminating the need for active humidification improves the health of a home's occupants.

Infiltration moisture transport scales proportionately with house size (volume) and blower door performance. From Figure 8, for example, a reasonably well sealed, 2000sqft home with 3ACH at 50Pa would have half the infiltration air flow as the 6ACH home shown. A 4000sqft home with 3ACH sealing would have twice the infiltration air flow as the 2000sqft, 3ACH home at the same wind speed. The moisture transport amounts also scale proportionately to the air flow such that a 2000sqft, 3ACH home would have an infiltration air flow of 50cfm for a 7mph wind speed, and a moisture transport rate of 2.5kg per day with a 0.001 humidity ratio difference between indoor and outdoor air.

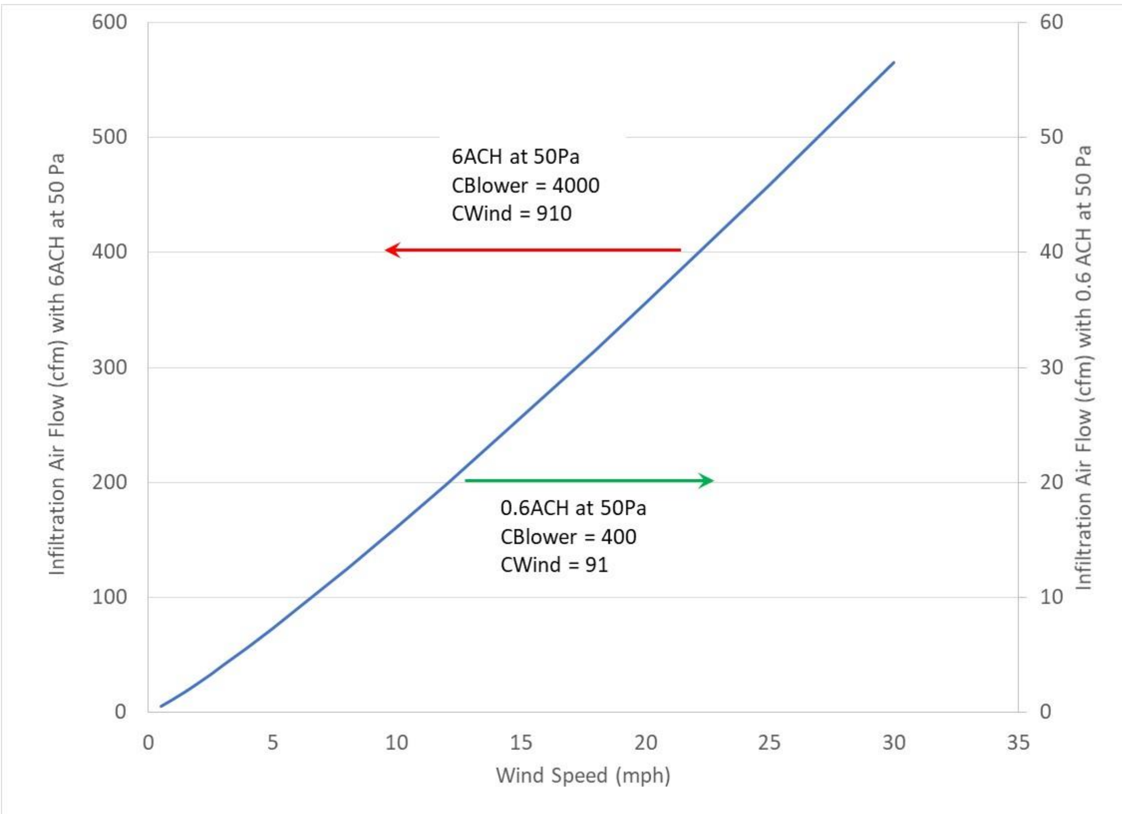

Figure 8 Infiltration air flow for a leaky home (6ACH at 50Pa) and a well-sealed home (0.6ACH at 50Pa) as a function of wind speed.

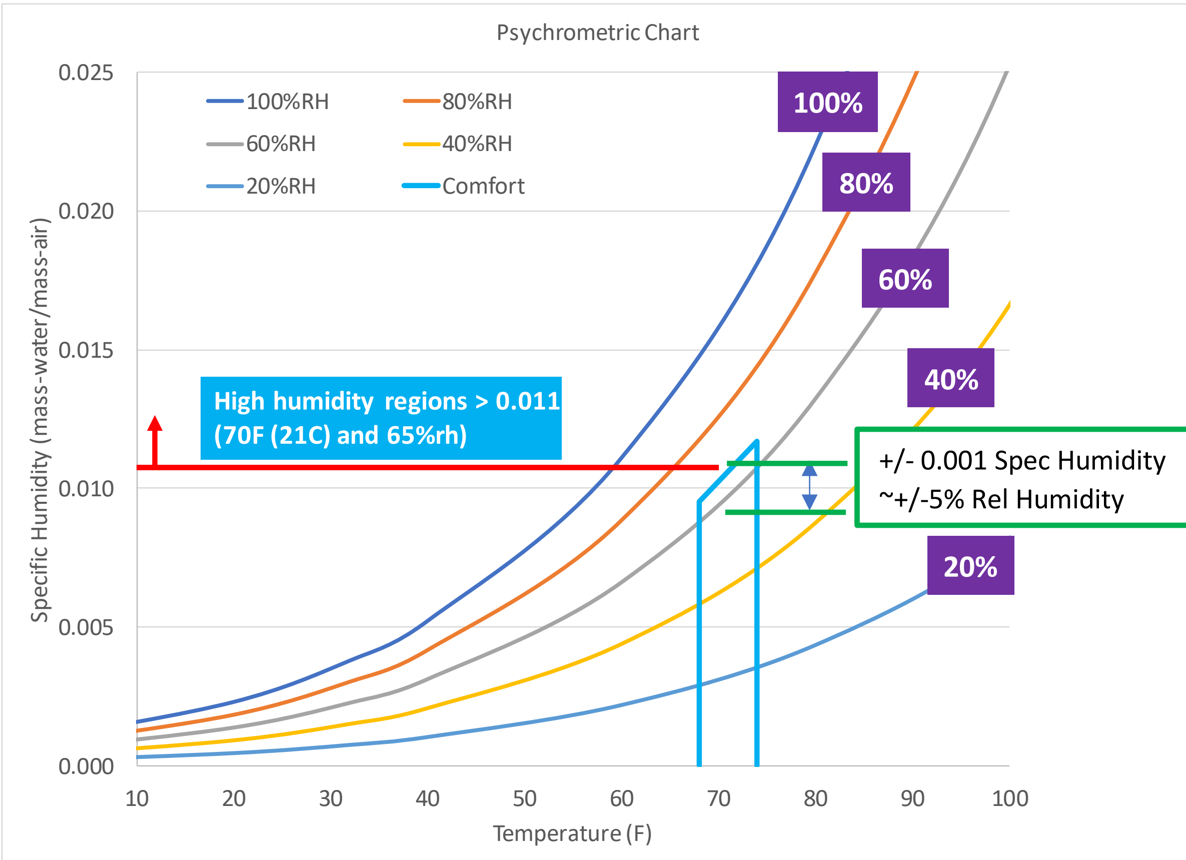

Figure 9 A difference of 0.001 water mass per air mass is equivalent to a relative humidity difference of approximately +/- 5% at 70F and 60%rh.

Ventilation Moisture Transport

We consider five methods of active ventilation for a home:

1) Supply air ventilation
2) Exhaust air ventilation
3) HRV (Heat Recovery Ventilator) ventilation
4) ERV (Energy or Enthalpy Recovery Ventilator) ventilation
5) CERV/CERV2 smart ventilation

The first four ventilation strategies are assumed to follow ASHRAE 62.2-2016 ventilation schedule (Table 2). The fifth ventilation strategy based on CERV (first generation) and CERV2 (second generation) smart ventilation systems significantly reduce moisture management in homes. CERV smart ventilation follows ASHRAE 62.2-2016 section 4.6 for alternative ventilation resulting in lower pollutant exposure than ASHRAE 62.2-2016's ventilation schedule.

A basic assumption built into ASHRAE 62.2-2016 ventilation schedule is that occupancy is equivalent to 1 plus the number of bedrooms. Two problems are readily observed with this approach for the first four ventilation systems listed. First, a 1000sqft home with 2 bedrooms and 4 occupants is under-ventilated and has poor air quality that impacts occupant cognition, health and sleep. Second, the average new US home with 2700sqft and 4 bedrooms should have 112 to 128cfm of ventilation air flow according to the highlighted region in Table 2. Average US home occupancy is 2.5 persons, which on average is overventilated at 48cfm per person. Ironically, air quality is often poor in occupied rooms in overventilated homes using the first four ventilation strategies due to poor air distribution.

Smart ventilation coupled with smart air distribution ensures excellent air quality in occupied regions of a home. Ventilation air is modulated relative to the number of occupants, indoor pollutant generation rates, wind-driven infiltration, buoyancy-driven infiltration, door openings, window openings, and flue/exhaust vents (eg, clothes dryer vents). Smart ventilation systems automatically adjust ventilation air flow in order to continuously maintain excellent air quality. Build Equinox research reports on Smart Ventilation and Smart Air Distribution provide detailed comparisons of smart ventilation and constant flow ventilation (Table 2) strategies.

Moisture impacts from ventilation can be determined in a similar manner as discussed for infiltration. A ventilation air flow with a humidity ratio difference of 0.005 and a ventilation air flow of 100cfm has 25 liters per day moisture transfer into or out of the house. The first 3 ventilation strategies (supply air ventilation, exhaust air ventilation and HRV ventilation) transfers this moisture directly. ERV and CERV2 ventilation systems alter ventilation moisture transfer in differing manners. ERVs sometimes alter moisture transfer in a beneficial manner, and sometimes transfers moisture in a detrimental manner. CERV2 smart ventilation has been designed to beneficially manage moisture transfer in all seasons through its heat pump energy recovery system. The following subsections provide additional descriptions of each ventilation strategy.

Supply Air and Exhaust Air Ventilation Systems

The first two ventilation strategies (supply ventilation and exhaust ventilation) are infiltration/exfiltration enhancements. Supply ventilation consists of a fan blowing air into a house, with an equal amount of air exiting the house in an uncontrolled manner through leakage paths formed by construction flaws, flues, dryer vents, etc. Exhaust ventilation is similar except that a fan blows air out of a house with infiltration air flowing into the house through leakage paths. Both strategies are energy inefficient and may not effectively distribute fresh air to occupied regions of a house.

Supply air ventilation systems typically have poor air filtration, allowing outdoor particulates to flow into a home. Proper filtration of outdoor air requires either a filter box mounted outside a home or an insulated filter box mounted in the fresh air supply duct. An insulated filter box is required to avoid moisture condensation inside the fresh air duct and filter during warm, humid outside conditions, and moisture condensation (and frost) on the outside of a fresh air supply duct and filter housing during cold winter conditions. The filter should have high filtration efficiency (eg, MERV 13) and a minimum filter face area of 200square inches (10”x20” filter). Exhaust ventilation has no filtration of outside air, increasing transport of outdoor particulates into a home.

Both supply air and exhaust air ventilation strategies increase the potential for building structure degradation caused by condensation of supply/exhaust air passing through a home’s infiltration/exfiltration paths. During the winter, warm, humid inside air condenses water vapor as it flows past cold building materials on its passage to the outside. Summer conditions with warm, humid outside air similarly condenses water on cooler, interior building materials as the air moves into a home. In both cases, condensed water creates the potential for mold growth and building structure degradation. Our report on the importance of home maintenance describes the relation between building structure, mold and home occupant environmental illnesses.

HRV Ventilation

A Heat Recovery Ventilator (HRV) is a simple device used to “recover” or exchange energy between fresh air and exhaust air streams for building ventilation. An HRV often consists of two fans (sometimes driven by a single motor) that move fresh air and house exhaust air through alternating passageways of a heat exchanger. Figure 10 shows a photo of a heat exchanger core fabricated from corrugated polymer sheets layered in alternating directions for each air stream. Figure 11 is a photo of an HRV showing the fresh air and exhaust air flow paths through the heat exchanger and two fans. Both air streams should be filtered to reduce house particulate level and to keep the HRV passageways clear.

Figure 12 shows the psychrometric paths followed by the fresh air and exhaust air streams as they move through an HRV during winter conditions. Also plotted on Figure 12 are hourly weather data from Champaign Illinois (2010 weather year), which is a location with cold winters and warm, humid summers. Two "comfort" boxes are drawn on Figure 12 showing the region where many people feel comfortable in "light" clothing and "heavy" clothing. The red line represents fresh air, and is drawn horizontally, which psychrometrically is a path that does not have any moisture change, only sensible temperature change. Indoor air that is being exhausted is assumed to enter the HRV at 70F and 40% relative humidity, a typical winter indoor condition for a well-sealed, high performance home. The exhaust air initially drops in temperature as energy is transferred to the colder outside air stream without moisture changes. As the exhaust air is cooled to "saturation" (aka, dew point) conditions, water condenses out of the exhaust air stream.

Some HRV's avoid moisture condensation by reducing their transfer efficiency (more formally, heat exchanger "effectiveness"). Higher efficiency HRVs include a condensate drain to manage moisture condensation. Notice that outdoor conditions colder than 20F are likely to freeze condensed moisture in an HRV heat exchanger, which blocks air flow and potentially damages the heat exchanger core. Many HRVs include a frost prevention strategy such as electric resistance preheating of outside air or reduced fresh air flow. Reduced fresh air flow reduces the HRV efficiency and therefore ability to condense moisture. Electric preheating of outside air during cold conditions is very energy inefficient. Reducing fresh air flow is never a good idea as it promotes transmission of wintertime illnesses (flu and colds), increases potential for asthma attacks and other respiratory sensitivities, and degrades cognition and sleep.

Condensation of moisture in HRVs imbalances air flow, which also degrades HRV performance. HRV performance certifications are based on "balanced" air flow, and laboratory test conditions avoid moisture condensation that occurs in the real world. Water condensed in an HRV core's small passageways can decrease the exhaust air's flow rate by 20 to 25%. An HRV with an 80% efficiency rating and a 20% air flow imbalance is reduced to an energy efficiency below 70%. Often, home occupants are unaware of the poor performance and degraded air quality in their home because human olfactory senses are not sensitive enough to detect good air quality.

Figure 13 shows a psychrometric map with HRV air flow process paths for summer conditions. Both process paths are horizontal, indicating no moisture variation in either fresh air supply or house exhaust air streams. Note, however, that there are several hourly weather conditions in Champaign Illinois during the spring, fall and summer when outside air temperature is cooler than indoor conditions. During these time periods, exchanging energy between house exhaust air and fresh air is undesirable. An efficient ventilation system should be capable of automatically detecting "nice" outdoor conditions, and simply bring in fresh air without energy exchange, as one would do by opening a window.

<u>ERV Ventilation</u>

A residential ERV (Energy or Enthalpy Recovery Ventilator) is identical to an HRV except that the heat exchanger core is constructed from a permeable material that allows water vapor to be transported between fresh air and exhaust air streams. One should note that many manufacturers claim that their ERV cores are only permeable to water vapor and nothing else. In the real world, other chemicals are permeable to some extent. Additionally, polymer heat exchanger cores, whether non-permeable for HRVs or permeable for ERVs, absorb chemicals over their lifetime (think of cigarette filters). Polymer heat exchangers degrade and off-gas their own polymer chemicals over their lifetime, too. Perhaps you have experienced this by eating food that has taken on the taste of the plastic container it has been stored in?

Figure 14 shows wintertime psychrometric paths for fresh air and house exhaust air passing through an ERV. Unlike an HRV, the vapor pressure difference between the two air streams drives water vapor from the higher vapor pressure stream (exhaust air) into the lower vapor pressure fresh air stream. Humidity in the fresh air is increased as the humidity of the exhaust air is lowered. During winter conditions, the moisture transport may be beneficial for keeping winter indoor humidity higher than it would be otherwise. In highly sealed homes, recycling moisture from the exhaust air stream into the fresh air stream is unneeded and sometimes undesirable because internal moisture generation is sufficient for maintaining comfortable humidity.

Figure 15 shows one of two possible summer conditions for an ERV. When indoor humidity is lower than outdoor humidity, fresh air will be lowered in humidity while exhaust air humidity is increased. Typical ERV mass transfer efficiency (more formally, effectiveness) is 0.5. With a humidity ratio difference of 0.005 between outdoor air and indoor air, 0.0025 humidity ratio change occurs, which ideally reduces latent ventilation loading by 50%. With 100cfm continuous ventilation air flow, 25liters per day of moisture loading may be reduced to 12.5 liters per day.

ERVs are not effective for home moisture control in humid climates. A detailed field study of 6 moisture control system strategies in Houston Texas found ERVs to be the least effective system for controlling indoor humidity[3]. The investigation monitored 20 homes over a two year period. Figure 16 shows how an ERV can increase the humidity in a home during humid weather. Exhaust air removed from the "wetter" areas of a home such as bathrooms, kitchen, laundry and mudrooms can be elevated above outdoor conditions. Instead of reducing fresh air humidity, an ERV increases fresh air moisture.

A common misconception is that ERV systems automatically dehumidify homes during warm, humid weather. In fact, the opposite is true. Without some type of active dehumidification system, ERV homes always increase indoor humidity levels above that of non-ERV homes (that is, HRV homes and homes with simple supply or exhaust ventilation)! Allison Bailes June 2018 blog ASHRAE 62.2 committee discussion includes several discussion comments on ERVs in humid climates.

CERV2 Smart Ventilation

CERV2 smart ventilation systems are designed to maintain excellent air quality during all seasons in an energy efficient manner. Our Smart Ventilation and Smart Air Distribution reports describe air quality and energy efficiency characteristics in comparison to a high efficiency HRV. In terms of moisture management, CERV2 operates beneficially in all climatic conditions. We will discuss quantitative moisture conditioning in Part 3 when discussing methods for managing house moisture. In this section, we are interested in moisture transport into and out of a home due to ventilation.

CERV2's air quality sensors (carbon dioxide and total VOC) ensure that only the amount of fresh air required is delivered to a home. For example, a US average 2700sqft home with 2.5 occupants who are home 16 hours per day would need 33cfm of fresh air ventilation rather than 120cfm as specified by ASHRAE 62.2-2016 for equivalent pollutant exposure.

We recommend 40cfm of fresh air per building occupant, or an average air flow of 67cfm for reduced pollutant exposure and improved human health for 16 hours per day for 2 occupants. Assuming a 0.6 ACH at 50 Pa highly sealed home with an average wind speed of 7mph, infiltration supplies 14cfm of ventilation air, which reduces active ventilation to 19cfm (ASHRAE 62.2 equivalent exposure) or 53cfm for improved home air quality. The overall effect is a significant reduction (more than 50%) of moisture increase and decrease relative to constant flow ventilation. Even though fresh air ventilation is reduced compared to ASHRAE constant flow ventilation, CERV2 smart ventilation improves air quality because fresh air is more effectively distributed to occupants unlike constant flow, one-and-done ventilation in which 20% or less of fresh ventilation air reaches a home's occupants.

CERV2 beneficially extracts latent heat from exhaust air during cold weather and converts latent energy into sensible heat added to the incoming fresh air through the CERV2's heat pump. Figure 17 shows exhaust air and fresh air psychrometric paths for a CERV2 during winter conditions. Unlike HRV and ERV units that avoid frost in inefficient manners, CERV2 "adaptive defrost" manages frost, allowing a CERV2 to continue removing sensible and latent energies from exhaust air. Figure 17 shows a horizontal psychrometric movement of fresh air, indicating a sensible energy change without moisture change. Extraction of both latent and sensible energy from exhaust air plus energy from the CERV2 heat pump compressor elevates the fresh air temperature above room temperature. As previously mentioned, moisture generation within a smart ventilated and sealed home keeps humidity comfortable throughout winter conditions without additional humidification. If humidification during winter is desired, sensible energy from the CERV2 can be converted to latent heat (vaporization) of water.

Figure 18 shows CERV2 psychrometric paths during summer conditions. Exhaust air humidity level, unlike an ERV, does not impact CERV2 performance. Fresh air is cooled and dehumidified by the CERV2 as it passes through the CERV2 heat pump's evaporator. Latent and sensible energy removed from fresh air is "pumped" to the house exhaust air. CERV2 dehumidification capacity depends on air humidity ratio, automatically increasing as humidity increases. Typical CERV2 dehumidification capacity for warm, humid conditions is 10 liters per day. More details of CERV2 dehumidification are included in Part 3.

Table 2 ASHRAE 62.2-2016 ventilation schedule for constant flow ventilation systems.

	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 10 Photo of an HRV heat exchanger core fabricated from corrugated polymer sheets.

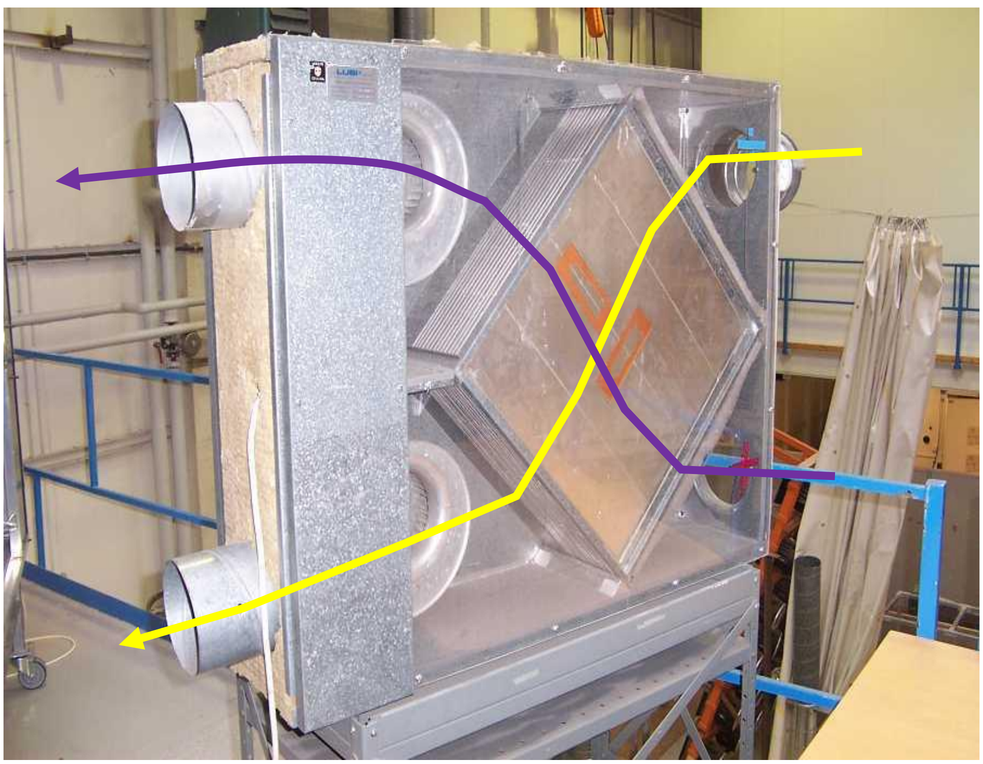

Figure 11 Photo of an HRV showing a heat exchanger core and two fans for fresh air and exhaust air streams.

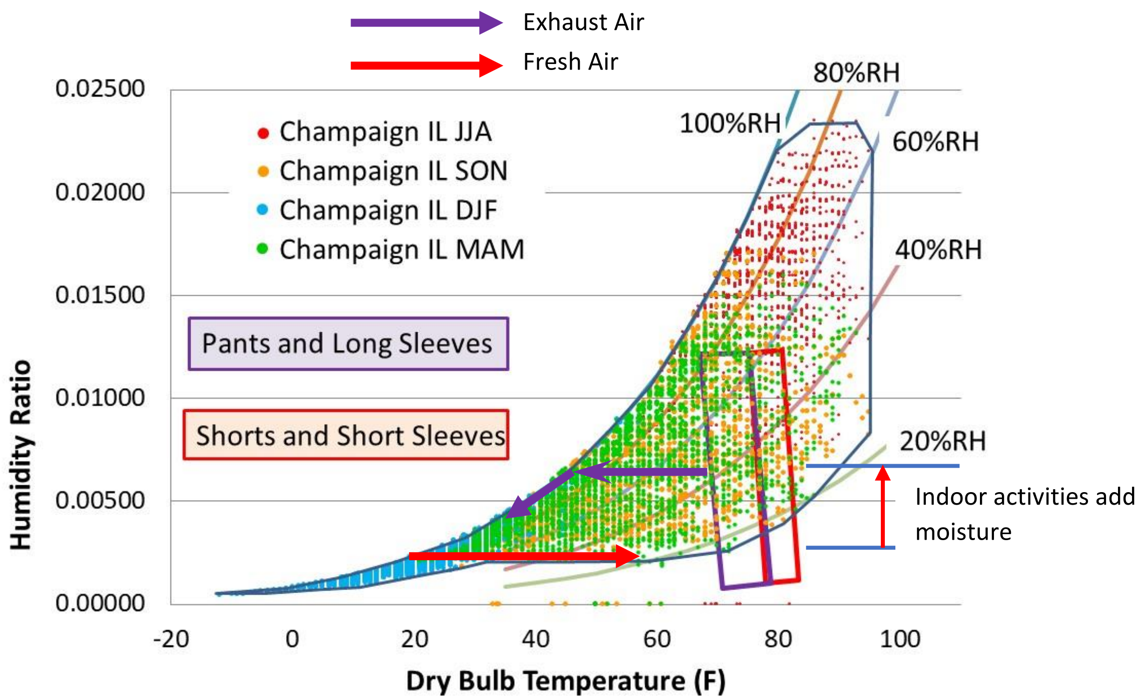

Figure 12 Psychrometric map of hourly Champaign weather data with fresh air and exhaust air paths through and HRV during winter heating.

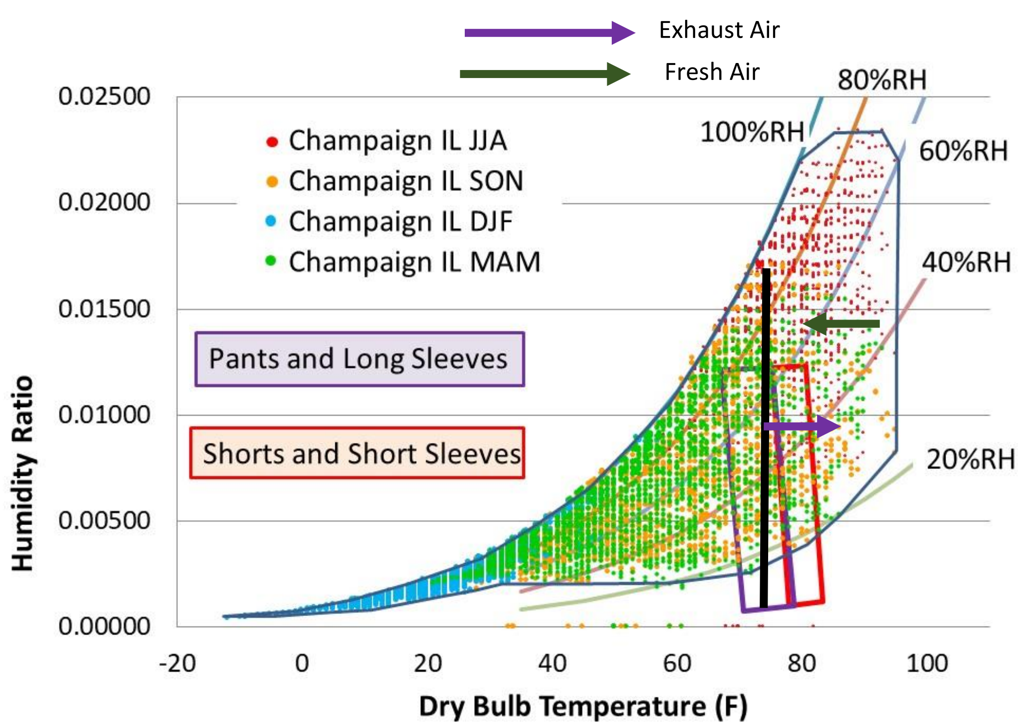

Figure 13 Psychrometric paths for an HRV during summer fresh air and exhaust air energy exchange.

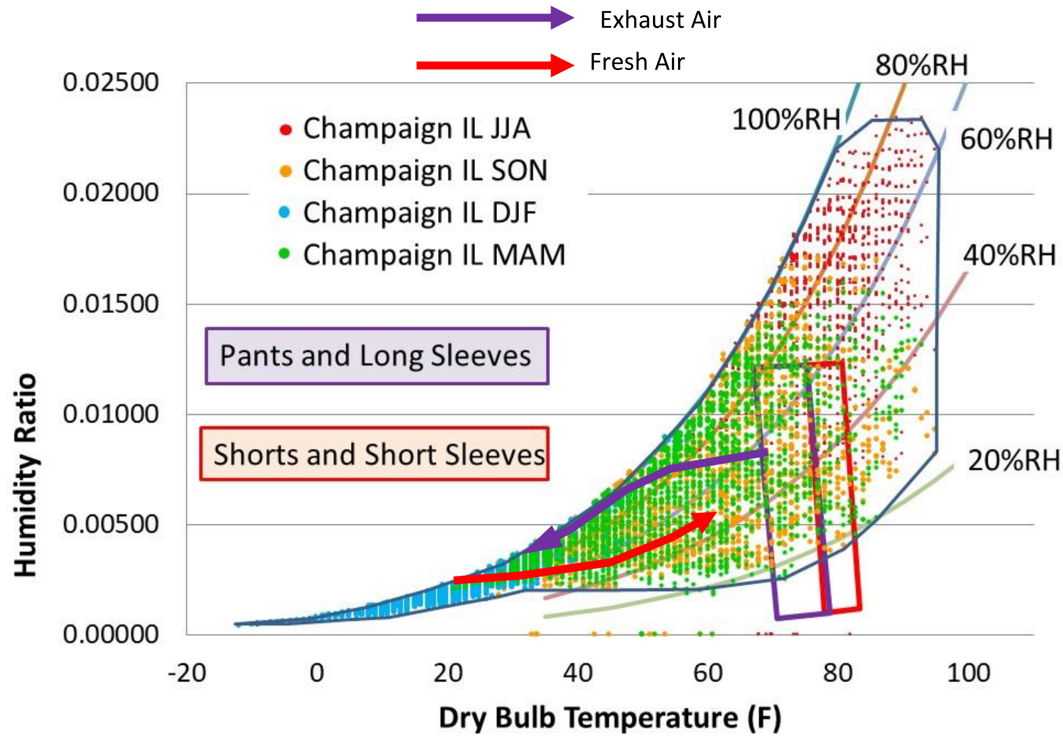

Figure 14 Psychrometric paths for energy exchange in an ERV between fresh air and exhaust air streams.

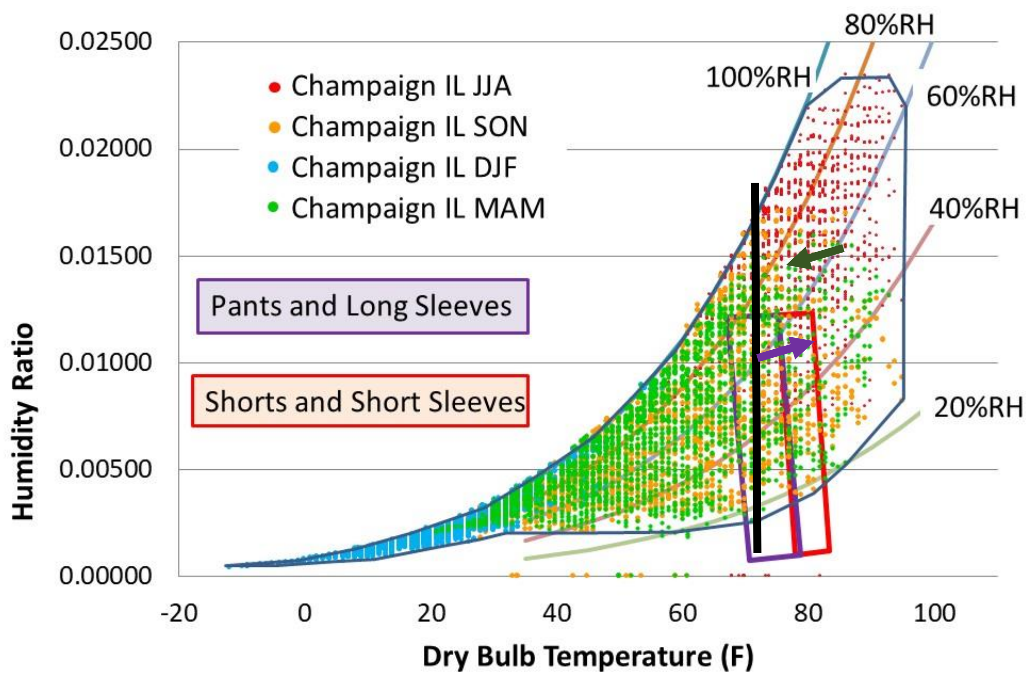

Figure 15 Psychrometric paths for fresh air and exhaust air energy exchange for an ERV during summer conditions when fresh air humidity is greater than exhaust air humidity.

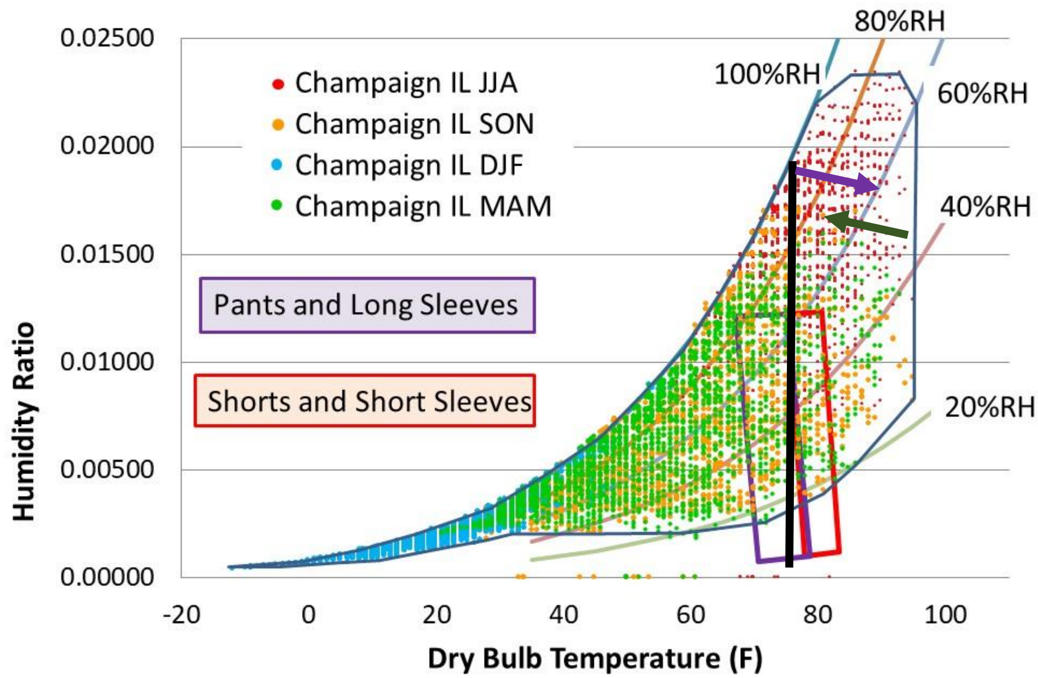

Figure 16 Psychrometric paths for fresh air and exhaust air in an ERV during summer conditions when fresh air humidity is lower than exhaust air humidity.

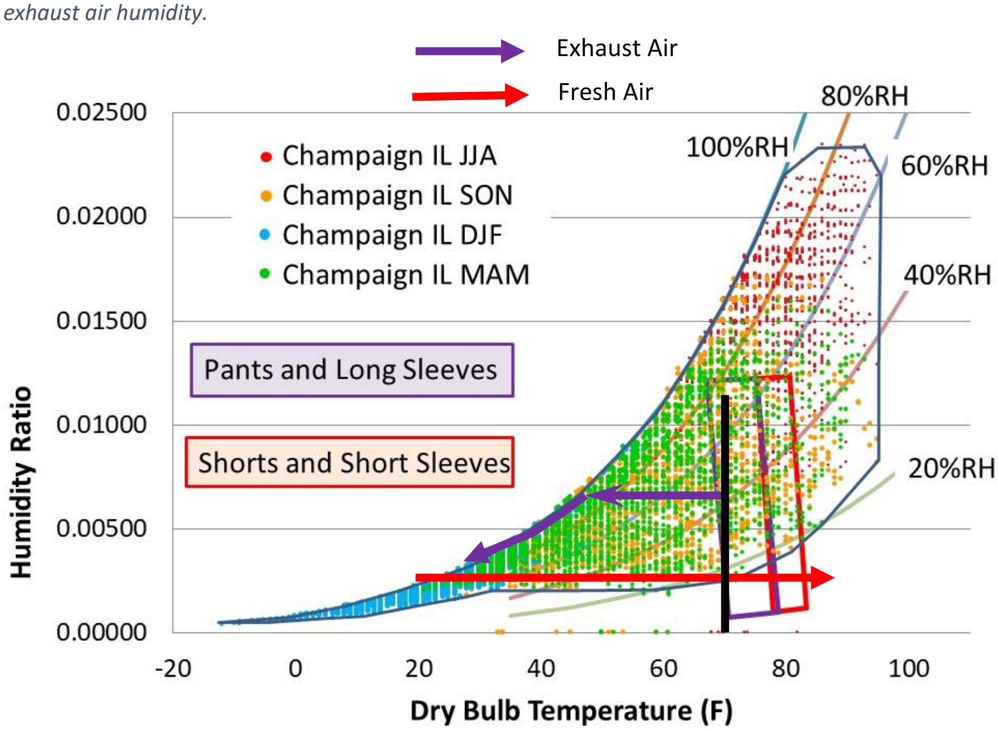

Figure 17 CERV2 winter energy exchange paths for fresh air and house exhaust air.

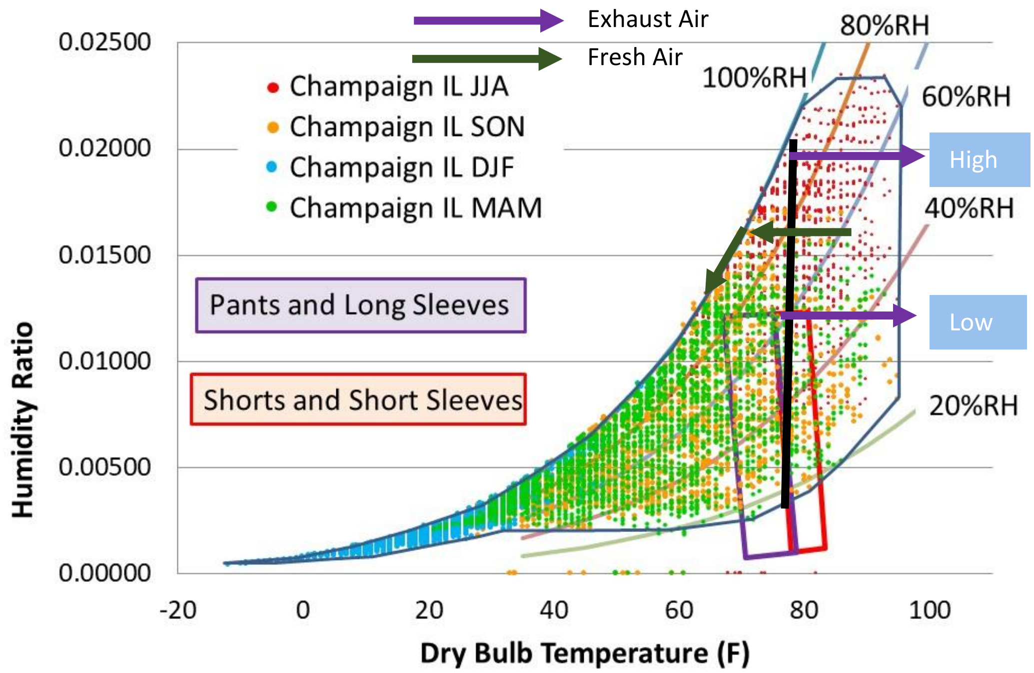

Figure 18 CERV2 summertime energy exchange paths between fresh air and house exhaust air.

Basic Moisture Relations

Simple relations for determining house moisture balances are useful for "back-of-the-envelope" estimation of dehumidification and humidification rates, and for predicting house humidity when no dehumidification or humidification occurs.

- Daily House Infiltration and Ventilation Water Balance

  Infiltration and Ventilation Water Transport per Day (kg/day) = $50 \times V \times (w_o - w_i)$

- Seasonal House Infiltration and Ventilation Water Balance

  Seasonal Infiltration and Ventilation Water Transport (kg/season) = $18{,}000 \times V \times (w_o - w_i) \times F$

- Net Daily House Water Balance

  Net Water per Day (kg/day) = $50 \times V \times (w_o - w_i) + G$

- Seasonal Net House Water Balance

  Seasonal Net Water Balance (kg/season) = $18{,}000 \times V \times (w_o - w_i) \times F + 365 \times F \times G$

- House Humidity Ratio with No Humidification or Dehumidification

  House Indoor Humidity Ratio = w_i (kg_w/kg_a) = $G/(50 \times V) + w_o$

Nomenclature:

V = infiltration + ventilation air flow rate (cfm)

w_o = outside humidity ratio (kg-water/kg-air)

w_i = inside humidity ratio (kg-water/kg-air)

F = fraction of year

G = sum of indoor moisture sources (kg/day, see Table 1)

Example: Contractors Loose, Tight, and Smart

Three homes are built side-by-side in Urbana Illinois. All homes are 2000sqft with 8ft high ceilings, and have 3 bedrooms. One home built by Contractor Loose measured 6ACH at 50Pa. The second home, built by Contractor Tight, is well-sealed and measured 0.6ACH at 50Pa. Contractor Loose and Contractor Tight homes have 2 occupants and are ventilated according to ASHRAE 62.2-2016. The third home also has 2 occupants and is built by Contractor Smart. The home is sealed to 0.6ACH at 50Pa sealing and has a CERV2 smart ventilation system.

Determine:

- hot and humid season daily average moisture ventilation and infiltration transport
- hot and humid seasonal moisture ventilation and infiltration moisture transport
- hot and humid season net daily house water balance
- hot/wet seasonal net water balance
- house indoor average humidity during hot/wet season with no dehumidification

Solution: Climate information is needed for Urbana Illinois' hot and humid (summer) season. The fraction of the year with temperatures and humidity greater than comfort conditions is 0.227. Comfort conditions for the homes are assumed to be 72F and 60% relative humidity (humidity ratio of 0.01) for the summer season. Urbana's average outdoor temperature is 77.4F, average humidity ratio is 0.013 (~70% relative humidity), and average wind speed is 8.4mph during summer. We will learn more about seasonal climate variations and the weather parameters assumed for this example in Part 2.

Contractor Loose's house has 140cfm of infiltration while Contractor Tight's house has 14cfm of infiltration based on a wind speed of 8.4mph (see Figure 8). Both homes must have 90cfm of ventilation with ASHRAE 62.2-2016 ventilation schedule (see Table 2 for a 2000sqft home with 3 bedrooms). Overall, Contractor Loose has 230cfm of infiltration and ventilation air flow while Contractor Tight has 104cfm of infiltration plus ventilation air flow.

Both homes have 2 occupants that generate 2.4kg of moisture loading per day (see Table 1).

For Contractor Loose's house, we find:

-Infiltration and Ventilation Water Transport per Day (kg/day) =

50 x 230cfm x (0.013 – 0.010) **= 34.5kg/day** water transported into house

-Hot and Humid Seasonal Infiltration & Ventilation Water Transport (kg/season) =

18,000 x 230cfm x (0.013 – 0.010) x 0.227 **= 2820kg/season** water transported into house

-Net Water per Day (kg/day)

= 50 x 230 x (0.0013 – 0.010) + 2.4 **= 36.9kg/day**

Seasonal Net Water Balance (kg/season)

= 18,000 x 230 x (0.013 – 0.010) x 0.227 + 365 x 0.227 x 2.4 **= 3020kg/season**

House Indoor Humidity Ratio = w_i (kg_w/kg_a) with no active dehumidification

= 2.4/(50 x 230) + 0.013 **= 0.0132** …. Infiltration and ventilation essential make indoor humidity the same as outdoor humidity, however, indoor relative humidity at 72F and 0.0132 humidity ratio is 90%!

For Contractor Tight's house, we find:

-Infiltration and Ventilation Water Transport per Day (kg/day) =

50 x 104cfm x (0.013 – 0.010) **= 15.6kg/day** water transported into house

-Hot and Humid Seasonal Infiltration & Ventilation Water Transport (kg/season) =

18,000 x 104cfm x (0.013 – 0.010) x 0.227 **= 1275kg/season** water transported into house

-Net Water per Day (kg/day)

= 50 x 104 x (0.0013 – 0.010) + 2.4 **= 18.0kg/day**

Seasonal Net Water Balance (kg/season)

= 18,000 x 104 x (0.013 – 0.010) x 0.227 + 365 x 0.227 x 2.4 **= 1474kg/season**

House Indoor Humidity Ratio = w_i (kg_w/kg_a) with no active dehumidification

= 2.4/(50 x 104) + 0.013 **= 0.0135** …. Note that indoor humidity for lower infiltration and ventilation air flow rates cause indoor humidity to increase, with 72F and 0.0135 humidity ratio for 90+% rh!

Contractor Smart builds well-sealed homes similar to Contractor Tight. Contractor Smart uses a CERV2 smart ventilator that adds fresh air as needed to maintain air quality of 1000ppm of carbon dioxide. Note: 20cfm per occupant during occupancy is typical of fresh air flow required to maintain 1000ppm of human generated carbon dioxide concentration. Occupants are at home for 16 hours per day. The smart ventilation system for 2 occupants, therefore, operates at an average flow rate of 27cfm (20cfm x 2 occupants x 16hours-occupation/24hours = 27cfm). Smart ventilation automatically includes the impact of infiltration air flow (14cfm), reducing active ventilation needs to 13cfm.

For Contractor Smart's house, we find:

-Infiltration and Ventilation Water Transport per Day (kg/day) =

50 x 27cfm x (0.013 – 0.010) **= 4.1kg/day** water transported into house

-Hot and Humid Seasonal Infiltration & Ventilation Water Transport (kg/season) =

18,000 x 27cfm x (0.013 – 0.010) x 0.227 **= 331kg/season** water transported into house

-Net Water per Day (kg/day)

= 50 x 27 x (0.0013 – 0.010) + 2.4 **= 6.5kg/day**

Seasonal Net Water Balance (kg/season)

= 18,000 x 27 x (0.013 – 0.010) x 0.227 + 365 x 0.227 x 2.4 **= 530kg/season**

House Indoor Humidity Ratio = w_i (kg_w/kg_a) with no active dehumidification

= 2.4/(50 x 27) + 0.013 **= 0.0148** …. With a tightly sealed, efficiently ventilated home, without dehumidification, 72F and 0.0148 humidity ratio is 95% rh! But, notice that dehumidification requirements are 1/3 of the tightly sealed home with constant flow ventilation, which significantly lowers dehumidification energy requirements. We explore energy related to managing moisture in Part 3.

It is important to note that the tightly sealed, smart ventilation home has better air quality than the other homes with much higher ventilation and infiltration because of more effective distribution of fresh air to occupied regions of the home. Leaky homes and overventilated homes are not homes with good air quality if air distribution within the home is poor.

Finally, the calculations in this section are tedious and best performed by computer simulation models. Part 4 utilizes our free-to-use, online ZEROs (Zero Energy Residential Optimization software) program to demonstrate seasonal moisture management and house humidity variations.

Making It Real – Moisture Data from Equinox House

Real world moisture data is difficult to collect over extended periods of time. Everyday, day-after-day, someone must collect condensate drained from air conditioning, heat pump ventilation and heat pump water heating systems. It is boring, tedious work, and, if you are running a study in someone else's home, it is intrusive.

For whatever reason, I seem to enjoy boring, tedious work, and over a 4 year period I collected an extensive amount of daily data from Equinox House (Figure 19), a 2100sqft ranch home located in Urbana, Illinois. An annual summary of Equinox House performance and features can be found in our publications section on our Build Equinox website. Also included in our publications is a 12 article ASHRAE Journal series authored by Ben and me on designing an economically optimized, net zero energy home.

Equinox House is my home, and serves as a test bed for Build Equinox research investigations. Among the daily data collected over a 4 to 5 year period were condensate data from air conditioning, CERV smart ventilation, heat pump water heater, and dehumidifier systems. Yes, these days of computer data acquisition would allow one to automatically log data, however, anyone with a background in automated data collection, knows that such systems require a constant vigil, maintenance, and calibration. Much of the data we collected for Equinox House (temperature, humidity, electric power usage, solar power production) was automated. Manual collection of moisture condensation data is a preferred method because it keeps one in tune with the rhythms of a house as weather changes and house activities (visitors, parties, etc) change. Daily notes written for each day are invaluable sources of information to assess reasons for "noise" in the data. Automated data tends to remove researchers from first hand knowledge of these variations.

Figures 20 through 23 present daily water condensate collection data for Equinox House for the summers of 2011, 2012, 2013, and 2014. We moved into Equinox House in the fall of 2010, and used the initial year as a "calibration" year. During the winter of 2010/2011, Equinox House was heated with two 1500W room space heaters. Using electric resistance allowed us to analyze Equinox House heat flow characteristics directly without using assumed heat pump efficiency (Coefficient of Performance) factors. During the 2011 summer season, a dehumidifier was used for moisture control, along with a CERV for fresh air ventilation and a heat pump water heater. A 1 ton, ductless minisplit heat pump was installed in Equinox House during the fall of 2011. Water condensate data for the summers of 2012, 2013, and 2014 are from the 1 ton ductless minisplit heat pump, CERV smart ventilation and heat pump water heater systems.

Equinox House is very similar to Contractor Smart's house in Urbana Illinois. Equinox House is super-insulated (in an economically optimized manner) and super sealed to 0.5ACH at 50Pa (see our ASHRAE Journal article on house sealing). The house is 2100sqft in floor area. Average ceiling height is 12ft, so the volume of Equinox House is larger than the example house. Two occupants live in the house, and both are out of the house approximately 10 hours per day (less on weekends).

Daily condensate amounts average 5 to 6 liters (kg) of water per day through the summer. Wide variations occur with some days requiring 20 to 25 liters of dehumidification while other days have none. Warm, humid weather and occupant activities both cause wide swings in dehumidification requirements. Overall, the 5 to 6 kg per day of condensate collection is in agreement with Contractor Smart's Urbana home.

Figure 19 Photo of Equinox House, a 2100 sqft ranch home that is zero plus. Equinox House is SIPs (Structural Insulated Panels) construction and is the first home permitted within an Illinois municipality to use rainwater harvesting (1700 gallon cistern). The home was built in 2010.

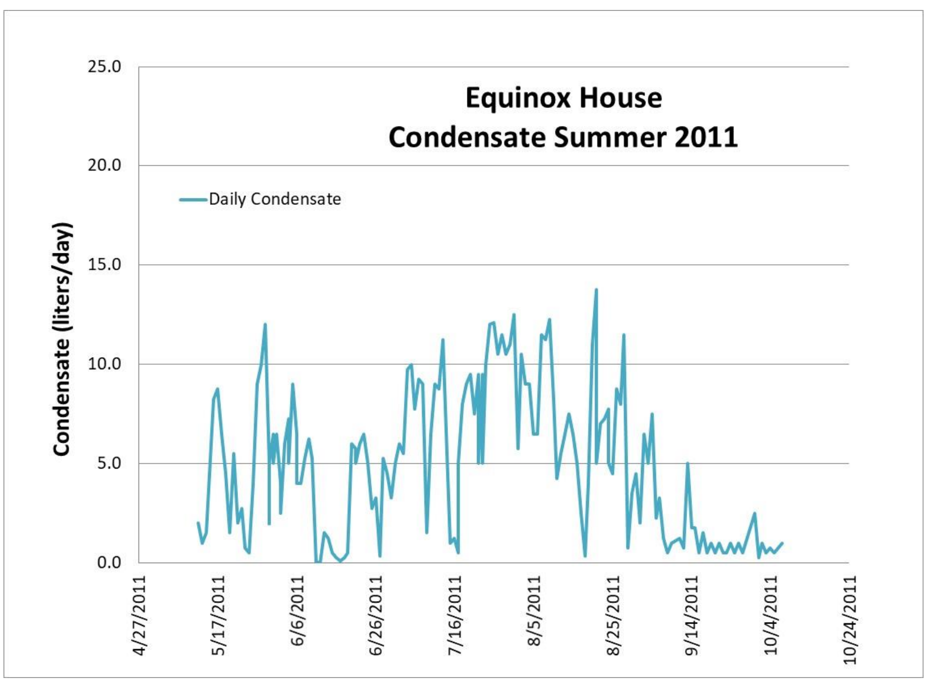

Figure 20 Daily condensate data from Equinox House for the 2011 summer season. Condensate was collected from a dehumidifier, a CERV (1st generation) smart ventilation system, and a heat pump water heater.

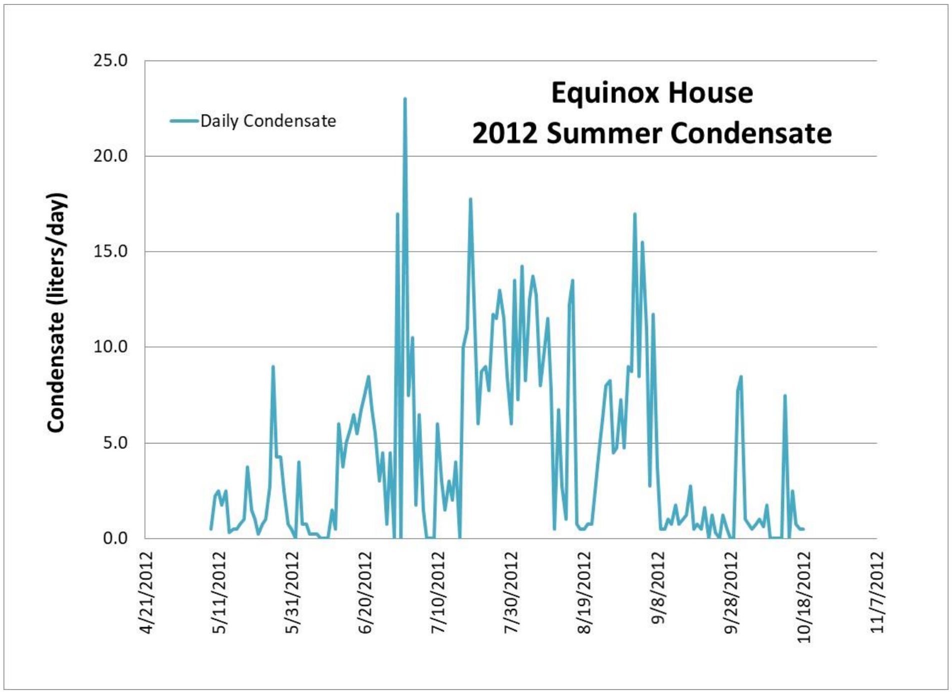

Figure 21 Daily condensate data from Equinox House for the 2012 summer season. Condensate was collected from a 1 ton ductless minisplit heat pump, a CERV (1st generation) smart ventilation system, and a heat pump water heater.

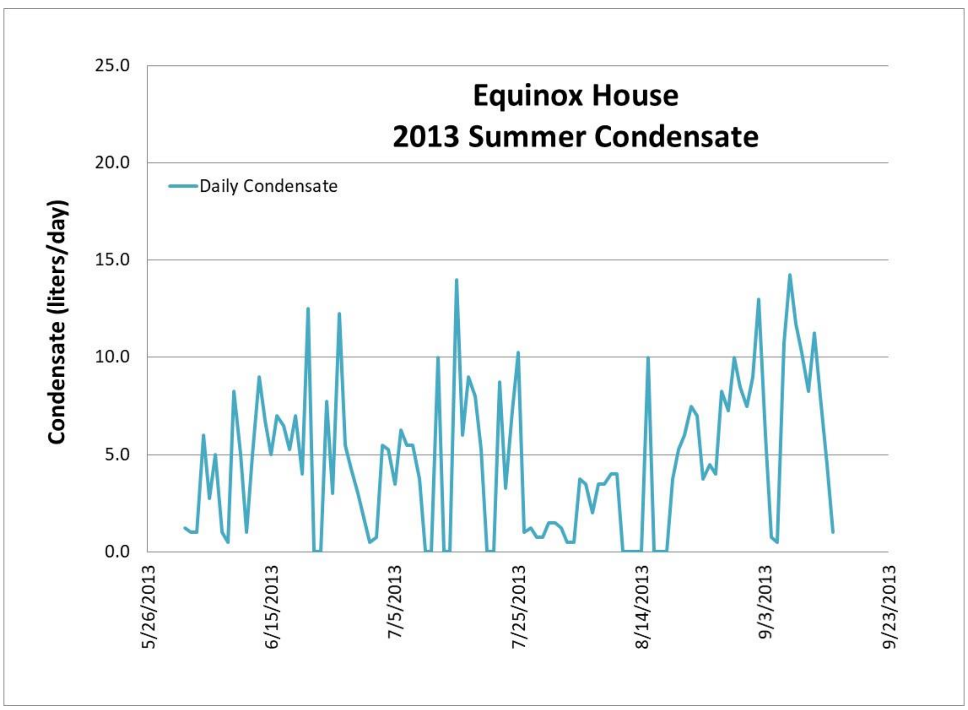

Figure 22 Daily condensate data from Equinox House for the 2013 summer season. Condensate was collected from a 1 ton ductless minisplit heat pump, a CERV (1st generation) smart ventilation system, and a heat pump water heater.

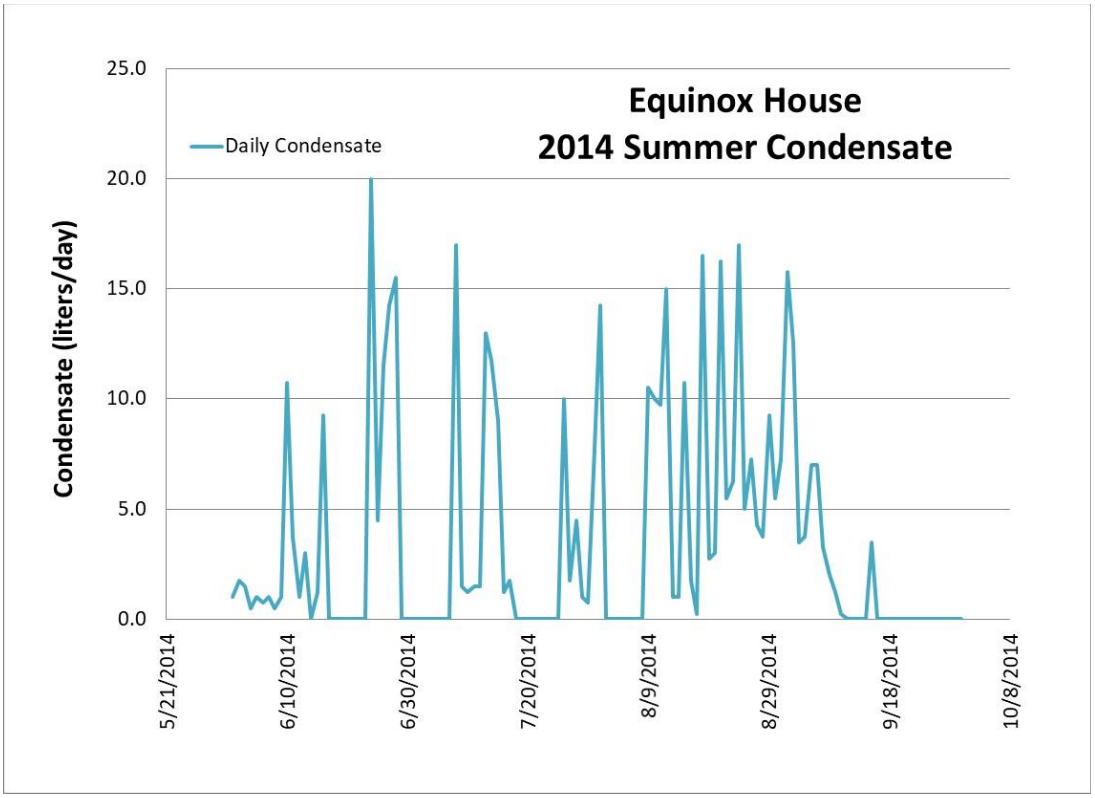

Figure 23 Daily condensate data from Equinox House for the 2014 summer season. Condensate was collected from a 1 ton ductless minisplit heat pump, a CERV (1st generation) smart ventilation system, and a heat pump water heater.

Part 1 – Summary

The objective of Part 1 is an understanding of moisture generated by home occupants coupled with moisture moving into and out of a home with infiltration and ventilation air   When outdoor humidity exceeds indoor humidity, excess moisture must be removed by some type of dehumidification process in order to maintain comfort. Dehumidification may still be desired when outdoor humidity is below indoor humidity if internal moisture generation causes significant indoor humidity increases. When outdoor humidity is significantly below indoor humidity, such as during cold winter conditions, additional moisture may be added to maintain a desired indoor humidity.

We found home occupants to add 1 to 4 kg (liquid liters) of water per day to home under typical conditions (Table 1). Human respiration, cooking, and washing are primary moisture contributors. An example problem comparing a leaky home with a tightly sealed home shows the impact of reduced infiltration on moisture during hot, humid summer conditions.

Smart ventilation significantly reduces moisture transport into and out of a home while reducing home occupant exposure to pollutants. The tightly sealed example home reduced dehumidification capacity to 1/3 of that for the same home with constant ventilation air flow. Real water condensate data from Equinox House agrees with our prediction of house dehumidification needs for our smart ventilation, well-sealed house example.

Part 2 explores climate variations in more detail to further explain the variation in dehumidification capacity needs. Part 3 supplies details on air conditioners, CERV smart ventilation, heat pump water heaters and dehumifiers abilities to manage moisture. Finally, Part 4 uses the free-to-use ZEROs (Zero Energy Residential Optimization software) to put everthing together and understand energy usage in various climates.

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