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Comparative Performance of Two Ventilation Strategies in a Hot-Humid Climate

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Comparative Performance of Two Ventilation Strategies in a Hot-Humid Climate

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

ACH 50	air changes per hour at 50 pascals of depressurization with respect to the outside
AER	air exchange rate
AHU	air handling unit
BEopt	Building Energy Optimization
cfm	cubic feet per minute
CEV	continuous exhaust ventilation
CFIS	central fan integrated supply
CFM 50	cubic feet per minute at 50 pascals of depressurization with respect to the outside
CFM 25 out/ft^2	cubic feet per minute at 25 pascals of depressurization with respect to the house per conditioned square footage
CO_2	carbon dioxide
CT	current transducer
DNPH	2,4-dinitrophenylhydrazine
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
°F	degree(s) Fahrenheit
Florida HERO	Florida Home Energy & Resources Organization
FSEC	Florida Solar Energy Center
ft^2	square feet
GCMS	gas chromatography with mass spectrometry
HCHO	formaldehyde
HPLC-UV	high-performance liquid chromatography with ultraviolet detector
hr	hour(s)
HVAC	heating, ventilation, and air-conditioning
IAQ	indoor air quality
IC	ion chromatography
LBNL	Lawrence Berkeley National Laboratory
mg	milligram(s)
min	minute(s)
mL	milliliter(s)
mm	millimeters
n.d.	no date
NIOSH	National Institute for Occupational Safety and Health
NO_2	nitrogen dioxide
NREL	National Renewable Energy Laboratory
OSHA	Occupational Safety and Health Administration
pCi/L	picocuries per liter
PFT	perfluorocarbon tracer
PM2.5	particulate matter with aerodynamic diameter less than 2.5 µm
PMCH	perfluoromethylcyclohexane
PNNL	Pacific Northwest National Laboratory
ppb	parts per billion

ppm	parts per million
RH	relative humidity
RTF	runtime fraction
RTV	runtime ventilation
SEER	seasonal energy efficiency rating
SOP	standard operating procedure
SRT	single return with transoms
T	temperature
TD	thermal desorption
TEA	triethanolamine
TVOC	total volatile organic compounds
VOC	volatile organic compounds
Wh	watt-hour
$\mu g/m^3$	micrograms per cubic meter

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Executive Summary

ASHRAE Standard 62.2, "Ventilation and Indoor Air Quality in Low-Rise Buildings," is the most commonly referenced residential ventilation standard in the United States. It is currently required by ENERGY STAR Version 3 (V3), the 2012 International Energy Conservation Code, the U.S. Department of Energy's Zero Energy Ready Home Program, many state weatherization programs, and many other home performance programs. The standard calls for ventilation levels that are perceived by some builders and contractors to cause indoor moisture issues in hot-humid climates unless mitigated by supplemental dehumidification systems, which increase overall energy consumption. Therefore, many high-performance home builders in a hot-humid climate use a supply ventilation strategy that delivers outside air only in conjunction with operation of the home's central heating and cooling system (runtime ventilation [RTV]), which results in ventilation air exchange rates that are significantly lower than ASHRAE 62.2.

In 2012 and 2013, Pacific Northwest National Laboratory (PNNL), Florida Solar Energy Center (FSEC), and Florida Home Energy & Resources Organization (Florida HERO) began a collaborative effort to evaluate the impact of two different ventilation strategies on interior comfort conditions, space-conditioning energy use, and certain indoor air contaminant concentrations. Specifically, this report compares the builder-standard RTV system to an ASHRAE 62.2-compliant ventilation system using a continuous exhaust fan. The ASHRAE 62.2-compliant system was selected to represent the most likely ventilation system builders would employ were they required to comply with the ASHRAE 62.2 requirements because it is the least cost solution in most instances. Relevant parameters were measured in 10 homes in Gainesville, Florida, along with corresponding outdoor conditions, to characterize the impact of the two differing ventilation strategies. The study design grouped the homes into two cohorts: flip-flop homes and control homes. The first cohort of homes consisted of six of the 10 homes that were flip-flopped between the two ventilation strategies approximately every two weeks. The second cohort of homes consisted of two homes that remained in the RTV configuration throughout the study period and two homes that were maintained in the CEV configuration throughout the study period. This study design allows for the effects of individual occupants, inconsistencies between the homes, as well as the impact of climate, outdoor concentrations, or other biasing variables to be identified and accounted for in the analysis.

This report provides information about the data collection method and results from more than one year of data collection during a period from summer 2013 through summer 2014. Indoor air quality was sampled in three discrete periods with the first occurring in August/September 2013 (summer 1), the second occurring in March/April 2014 (winter/mixed), and the third occurring in August 2014 (summer 2).

During summer conditions the continuous exhaust ventilation (CEV) systems resulted in approximately 9% more cooling energy use on average to maintain the desired temperature set points in the homes. Ventilation strategy was found to be among the most significant variables driving the runtime of the air conditioners. Despite the added air conditioner runtime, the resulting relative humidity (RH) was higher in the homes while under continuous exhaust, resulting in the CEV homes experiencing more hours of elevated RH (>60% and >65% RH) than while under RTV. Regression analysis showed that ventilation strategy was the most significant

variable tested in predicting hours >60% RH, and slightly less significant in predicting hours >65% RH. However, the extent and persistence of the elevated RH is variable among homes, suggesting other parameters are also impactful. In the short term, the observed elevated RH levels are not expected to cause durability problems, but they may impact occupant comfort. During the visits to the homes no signs of mold were observed, and few comfort complaints were logged. Because of the duration of the study, the long-term effect of elevated RH in these homes is unknown. Condensate collected during the summer of 2014 showed a causal relationship to ventilation strategy, and regression analysis revealed that condensate volumes are more highly correlated to occupancy. The relationship with occupancy suggests that interior moisture generation is not only a significant source of moisture; it is highly variable from day to day. Conditioned house size was also found to be significant, but in an inverse relationship; the larger the house, the less condensate was generated. One explanation is that a larger house has more capacity to buffer moisture than a smaller house.

During the mixed season between October and April, homes operated under a mix of heating, cooling, and floating space-conditioning operations. Space-conditioning and natural ventilation preferences are highly variable during this period, and analysis of limited heating data did not show a significant impact related to ventilation strategy. Ventilation strategy appears to have a statistically significant, but overall minor impact on indoor RH during the mixed period compared to the summer period, and RH trends seem to be dominated by other factors including outdoor conditions and occupant preferences.

Carbon dioxide (CO_2) data, which show higher average CO_2 levels in homes with RTV systems, indicate that such systems may generate less air exchange and less of a dilution effect than the continuous exhaust systems. However, preferences for enhanced natural ventilation during the mixed period that could counteract this effect and variable occupancy and operation of the homes do not allow a definitive conclusion to be drawn. The estimated air exchange rate (AER) calculated during the indoor air quality (IAQ) sampling periods also corroborated such trends in the winter or mixed sampling periods. Specifically, the CEV ventilation strategy resulted in 30% higher AERs than the RTV configuration in the flip-flop homes and 79% higher mechanical ventilation rates on average. However, comparing the relative increase in estimated AER to the relative decrease in CO_2 shows that an increase in AER did not consistently result in a decrease in average CO_2 concentration during the IAQ sampling periods. While concentrations of CO_2 may be variable due to occupancy or other factors, this may suggest that the CEV ventilation strategy is not in fact increasing the dilution rate in all areas of the home as much as the increase in AER might suggest.

Despite the fact that CEV systems may generate greater air exchange in some seasons, there is also some question about the unknown source of the ventilation air, and therefore the potential for a negative impact on IAQ.

Concentrations of formaldehyde, acetaldehyde, volatile organic compounds (VOCs), and nitrogen dioxide (NO_2) were determined in paired sampling periods during the summer of 2013, winter of 2013/2014, and summer of 2014. While the observed concentrations of sampled contaminants are variable among the homes and suggest the importance of occupant activities and behavior, analyses of the data indicate that increased ventilation via a continuous exhaust fan, as was employed in the CEV strategy, may not be effective in decreasing concentrations of all IAQ contaminants, consistent with the findings for CO_2. Concentrations of formaldehyde, acetaldehyde, and VOCs did not show a significant dependence on ventilation approach, despite the presumed increased ventilation achieved via the CEV method, especially in the winter/mixed season. That is, operation using the CEV method, which provides significantly higher continuous mechanical ventilation rates than the RTV method, did not significantly decrease observed concentrations of formaldehyde, acetaldehyde, and VOCs. Generally, the concentrations of VOCs and aldehydes appeared slightly higher in the RTV homes compared to the CEV homes, although in some cases concentrations were observed to increase in the CEV configuration. As a result, consistent and significant trends were not discernable from the data due to variability among the homes and between sampling periods in the same home.

This contradicts findings from previous researchers that concentrations of IAQ contaminants exhibit an inverse relationship to ventilation rate (Lajoie et al. 2015; Hult et al. 2014). The fact that the concentrations of formaldehyde, acetaldehyde, and VOCs measured in this study were variable and not correlated to a change in ventilation strategy, despite the higher ventilation rates achieved by the CEV system, suggests that other factors in addition to ventilation rate, such as ventilation system design (i.e., balanced versus supply-only versus exhaust-only and distributed versus non-distributed), may be important in determining the efficacy of a ventilation system in achieving the desired dilution effect. Hun et al. (2014) has also observed that supply-based systems may be more effective at reducing formaldehyde concentrations than exhaust-based systems. Conversely, NO_2, which was measured in two homes (one with gas cooking and one without) during each sampling period, appeared to be effectively mitigated by the CEV method. While this may suggest that for some sources of pollutants, such as those generated by cooking, the efficacy of the ventilation system may be less affected by ventilation system design, the data are not sufficient to draw definitive conclusions.

While the concentrations of acetaldehyde, VOCs, and NO_2 were far below exposure levels established by health-based exposure guidelines and are not likely to cause negative health effects at these low levels, formaldehyde concentrations were, on average, above the exposure limit of 16 parts per billion (ppb) recommended by the National Institute for Occupational Safety and Health. Future work to further explore the efficacy of different ventilation systems and disaggregate the impact of ventilation rate and system type is necessary to understand how to apply these findings in the field to achieve optimum IAQ and homeowner comfort in new homes for the least cost and lowest energy impacts.

1 Introduction

Whole-building air exchange is required to maintain healthy indoor air quality (IAQ) in residential buildings. Air exchange is intended to dilute indoor air pollutants with outdoor air with the goal of maintaining concentrations below levels that may lead to negative health impacts. Other components that make up a comprehensive strategy for IAQ include limiting materials and activities that provide the source of pollutants, and employing local exhaust in dedicated areas where high concentrations of contaminants are likely to occur (e.g., kitchens).

Several residential codes and standards require whole-building mechanical ventilation in addition to natural air exchange (Martin 2014). The various differences among these requirements, along with the lack of mechanical ventilation requirements in many state and local codes, indicate that there is some uncertainty regarding the perceived appropriate level of ventilation in different geographic or climate regions. ASHRAE Standard 62.2, "Ventilation and Indoor Air Quality in Low-Rise Buildings" (ASHRAE 2013b) is the most commonly referenced residential ventilation standard in the United States. It is currently required by ENERGY STAR Version 3 (V3), the 2012 International Energy Conservation Code, U.S. Department of Energy's (DOE's) Zero Energy Ready Home Program, many state weatherization programs, and many other home performance programs (EPA 2013; DOE 2014).

However, in a hot-humid climate, many builders of high-performance homes and their mechanical contractors have expressed concern that the ventilation rates prescribed by ASHRAE Standard 62.2-2013 call for greater amounts of whole-building controlled ventilation than what they have grown accustomed to and are comfortable with. Some state that the ASHRAE 62.2-2013 ventilation rates are too high and believe they will lead to increased energy consumption, increased risk of mold growth, and comfort concerns. While whole-building mechanical ventilation is important to maintain good IAQ, in high-performance housing, humidity control is becoming increasingly important to maintain good IAQ, occupants' comfort, and the durability of the home. Reduced sensible loads in new and existing high-performance houses call for reduced space-conditioning capacity and runtime, thereby reducing incidental dehumidification from air-conditioning operation. In addition, latent generation in high-performance homes is typically not reduced along with the sensible loads. Given this, some builders and contractors in hot-humid climate regions are concerned about the implications associated with introducing additional humid outside air via ventilation systems into new high-performance houses that have a decreased capacity to remove excess moisture.

Data directly relating the effect of mechanical ventilation to IAQ in occupied homes in a hot-humid climate are limited. Several studies have demonstrated that contaminant concentrations typically decrease with higher ventilation rates (Lajoie et al. 2015; Hult et al. 2014; Offermann 2009; Hun et al. 2014). However, Hun et al. (2014) and Rudd and Bergey (2013) have demonstrated that supply-based systems may be more effective at reducing formaldehyde concentrations than exhaust-only systems.

In practice, effective IAQ is often judged by perceptions of odor and moisture control, which have little to do with occupants' health.

Regarding the energy and comfort impacts of different ventilation strategies, the DOE Building America Program has been conducting research leading to optimization of residential building energy performance, durability, quality, affordability, and comfort for more than 15 years. Integrating whole-house mechanical ventilation has been an ongoing aspect of the program's research. Tens of thousands of homes have been constructed as part of this research, and many different approaches to whole-house mechanical ventilation have been incorporated and evaluated. Martin (2014) reviewed some of this experience and provided detailed results of simulations conducted to quantify the relationship between ventilation rate and supplemental dehumidification energy required to maintain comfort. However, few monitored data are available that compare energy use and moisture levels of differing ventilation approaches in homes in a hot-humid climate.

To balance factors related to comfort, energy use, and odor and moisture control, some builders of high-performance homes in hot-humid climates are using a supply-based whole-house mechanical ventilation strategy linked to the runtime of the central heating, ventilation, and air-conditioning (HVAC) system—often termed "central fan integrated supply" or CFIS (Chandra 2008; Rudd and Lstiburek 2008). This system has been employed since the mid-1990s and has been implemented in thousands of homes (Chandra 2008; Rudd and Lstiburek 2008). Outdoor air flow rates induced by the central system fan, and hence ventilation air volumes, have varied from 1% to more than 100% of ASHRAE 62.2-2013-required rates for continuous fan flow. Because of energy and comfort concerns, rather than delivering the outdoor air continuously—many builders that implement a CFIS whole-house mechanical ventilation system include a fan-cycling controller that enables delivery of outdoor air on a timed schedule, often 10 minutes on and 20 minutes off. Other builders have opted to only deliver mechanical ventilation during heating and cooling operation, which is termed runtime ventilation (RTV).

Some data have been collected on indoor relative humidity (RH) and space-conditioning energy use in homes with CFIS systems, but these data do not address the potential for health issues associated with ventilation provided by such systems. Kerrigan (2014) reported results from homes with CFIS systems and fan cycling controllers in a hot-humid climate, both with and without supplemental dehumidifiers (Kerrigan 2014). Some data on temperature and RH have been collected in homes using the RTV system as well. In general, surveyed homeowners have expressed satisfaction with the resulting conditions. Figure 1 shows representative data from a study conducted by Pacific Northwest National Laboratory involving 10 recently constructed high-performance homes in Gainesville (Alachua County), Florida.[1] As seen in the figure, RH is maintained well below 60% on average during months with consistent air conditioner operation. Excursions approaching and exceeding 60% are evident during swing season months that feature inconsistent and little air conditioner operation. However, the authors note that while comfort and homeowner satisfaction are important metrics for determining overall HVAC performance, they are not good indicators of IAQ because some IAQ contaminants are not easily perceived by humans at chronic levels that can be harmful to human health. RH is also elevated during the winter months with sporadic heating operation resulting in minimal mechanically induced air

[1] Widder S., and K. Fonorow. 2013 [unpublished]. "Don't Waste Your Money: The Performance of Passive Transom Returns as a Return Air Strategy in High Performance Homes."

exchange. The temperature was maintained, on average, between 71 and 76°F throughout the period studied.

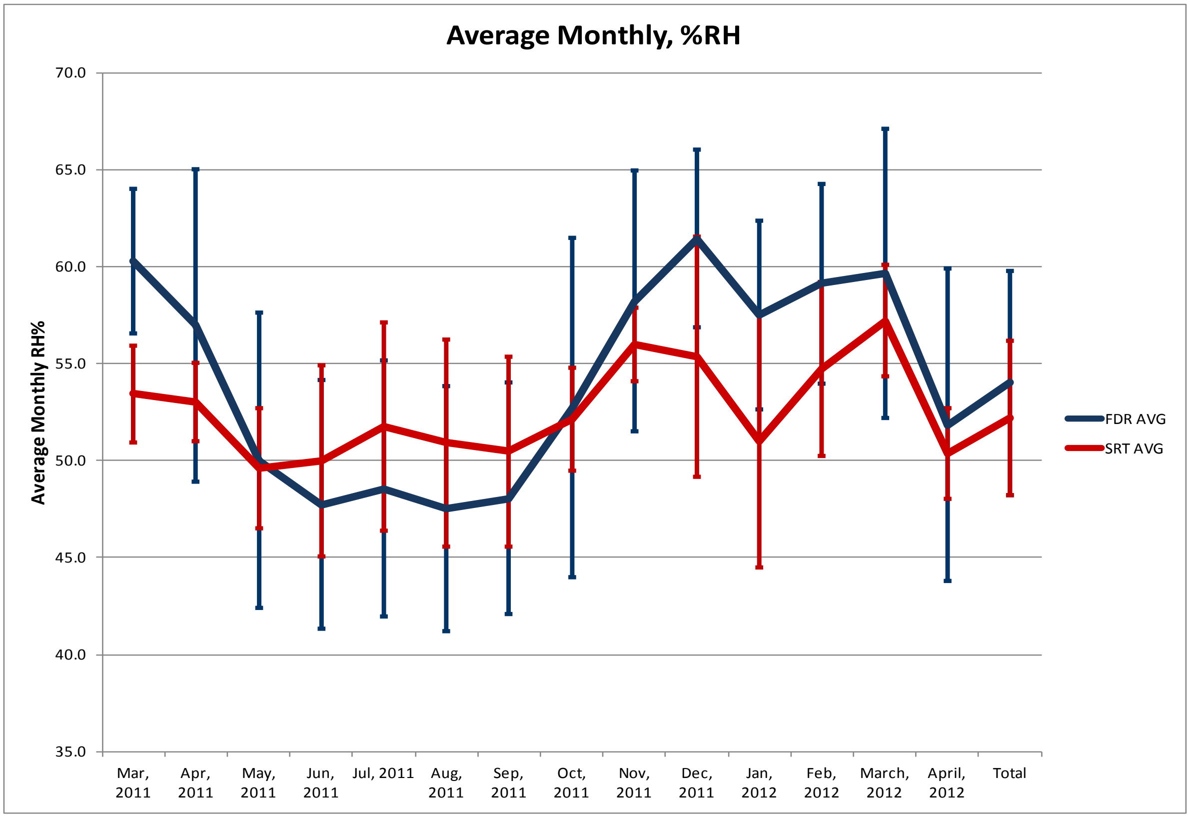

Figure 1. Average and range of monthly RH for fully ducted return (FDR) and single return with transoms (SRT) homes with the runtime ventilation system in Gainesville, Florida

This report describes a yearlong field study in which PNNL, Florida Solar Energy Center (FSEC), and Florida Home Energy & Resources Organization (Florida HERO) collected data to evaluate the impact of ventilation on energy use, interior moisture levels, and indoor air contaminant concentrations. Specifically, concentrations of indoor air contaminants, ventilation system flow rates, building infiltration rates, space-conditioning energy use and condensate generation, indoor temperatures, and RH were measured in 10 occupied high-performance homes in Gainesville, Florida, that operated with two different ventilation strategies:

- The runtime ventilation (RTV) system originally provided with the homes, which delivers approximately 16% of ASHRAE 62.2-2013 requirements annually[2] and provides an average flow rate of 35 cubic feet per minute (cfm) during heating/cooling operation.

[2] This figure was calculated based on the run time of the air handling unit and measured flow through the supply air duct; see Section 3.2.1.

- A continuous exhaust ventilation (CEV) approach that approximates ASHRAE 62.2-2013 requirements for whole-house mechanical ventilation and provides an average of 60 cfm 24 hours a day.

To achieve the target continuous exhaust flow, a bathroom exhaust fan in each home was replaced with a larger capacity fan. The study design grouped the homes into two cohorts: “flip-flop” homes and control homes. The first cohort consisted of 6 of the 10 homes that were flip-flopped between the two ventilation strategies approximately every two weeks. The second cohort consisted of two homes that remained in the RTV configuration throughout the study period and two homes that were maintained in the CEV configuration throughout the study period. This study design allowed for the effects of individual occupants and inconsistencies among homes to be mitigated by the flip-flop homes because the two ventilation strategies were compared in the same home. The design assumed that behavior and home operation are substantially the same from one week to another in each home. In addition, the control homes (RTV and CEV) allowed for the impacts of climate, outdoor concentrations, or other biasing variables impacting all the houses to be identified and accounted for in the analysis. The control house cohorts also allowed for the observation of any long-term or seasonal impacts resulting from the different ventilation strategies.

The remainder of this report describes the materials and methods, results, and conclusions from this yearlong study. Section 2 presents the methods used for data collection, including details on the study design and instrumentation. Section 3.1 describes the study results for the continuously monitored variables, including temperature, relative humidity, energy, and carbon dioxide (CO_2). Section 3.2 describes the IAQ results. Section 4 presents the key conclusions from the study and highlights opportunities for future work.

2 Materials and Methods

Precise equipment and data collection methods are required to collect robust data and reduce measurement errors. The following sections describe the study logistics, including the study location and schedule (Section 2.1) and the monitoring equipment and data collection procedure (Section 2.2).

2.1 Logistics

Space-conditioning energy use, indoor temperature, indoor RH, and outdoor conditions were monitored continuously throughout the study, which spanned the summer of 2013 and the summer of 2014. Condensate was collected during the summer of 2014 only. IAQ sampling was conducted in three paired IAQ analysis periods, designed to capture the difference between higher and lower levels of ventilation produced by the RTV systems, which are driven by space-conditioning system runtime, during different seasons in a hot-humid climate. The IAQ analysis periods occurred in August/September 2013, March/April 2014, and August 2014. The following sections describe the10 study homes in Gainesville, Florida (Section 2.1.1), the IAQ sampling schedule (Section 2.1.2), and the IAQ contaminants of concern identified for monitoring in this study (Section 2.1.3).

2.1.1 Study Location and Study Homes

Some of the 10 homes in which data were collected were selected based on occupants' participation in a previous study, while other similar homes in the same community constructed at the same time by the same builder were recruited specifically for this study. The homes were all newly occupied in 2009 and 2010, are in the same subdivision, have similar specifications, and were built to Builders Challenge 1.0 guidelines (see Table 1).[3] Most homes are single story,[4] slab-on-grade, with ductwork located in vented attics. The HVAC systems in the homes are single-stage heat pumps with a seasonal energy efficiency rating (SEER) of 15 or 16 that employ the RTV system.

Table 1. Construction Characteristics of the Study Homes

Building Envelope	Characteristics
Roof finish/attic	Medium shingle roof, radiant barrier, and vented attic
Roof/ceiling insulation	R30 blown, 10” heel truss/R19 knee walls
Wall type	2x4 16” on-center frame with ladder T and two-stud corners
Wall insulation	R-13 cellulose
Windows	Double pane, low-E (U-0.34, SHGC-0.25)
Floors	Slab-on-grade, 70% tile, and 30% carpet

[3] The Builders Challenge was a program sponsored by the U.S. Department of Energy's Building America program to promote high-performance new homes and new home builders. Since the construction of the study homes, the program has been revised and renamed it is now referred to as the Zero Energy Ready Home (ZERH) program. For more information, see http://energy.gov/eere/buildings/zero-energy-ready-home.

[4] One home has a second-floor “bonus” room.

Building Envelope	Characteristics
HVAC System	
Heating and cooling system	Air source heat pump, 15-16 SEER/9-9.6 HSPF, program. T-stat
Capacity	2.0 to 2.5 tons
Air handler location	Interior closet
Outdoor air ventilation	Runtime ventilation system, kitchen and bath exhaust to out
Ducts and location	Supply: R6 flex in vented attic; return: mix of ducted and un-ducted
Water heating	"Tankless" gas EF-0.82
Lighting	100% fluorescent
Appliances	Energy Star

A schematic of the RTV system is shown in Figure 2. The RTV system only delivers outdoor air during heating or cooling operation, and it has no provisions for enhanced humidity control beyond the standard latent capacity of the air conditioner.

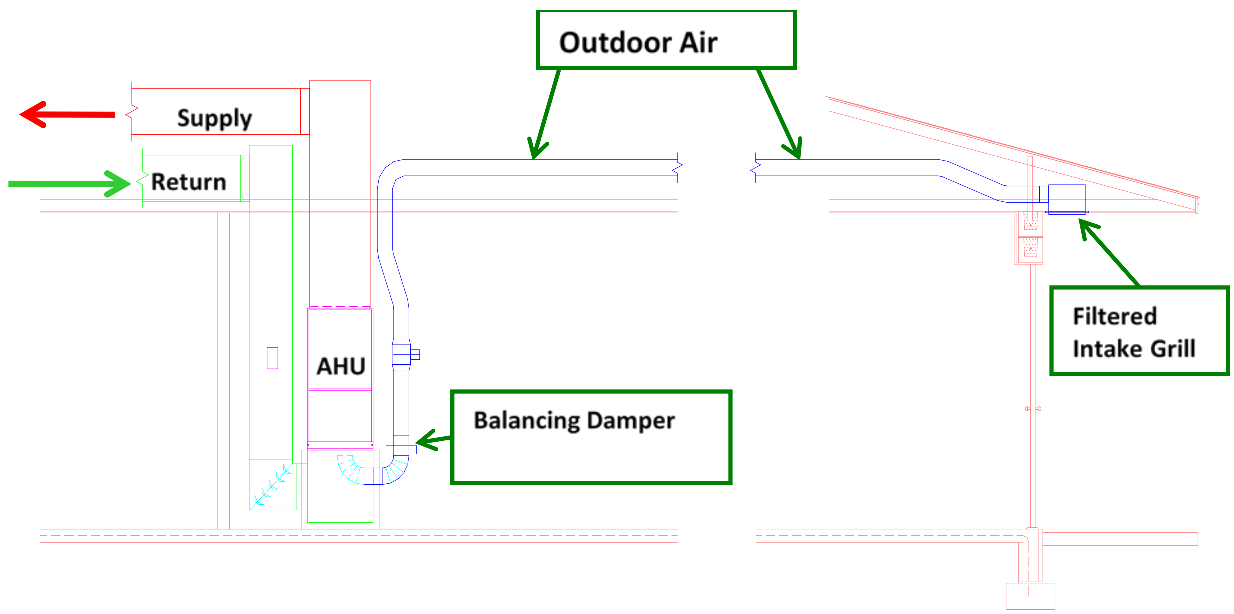

Figure 2. Schematic of runtime ventilation system

AHU = air handling unit

CEV was induced in flip-flop and CEV control homes through continuous operation of a bathroom exhaust fan. An existing bath fan was replaced with an ENERGY STAR fan, rated at 110 cfm, for this purpose, along with 6" insulated flex duct connecting the fans to the existing roof jack. Restrictions in fan ducting and roof terminations severely degraded the capacity of the newly installed fans, with installed flow rates ranging from 54 to 78 cfm[5] (see Table 2). Occupants were instructed to operate the homes and use the fans as they normally do. During periods of CEV, switch posts were installed under existing switches to control fan operation and lock them in the "on" position to prevent accidental disruption of the continuous ventilation flow by the occupants, and the RTV outdoor air flow was blocked at the intake (external to the home).

Characteristics specific to the homes, including parameters measured as part of this study are shown in Table 2. These include whether the home was part of the flip-flop group or the RTV/CEV control group, the conditioned floor area in square feet (ft^2), building air leakage in air changes per hour at 50 pascals of depressurization with respect to the outside (ACH50), relative duct leakage to the outside in terms of cubic feet per minute at 25 pascals of depressurization with respect to outdoors per conditioned square footage (CFM 25 out/100 ft^2), the steady-state RTV flow rate in cubic feet per minute (cfm), the CEV fan flow rate in cfm, the ASHRAE 62.2-2010 ventilation fan requirement in cfm, and the higher ASHRAE 62.2-2013 ventilation fan requirement. Except for one case, the ventilation rates provided by the exhaust fans in the homes achieved the ventilation required by ASHRAE 62.2-2010, but most did not achieve the flow rate required by ASHRAE 62.2-2013. Both the ASHRAE 62.2-2010 and ASHRAE 62.2013 ventilation flow rates were calculated using the infiltration credits allowed for in the standards, based on the measured infiltration rate (ACH50) of the homes.

[5] One home had a very short exhaust duct run that enabled it to achieve 78 cfm while the remainder of the homes were in 55−64 cfm range.

Table 2. Characteristics of the Study Homes

Home	Cohort	Area (ft^2)	Bedrooms	Occupants (Adult/Child)	ACH50	Qn, out	RTV Flow	Exhaust Fan Flow	62.2-2010/2013 Fan Req. (cfm)
1[a]	Flip-flop	2,158	5	2/2	5.1	3.4	40	57	67/71
2	Flip-flop	1,508	3	2/2	4.4	NA[b]	34	55	45/52
3	CEV	1,542	3	1/2	3.0	2.2	N/A	54	45/60
4	Flip-flop	1,984	4	2/0	3.4	3.0	26	55	57/73
5	CEV	1,950	4	2/2[c]	3.0	1.6	NA	59	57/75
6	Flip-flop[d]	1,679	3	2/0	3.5	1.8	42	55	47/60
7	RTV	1,878	4	2/3	3.4	1.0	35	NA	56/71
8	Flip-flop	1,508	3	1/1	2.9	1.5	39	78	45/60
9	Flip-flop	1,542	3	3/0	4.8	2.0	24	64	45/50
10	RTV	2,416	4	2/1	2.6	4.6	37	NA	62/87
	Flip-flop average	**1,730**	**3.5**	**2.0/0.8**	**4.0**	**2.1**	**34**	**61**	**51/61**
	Control average	**1,947**	**3.8**	**1.8/2.0**	**3.0**	**2.4**	**36**	**57**	**55/73**
	Overall average	**1,817**	**3.6**	**1.9/1.3**	**3.6**	**2.2**	**35**	**60**	**53/66**

[a] Home 1 dropped from the study in January 2014.

[b] Duct leakage for Home 2 was not obtained.

[c] Home 5 dropped from the study in July 2014.

[d] Home 6 became an RTV control home in June 2014.

[e] Home 8 was sold in June 2014.

Figure 3 shows the general specification for the homes results in a predicted annual source energy savings of 26% and 29% over the Building America Benchmark[6] for continuous exhaust (modeled as ASHRAE 62.2-2010) and runtime ventilation systems, respectively. Simulations were conducted using the National Renewable Energy Laboratory's (NREL's) Building Energy Optimization (BEopt) software Version 2.1.0.2.

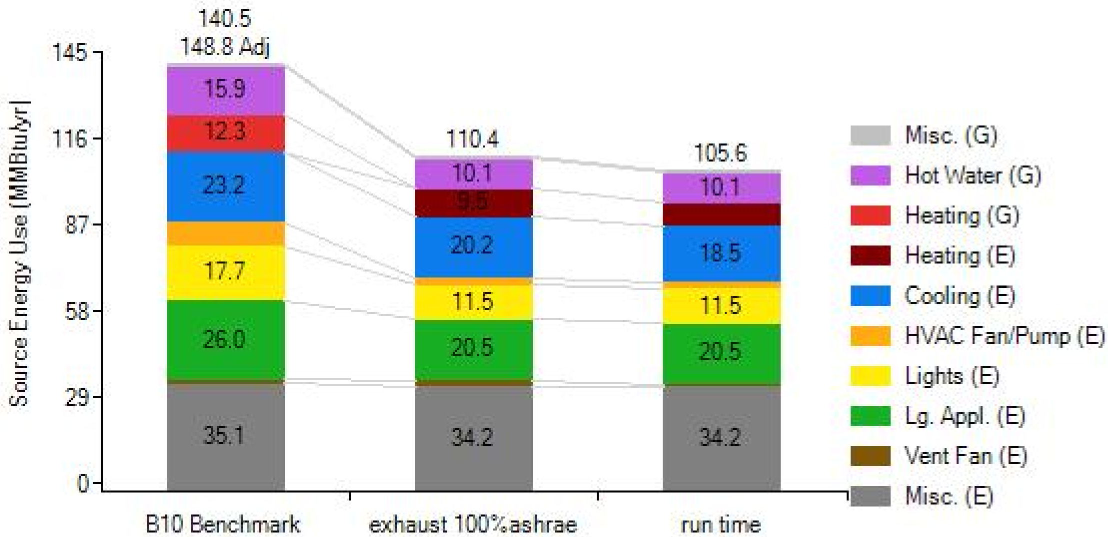

Figure 3. Whole-house source energy use predicted by BEopt software

2.1.2 Experimental Schedule

The homes were divided into two cohorts: (1) four control homes that are maintained in the same ventilation operating strategy for the duration of the study, consisting of two CEV control homes and two unmodified RTV control homes and (2) six homes that are varied, or "flip-flopped," biweekly (i.e., every other week) between CEV and RTV. The control cohort of homes provides useful data regarding the seasonality of moisture and IAQ levels in homes, and it may provide additional insights regarding any longer-term effects of increased ventilation rates. The homes that were flip-flopped enable comparison of the two ventilation systems in the same home during similar weather and occupancy periods.

Approximately once each season, in the second week of a two-week ventilation period (to enable achievement of equilibrium), IAQ sampling and tracer gas sampling took place. One-week sampling periods were chosen to characterize longer-term exposures in homes, including any weekly or daily variations. For example, different occupancy patterns on weekdays versus weekends could affect the average concentrations of constituents of concern. While the passive sampling method does not allow for quantifying the time-dependent variation of these parameters, the average long-term impact of any increased or decreased concentrations are

[6] The Building America Benchmark is consistent with the 2009 International Energy Conservation Code, with additional definitions that allow evaluation of all residential end uses consistent with typical homes built in 2010.

reflected in the weekly time-averaged sample. IAQ sampling events were planned to differentiate seasonal changes in contaminants of concern. In the flip-flop homes, two week-long sampling periods were necessary for each sampling event to measure differences between continuous exhaust and runtime ventilation. In the side-by-side homes, each week-long sampling period could be compared to give an indication of the consistency of measured concentrations within each season in addition to the comparison between seasons.

This study evaluated radon concentrations on an annual basis to provide better resolution of the low levels of radon expected in the moderate risk area of Alachua County, where Gainesville, Florida, is located. To characterize the presence of mold or moisture-related problems, homes were visually inspected for mold and mildew during each IAQ sampling event and interior RH levels were continuously monitored throughout the study period.

2.1.3 IAQ Contaminants of Concern

The contaminants of concern in this study were chosen to characterize the IAQ in residential homes in Florida. Indoor air pollutants are introduced by a range of sources, including building materials or activities within the building, mold growth, combustion appliances, and outdoor pollutants (Spengler and Sexton 1983). Building-related pollutant sources consist of cleaning products, paints, adhesives, carpets and fabrics, pesticides, and synthetic building materials (Spengler and Sexton 1983; Weschler and Nazaroff 2008). The indoor air pollutants most commonly associated with building materials and building-related activities are formaldehyde and volatile organic compounds (VOCs) (Dales et al. 2008). A recent meta-analysis by Lawrence Berkeley National Laboratory (LBNL) identified 15 pollutants as chronic hazards in more than 50% of homes studied and 9 as priority pollutants in U.S. homes (Logue et al. 2010). The priority pollutants identified are select total volatile organic compounds (TVOC; acrolein, benzene, 1,3 butadiene, 1,4-dichlorobenzene, napthalene), formaldehyde and acetaldehyde, nitrogen dioxide (NO_2), and fine particulate matter (PM2.5). The concentrations of these contaminants are compared to relevant standard levels in Figure 4. In addition, radon and mold have been identified as constituents of concern in some climates (Committee on Health Risks of Exposure to Radon [BIER IV] 1999; Tsongas 2009).

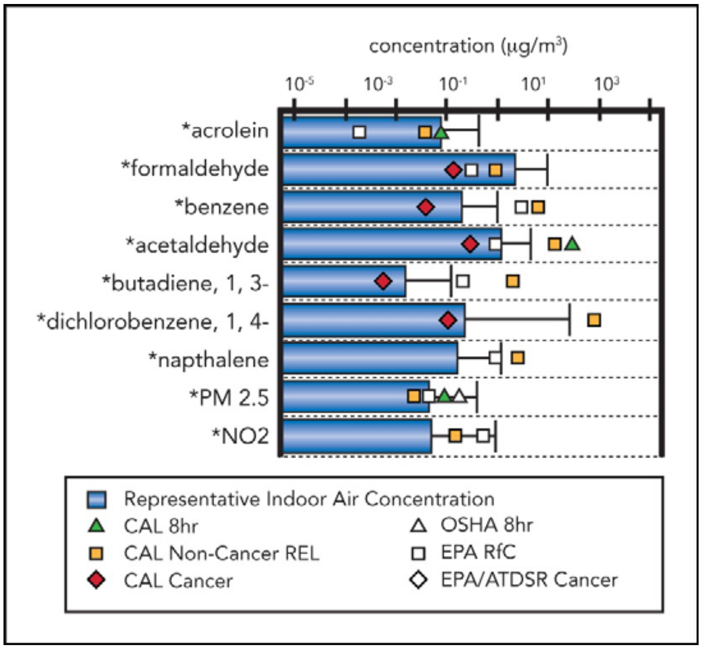

Figure 4. Nine priority pollutants in U.S. homes

Source: Logue et al. 2010

Higher levels of ventilation are expected to lower concentrations of pollutants that mostly originate from indoor sources via dilution, and many pollutants exhibit an inverse relationship to increased ventilation rate (i.e., $1/ACH_n$) (Lajoie et al. 2015; Hult et al. 2014). However, research has also shown that formaldehyde exhibits a nonlinear, or concentration-dependent, emission rate, whereby increased ventilation rates do not decrease concentrations as much as would be expected based on the increased dilution rate (Hult et al. 2014). In addition, the degree to which increased ventilation air reduces concentrations of some contaminants has been shown to be dependent on the ventilation system type, particularly with respect to formaldehyde concentrations (Hun et al. 2014; Offerman 2009; Rudd and Bergey 2013).

2.2 Monitoring Equipment and Methodology

Table 3 lists the various measurement parameters, measurement equipment, and sampling rates for the environmental, energy, and IAQ metrics.

Table 3. Data Collection Details

Measurement	Equipment Used	Sampling/Storage Interval
Initial Baseline Measurements		
Infiltration (CFM 50)	Blower door	Initial baseline
Runtime ventilation supply airflow (cfm)	Exhaust fan flow meter	Initial baseline
Exhaust fan flow (cfm)	Exhaust fan flow meter/powered flow	Initial baseline

Measurement	Equipment Used	Sampling/Storage Interval
	hood	
Continuously Monitored Parameters		
Total energy (Wh)	eMonitor (current transducer [CT])	Hourly
Air handler energy (Wh)	eMonitor (CT)	Hourly
Condenser energy (Wh)	eMonitor (CT)	Hourly
Bath fan circuit power (Wh)	eMonitor (CT) or U-12 HOBO (CT)	Hourly
AC condensate (mL/hr)	HOBO Rain Gauge - RG3	Hourly
Space temperature and RH (4 interior locations)	(1) Extech[a] T/RH/CO_2, (3) U-10 HOBOs	15 min
Outdoor temperature and RH	Extech T/RH/CO_2	15 min
Interior CO_2 (ppm)	Extech CO_2/T/RH	15 min
Outdoor CO_2 (ppm)	Extech CO_2/T/RH	15 min
Seasonally Sampled Parameters		
Formaldehyde (ppb)	Passive sorbent badge[b]	Weekly, four events/year
Acetaldehyde (ppb)	Passive sorbent badge[b]	Weekly, four events/year
VOCs (ppb)	Passive sorbent badge[b]	Weekly, four events/year
NO_2/nitrogen dioxide (ppb)	Passive sorbent badge[b]	Weekly, four events/year
Infiltration (ACH)	Perfluorocarbon Tracer (PFT)[b]	Weekly, two events
Mold[c]	Visual inspection	Every other week with ventilation flip-flop events
Radon[d]	Charcoal passive badge	Once—duration of study

[a] The Extech device uses infrared technology to measure CO_2.

[b] Passive infiltration and IAQ samplers were mailed to a laboratory for analysis. Analysis was performed using standard U.S. Environmental Protection Agency protocols for the identification of volatile organics (TO-17) and formaldehyde/acetaldehyde (TO-11A).

[c] Mold was sampled sporadically (i.e., it was observed every other week on flip-flop visits and especially in conjunction with the IAQ surveys prior to IAQ sampling events).

[d] Radon was sampled once with a passive measurement that extended through the duration of the study period (June 2013–June 2014).

IAQ sampling occurred at one to three indoor locations indoors in each home and at one outdoor location during each sampling period. Outdoor samples were collected in an open area, away from large trees, above the ground, and in areas sheltered from the elements. Indoor samples were collected in a commonly used room, usually the living room, as well as the master bedroom, a bedroom located farthest away from the return air grille, or both bedrooms.

Details about the sample collection methodology are discussed below. A detailed sampling protocol is included in Appendix A. A field data sheet is included in Appendix B. Quality assurance and quality control procedures are included in Appendix C. A table summarizing samplers, sensitivities, detection ranges, accuracy, and relevant standard levels is included in Appendix D. For additional information about the IAQ sample analysis, refer to the Laboratory Analysis Summary in Appendix F. Analysis of TVOC, formaldehyde (HCHO), NO_2, and perfluorocarbon tracer (PFT) sample badges was conducted at ALS Laboratory Group (formerly DataChem Laboratories, Inc.), an American Industrial Hygiene Association-accredited laboratory, using the methods described below.

2.2.1 Whole-House Mechanical Ventilation Fan Flow Rate

All mechanical ventilation fan flow measurements occurred as a one-time measurement during the initial audit. The Energy Conservatory Exhaust Fan Flow Meter was primarily used to measure mechanical ventilation flows in the homes. The accuracy of the device was initially a concern, especially considering the small flows being measured in this study, typically around 30–70 cfm. So, during the audit of the 10 homes, results were periodically spot-checked with a powered flow hood, which has been shown to yield improved accuracy (Wray et al. 2002). The powered flow hood apparatus consists of a FlowBlaster Capture Hood, a DG-700 Digital Pressure Gauge, and a DuctBlaster fan, all produced by Minneapolis Blower Door. Results obtained with both measurement techniques yielded appreciable similarities, especially considering the variable wind conditions.

2.2.2 Building Envelope and Duct System Performance

Building envelope leakage testing was conducted during the initial audit using a Minneapolis Blower Door apparatus in accordance with ASTM E779, "Standard Test Method for Determining Air Leakage Rate by Fan Depressurization" (ASTM 2010).

Duct leakage testing was conducted during the initial audit using a Minneapolis Duct Blaster apparatus in accordance with ASHRAE 152, "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems" (ASHRAE 2004). The test determines total duct leakage and duct leakage to the outside by measuring the quantity of air required to reach a depressurization of −25 pascals with respect to outside air.

2.2.3 Air Exchange Rate

The air exchange rate (AER) is a measure of total air movement into or out of the house, including natural infiltration/exfiltration and mechanical ventilation. The AER was determined based on perflouromethylcyclohexane (PMCH) tracer gas measurements. PMCH emitters, consisting of a 2-dram (7.5-mL) glass vial filled with PMCH, were placed throughout the home (approximately three emitters per home). The emitter was placed right side up in the air distribution pathway to encourage mixing. Each vial septum cap was modified to provide the same amount of diffusion through each cap and maintain emission rates throughout the week. The emission rate of the PMCH emitters has been preliminarily determined in the laboratory to be approximately 1 milligram per hour (mg/hr), and it is determined in the field by weighing the emitters before and after each week-long IAQ sampling event, as well as over time. The PMCH samplers are passive charcoal badges that have been verified in the laboratory to have a sampling rate of 10.2 milliliters per minute (mL/min) and a sensitivity of 6.7 parts per billion (ppb). Analysis occurred through an accredited laboratory (DataChem/ALS Laboratories) via gas chromatography with mass spectrometry (GCMS).

2.2.4 Electric Energy Use

Whole-house electricity use, as well as disaggregated energy use consisting of air handler, condenser, water heater,[7] clothes dryer, and bath fan circuit were monitored using the Powerwise 14-channel eMonitor4-14 home energy monitor, which relies on circuit transducers (CTs) to directly measure current. Voltage was measured on one phase of the split-phase systems. The eMonitor stores data at a frequency of one minute and collects data based on a user-specified setting. Data were stored on the eMonitor and transferred to a data collection gateway via a wireless 2.4-GHz signal. The gateway uploads the data to a server via the home's internet connection. The data from the eMonitor server was accessed and archived by FSEC's Infomonitors system. Energy-use data were stored on an hourly basis for this study.

2.2.5 Temperature and Relative Humidity

Temperature and RH were measured primarily using HOBO U12-011 loggers,[8] which record temperature and RH in the ranges expected in homes: −4°F to 158°F and 5% to 95% RH, respectively. The accuracy of the HOBO U12-011 over the range of interest is ±0.35°F and 0.3% RH, which is more than sufficient to resolve differences resulting from changes in ventilation rate. The meters were set up to sample every 15 seconds and average over 5 minutes, or 20 measurements. The meters measure and record data every 15 minutes. HOBO data were downloaded every two weeks and loaded into the FSEC Infomonitors system for archiving and analysis.

Each home was equipped with three HOBO loggers: one near the main return, one in the master bedroom, and one in another bedroom. A Lacrosse TX-60U-SET online wireless temperature and RH sensor was also temporarily employed in the main living space to provide near real-time, hourly data for temperature and RH and to help monitor whether RH levels and home conditions were within acceptable ranges. Data collected by the Lacrosse sensor proved to be unreliable and were not used for analysis purposes.

Each home also had a combined CO_2/T/RH data logger, discussed below. A model center home in the community hosts a CO_2/T/RH data logger on its exterior that monitors outdoor conditions. Weather data from the Gainesville Regional Airport (KGNV) were also processed through the FSEC Infomonitors system and were available for analysis.

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[7] The electricity use of the "tankless" gas water heaters is measured. Gas use is not measured.
[8] http://www.onsetcomp.com/products/data-loggers/u12-011

2.2.6 CO_2 Measurement

The Extech SD 800 CO_2/Humidity/Temperature Datalogger[9] was used to continuously record temperature, RH, and CO_2 throughout the measurement period. The CO_2 sensor is a non-dispersive infrared sensor with an accuracy of ±5% of the reading for concentrations greater than 1,000 parts per million (ppm) and ±40 ppm for concentrations less than 1,000 ppm, and it is capable of resolving CO_2 concentrations from 0 to 4,000 ppm, which is appropriate for the expected outdoor and indoor concentrations of 380 to 2,000 ppm and the expected variation in CO_2 resulting from changes in ventilation strategy.

One Extech data logger was placed in the main body of each home. One of the homes also hosted an Extech on the back porch for an outdoor measurement. Data were downloaded from each Extech data logger every two weeks, and they were processed through the FSEC Infomonitors system for archiving and analysis.

2.2.7 Condensate Measurement

Condensate was measured by tipping bucket rain gauges with the number of tips stored to a HOBO data logger (HOBO Pendant Event Data Logger - UA-003-64). Using the event logger memory capacity created difficulties because it would reach its limit within about a week to 10 days depending on the volume of condensate measured. This resulted in periods of lost data.

The rain gauges can be prone to clogging from debris in the condensate water. Condensate was directed through a loose filter material to reduce backups, but clogs did occur in two cases resulting in lost data.

2.2.8 Total Volatile Organic Compounds

Sampling of speciated VOCs was accomplished using the SKC Ultra III sorbent badge[10] with Carbograph 5 thermal desorption (TD) sorbent. SCK Ultra III sorbent badges operate on a passive air transfer and diffusion mechanism to deposit the constituent of concern on the sorbent. Carbograph 5 was selected as the sorbent based on previous research by Coyne et al. (n.d.), who evaluated the Ultra III passive sampler with Carbograph 5 sorbent for a suite of VOCs as compared to canisters, 226-01 charcoal sorbent tubes, and 575-001 sorbent badges (Coyne et al. n.d). This work has shown sensitivity of 0.027 to 0.4 micrograms per cubic meter (µg/m3), depending on the compound and accuracy that is similar to that of sorbent badges over a seven-day period. Sampling rates are determined for each compound experimentally (Coyne et al. n.d.). Analysis was performed using GCMS in accordance with the U.S. Environmental Protection Agency's (EPA's) TO-17 method to identify and quantify the full suite of VOCs (EPA 1999b).

2.2.9 Formaldehyde and Acetaldehyde

Formaldehyde and acetaldehyde sampling was conducted with a UMEx 100 passive sampler,[11] which uses tape treated with 2,4-dinitrophenylhydrazine (DNPH) for collection of formaldehyde and other aldehydes. These passive samplers can measure formaldehyde concentrations as low

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[9] http://www.extech.com/instruments/product.asp?catid=7&prodid=628
[10] http://www.skcinc.com/prod/690-101.asp
[11] http://www.skcinc.com/prod/500-100.asp

as 0.2 ppb for a seven-day sampling period, although the sampling rate has not been evaluated experimentally over seven days. Analysis was performed using high-performance liquid chromatography with an ultraviolet high-performance liquid chromatography with ultraviolet detector (HPLC-UV) in accordance with EPA IP-6C, "Determination of Formaldehyde and Other Aldehydes in Indoor Air using Solid Adsorbent Cartridge" (EPA 1990) and EPA TO-11A, "Methods for Determination of Formaldehyde in Ambient Air" (EPA 1999a). Duplicate formaldehyde sampling occurred for the first one-week IAQ sampling period using the Waters Sep Pak XPoSure sampler, which also employs DNPH-coated silica as the sampling media. Analysis was performed using HPLC at LBNL. However, duplicate sampling was not repeated for subsequent sampling periods.

2.2.10 Nitrogen Dioxide

For NO_2 measurement, samples were taken using an SKC Inc. UMEx 200 passive sampler[12] treated with triethanolamine (TEA). The passive NO_2 sampler has been validated between 0.4 ppm and 8 ppm but only for periods up to eight hours (Kuhlman and Zovack 2013). The accuracy of the sampler is ±30%. The sampler was then sent to an accredited laboratory for analysis by solvent extraction ion chromatography (IC) with conductivity detection. During all sampling periods, NO_2 sampling only occurred in two homes: one with gas cooking and one without gas cooking. An outdoor sample was also collected.

2.2.11 Radon

For radon sampling, passive radon detectors were used. The passive samplers employ the charcoal liquid scintillation method with a diffusion barrier to maintain relatively constant radon diffusion rates over the long-term sampling period. The mechanism for liquid scintillation measurement is described by Prichard and Marien (1985). Radon analysis occurred at ProLab Inc., the manufacturer of the radon detectors.[13]

Radon sampling occurred on a long-term basis and was deployed during the first sampling event and was collected after a little more than one year (60 weeks) of passive sampling after the end of the last IAQ sample period. Long-term sampling was selected because it would increase the sensitivity and accuracy of the radon measurements at low levels, which were expected due to the moderate radon risk in Alachua County (where Gainesville is located). Moderate radon risk is associated with predicted average indoor radon screening levels between 2 and 4 picocuries per liter (pCi/L).

2.2.12 Mold

The presence of mold was assessed based on visual inspection biweekly during the visit to flip-flop ventilation rates in the flip-flop homes (six homes in the second cohort) and during every IAQ event in the side-by-side homes (four homes in the first cohort).

[12] http://www.skcinc.com/prod/500-200.asp
[13] http://www.prolabinc.com/radon-test-kits2.asp

2.2.13 Homeowner Surveys

The purpose of the homeowner surveys was to determine activities that may affect IAQ that occurred during sampling and address general homeowner comfort and satisfaction. The homeowner survey consisted of three sections:

1. An initial HVAC questionnaire that was to be administered once at the beginning of sampling to gauge homeowners' existing perceptions of their comfort and HVAC system performance
2. A follow-on HVAC questionnaire that was to be administered following every change in ventilation approach
3. An IAQ supplement that was to be administered following every IAQ sampling period.

A complete copy of the homeowner survey is included in Appendix E. The questions included in the Indoor Air Quality Supplement were used primarily to identify and document activities conducted in the homes that may affect the IAQ sample collection or results and yield unrepresentative information. Homeowners were also given information prior to every IAQ sampling event regarding any prohibited activities that should be avoided during and immediately prior to the IAQ sampling events.

3 Results and Discussion

The results from this study are presented as continuously monitored parameters (Section 3.1) and seasonally sampled parameters (Section 3.2). Specifically, Section 3.1 presents the energy use, temperature relative humidity, and CO_2 results, while Section 3.2 discusses the IAQ results.

3.1 Continuously Monitored Parameters: Energy Use, Temperature, Relative Humidity, and Carbon Dioxide

Data collected during the yearlong monitoring period spanning June 2013 to June 2014 have been broken into different periods for analysis: summer 2013 (6/24/2013–10/15/2013), mixed (10/16/2013–4/16/2014), and summer 2014 (4/17/2014–6/24/2014). Figure 5 characterizes the weather conditions in Gainesville, Florida, during the yearlong monitoring period; the plot in the figure is shown in a larger format in Appendix G. Average daily outdoor dry bulb temperature is shown along with average hourly outdoor dew point temperature. Both parameters remain relatively constant throughout the first summer period, with a peak occurring around August 20. After this peak, outdoor dry bulb and dew point temperatures begin to trend downward, and they become increasingly variable toward the end of October. Also shown in Figure 5 is the average indoor dew point temperature among the flip-flop homes. Red indicates periods when these homes were operating with CEV, and blue indicates periods when these homes were operating with RTV. During the first summer, the indoor dew point data, in general, show lower moisture content inside the homes than that found outdoors. This is because the air-conditioning system removes much of the moisture introduced through both air exchange and internal generation. While indoor dew point can be seen as somewhat influenced by outdoor dry bulb temperature driving the runtime of the air conditioner, an overall trend is apparent showing lower average indoor dew point temperatures during RTV than during continuous exhaust.

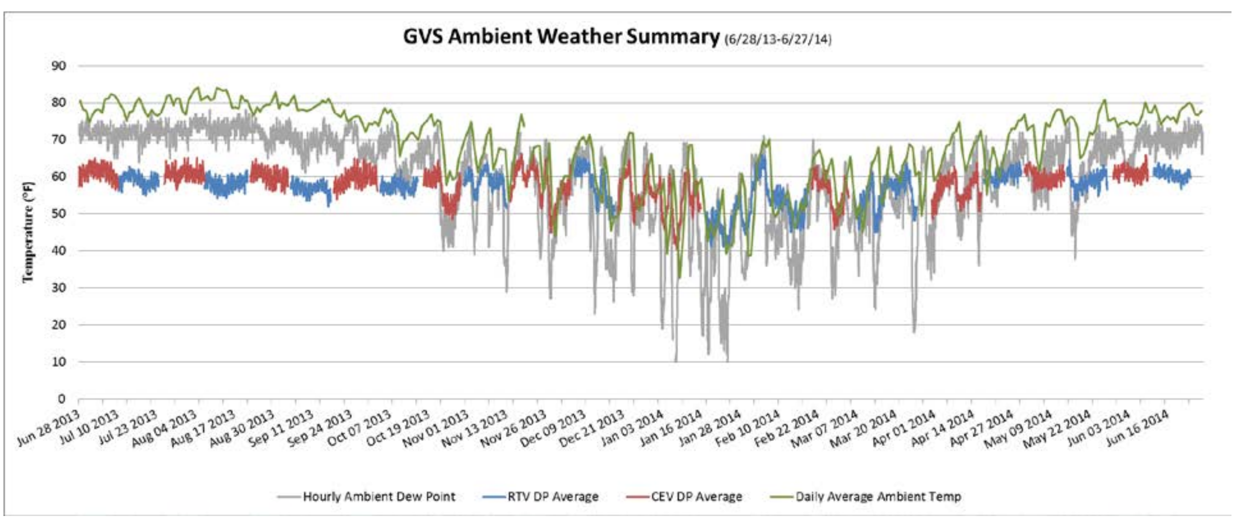


Figure 5. Outdoor dry bulb and dew point temperatures from the local National Weather Service station and average indoor dew point temperature among the flip-flop homes

Red indicates continuous exhaust (CEV in the figure) configuration and blue indicates the runtime ventilation (RTV in the figure) configuration.

As the summer cooling season concludes toward the middle of October, indoor dew point is observed to be largely influenced by outdoor dew point, with no noticeable influence by ventilation strategy. This trend continues through the “mixed” period of late October through mid-April, when homes operate under an intermittent mix of heating, cooling, and floating space conditioning. By the beginning of May, the trends observed the previous summer return for the summer of 2014. Appendix H contains plots for each home illustrating variations in indoor and outdoor conditions for the yearlong monitoring period.

3.1.1 2013 Cooling Season Data and Analysis (6/28/13–10/15/13) [14]

As seen in Appendix H, individual homes show generally similar RH response to the different ventilation strategies. In general, homes operating under RTV show lower average RH, with less variation, than homes operating under CEV. RH is maintained, on average, below 60% under both ventilation configurations, but intermittent episodes exceeding 65% RH are more common under CEV. Figure 6 shows the number of hours during the 2013 summer period each of the homes spent in specific RH ranges (<60%, 60%−65%, and >65%), broken into the two ventilation periods. The left bar for each home shows the hours during the RTV periods and the right bar shows the CEV periods. The total number of hours varies among homes and periods because logistics prevent the flip-flop homes from all being switched over on the same day. Data have also been removed from this plot and all subsequent analysis representing extended vacation periods (Home 5 and Home 6) and air conditioner failures/repairs (Home 1 and Home 10). In Figure 6, control home data have also been broken into two periods representing the average date ranges the flip-flop homes spent in each ventilation configuration. In general, the hours that are >60% for the control homes are two times greater in the continuous exhaust (right bar) periods than in the RTV periods (left bar). The increase largely occurs in the hours between 60% and 65% RH, and it could be explained by slight differences in average outdoor dew point between the periods. However, the flip-flop homes log significantly more hours >60% RH during the continuous exhaust periods than the RTV periods, including in hours >65% RH.

Also displayed in Figure 6 are average interior temperatures, which are seen to vary slightly among the periods in some homes. To isolate the influence that ventilation strategy has on RH, a multivariable regression was performed. Ventilation strategy was found to be the most significant driver of hours >60% RH, with CEV adding 3.7 hours per day >60% RH on average, and nearly one hour per day >65% RH. Other parameters found to be significant at the 99% level or better include indoor/outdoor temperature difference (which is an indicator of air conditioner runtime), outdoor dew point, conditioned house size, and ACH50.

[14] Temperature and RH data collected from the HOBO in the main bedroom are used for this analysis because the HOBOs near the return grilles in the main body of a few homes showed periods of unexplainably high RH. These HOBOs were later moved to be adjacent to the homes’ thermostats.

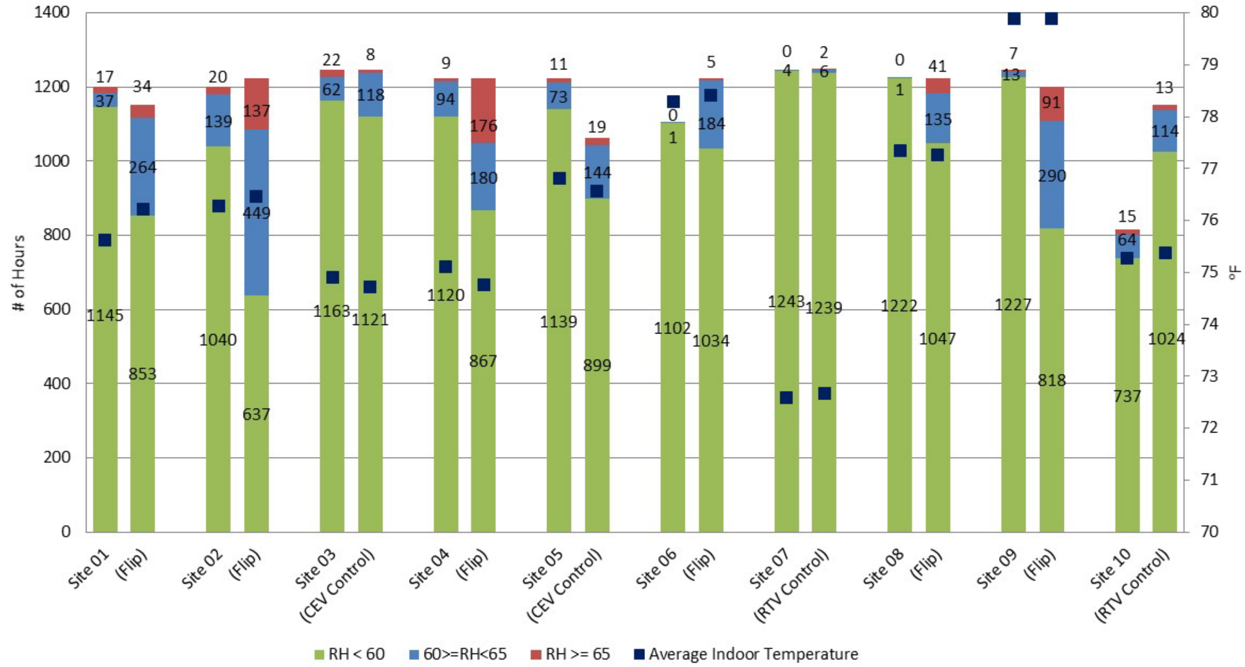


Figure 6. Distribution of hours at various percent (%) RH ranges during summer 2013, broken into runtime ventilation (left bar) and continuous exhaust ventilation (right bar) periods, each corresponding to the left axis

Numeric data labels correspond to hours, and black squares correspond to average indoor temperature (on the right axis). Home 3 and Home 5 always operate with continuous exhaust ventilation, and Home 7 and Home 10 always operate with runtime ventilation.

Figure 7 shows the average daily cooling energy use per day for each of the homes, broken into the different ventilation periods. This energy use includes both the air handler fan and the compressor, but it does not include bathroom exhaust fan energy for the continuous exhaust condition. With the exception of Home 10, whose trend is unexplained, the control homes (Homes 3, 5, 7, and 10) show little variation in cooling energy use among the periods. The flip-flop homes, however, show greater cooling energy use during the CEV period indicating as expected that the additional ventilation places additional load on the air conditioner.

There is no correlation between minor differences in average indoor temperature between the periods in a given home (black squares in Figure 6) and differences in average daily cooling energy between the periods in a given home. However, the thermostat set points are a driver of differences in cooling energy use among homes. To remove the influence of differing indoor and outdoor temperatures from the comparison of cooling energy between the two ventilation strategies, Figure 8 plots average daily cooling energy versus average daily outdoor and indoor temperature difference for the flip-flop homes. Similar analysis has been used to compare the performance of various highly efficient homes to conventional counterparts (Chasar et al. 2006). In this plot, each data point represents a single day. The x-axis coordinate is the difference between average outdoor temperature for the day and the average indoor temperature averaged for the flip-flop homes for that day. The y-axis coordinate is the average of the total cooling energy use for each flip-flop home for that day. Assuming the area under each line is directly proportional to cooling energy use, the flip-flop homes use approximately 9% more cooling energy while operating under CEV, over the delta temperature range of -4°F to 6°F.

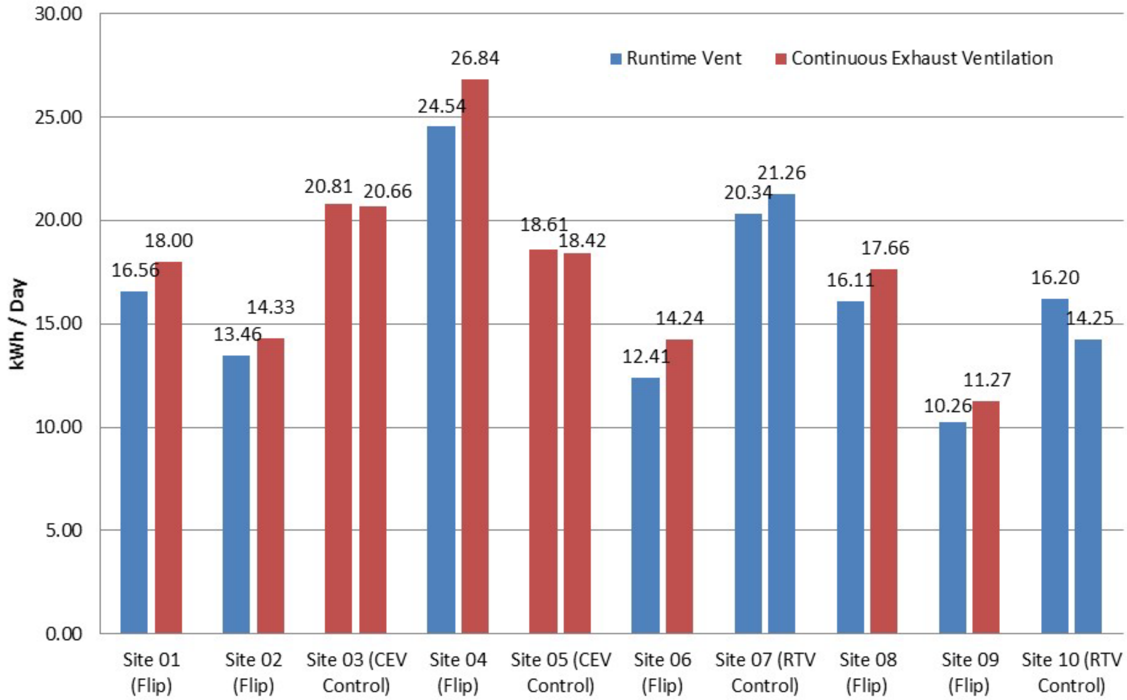


Figure 7. Average cooling energy use per day, broken into runtime ventilation (left bar) and continuous exhaust (right bar) periods

Home 3 and Home 5 always operate with continuous exhaust, and Home 7 and Home 10 always operate with runtime vent.

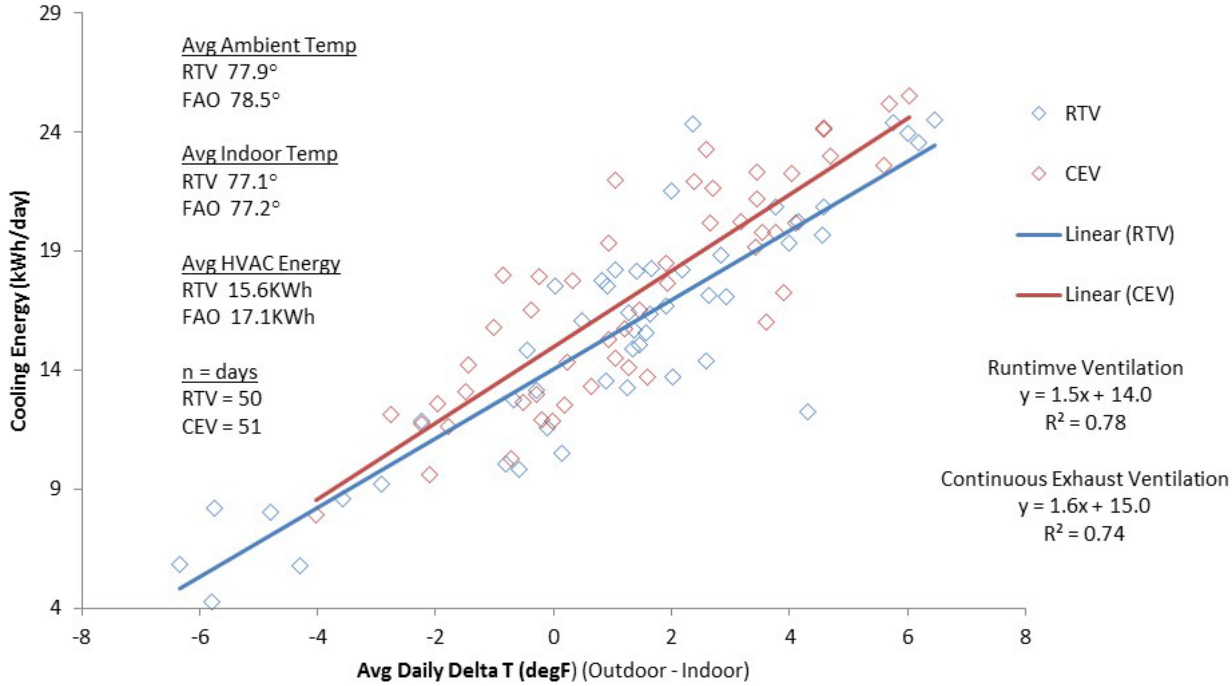


Figure 8. HVAC energy use as a function of differences in indoor and outdoor temperatures

To further isolate the effect of ventilation strategy on cooling energy use, a multivariable regression was performed with data from all flip-flop and control homes. While air conditioner runtime and conditioned house size were found to be the most significant variables affecting cooling energy use, ventilation strategy was also found to be significant at the 99% level, with CEV adding 2 kilowatt-hours (kWh) of cooling energy per day on average. Outdoor dew point and ACH50 were also found to be significant variables at the 99% level.

The general trend for the continuous exhaust configuration to result in greater cooling energy use and slightly higher dew point temperatures is seen in Figure 9, which displays a representative average day profile for the flip-flop homes operating under the two ventilation configurations. This plot is generated by averaging hourly data for all flip-flop homes while in each of the two configurations. Much of the difference in cooling energy occurs during the daytime hours, when outdoor temperatures are at their warmest. By 12 p.m., the extra load placed on the systems by the CEV strategy has enough of an effect on air conditioner runtime that the indoor dew point (red squares in the figure) begins to trend downward, while the indoor dew point in the RTV homes (blue triangles in the figure) continues to trend upward. Around 5 p.m., thermostats are set back, and indoor dew point is seen to steadily decrease in both the CEV and RTV cases.

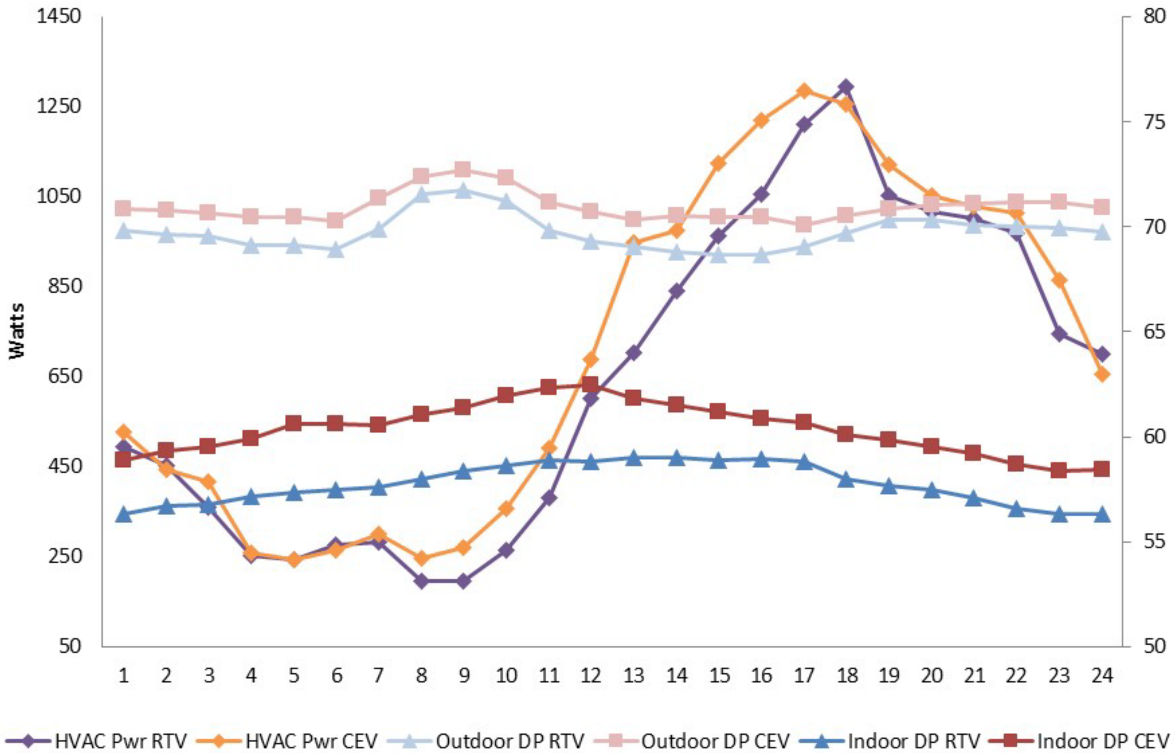


Figure 9. Average hourly indoor and outdoor dew point temperatures and cooling energy use for the flip-flop homes in the runtime ventilation (RTV) and continuous exhaust (CEV) configurations

As can be seen in the individual home plots in Appendix H, indoor CO_2 concentration is noticeably affected by ventilation strategy, with CEV producing consistently lower indoor CO_2 concentrations. Figure 10 shows daily average CO_2 concentrations for all homes for 8/15/2013 through 10/15/2013. It is clear that CO_2 concentration is reduced in the flip-flop homes when operating with continuous exhaust. With the exception of Home 10, the control homes also show a reduction in CO_2 concentration during the continuous exhaust period despite the outdoor concentration remaining nearly constant, which is unexplained. The difference could be related to occupancy, which was not tracked in detail. It could also be related to the accuracy of the Extech SD 800 CO_2 sensor (+/- 40 ppm). However, the reduction in CO_2 concentration in the flip-flop homes is two times greater on average than the reduction in CO_2 in the control homes during the same periods, which indicates the additional ventilation provided via the continuous exhaust system is likely producing a dilution effect.

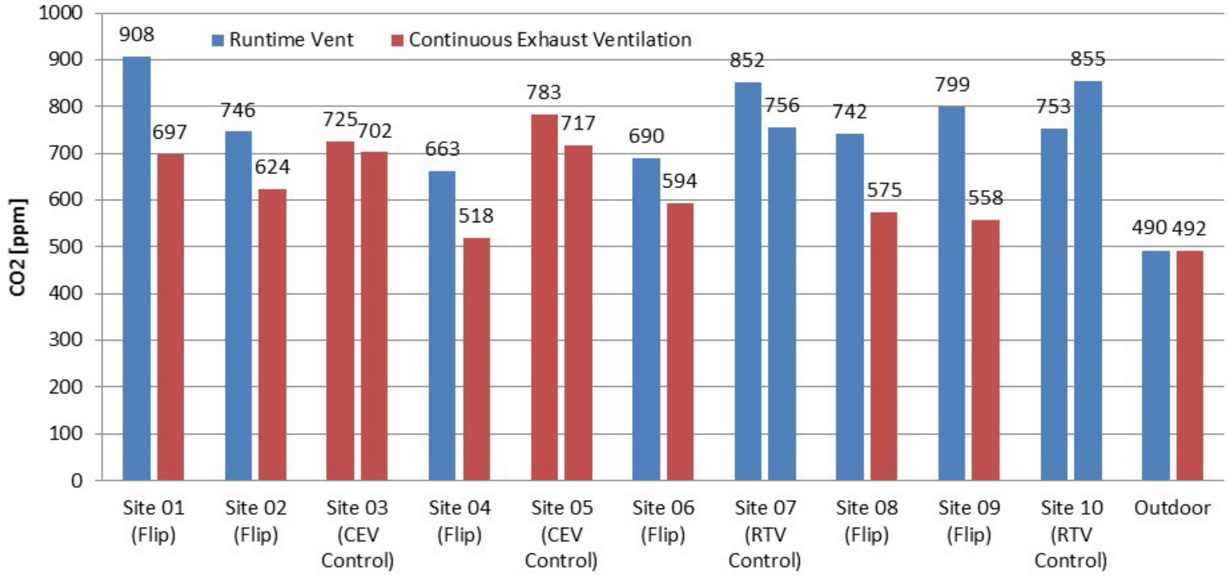


Figure 10. Daily average CO_2 concentration, broken into runtime ventilation (left bar) and continuous exhaust (right bar) periods

Home 3 and Home 5 always operate with continuous exhaust, and Home 7 and Home 10 always operate with runtime ventilation.

To isolate the effect of ventilation strategy on CO_2 concentration, a multivariable regression was performed with data from flip-flop and control homes. Ventilation strategy was found to be the most significant variable with CEV reducing daily average CO_2 concentration by an average of 148 ppm/day. Other variables found to be significant to the 99% level were occupancy, which is expressed generically as the number of persons per household and water heating energy, which provides a more detailed indication of occupancy patterns.

Table 4 summarizes the monitored data collected over the summer period for the six flip-flop homes. Outdoor conditions were relatively consistent among the ventilation periods. As expected, the CEV system requires slightly more cooling energy use to maintain the desired temperature set points in the homes. Also, because these homes have no mechanism to control RH, the resulting RH and dew point are higher in the homes while under CEV.

Table 4. Summary of Monitored Data over the Summer Period, Averaged for the Six Flip-Flop Homes

	Continuous Exhaust	Runtime Ventilation	Δ
Indoor temperature (°F)	77.2	77.1	0.1
Indoor RH (%)	56.5	51.6	5.1
Indoor dew point (°F)	60.4	57.8	2.6
Hours 60%–65% RH	250	48	202
Hours >65% RH	80	9	71

	Continuous Exhaust	Runtime Ventilation	Δ
AC energy (kWh/day)	17.1	15.6	1.5
Indoor CO_2 concentration (ppm)	594	758	-164
Outdoor temperature (°F)	78.5	77.9	0.6
Outdoor RH (%)	79.4	78.3	1.1
Outdoor dew point (°F)	70.9	69.8	1.1
Outdoor CO_2 concentration (ppm)	492	490	2

These trends correspond with the hourly predictions from BEopt simulation, which uses TMY3 weather data (Table 5). BEopt does not predict any hours >65% RH, while some hours are evident at this condition in the monitored data.

Table 5. Comparison of Monitored and Simulated Data over the Summer 2013 Period

		CEV	RTV	Δ
Monitored Data	Indoor Temperature (°F)	77.2	77.1	0.1
	Hours 60%−65% RH	250	48	202
	Hours >65% RH	80	9	71
	AC Power (kWh/day)	17.1	15.6	1.5
Simulated Data	Indoor Temperature (°F)	76	76	0
	Hours 60%−65% RH	249	0	249
	Hours >65% RH	0	0	0
	AC Power (kWh/day)	11.5	10.3	1.2

3.1.2 Summer Condensate Data and Analysis (6/24/2014–8/19/2014)

Data collection actually continued beyond June 2014 and lasted until August 2014. However, by June 2014, several changes had taken place in some of the homes, including changes in occupancy, ownership, and ventilation schedule. These changes, along with subtle weather variations, make comparing summer 2014 data to summer 2013 data difficult. However, beginning in June 2014, collection of air conditioner condensate was instituted for approximately two months, and the associated data provide an opportunity to look at the relative contributions of different moisture sources, including outdoor air and occupancy. Daily condensate volumes varied widely from day to day for a given home, and between homes. Figure 11 shows the average, minimum, and maximum daily condensate volumes collected for each home during the summer 2014 condensate collection period.

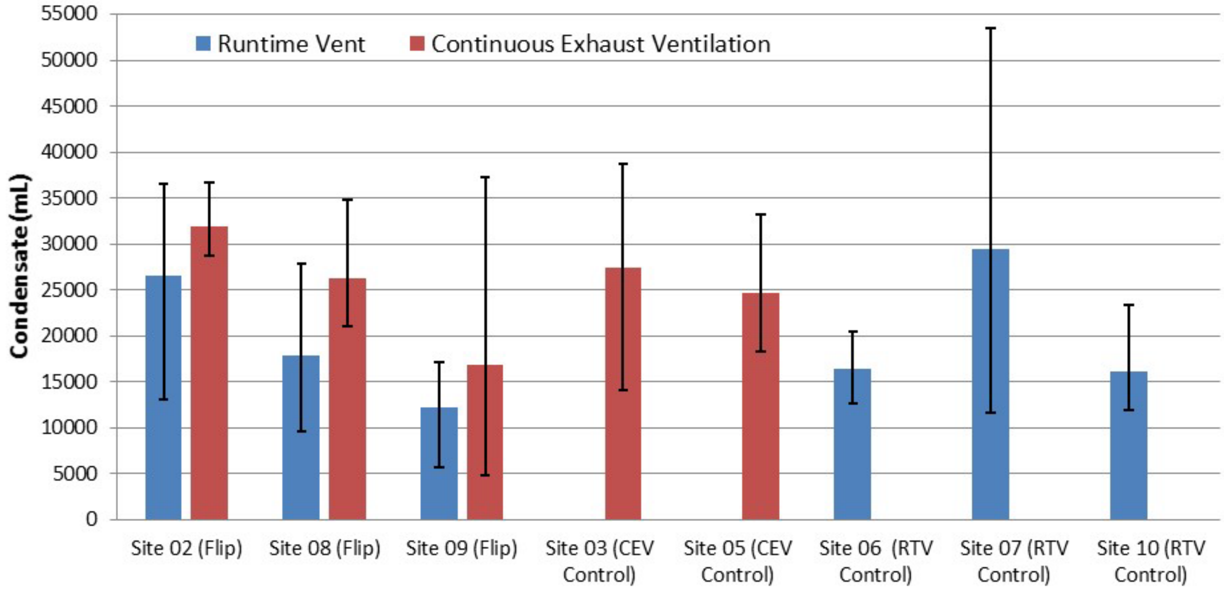


Figure 11. Average, minimum, and maximum daily condensate volumes collected from 6/24/14 to 8/19/14

Unlike with the bar graphs shown in figures above, flip-flop homes were not on the same cycle; therefore, control home data are presented as a single bar rather than broken into periods.

For homes that were flip-flopped between the two ventilation strategies during this period, CEV operation appears to generate more condensate. Condensate volumes collected in the CEV control homes are similarly higher than the condensate volumes collected in the RTV control homes, with the exception of Home 7; it maintains one of the lowest indoor temperature set points of the group, possibly accounting for the relatively large condensate volumes. To investigate the effect of ventilation strategy on condensate generation, a multivariable regression was performed with data from flip-flop and control homes. Ventilation strategy was not found to be significant, and outdoor dew point was only marginally significant. The largest drivers of condensate generation were occupancy (expressed as the number of persons per household) and temperature difference between outdoors and indoors (an indicator of air conditioner runtime). The relationship with occupancy suggests that interior moisture generation is not only a significant source of moisture but is also highly variable from day to day. Conditioned house size was also found to be significant, but an inverse relationship was found; the larger the house, the less condensate was generated. One explanation for this is that a larger house has more capacity to buffer moisture than a smaller house. ACH50 was also found to have a significant, yet inverse, relationship with condensate generation.

3.1.3 Heating Season Data and Analysis

Florida does not have long periods of consistent heating during a year. Rather, heating occurs sporadically and intermittently, typically in conjunction with passing cold fronts. Analysis of space heating was limited to a relatively short period from December 20, 2013, to February 6, 2014, which included most of the coldest winter days but also a few days when space cooling was evident. Twenty-day periods were chosen during each of the two ventilation strategies, excluding nine days between them when strategies were switched. Within each 20-day data set, four days were removed when cooling was evident in most homes. With the remaining data set of heating energy use, a linear regression was performed for each home by plotting total daily heating energy (compressor plus air handler) against the difference between average outdoor and indoor temperatures for 16 days during each of the two ventilation periods. Fan energy for the CEV strategy (bath fan) was not included in the analysis. Two of the 10 homes (Home 1 and Home 4) were dropped from the analysis due to lack of collected data.[15]

Heating thermostat settings varied widely among the eight homes analyzed (66.3°F to 75.8°F). One home used space heating during all days in both periods, but the other seven homes had various numbers of days without heating. Space-heating regressions were refined by removing days with minimal or no heating activity. Figure 12 compares daily average heating energy in the homes during the two ventilation periods. The bars in Figure 12 result from evaluating each regression equation at the average temperature differential between outdoors and indoors during both heating periods. This helps account for varying heating set points in the homes (red and blue boxes) as well as the different outdoor conditions between periods. The ventilation strategy in each home is designated by color with CEV shown in red and RTV shown in blue. The results in Figure 12 drawn from this limited heating period imply no significant difference in space-heating energy between the two ventilation strategies.

[15] Home 1 left the study permanently in January 2014, and the homeowner in Home 4 was not heard from between April 2014 and August 2014.

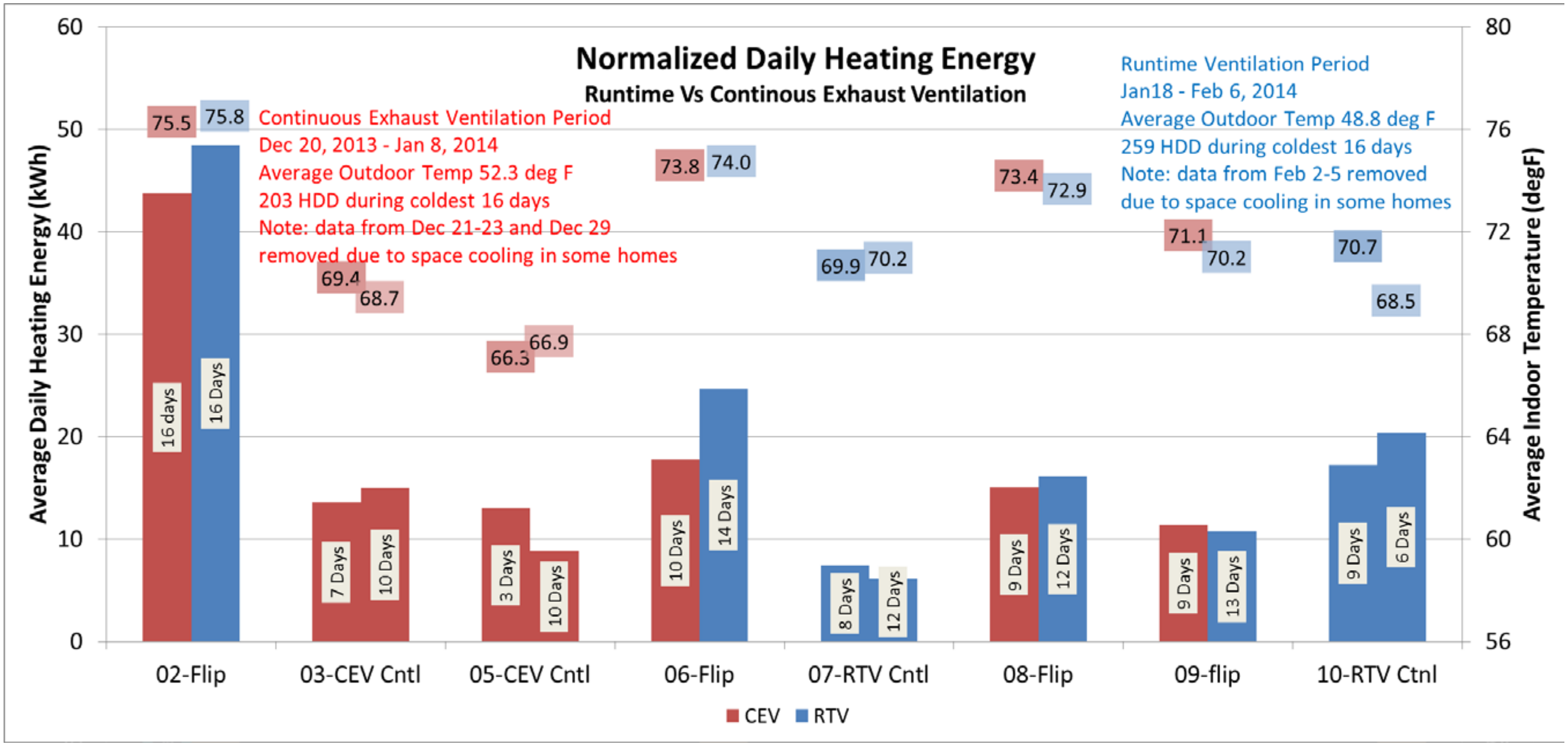


Figure 12. Daily heating energy in four flip-flop and four control homes

Red designates continuous exhaust (CEV) and blue designates runtime ventilation (RTV).
Data from two homes were lost during this period.

Examples of regressions for select homes are shown in Figure 13 and Figure 14. Home 2 (Figure 13) exhibits well-defined results as evidenced by the high R-squared value and space heating that occurred during all 16 days. Heating was much more limited at Home 5 (Figure 14), which results in poorly defined linear trends. Regressions for the remaining homes are included in Appendix I.

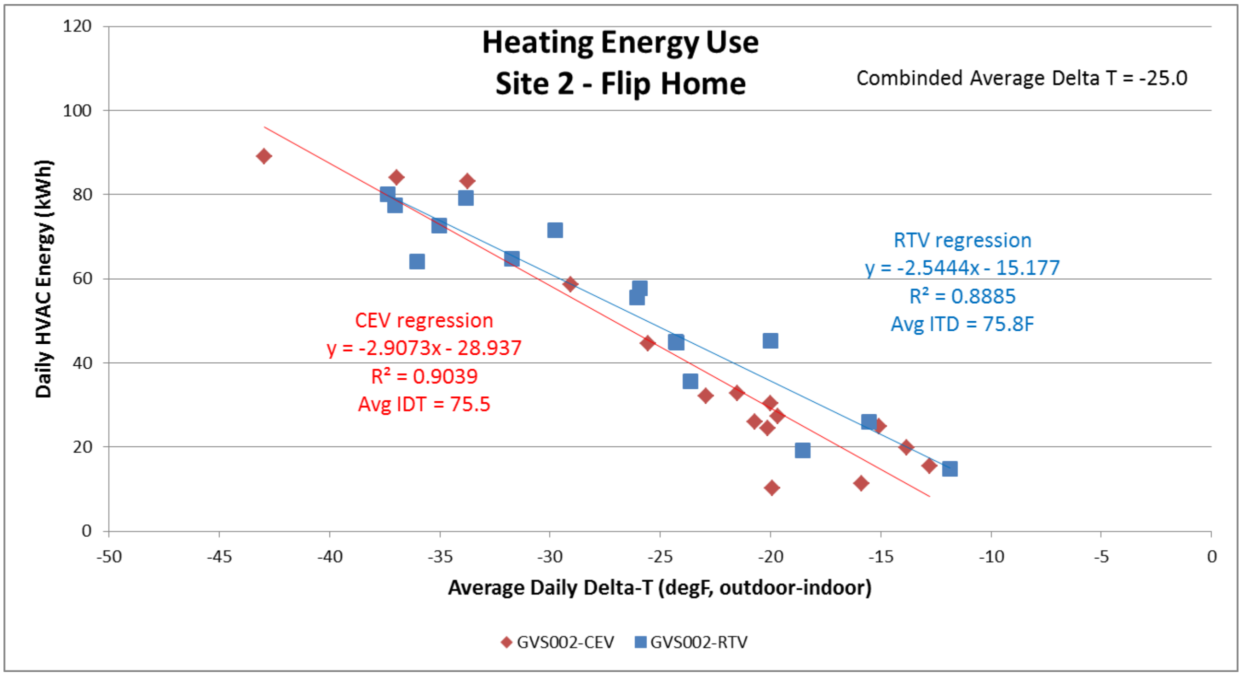


Figure 13. Example of daily heating energy regressions for Home 2 (a flip-flop home) exhibiting well-defined results with a high R-squared value

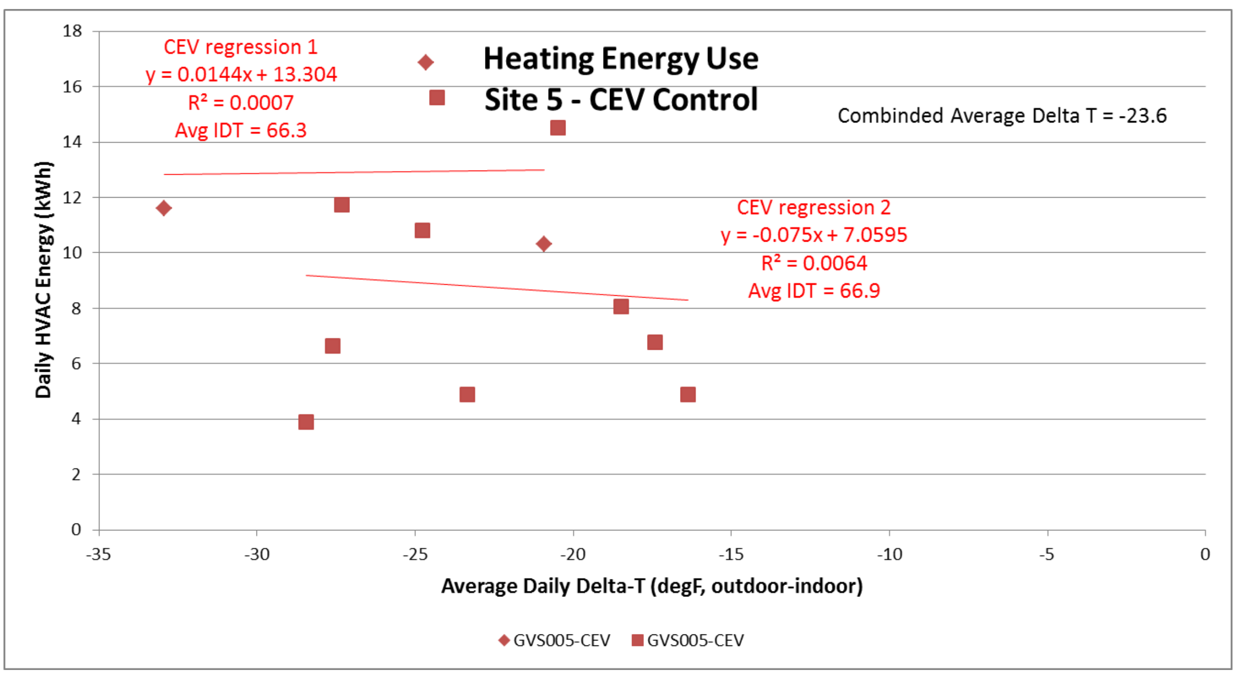


Figure 14. Example of daily heating energy regressions for Home 5 (a CEV control home) exhibiting poorly defined results with a low R-squared value

3.1.4 Mixed Season and Annual Data and Analysis

To reiterate, data collected between June 2013 and June 2014 were broken into different periods for analysis: summer 2013 (6/24/2013–10/15/2013), mixed (10/16/2013–4/16/2014), and summer 2014 (4/17/2014–6/24/2014). As seen in the individual home plots in Appendix H, RH becomes highly variable in the homes during this period. The influence of consistently warmer indoor temperatures can be seen in Home 2, and the influence of consistently cooler indoor temperatures can be seen in Home 7. Quantifying relationships between ventilation strategy and RH or space-conditioning energy in the flip-flop homes during the mixed period—when homes have a combination of heating, cooling, and floating space-conditioning operation—is difficult for the following reasons:

- A perfect biweekly flip-flop schedule was not adhered to because of holidays, vacations, and homeowner preferences. This resulted in differing amounts of time flip-flop homes spent in ventilation configurations, and it introduces bias when counting hours RH >60% as was done and as shown in Figure 6.
- During this time of the year in Florida, weather can be highly variable from one week to another, resulting in different average outdoor conditions among ventilation periods, preventing simple comparisons as were done as shown in Figure 7.
- Homeowner preferences for heating and cooling versus natural ventilation in the mixed period are highly variable, sporadic, and unpredictable.

However, the CEV and RTV control homes provide an opportunity to look at how instances of RH >60% change seasonally in homes with different ventilation strategies. Figure 15 shows the total number of hours the CEV control homes (Home 3 and Home 5) and the RTV control homes (Home 7 and Home 10) spent at RH >60%. The pie charts show the relative distribution of those hours during consistent cooling operation (summer 2013 and summer 2014) and during inconsistent space-conditioning operation ("mixed"). The hatching defines hours when no space-conditioning operation occurred ("floating"). In the case of RTV homes, this also indicates hours when no mechanical ventilation was occurring.

Annual hours >60% RH in CEV Home 3 and Home 5 generally match the simulation results presented by Martin (2014) for similarly constructed high-performance homes achieving ASHRAE 62.2-2013 standards with CEV in Orlando, Florida. One principal difference is Martin (2014) finds a nearly even mix of hours >60% in cooling and floating, where these data show that more than 80% of the hours >60% RH occur during floating operation. The discrepancy is likely due to the robotic nature of simulations, which activate space cooling anytime throughout the year when the interior temperature is greater than the cooling set point. In reality, homeowners in Florida often let their homes float above the summer cooling set point during the mixed period, when outdoor dew point temperatures are reasonably low. Minimal cooling system operation, and therefore minimal dehumidification during the mixed period, in part, accounts for the fact that the majority of hours >60% RH occur during the mixed period.

RTV Homes 7 and 10 also show that the majority of their hours >60% RH occur while floating, mostly during the mixed period. However, occupant preferences in these homes make comparison to the CEV homes to investigate effects of ventilation strategy difficult. Note that RTV 7 maintains an exceptionally low cooling set point, resulting in exceptionally high space-conditioning runtime fractions (RTFs), and therefore barely any hours >60% RH. Also note that RTV 10, while maintaining a reasonable set point profile (average, setup, and setback), has exceptionally low space-conditioning RTFs, resulting in its being the home with the greatest number of hours >60% RH. A close look at the data reveals that this home has an exceptional ability to “coast” from the early morning hours through midafternoon to late afternoon without space-cooling operation, yet it is able maintain a reasonable interior temperature, even on warm days. This could result from the home’s favorable orientation, window area, and exterior/interior shading.

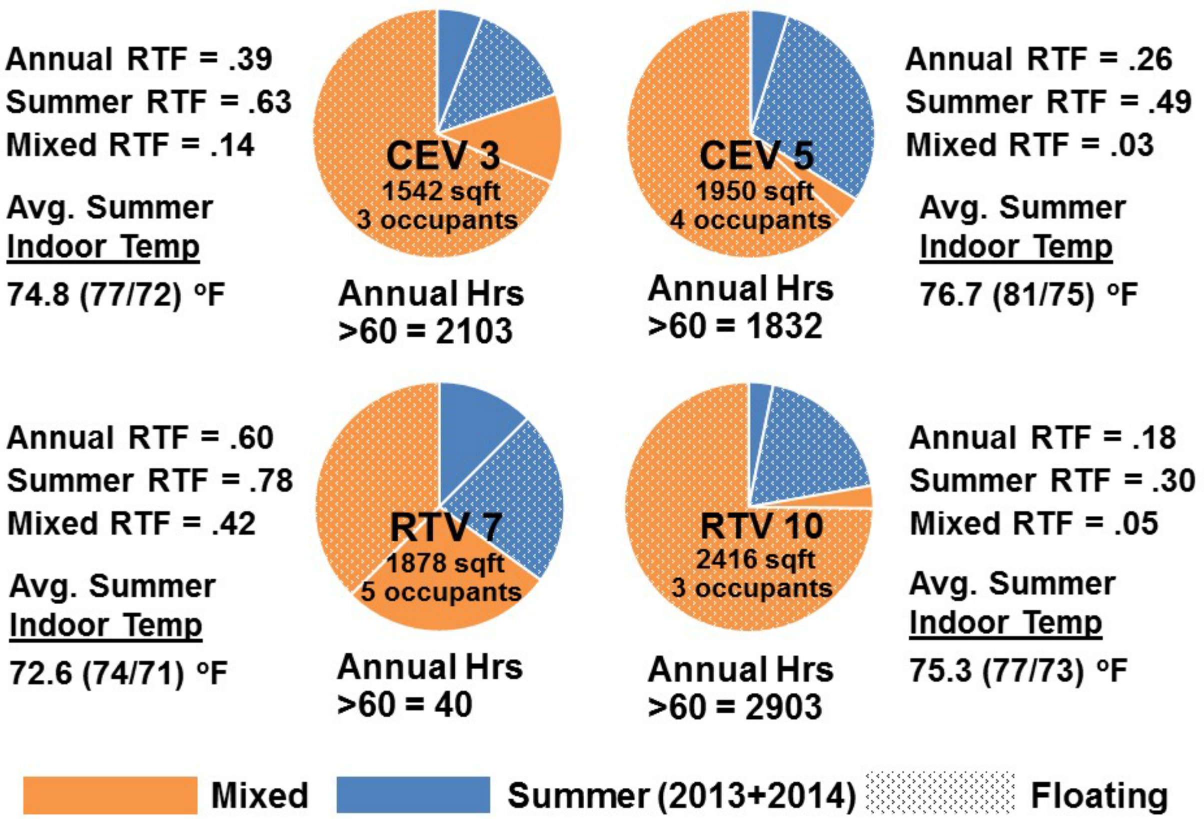


Figure 15. Number of hours >60% RH, and their relative distribution among the cooling and mixed periods for CEV-control Homes 3 and 5 and RTV-control Homes 7 and 10

Space-conditioning runtime fractions (RTFs) are also shown along with the average summer indoor temperature (with monitored setup/setback profile).

The exceptional operational characteristics of RTV 7 and 10 make direct comparison for the purposes of identifying the influence of ventilation strategy on RH during a “swing” or “mixed” season difficult. However, it is evident from the control homes that whether CEV or RTV is in use, the vast majority of annual hours >60% RH occur in the absence of cooling system operation. This remains true even in RTV homes, where without space-conditioning operation, no mechanical ventilation is delivered. To some degree, this indicates that occupants, their preferences, and their habits play a large role in the resulting indoor RH during the variable mixed period.

To isolate the effect of the mechanical ventilation strategy on indoor RH during the mixed period, a multivariable regression was performed with data from flip-flop and control homes. Ventilation strategy was found to be the least significant variable tested, with CEV adding 1.4 hours >60% RH per day. This is much less than the 3.7 hours per day found in the summer 2013 regression. Considering the large increase in hours >60% RH in the mixed period compared to the summer 2013 cooling period, the regression underscores that other factors more significant than ventilation strategy are driving high RH during the mixed period. Variables found to be most significant for hours >60% RH during the mixed period were outdoor dew point temperature (as evident in Figure 5), the number of daily floating hours (as evident in Figure 15), indoor/outdoor temperature difference (an indicator of cooling system runtime—also evident in Figure 15), and conditioned house size. ACH50 was not found to be a significant variable during this period.

Analyzing CO_2 data during the mixed period provides an opportunity to evaluate relative air change in homes operating under RTV during this period. Because RTV systems inherently depend on space-conditioning runtime to deliver ventilation, minimal runtime during the mixed season could likely result in minimal air change. However, occupant preferences for natural ventilation could produce air exchange rates similar to what was found in the summer 2013 season or rates that are even greater. Upon investigating the individual home plots in Appendix H, it is evident that, compared to the summer 2013 period, the influence of ventilation strategy on indoor CO_2 concentration among homes is less consistent. In some cases, such as in Home 6, CO_2 concentration seems equally or even less variable among the ventilation strategies. In other cases, such as with Home 9, consistently higher average indoor CO_2 concentrations are seen with RTV during the mixed period compared to the summer period. This variance is also seen in Figure 16, which compares daily average CO_2 concentrations during the mixed period between RTV and CEV operation.

Comparing Figure 16 to Figure 10 does not reveal a direct correlation of CO_2 concentration and time of year (summer versus mixed period). However, it is worth noting that in both the summer (Figure 10) and winter/mixed (Figure 16) analysis periods, the highest CO_2 concentrations are observed in RTV homes, which may suggest that the RTV ventilation strategy is not providing as much dilution or air exchange as the CEV system (see Section 3.2.1). However, comparing Figure 16 to Figure 12 shows that Home 2 and Home 6—the two flip-flop homes with the least difference between the RTV and CEV periods in the heating season—also have among the highest heating energy of all homes. Because high heating energy use would also suggest higher space-conditioning runtime and, thus, increased ventilation during the RTV periods compared to the other RTV homes, it is possible that the effective ventilation achieved between the CEV and RTV systems in these homes is similar. However, as discussed in Section 3.2.1, the amount of ventilation air provided during the RTV periods is still 38% and 44% lower than the ventilation air provided during the CEV periods, suggesting system type may play a role in the amount of ventilation air required to reach a desired level of air exchange.

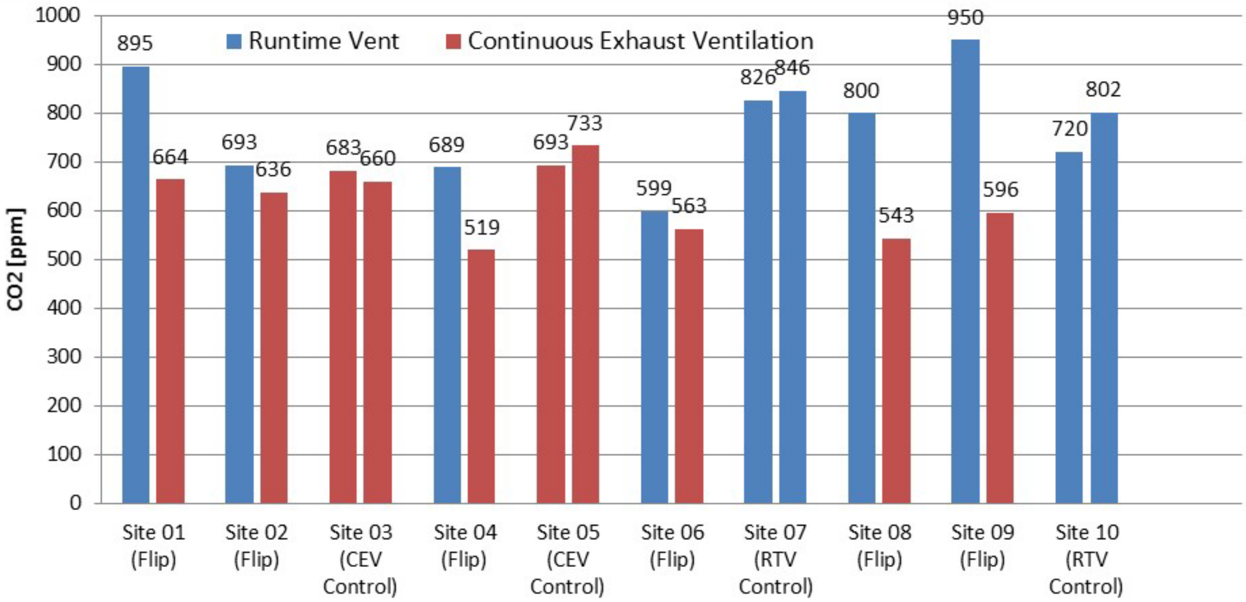


Figure 16. Daily average CO_2 concentration during the mixed period, broken into runtime ventilation (left bar) and continuous exhaust (right bar) periods

To isolate whether there is a significant difference in air change in the RTV homes between the summer and mixed period, a multivariable regression was performed on data involving RTV operation only.

3.2 Seasonally Sampled Parameters

The data collected during the initial paired IAQ sampling periods were analyzed to determine the difference in interior concentrations of formaldehyde, acetaldehyde, VOCs during the IAQ sampling weeks. In addition, the AER was determined during each one-week IAQ sampling period. Over the course of the one-year study period, six one-week IAQ sampling periods were conducted. The IAQ sampling periods were conducted in pairs to enable the IAQ measurements to be sampled when the flip-flop homes were in both the RTV and the CEV configurations in each season, as shown in Table 6.

Table 6. IAQ Sampling Time Periods and Configuration of Flip-Flop Homes

Season	IAQ Sampling Period	Dates	Flip-Flop Homes Configuration[a]
Summer 2013	SUM1.1	8/14/2013–8/20/2014	RTV
	SUM1.2	9/18/2013–9/26/2013	CEV
Winter/Mixed 2014	WIN1	3/19/2014–3/27/2013	RTV
	WIN2	4/10/2014–4/17/2014	CEV
Summer 2014	SUM2.1	7/16/2014–7/23/2014	RTV
	SUM2.2	8/12/2014–8/20/2014	CEV

[a] Control homes are in the RTV or CEV state for all sampling periods.

The first IAQ sampling period occurred from August 14 to August 20, 2013, during a period when the flip-flop homes were in the RTV configuration. The second of the paired sampling periods occurred from September 18 to September 26, 2013, when the flip-flop homes were in the configuration with the exhaust fan in the bathroom always on to deliver the amount of ventilation air required by ASHRAE 62.2-2010 (CEV). For the first of the paired sampling periods, the IAQ sampling occurred the second week of the two-week period the homes were in the RTV configuration, while for the second of the paired sampling periods, the IAQ sampling occurred the first week of the two-week ventilation flip-flop. During this first summer sampling period, the second sampling was delayed because of homeowners or equipment were unavailable. The homes were flip-flopped every two weeks, as designed in the experimental plan. However, the second of the IAQ sampling periods was delayed until the subsequent CEV period, and a flip-flop occurred between the first and second sampling periods, as shown in Table 7.

Table 7. Timing of IAQ Sampling and Ventilation Flip-Flop During the First Summer Sampling Period

Event	Dates	Flip-Flop Homes Configuration
Switch to Ventilation Configuration A	8/8/2013	RTV
Deploy IAQ Samplers	8/14/2013	RTV (no change)
Pick up IAQ Samplers and Switch to Ventilation Configuration B	8/20/2013	CEV
Switch to Ventilation Configuration A	9/3/2013	RTV
Switch to Ventilation Configuration B	9/17/2013	CEV
Deploy IAQ Samplers	4/10/2014	CEV (no change)
Pick up IAQ Samplers	4/17/2014	RTV

While this arrangement is different than those experienced in subsequent sampling periods, it is believed such an arrangement does not significantly affect the comparability of the results obtained, especially for the second sampling period. The weather between the first and second sampling periods was similar during this (and subsequent) paired sampling periods, such that climatic effects should not play a significant role. Further, the samples are taken indoors and corrected for changes in outdoor concentrations, and each home, for the most part, is maintained at a consistent indoor temperature. As noted above, some homes were maintained at warmer or cooler temperatures because of homeowner preference, which would affect the extent of chemical off-gassing.

With regard to the comparability of data depending on whether the IAQ sampling period occurred the first week or second week of the two-week flip-flop, the authors believe, based on previous studies, that such timing would be unlikely to significantly affect the measurements, as the IAQ samples were passive one-week samples. Data collected from Willem et al. (2013) suggest that the time to respond to a change in ventilation rate is two days. It is possible that in the first week, emission rates of certain contaminants may be temporarily higher or lower than their steady-state value as the home adjusts to a new ventilation configuration. However, such changes are generally believed to occur over the course of several hours and up to one day. Because the one-week IAQ sampling period would then capture at most one transition day and at least[16] six steady-state days, we do not believe the effect of the transition day would significantly impact the ability of the measurement to represent the "steady-state" characteristics of a given ventilation period. It is also worth noting that many things do significantly affect IAQ measurements in occupied homes, including homeowner activities. While homeowners were asked to limit their activities during the IAQ sampling weeks to only "typical" activities that may affect IAQ, the variability from this factor likely far outweighs any variability incurred from the timing of IAQ sample weeks with respect to flip-flop ventilation periods.

The second paired IAQ sampling period occurred in March and April of 2014 in conditions that included some heating energy use, representative of the winter season for Florida. The first sample was taken from March 19 to March 27, 2014, and the flip-flop homes were in the RTV configuration. The second of this "winter/mixed" paired sample occurred from April 10 to April 17, 2014, when the flip-flop homes were in the CEV configuration. For this sampling period, the IAQ sampling occurred during the second week of the two-week ventilation flip-flop periods in both cases, and no flip flops occurred in between.

IAQ sampling was repeated in the summer of 2014 to investigate the repeatability and consistency of the observed trends in each season. This second summer paired sampling period occurred from July 16 to 23, 2014, and from August 12 to 20, 2014. For this sampling period, as with the previous sampling periods, the first IAQ samples were collected when the flip-flop homes were in the RTV configuration and the second IAQ samples were collected when the flip-flop homes were in the CEV, or ASHRAE 62.2-compliant, configuration. In this case, both samples were also collected during the latter portion of the flip-flop period; that is, the home had already been in the sampled ventilation configuration for at least one week. It is worth noting that during this sampling period, an additional 19 days elapsed between the first sampling period and the second sampling period to accommodate homeowner vacation schedules. The authors

[16] Some sample periods were approximately one week long, but the sample periods ranged from six to eight days in most cases to accommodate homeowner schedules. In all cases, the specific sampling duration (in hours) was recorded and used for subsequent quantification of the sample volumes.

elected to delay sampling to capture periods that would be representative of normal occupancy. During this 19-day period, the home was maintained in the CEV configuration throughout and no intermediate flip flops occurred.

Occasionally, sample deployment or retrieval occurred on the day before or after the date noted in Table 6 to accommodate homeowner schedules. In each case, the precise time and date of sampler deployment and retrieval were recorded for each sampler (or emitter) in each house so that the specific sample volume was known. However, the sample volume was sometimes up to 24 hours longer or shorter than the originally envisioned seven-day period.

Also, because sampling during the three paired IAQ sampling periods always involved first sampling the flip-flop homes in the RTV configuration and then in the CEV configuration, the order of ventilation configuration samples could have been a source of bias in results. The effect of any bias would depend on the storage capacity and change of emission rate of household materials as a function of any change in ventilation rate or spatial pressure distributions caused by the change in ventilation approach.

3.2.1 Air Change Rate

The observed AER was measured using passive PFT gas emitters and samplers over each one-week sampling period. In each home, two to three PFT samplers were deployed, depending on the size of home.

Using the PFT data, the AER was calculated for each home as the total hourly emission rate of PFT for the emitters deployed in the home, divided by the volume of the home, divided by the average measured concentration of PFT, as shown in the following equation:

$$AER\ [hr^{-1}] = \frac{E_{Total}\left[{}^{\mu g}/_{hr}\right]}{V[m^3] \times C_{avg}\left[{}^{\mu g}/_{m^3}\right]}$$

The AER was calculated for each home and each sampling period. However, because of the variability in the PFT data, the AERs calculated based on these measurements do not provide sufficient granularity to determine any changes based on the ventilation strategy. Therefore, the impact of different ventilation schemes was also calculated based on mechanical and infiltration-driven air flows. Specifically, the unbalanced air flow rate from mechanical ventilation was calculated based on the runtime of the ventilation system and the measured flow rate, as installed. The measured flow rate was taken using an exhaust fan flow box at the time of installation, as described in Section 2.2.1.

For homes in the CEV configuration, the ventilation fan flow rate was that of the bathroom exhaust fan, and the runtime was 100%. For homes in the RTV configuration, the ventilation fan flow rate was the air flow through the outdoor air duct connected to the air handling unit (AHU), and the runtime fraction was determined based on the measured energy consumption of the AHU in a given hour expressed as a percentage of energy consumption if the AHU ran continuously for an entire hour. The infiltration-related component of AER was calculated using the known air leakage measured with the blower door and characteristics of the homes. The calculated mechanical and infiltration-driven air flows were combined using quadrature in accordance with the methods described in the ASHRAE Fundamentals Handbook (ASHRAE 2013a).

The AERs for the two ventilation configurations were compared in each season based on the theoretical calculations described above; they are shown in Figures 17, 18, and 19.

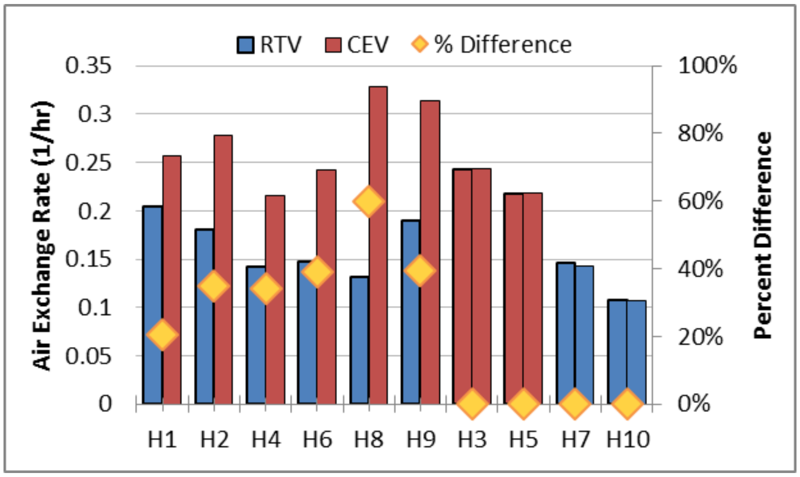


Figure 17. Overall AER determined in each of the RTV and CEV homes in the first summer sampling period

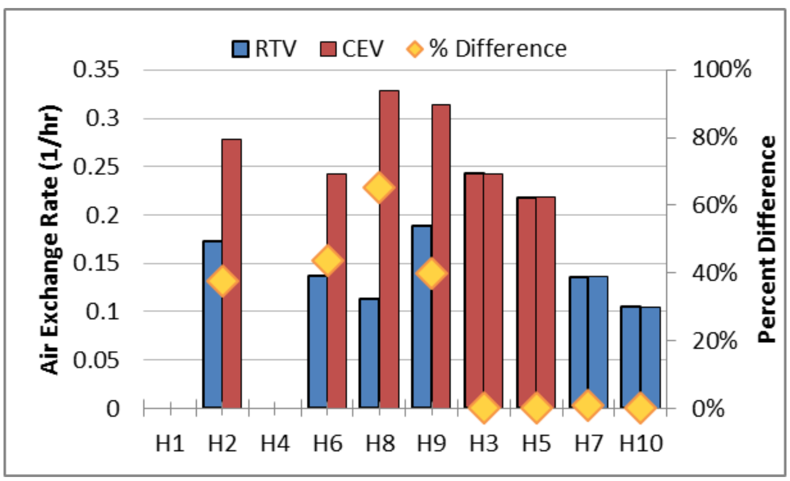


Figure 18. Overall AER determined in each of the RTV and CEV homes in the winter sampling period

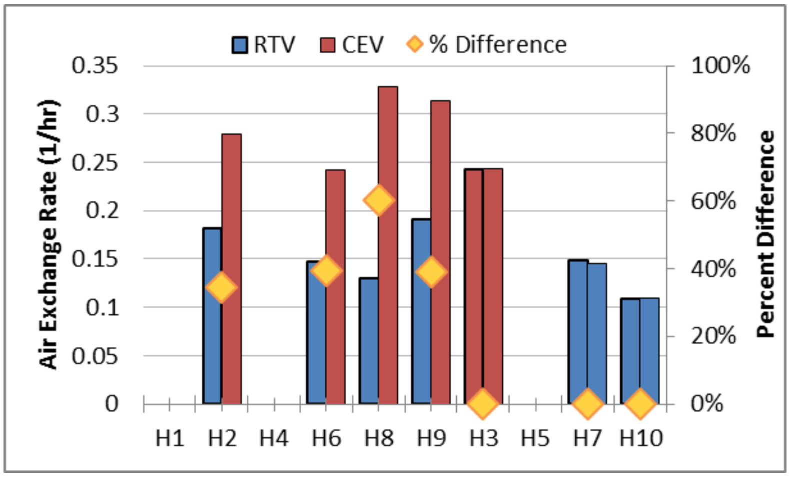


Figure 19. Overall AER determined in each of the RTV and CEV homes in the second summer sampling period

In general, the CEV ventilation strategy resulted in AERs that were 30% higher than they were with the RTV configurations in the flip-flop homes and mechanical ventilation rates that were 79% higher. The difference in AER between the two ventilation strategies is less extreme than the difference in mechanical ventilation flow rate because of the impact of infiltration air on overall air exchange rate. For RTV homes, the unbalanced mechanical ventilation flow rate was an average of 28% of total mechanical and infiltration-driven ventilation airflow in the summer and 5% in the winter, while for CEV homes, the mechanical ventilation flow rates were 82% and 84% of the total airflow for the summer and winter, respectively.

Interestingly, despite significantly lower runtimes, the AERs in the winter/mixed season for the RTV homes were only 6% lower than those determined in the summer. Specifically, during the summer season, RTFs were around 0.40, while in the winter, RTFs ranged from 0.05 to 0.19, with an average of 0.12. However, the infiltration component of the airflow dominates the calculated AER in both the summer and the winter season, resulting in less significant changes in overall AER even though the unbalanced mechanical ventilation provided in the summer is higher than it is in the winter.

In addition, the difference in AER calculated between the RTV and CEV ventilation periods was not observed to consistently impact the average CO_2 concentration in each home and sampling period. In the first summer sampling period, in Homes 1, 2, 4, and 6, the percentage increase in AER due to the change in ventilation strategy was observed to decrease the CO_2 concentration a similar amount, suggesting an inverse linear relationship, as shown in Figure 20. In the other homes, the change in AER was observed to decrease the CO_2 concentration but not in proportion to the change in AER.

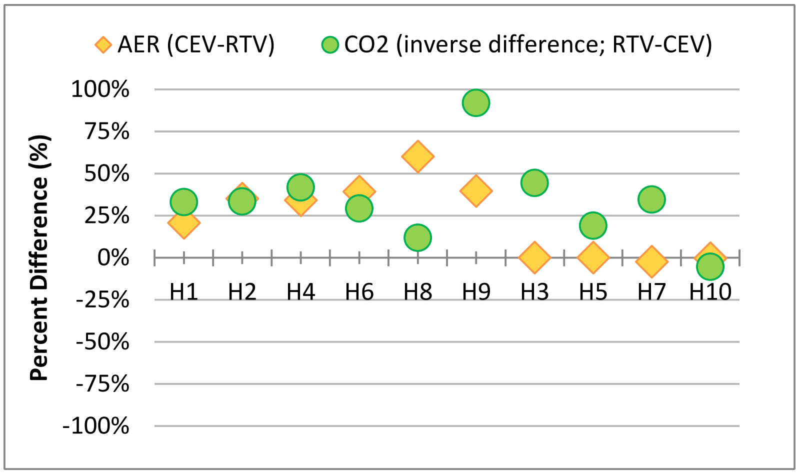


Figure 20. Relationship of percent difference in AER (calculated as [CEV-RTV]/RTV) and percent difference in CO_2 concentration (calculated as [RTV-CEV]/RTV) for first summer sampling period

In subsequent sampling periods, most homes diverged from the previous inverse linear relationship (except one control home, Home 3, which did not change significantly in AER or CO_2 concentration between the sampling weeks). In the winter/mixed sampling period, the average CO_2 concentrations in all flip-flop homes increased when moving from RTV to CEV, even though the AER increased.

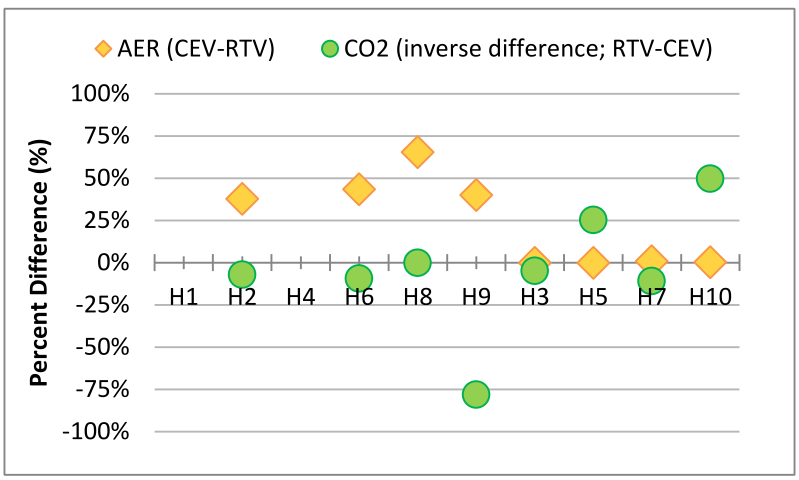


Figure 21. Relationship of percent difference in AER (calculated as [CEV-RTV]/RTV) and percent difference in CO_2 concentration (calculated as [RTV-CEV]/RTV) for winter/mixed sampling period

In the second summer sampling period, the relationship between relative increase in AER and relative decrease in CO_2 concentration is varied; in Home 1 and Home 3, the relationship is still somewhat inverse linear, although it is not proportional. In Home 6 and Home 9, the opposite trend is observed (i.e., an increase in CO_2 concentration is observed despite an increase in AER). In Home 7 and Home 10, the AER did not change from one week to another, but the CO_2 concentration in Home 7 decreased. If CO_2 is a reasonable indicator for dilution effectiveness, these data suggest the CEV method may not provide better dilution in all cases. However, the variability of the CO_2 data also suggest that many factors may affect the average CO_2 concentration in homes, such as occupancy, and that these other factors may overwhelm the impact of different ventilation strategies.

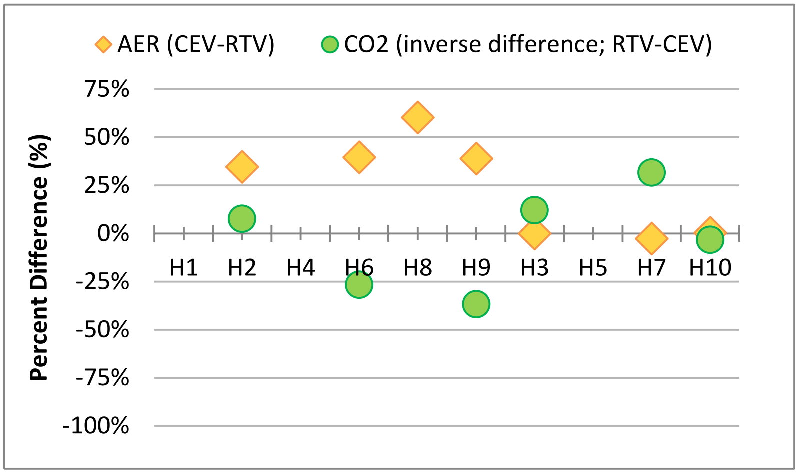


Figure 22. Relationship of percent difference in AER (calculated as [CEV-RTV]/RTV) and percent difference in CO_2 concentration (calculated as [RTV-CEV]/RTV) for second summer sampling period

The complete calculated AER and ventilation flow rate data are provided in Appendix K.

3.2.2 Formaldehyde

Formaldehyde is one of the most important air contaminants measured in new homes, because it is frequently found in levels above the National Institute for Occupational Safety and Health (NIOSH)-recommended chronic exposure limit (chREL) of 16 ppb (CDC 2011; Rudd and Bergey 2014; Hun et al. 2014; Offerman 2009; Salthammer et al. 2010). In this study, formaldehyde levels in all of the study homes were similarly found to be higher than the NIOSH-recommended level, and the levels found were consistent with average concentrations measured in other newly constructed U.S. homes (Salthammer et al. 2010). It should be noted that the NIOSH-recommended exposure limit is one of the strictest in the world; the limit is set based on (1) the fact that formaldehyde is a known carcinogen (Salthammer et al. 2010) and (2) a philosophy that exposure to carcinogenic compounds should kept below the limit of detection (CDC 2011). By comparison, the Occupational Safety and Health Administration (OSHA)-permissible level for chronic exposures to formaldehyde is much higher (750 ppb). However, the OSHA limit is designed primarily for work environments where eight-hour exposures are typical, while people are often in their homes significantly more than eight hours per day. The authors note that there is significant variability in the recommended standard limit for formaldehyde both domestically and internationally, indicating some disagreement on the potential for harmful effects resulting from chronic exposure to low levels of formaldehyde. Specifically, the NIOSH chREL is higher than that established in California by the Office of Environmental Health Hazard Assessment under the California Environmental Protection Agency, which establishes a chREL of 9 ppb (OEHHA 2014), and it is significantly lower than the "no observed adverse effect level" established by the World Health Organization of approximately 81 ppb (specified as 0.1 µg/m^3; WHO 2010) or the OSHA time-weighted average, permissible exposure limit.

Because formaldehyde concentrations will vary based on the materials used in home construction and the activities of the occupants, formaldehyde data were analyzed by comparing the changes in formaldehyde levels in the flip-flop homes to those observed in the control homes (which should account for any weather-related effects).

The formaldehyde concentrations in each home and each sampling period were also corrected to account for the outdoor concentration of formaldehyde measured during that sampling period and they were blank-corrected. The blank- and outdoor-corrected concentrations of formaldehyde measured in the homes in each of the sampling periods are presented in Figure 23, Figure 24, and Figure 25, for the summer, winter, and second summer sampling periods, respectively.

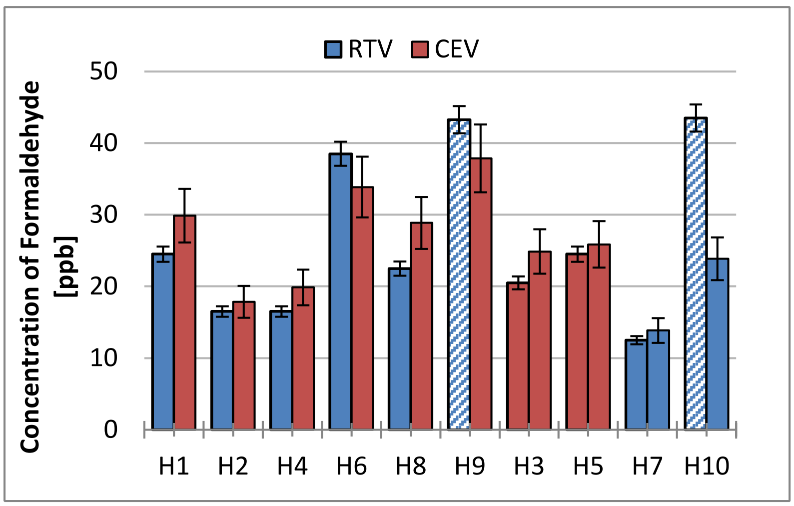


Figure 23. Concentrations of formaldehyde (ppb) in Home 1 through Home 10 during the first summer IAQ sampling period

Striped bars indicate unusual data.

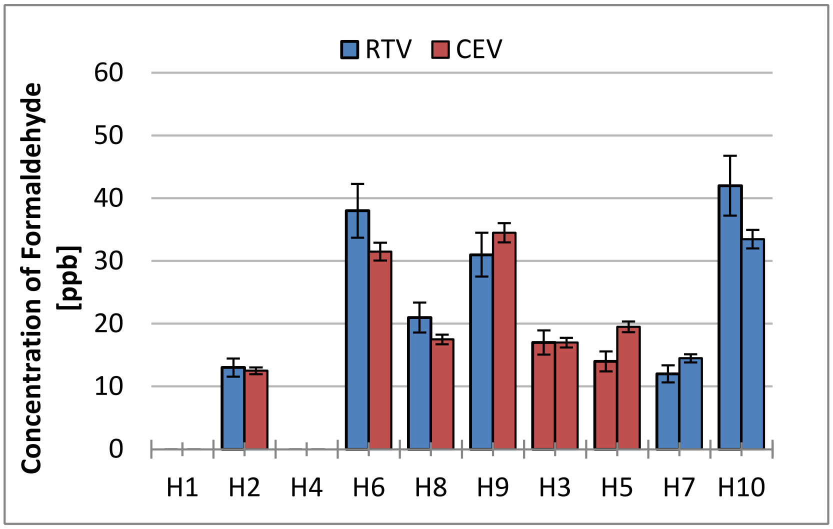


Figure 24. Concentrations of formaldehyde (ppb) in Home 1 through Home 10 during the winter IAQ sampling period

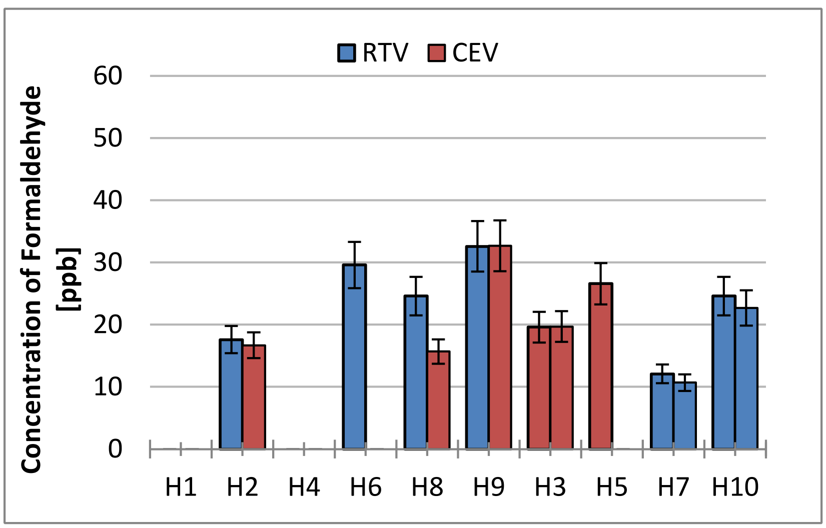


Figure 25. Concentrations of formaldehyde (ppb) in Home 1 through Home 10 during the second summer IAQ sampling period

The difference between homes with RTV versus those with CEV was variable among the homes, and it was difficult to discern clear trends as a function of ventilation strategy (e.g., RTV versus CEV). In the first summer sampling period, formaldehyde levels increased in many of the flip-flop homes between the RTV ventilation configuration (first week) and the CEV ventilation configuration (second week) despite an average increase in theoretical AER of 30% and an increase in mechanical ventilation flow rate of 79%. However, slight increases were also observed in the CEV control homes (Home 3 and Home 5) and one of the RTV control homes (Home 7). Home 10 exhibited unusual behavior, with very high concentrations measured during the first summer sampling period and much lower concentrations measured during the second sampling period. The authors hypothesize this may be due to the introduction of new furnishings or a specific cleaning event that led to the unusually high concentrations. Notably, Home 10 had the lowest calculated AER (see Section 3.2.1); however, this does not explain the variability from one week to another in the house observed in the first summer sampling period.

In addition, the measurement in Home 9 during the first sampling period taken with the study samplers appears to be an outlier based on the data. After further investigation, it was determined that the sampling cap was erroneously left on the sampler. During the first summer sampling period, duplicate formaldehyde data were collected, using both UMEx 100 and Waters Sep Pak Xposure samplers. In general, the XPosure samplers reported 32% higher concentrations of formaldehyde than the UMEx 100 samplers (see Appendix J). In the case of Home 9, the data from the duplicate XPosure data were used, and they were corrected for the average bias observed between the two samplers so that the data could be better compared to the other measurements collected using the UMEx 100 samplers. The formaldehyde concentration reported with the Xposure sampler—even after being corrected based on the average increased concentration reported by the Xposure samplers, compared to the UMEx 100 samplers—is the highest reported concentration among all the homes and sampling periods. Comparing Figure 10 with Figure 19, Home 9 also exhibited one of the highest CO_2 concentrations during the first summer analysis period; while the data are inconclusive, high CO_2 and HCHO measurements suggest a low effective AER in this home using the RTV method. The theoretical AER measurements discussed in Section 3.2.1 do not suggest lower AER than the other RTV homes; however, the theoretical calculations may not account for the *effective* dilution rate, which may be impacted by other factors, such as distribution and mixing.

In the winter and subsequent second summer sampling periods, there were also no clear relationships between the formaldehyde concentration and ventilation approach. Thus, it is difficult to make strong conclusions regarding the relationship of the absolute formaldehyde concentration to ventilation approach based on the data.

In addition to the absolute formaldehyde concentrations, the percentage change in formaldehyde concentrations was also analyzed and compared among the sampling periods and homes. Figure 26, Figure 27, and Figure 28 show the absolute difference (in ppb) and the percentage difference in formaldehyde concentration observed in each of the homes for each of the sampling periods. Based on these data, the percentage change between each of the sampling periods for the flip-flop and control homes was compared. However, as discussed above, no significant difference or trend was observed with respect to ventilation strategy.

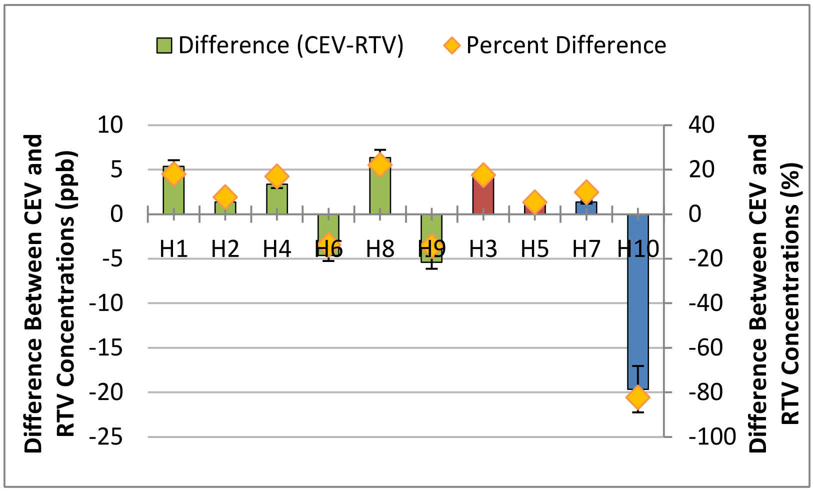


Figure 26. Absolute (ppb) and percent (%) difference in concentrations of formaldehyde in Home 1 through Home 10 during the first summer IAQ sampling period

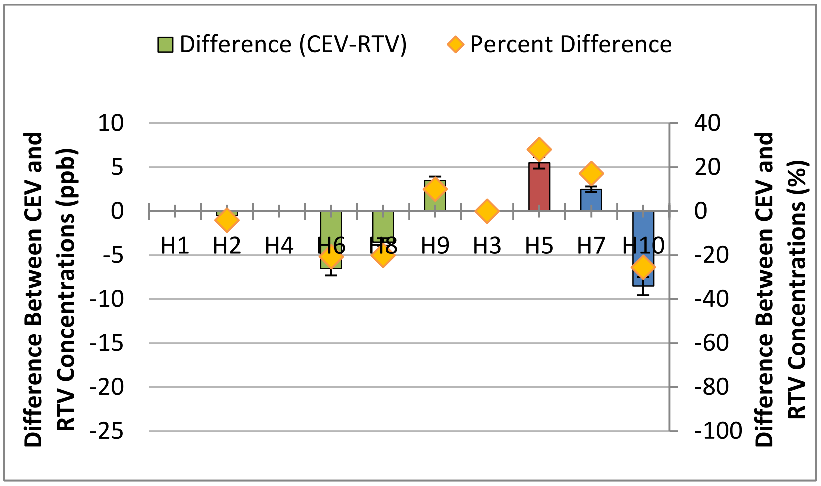


Figure 27. Absolute (ppb) and percent (%) difference in concentrations of formaldehyde in Home 1 through Home 10 during the winter IAQ sampling period

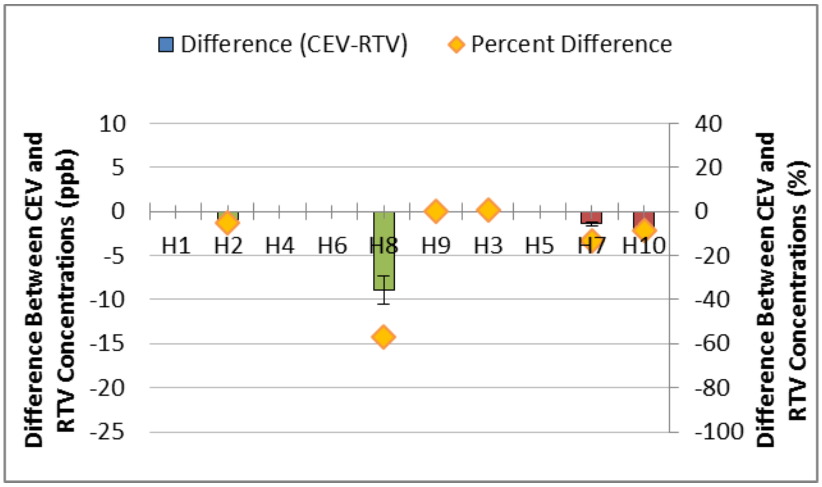


Figure 28. Absolute (ppb) and percent (%) difference in concentrations of formaldehyde in Home 1 through Home 10 during the second summer IAQ sampling period

While no significant trend between ventilation approaches (RTV versus CEV) was observed, it is worth noting that the observed (estimated) AER was significantly higher in the homes in the CEV configuration than it was in homes in the RTV configuration, as shown in Section 3.2.1. Thus, it is somewhat unexpected that a commensurate decrease in formaldehyde concentration was not observed with increasing ventilation rate and overall AER. This finding conflicts with the results of previous research that have suggested, despite the dependence of formaldehyde emission rates on concentration, increasing ventilation rate will decrease formaldehyde concentrations (Lajoie et al. 2015; Hult et al. 2014). However, these previous studies isolated the impact of ventilation rate, which increases the amount of ventilation air provided with the same ventilation strategy. The results of this study suggest that ventilation strategy may be a significant factor in determining the overall efficiency of ventilation systems and that, despite significantly higher AER and mechanical ventilation flow rates, the CEV ventilation system was not more effective than the RTV system at diluting formaldehyde concentrations. This result is consistent with other research that has analyzed different ventilation system types. Specifically, Hun et al. (2014) have also observed reduced efficacy of exhaust-only ventilation in reducing formaldehyde concentrations. Rudd and Bergey (2013) measured lower formaldehyde concentrations in a study house ventilated with the supply-based continuous fan integrated supply (CFIS) system than in the same house when it was ventilated with an exhaust fan and similar effective ventilation rates. Though not comparing exhaust versus supply-based systems, Offerman (2009) also identified that formaldehyde concentrations were higher in homes with mechanical dedicated outdoor air ventilation systems than in homes with heat recovery ventilators, although this difference may have been due to a variety of factors, including effective ventilation rate, distribution, or differences in house characteristics and occupancy.

When the formaldehyde concentrations in each home (Figure 29) are analyzed, formaldehyde levels generally appear to decrease over time in some homes and more significantly in homes with higher initial concentrations. This confirms the general understanding of the nature of off-gassing and emission rates over time in homes. However, because of changes in temperature and RH—as well as climate—between sampling periods (especially summer to winter/mixed), we may not expect to see a decrease over all sampling periods. Notably, in Homes 2, 3, and 5, the formaldehyde concentration during the second summer sampling period increased following the winter/mixed sampling period, and it returned to levels more consistent with the previous first summer sampling period.

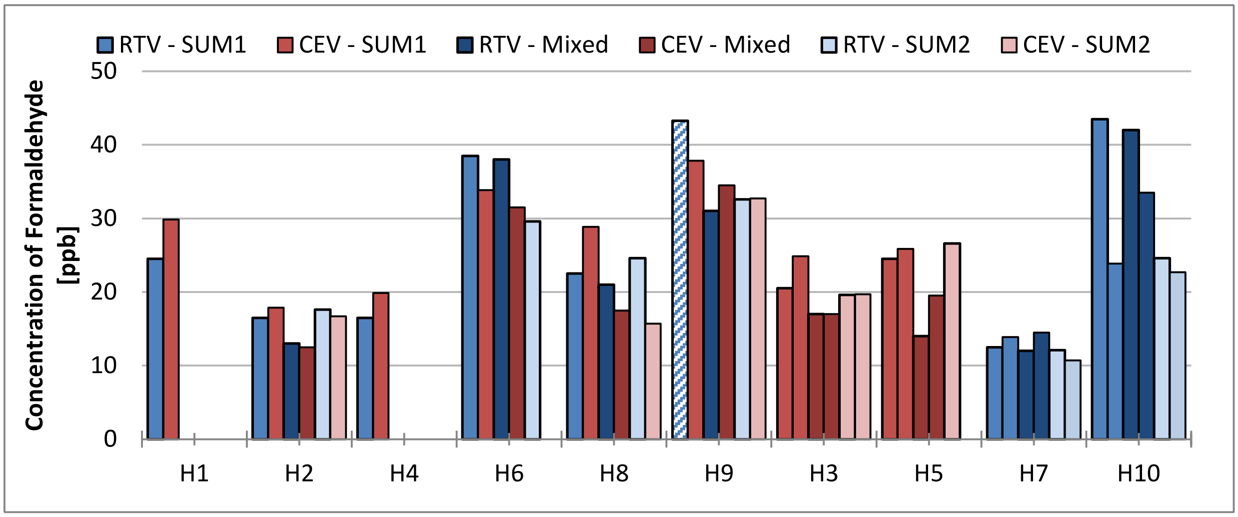


Figure 29. Concentrations of formaldehyde (ppb) in all homes during all sampling periods

3.2.3 Acetaldehyde

Acetaldehyde was also sampled in all of the homes and outdoors on the same aldehyde sampler as the formaldehyde measurements were made (see Section 1.1.1). In general, concentrations of acetaldehyde measured in these homes were very low, ranging from 0.7 ppb to 6.0 ppb during all the sampling periods, as shown in Figure 30. These levels are well below published recommended exposure limits for acetaldehyde. Acetaldehyde standard levels vary among organizations, based on the data used to inform the standards and the acceptable degree of risk based on the circumstances for which the standard is designed (EPA 2012). The OSHA limit, designed to protect workers in industrial environments, is 200 ppm (OSHA 2016), while the American Industrial Hygiene Association sets an Emergency Response Planning Guideline Level 1 limit of 10 ppm, which is meant to represent the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing anything other than mild transient health effects or perceiving a clearly defined, objectionable odor (AIHA 2013).

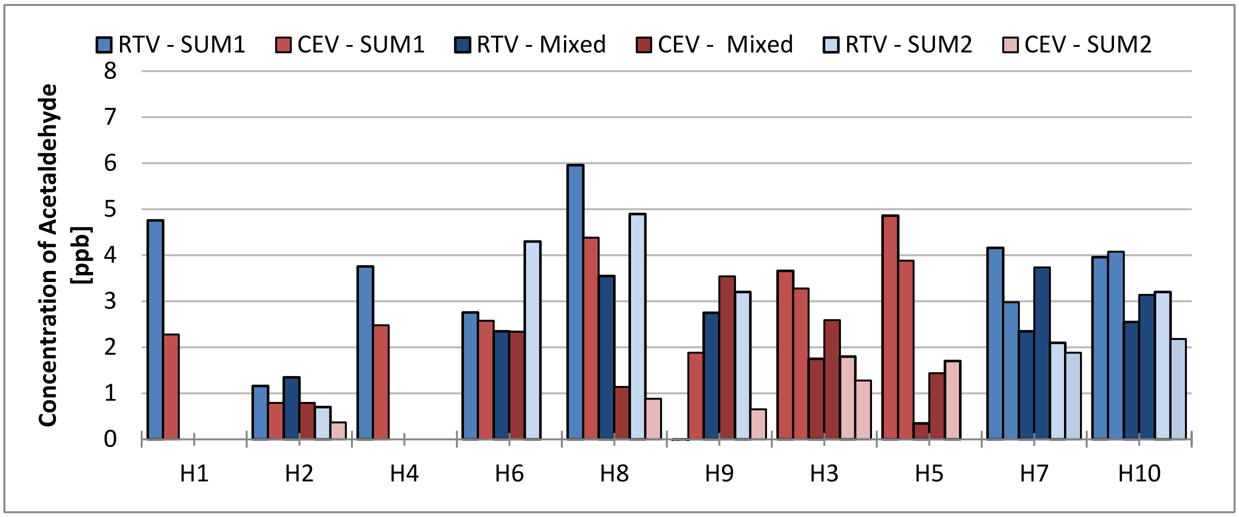


Figure 30. Concentrations of acetaldehyde (ppb) in all homes during all sampling periods

Figure 30 also depicts the temporal trend of acetaldehyde concentrations in each home. In some homes, acetaldehyde concentrations were observed to decrease over time, although a consistent decay was not observed. In addition, in other homes (e.g., Homes 6, 8, and 9), this was not the case, and concentrations were variable from one week to another. This may indicate that, while acetaldehyde is primarily introduced into the building as a constant source, typically as part of the building materials used in home construction, it may have more diverse and potentially more variable sources. Therefore, acetaldehyde may be reintroduced at different times into the indoor environment, which would confound the off-gassing decay trend.

Figure 31, Figure 32, and Figure 33 show the measured concentration of acetaldehyde in each home in the first summer, winter, and second summer IAQ sampling periods, respectively. In the first summer sampling period, the average concentration of acetaldehyde measured in the flip-flop homes decreased from the first sampling week to the second or from the RTV condition to the CEV condition. However, the measured concentration in the control homes decreased by a similar amount, so it is not possible to determine the impact of the ventilation strategy on the measured concentrations of acetaldehyde. Similarly, in the winter and subsequent second summer sampling periods, no clear trends were observed between acetaldehyde concentration and ventilation strategy. In the winter sampling period, the acetaldehyde concentration increased in most homes, including the control homes. In the second summer sampling period, the acetaldehyde concentrations decreased in most homes, including the control homes. While the concentrations of acetaldehyde were observed to decrease significantly in Home 8 and Home 9, it is worth noting that the concentrations also decreased in the control homes and outdoors, making it difficult to discern the impact of the ventilation strategy from that of other environmental factors; however, the ventilation strategy is likely contributing to the more effective dilution of acetaldehyde in the CEV periods. Figures 31, 32, and 33 generally demonstrate the concentration of acetaldehyde to be lower in CEV homes than in RTV homes, although this is not true in every case.

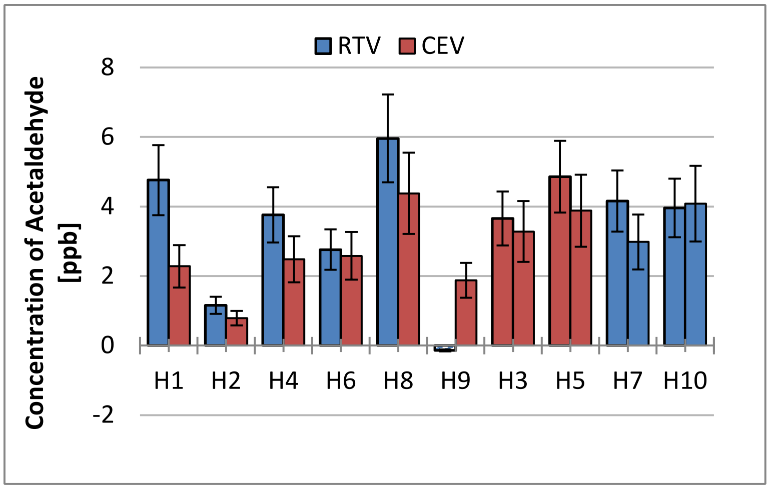


Figure 31. Concentrations of acetaldehyde (ppb) in Home 1 through Home 10 during the first summer IAQ sampling period

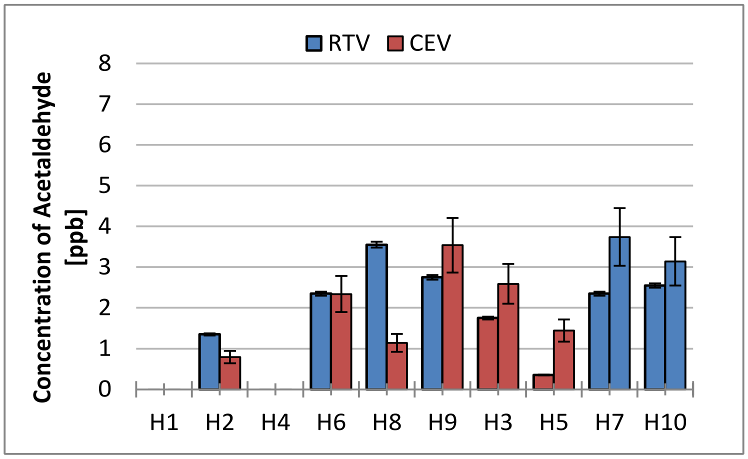


Figure 32. Concentrations of acetaldehyde (ppb) in Home 1 through Home 10 during the winter IAQ sampling period

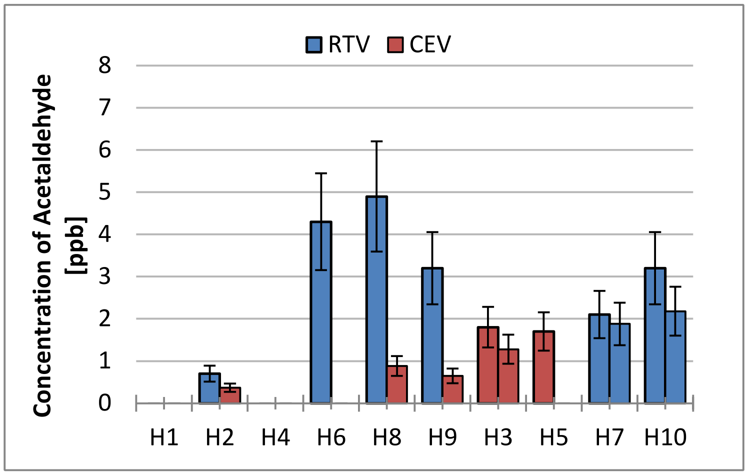


Figure 33. Concentrations of acetaldehyde (ppb) in Home 1 through Home 10 during the second summer IAQ sampling period

As with formaldehyde, the absolute and percentage changes in acetaldehyde concentrations were compared and no statistically significant differences were observed between the RTV and CEV homes. Figure 34, Figure 35, and Figure 36 depict the absolute difference (in ppb) and percentage difference observed in the flip-flop and control homes during each sampling period.

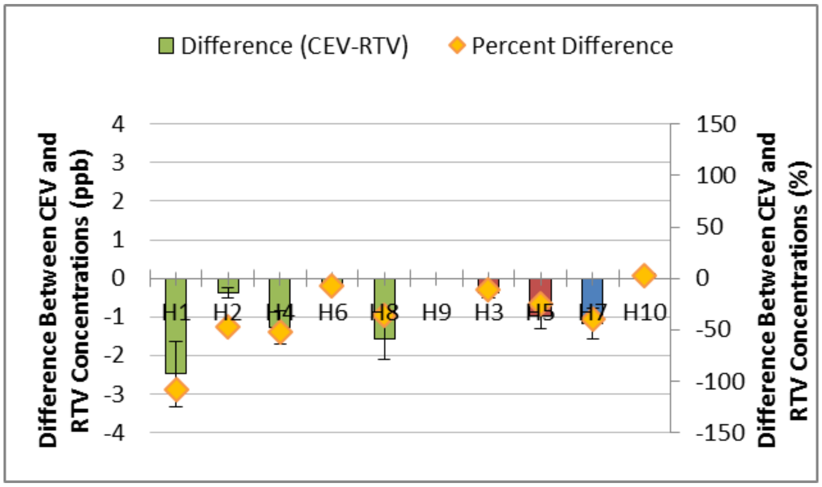


Figure 34. Absolute (ppb) and percent (%) difference in concentrations of acetaldehyde in Home 1 through Home 10 during the first summer IAQ sampling period

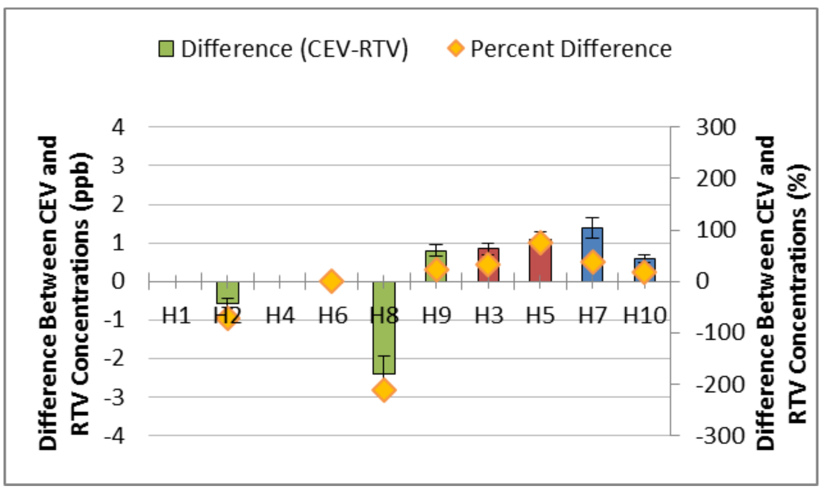


Figure 35. Absolute (ppb) and percent (%) difference in concentrations of acetaldehyde in Home 1 through Home 10 during the winter IAQ sampling period

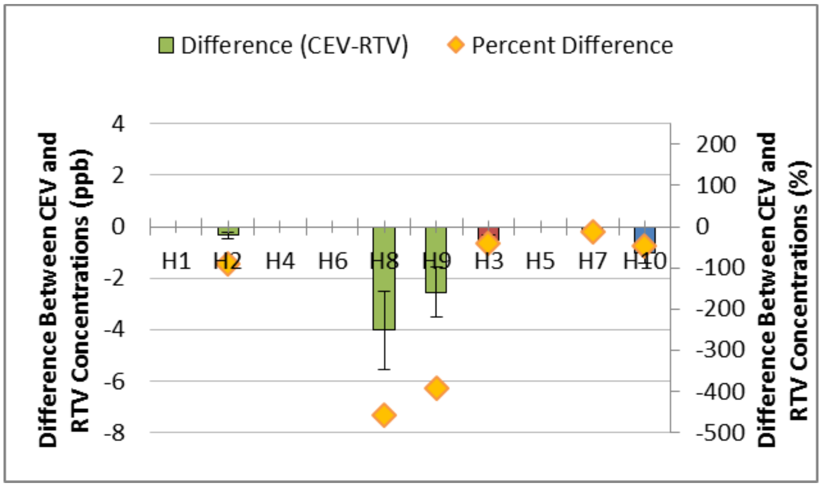


Figure 36. Absolute (ppb) and percent (%) difference in concentrations of acetaldehyde in Home 1 through Home 10 during the second summer IAQ sampling period

Complete acetaldehyde data are provided in Appendix K.

3.2.4 Volatile Organic Compounds

Concentrations were determined for a suite of VOCs based on the passive sampler measurements in each home, and outdoors, for each sampling period. As for other compounds, all concentrations are presented as outdoor and blank-corrected concentrations. The full VOC data set of outdoor- and blank-corrected concentrations is presented in Appendix K.

Because the health effects caused by different VOCs vary greatly, from those that are highly toxic to those with no known health effects, increased levels of various VOCs may or may not result in negative health effects.[17] Therefore, the VOC analysis presented in this section focuses on a specific set of VOCs that are better indicators of IAQ in homes.

To determine the impact of different ventilation strategies on overall VOC levels that are likely to affect IAQ, a unique “overall VOC” metric was calculated as the sum of 44 specific VOCs (listed in Table 8) that are likely found in the indoor environment and are potentially of health concern. The concentrations of these individual compounds were summed to obtain a metric for VOC concentrations generally.

[17] In general, VOCs tend to cause or contribute to eye, nose, and throat irritation; headaches, loss of coordination, nausea; and damage to the liver, kidney, and central nervous system. Some VOCs are likely or known carcinogens (EPA 2012).

Table 8. Forty-Four "Overall VOC" Pollutants

1-Hexanol, 2-ethyl-	Butanal	Ethylbenzene	Octane
2-Butoxyethanol	D3	g-Terpinene	o-Xylene
3-Carene	D4	Heptanal	Phenol
a-Pinene	D5	Heptane	Styrene
a-Terpineol	Decanal	Hexadecane	Tetrachloroethylene
Benzaldehyde	Decane	Hexanal	Tetradecane
Benzene	Dibutyl phthalate	Hexane	TMPD-DIB
Benzene, 1,2,3-trimethyl-	Diethyl phthalate	m/p-Xylene	TMPD-MIB
Benzene, 1,2,4-trimethyl-	Dimethyl phthalate	Naphthalene	Toluene
Benzene, 1,4-dichloro	D-Limonene	Nonanal	Trichloromethane
Benzene, butyl-	Dodecane	Octanal	Undecane

Of the 44 compounds shown in Table 8, only 10 were observed with any frequency in the homes during the two summer sampling periods and one winter paired sampling period. For reference, the 30 most commonly observed VOCs are listed in Table 9, with the 10 VOCs that are also included in the list of 44 VOCs of concern highlighted in orange. Table 9 also presents the average measured concentration in each home over all the sampling periods and the average concentration among all the homes for all the sampling periods. This gives an indication of the types of VOCs most commonly observed. In general, concentrations of VOCs were low, especially for those VOCs that may pose a risk to human health.

Table 9. Average Concentration (ppb) of 30 Most Commonly Observed VOCs in Each House over All Sampling Periods, in All Houses over All Sampling Periods, and Total Concentration (ppb) of 30 Most Commonly Observed VOCs in Each House over All Sampling Periods

Specific Volatile Organic Compound	H1 (FF)	H2 (FF)	H4 (FF)	H6 (FF)	H8 (FF)	H9 (FF)	H3 (CEV)	H5 (CEV)	H7 (RTV)	H10 (RTV)	Overall Average
1,2,4-Trimethylbenzene	0.15		0.07							0.13	**0.12**
1,2-Dichloroethane	4.05		0.23		0.72	1.73	0.12	0.15	1.00	0.98	**1.12**
2-Hexanone	0.19	0.11	0.18		0.17	0.20	0.23	0.13	0.15	0.47	**0.20**
4-Ethyl toluene	0.20									0.27	**0.24**
Acetone	8.15	10.40	4.10	7.80	17.04	74.45	19.64	10.10	10.32	11.80	**17.38**
Benzene	2.45	0.23	1.32	0.07	0.37	1.05	0.60	0.61	1.01	1.53	**0.92**
Bromodichloromethane	0.25	0.07		0.08	0.10	0.08	0.09	0.09	0.14	0.22	**0.12**
Carbon disulfide	0.60	-0.12	-0.06	0.10	0.30	1.96	1.00	0.23	-0.14	0.11	**0.61**
Carbon tetrachloride	0.04	0.04	0.04	0.05	0.06	0.09	0.05		0.05	0.07	**0.05**
Chloroform	0.38	0.20	1.20		0.38	0.69	0.32	0.18	0.46	0.49	**0.48**
Cyclohexane	1.03	0.17	0.77	0.11	0.19	0.85	0.54	0.77	0.90	1.06	**0.64**
Ethanol	3.00	-1.15	2.00	0.50	0.02	19.73	52.90	-1.48	-3.65	-0.23	**13.03**
Ethyl acetate	2.56	2.14	4.21	49.11	5.24	28.74	20.61	3.19	3.17	3.19	**12.22**
Ethyl benzene	1.19	0.10	0.27	0.09	0.06	0.13	0.11	0.15	0.17	3.33	**0.56**
Freon 11	-0.08	0.04	-0.05	-0.08	-0.03	0.02	0.17	-0.02	-0.05	0.00	**0.08**
Freon 113		0.03	0.00	0.20	0.02	0.05	0.09	0.02	0.00	-0.01	**0.06**
Heptane	1.60	0.12	2.00	0.26	0.65	0.31	0.37	0.22	0.41	0.99	**0.69**
Isopropyl alcohol	2.01	3.67	2.76	6.80	252.80	31.95	15.97	9.40	23.56	5.70	**35.46**
m,p-Xylene	1.17	0.01	0.19	0.08	0.04	0.09	0.09	0.08	0.10	2.50	**0.43**
Methyl ethyl ketone	6.93	2.17	4.83	24.29	2.89	7.04	4.32	3.16	4.26	4.62	**6.45**
Methyl isobutyl ketone	0.13	0.23	1.04	0.54	0.30	0.56	0.42	0.33	0.32	1.60	**0.55**
Methylene chloride	-6.90	14.84	-4.80	15.60	1.09	20.62	64.66	9.28	2.72	6.10	**16.86**

Specific Volatile Organic Compound	H1 (FF)	H2 (FF)	H4 (FF)	H6 (FF)	H8 (FF)	H9 (FF)	H3 (CEV)	H5 (CEV)	H7 (RTV)	H10 (RTV)	Overall Average
n-Hexane	4.09	0.29	5.40	-0.11	0.17	1.94	1.24	0.68	1.66	2.78	**2.03**
o-Xylene	0.94		0.28	0.07		0.13	0.12	0.12	0.11	2.81	**0.57**
Styrene	0.19	0.11	0.16	0.16		0.14	0.07	0.04	0.14	0.61	**0.18**
Tetrachloroethene	0.19	0.04	0.53		0.08	0.05	0.12		0.06	0.16	**0.15**
Tetrahydrofuran	1.41	1.16	1.16	4.71	0.51	1.76	1.75	0.52	1.23	1.63	**1.58**
Toluene	5.33	0.81	2.68	0.32	0.76	1.92	0.97	2.54	1.78	3.67	**2.08**
Trichloroethene	0.52				0.07				0.03		**0.20**
Total of 30 Most Common VOCs	**41.72**	**35.72**	**30.48**	**110.74**	**283.99**	**196.27**	**186.54**	**40.48**	**49.91**	**56.56**	**115.06**

VOCs in rows highlighted in orange are the VOCs that were frequently detected in the study home.

In the first summer sampling period, the sum of the 10 frequently detected VOCs was observed to increase from the first week to the second week in all homes, including the control homes (except H10). However, the most significant increases were observed in the flip-flop homes. The sum of the 10 VOCs of concern that were detected in the homes for each of the homes for the two one-week samples in the first summer sampling period are shown in Figure 37.

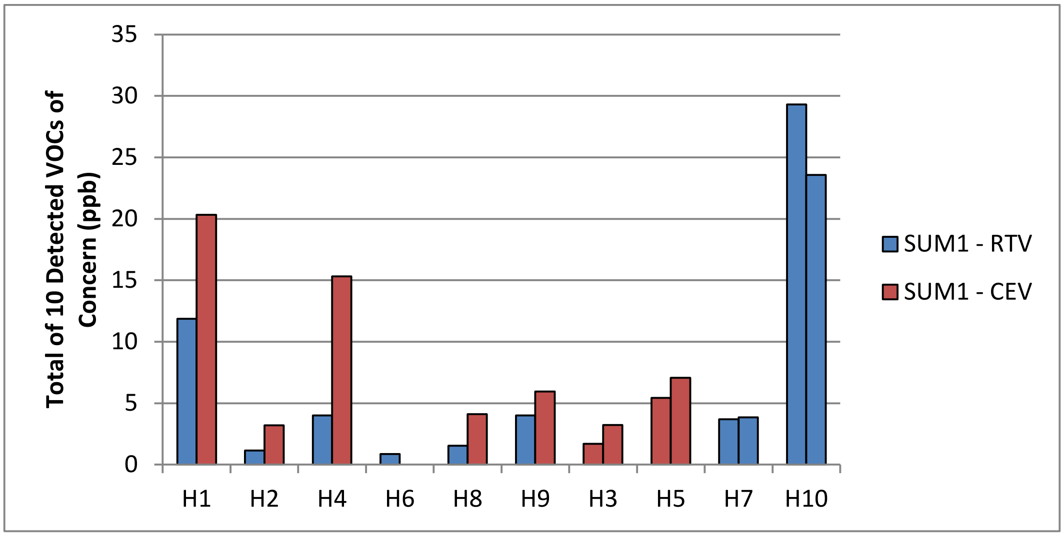


Figure 37. Total concentration of 10 detected VOCs of concern (ppb) in Home 1 through Home 10 during the first summer IAQ sampling period

While the presented data were corrected for the measured outdoor concentration, it is worth noting that the concentration of these 10 VOCs outdoors did not change significantly. And, the indoor climate conditions were similar between the sampling periods, so it is not clear why such an increasing trend was observed. The second sampling period was slightly cooler than the first IAQ sampling period, with an average outdoor temperature of 82°F in the first week versus 79°F in the second week, but that is not expected to significantly impact the overall VOC concentrations indoors. In addition, because the two sampling weeks were not consecutive, it is not likely that temporal changes in uptake, storage, or off-gassing of materials in the home affected the measurements.

In subsequent IAQ sampling periods, as can be seen in Figure 38 and Figure 39, the summed concentration of these 10 VOCs was significantly reduced. In the winter sampling period, for example, of the 10 detected VOCs of concern, only benzene, n-hexane, and toluene were detected consistently in most of the homes.

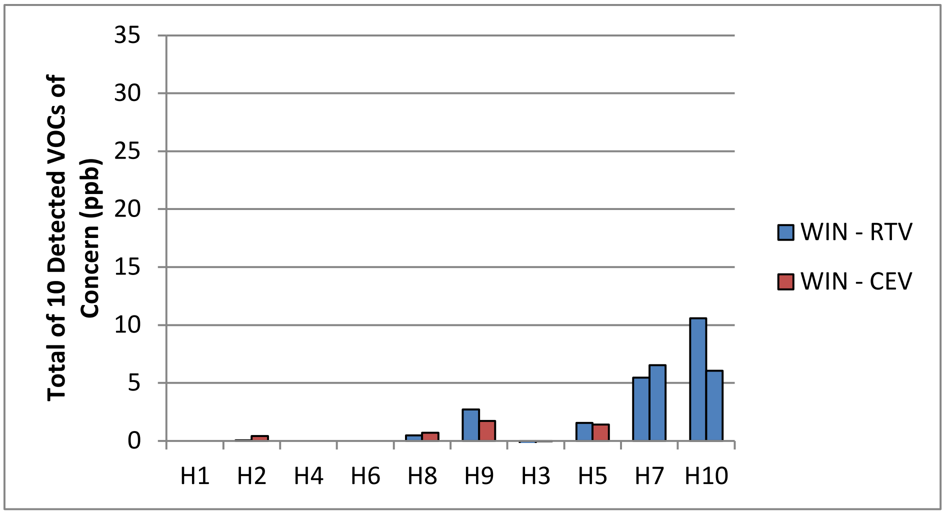


Figure 38. Total concentration of 10 detected VOCs of concern (ppb) in Home 1 through Home 10 during the winter IAQ sampling period

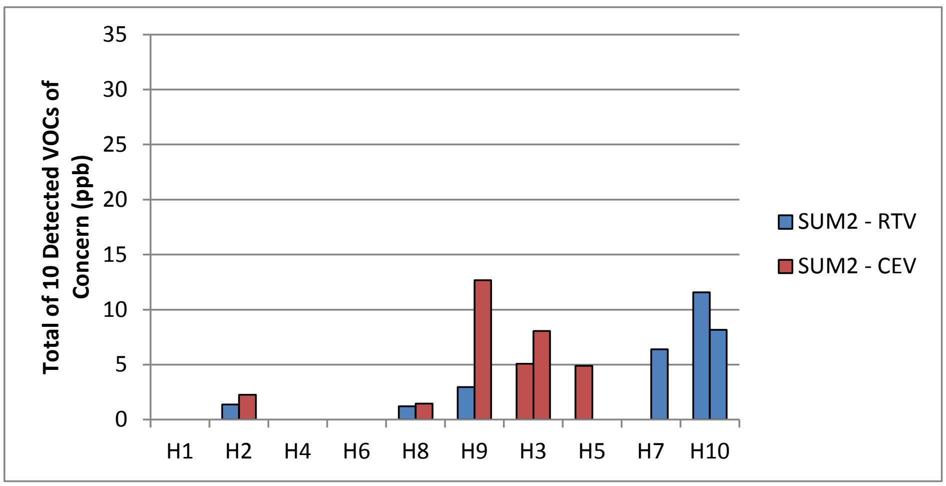


Figure 39. Total concentration of 10 detected VOCs of concern (ppb) in Home 1 through Home 10 during the first summer IAQ sampling period

Even though a course metric such a TVOC (representing all measured VOCs using the TO-17 method) was employed, concentrations of VOCs in the winter and second summer sampling periods were generally much lower than those measured in the first summer sampling period, as shown in Figure 40.

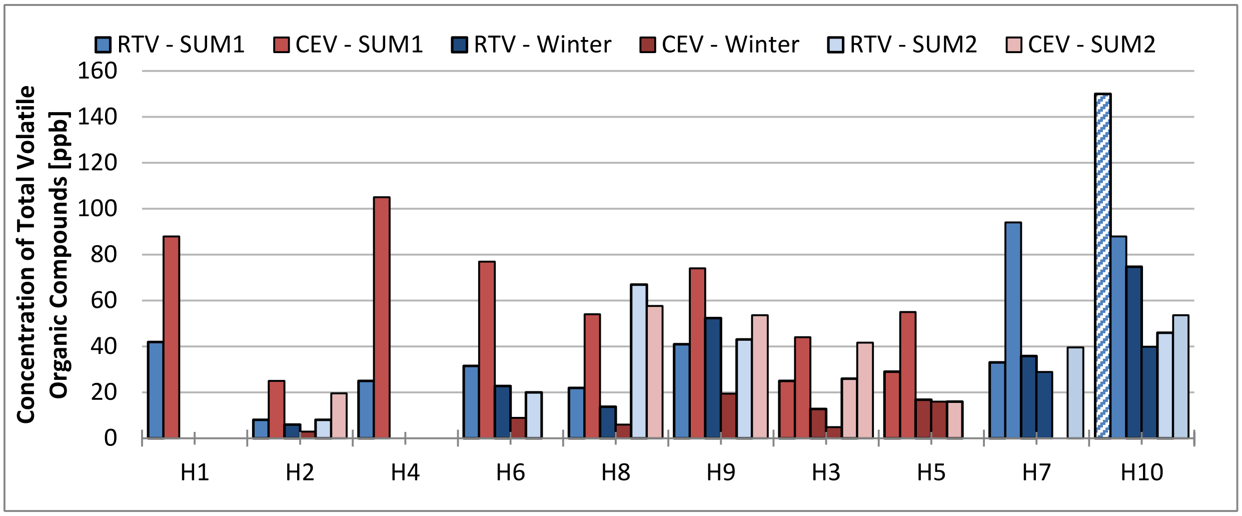


Figure 40. Concentration of total volatile organic compounds (TVOC; ppb) in Home 1 through Home 10 during all the sampling periods

The overall trend in the 10 detected VOCs of concern identified earlier (shown in Figure 41) demonstrates trends similar to those observed in the TVOC data (shown in Figure 40).

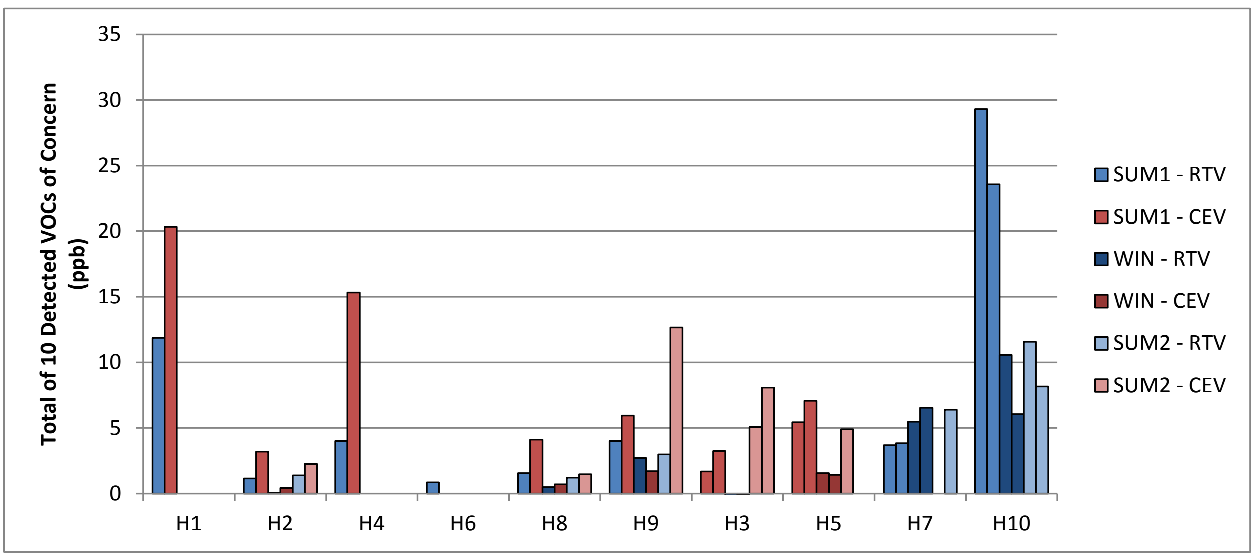


Figure 41. Total concentration of 10 detected VOCs of concern (ppb) in Home 1 through Home 10 during the all of the sampling periods

Overall, VOCs occur in the indoor environment due to a variety of sources with significant variability in time and space. For this reason, discerning trends between the ventilation approach and the measured concentration of VOCs is difficult. In addition, all measured VOCs concentrations were generally low, and the detected VOCs are not a known health concern at the observed levels. However, as with formaldehyde and acetaldehyde, increased ventilation via an exhaust-only system (CEV) was not observed to decrease the concentration of VOCs based on the TVOC, individual VOC, or 10-VOC analysis methods. In this case, especially in the first summer sampling period, it appears the CEV configuration may actually have increased VOC concentrations. While the cause of this effect is unknown, the authors hypothesize that this relationship may be due to the exhaust-only ventilation method employed in the CEV homes causing air to be pulled through the building envelope and, thus, increasing emission of VOCs indoors. In addition, this trend is not statistically significant due to the small sample sizes and variability observed in the control homes.

3.2.5 Nitrogen Dioxide

Nitrogen dioxide (NO_2) was sampled in one home with gas cooking equipment and one home without, as well as outside, during each sampling period. The sampled homes varied among the sampling periods (but one with gas and one without gas were always sampled), and the measured concentrations were corrected based on the outdoor concentration of NO_2 and the field blank.[18] As shown in Figure 42, NO_2 exhibited a more predictable trend with respect to ventilation rate, where increased ventilation associated with the CEV approach resulted in decreased NO_2 concentrations indoors. Figure 42 also illustrates that concentrations of NO_2 were higher in the homes with gas cooking than in the homes without it, and CEV was effective in reducing the concentration to levels equivalent with those observed in the homes without gas cooking. Here all data sampled from homes with gas cooking in a given ventilation configuration were averaged, which potentially masks some seasonal variability. It is worth noting that the measured NO_2 concentrations were generally higher in the winter than in the summer. There also is likely variability among homes, but the sample set is too small to quantify home-to-home variability for this analysis. The complete NO_2 data are provided in Appendix K.

[18] The NO_2 concentration outdoors during the second week in the first summer sampling period did not resolve. For this reason, neither of the weeks in the first summer sampling period was corrected for the outdoor measurement to allow for better comparability between the samples.

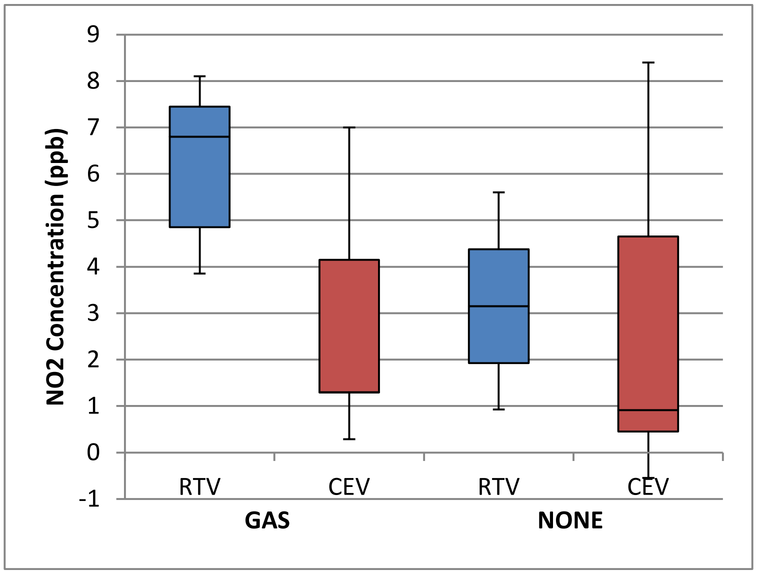


Figure 42. Average concentration of NO_2 (ppb) in homes with gas cooking and homes without gas cooking in the RTV and CEV configurations, corrected for outdoors

NO_2 was corrected for outdoor concentrations by subtracting the outdoor concentration from the indoor concentration, and, therefore, Figure 41 does not account for any indoor deposition of NO_2.

Comparing the change in NO_2 concentration resulting from switching from the RTV to the CEV strategy, Figure 43 shows that CEV ventilation was effective in reducing the NO_2 concentration indoors by a statistically significant amount in homes with gas cooking.

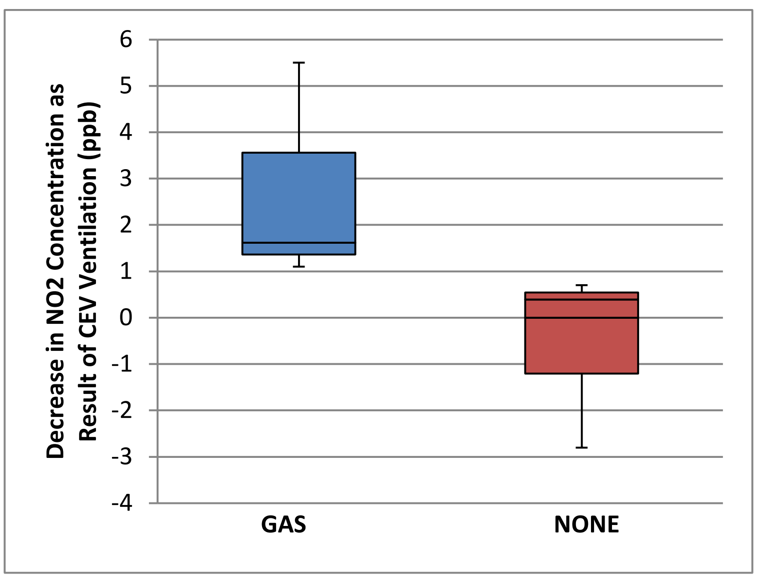


Figure 43. Average decrease in concentration of NO_2 (ppb) as a result of switching from RTV to CEV configurations in homes with gas cooking and homes without, corrected for outdoors

While a decrease in concentrations of NO_2 is beneficial, because it illustrates a dilution of cooking-related contaminants resulting from the whole-house ventilation, no standards have been agreed upon for nitrogen oxides in indoor air. The concentrations measured here are an order of magnitude lower than the EPA's National Ambient Air Quality Standard of 53 ppb NO_2 in outdoor air averaged over a 24-hour period.

3.2.6 Radon

As mentioned in Sections 2.1.3 and 2.2.11, radon is also a key contaminant of concern in residences in some areas of the United States, and it was passively sampled over the entire study period (June 2013–June 2014). No homes were observed to be above the EPA action limit of 4 pCi/L (EPA 2009). Average radon concentrations—which were assessed in the kitchen of each home; none of the homes had basements—ranged between 1.3 and 2.5 pCi/L, and they are presented for each house in Table 10. Outdoor concentrations were not determined. For three homes, the radon sampler was not retrieved because homeowners moved or left the study before the sampler could be retrieved and analyzed.

Table 10. Average Radon Concentration (pCi/L) in All Houses over the Entire Sampling Period (June 2013 to June 2014)

Ventilation Configuration	House	Sampler ID	Radon Concentration (pCi/L)
FF	H1	2522100	not analyzed
FF	H2	2521944	1.4
FF	H4	2521911	not analyzed
FF	H6	2521996	1.3
FF	H8	2521975	2.2
FF	H9	2521955	not analyzed
CEV	H3	2521947	1.4
CEV	H5	2521903	1.5
RTV	H7	2521920	1.4
RTV	H10	2521956	2.5

3.2.7 Mold

Each home was visually inspected for the presence of mold during each IAQ sampling period, and because of the brevity of the study, none was observed. In addition, the homeowners' HVAC systems worked to maintain reasonable temperature and RH conditions indoors that would effectively mitigate significant mold problems in the short term. However, the relationship between temperature, RH conditions, and mold growth over time is not as well known. It is unclear whether in the long term, conditions associated with RTV or CEV configurations would have led to mold and moisture problems.

3.2.8 Homeowner Survey Data

Homeowners were also surveyed regarding their perceptions of comfort and IAQ; the survey instrument is included in Appendix E. While anecdotal in nature, homeowner perceptions are an important data source when considering the persistence of any home performance measures or interventions. For example, if increased or decreased ventilation decreased homeowner comfort, it is less likely that the goal of any such ventilation would be achieved and maintained over time because homeowners may be inclined to modify or disable the ventilation system to better address their families' comfort concerns.

Consistent homeowner survey data are not available because surveys were not consistently conducted at regular intervals as initially envisioned. However, in this study, two significant homeowner reports are worth mentioning. One homeowner, very early in the study, reported sensing stuffy "stagnated air" during the CEV periods. Another homeowner, in June 2014 (the second summer), when the homes were left in the CEV configuration for a longer period of time than normal (outside IAQ sampling periods), reported their house smelling of "old socks" and feeling uncomfortable. They requested their home be returned to the "normal" (i.e., RTV) configuration. The authors followed up the next week to ensure the homeowner's concerns had been resolved, and the homeowner reported the smell and discomfort had dissipated within 24 hours of switching the ventilation system. At the request of the homeowner, the home was not flip-flopped for the remainder of the study period.

4 Conclusions

Concentrations of certain indoor air contaminants, ventilation system flow rates, space-conditioning energy consumption and condensate generation, and indoor and outdoor conditions were measured in 10 high-performance new homes in Gainesville, Florida, to characterize the impact of differing ventilation approaches on these parameters. Data were collected during June 2013 through August 2014. Continuous exhaust ventilation (CEV), with rates approximating rates required by ASHRAE 62.2-2013, was compared to intermittent runtime ventilation (RTV), which delivers approximately 16% of ASHRAE 62.2-2013 requirements annually.

For summer conditions, the CEV systems result in approximately 9% more cooling energy use on average to maintain the desired temperature set points in the homes. Ventilation strategy was found to be among the most significant variables driving runtime of air conditioners. Despite the added air conditioner runtime, the resulting relative humidity (RH) was higher in the homes while under CEV, causing them to log more hours >60% and >65% RH than while under RTV. Regression analysis showed that ventilation strategy was the most significant variable tested in predicting >60% RH, and it was slightly less significant in predicting hours >65% RH. However, the extent and persistence of the elevated RH was variable among homes, suggesting other parameters are also impactful. In the short term, the elevated RH was more likely to cause comfort issues than it was to cause durability or mold issues. During visits to the homes, no signs of mold were observed, and few comfort complaints were logged. The long-term effect of elevated RH in these homes is unknown. Condensate collected during the summer of 2014 showed a causal relationship to ventilation strategy, but regression analysis revealed that condensate volumes are more highly correlated to occupant behavior, suggesting significant and highly variable internal moisture generation rates. Conditioned house size was also found to be significant, but it revealed an inverse relationship, which may indicate that a larger house has more capacity to buffer moisture than a smaller house.

During the mixed season between October and April, homes operated under a mix of heating, cooling, and floating space-conditioning operation. Space-conditioning and natural ventilation preferences are highly variable during this period, and analysis of limited heating data did not show a significant impact related to ventilation strategy. Ventilation strategy appears to have a statistically significant but overall minor impact in indoor RH during the mixed period compared to the summer period, and RH trends seem dominated by outdoor conditions and occupant preferences.

CO_2 data show that RTV systems, which inherently depend on space-conditioning system runtime, generate less air change than continuous exhaust systems. Preferences for enhanced natural ventilation during the mixed period that could counteract this effect seem variable.

In general, the CEV ventilation strategy resulted in 30% higher estimated air exchange rates (AERs) than the RTV configurations in the flip-flop homes and 79% higher mechanical ventilation rates. The difference in AER between the two ventilation strategies is less extreme than the difference in mechanical ventilation flow rate because of the impact of infiltration air on overall air exchange rate. For RTV homes, the unbalanced mechanical ventilation flow rate was an average of 28% of total mechanical and infiltration-driven ventilation airflow in the summer and 5% in the winter; for CEV homes, the mechanical ventilation flow rates were 82% and 84% of the total airflow for the summer and winter, respectively. However, it is worth noting that the increase in AER did not consistently decrease CO_2 concentrations during the sampling periods in all homes. While concentrations of CO_2 may be variable due to occupancy or other factors, this may suggest that the CEV ventilation strategy is not actually increasing the dilution rate in all areas of the home as much as the increase in AER might suggest.

Concentrations of formaldehyde, acetaldehyde, VOCs, and NO_2 were determined in paired sampling periods during the summer of 2013, winter of 2013/2014, and summer of 2014. While the observed concentrations of sampled contaminants were variable among the homes and suggest the importance of occupant activities and behavior, analyses of the data indicate that increased ventilation via a continuous exhaust fan, as was employed in the CEV strategy, may not be effective in decreasing concentrations of all indoor air quality (IAQ) contaminants, which is consistent with the finding for CO_2. Notably, despite significant increases in mechanical ventilation flow rate and AER during all IAQ sampling periods, concentrations of formaldehyde, acetaldehyde, and VOCs did not show a significant dependence on ventilation approach. That is, operation of the CEV approach at ventilation rates 79% higher than the RTV method did not significantly decrease observed concentrations of formaldehyde, acetaldehyde, or VOCs. Generally, the concentrations of VOCs and aldehydes appeared slightly higher in the RTV homes than in the CEV homes, although, in some cases, concentrations were observed to increase in the CEV configuration. As a result, consistent and significant trends were not discernable from the data because of variability among the homes and between sampling periods in the same home. This contradicts findings from previous researchers that concentrations of IAQ contaminants exhibit an inverse relationship to ventilation rate (Lajoie et al. 2015; Hult et al. 2014). The fact that the concentrations of formaldehyde, acetaldehyde, and VOCs measured in this study were variable and not correlated to a change in ventilation strategy—despite the higher ventilation rates achieved by the CEV system suggests that other factors in addition to ventilation rate—such as ventilation system design (e.g., balanced versus supply-only versus exhaust-only) may be important in determining the efficacy of a ventilation system in achieving the desired dilution effect. This result is consistent with other research that has analyzed different ventilation system types. Specifically, Hun et al. (2014) have also observed reduced efficacy of exhaust-only ventilation in reducing formaldehyde concentrations. Rudd and Bergey (2013) measured lower formaldehyde concentrations in a study house ventilated with the supply-based continuous fan integrated supply (CFIS) system than in the same house when ventilated with an exhaust fan and similar effective ventilation rates.

Conversely, NO_2, which was measured in two homes (one with gas cooking and one without it) during each sampling period, appeared to be effectively mitigated by the CEV method, suggesting that for some sources of pollutants, the efficacy of the ventilation system may be less affected by ventilation system design.

While the concentrations of acetaldehyde, VOCs, and NO_2 were far below published standard levels and are unlikely to cause negative health effects at these low levels, formaldehyde concentrations were, on average, above the NIOSH-recommended exposure limit of 16 ppb.

Future work to further explore the efficacy of different ventilation systems and disaggregate the impact of ventilation rate and system type is necessary to understand how to apply these findings in the field to achieve optimum IAQ and homeowner comfort in new homes for the lowest cost and energy impacts.

5 References

AIHA (American Industrial Hygiene Association). 2013. *Emergency Response Planning Guidelines. American Industrial Hygiene Association*. Falls Church, Virginia. https://www.aiha.org/get-involved/aihaguidelinefoundation/emergencyresponseplanningguidelines/Pages/default.aspx.

ASHRAE Standards Committee. 2013a. *ASHRAE Fundamentals Handbook: Chapter 16 – Ventilation and Infiltration*. Atlanta, Georgia.

———. 2013b. *ASHRAE Standard 62.2 - Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta, Georgia.

———. 2004. *ASHRAE Standard 152: Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*. Atlanta, GA.

ASTM International. 2010. *ASTM E779-10: Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*.West Conshohocken, PA.

BIER IV (Committee on Health Risks of Exposure to Radon). 1999. *Health Effects of Exposure to Radon: BIER IV*. National Academies Press, Washington, D.C.

CDC (Center for Disease Control and Prevention). 2011. *NIOSH Pocket Guide to Chemical Hazards: Appendix A − NIOSH Potential Occupational Carcinogens*. Atlanta, Georgia. http://www.cdc.gov/niosh/npg/nengapdxa.html.

Chandra S., D. Parker, J. Sherwin, C. Colon, K. Fonorow, D. Stroer, E. Martin, J. McIlvaine, D. Chasar, N. Moyer, S. Thomas-Rees, D. Hoak, D. Beal, and C. Gil. 2008. "An Overview of Building America Industrialized Housing Partnership (BAIHP) Activities in Hot-Humid Climates." *Sixteenth Symposium on Improving Building Systems in Hot and Humid Climates*. December 15–17, 2008, Dallas, TX.

Chasar, D., S. Chandra, D. Parker, J. Sherwin, D. Beal, D. Hoak, N. Moyer, and J. McIlvaine. "Cooling Performance Assessment of Building America Homes." *Fifteenth Symposium on Improving Building Systems in Hot and Humid Climates*. July 24–26, 2006, Orlando, FL.

Coyne L., C. Kuhlman, and J. Chada. *Validation of the 575 and the ULTRA Series Diffusive Samplers: Long-term Sampling in Indoor and Ambient Air Environments*. SKC Inc., Eighty Four, Pennsylvania. http://www.skcinc.com/pdf/1812.pdf.

Dales R., L. Liu, A. J. Wheeler, and N. L. Gilbert. 2008. "Quality of Indoor Residential Air and Health." *Canadian Medical Association Journal* 179(2):147–152.

DOE (U.S. Department of Energy). 2014. *DOE Zero Energy Ready Home National Program Requirements*. Rev. 04. Washington, D.C.: U.S. Department of Energy Building Technologies Office. http://energy.gov/sites/prod/files/2014/04/f15/doe_zero_energy_ready_home_requirements_rev04.pdf.

EPA (U.S. Environmental Protection Agency). 1990. *Determination of Formaldehyde and Other Aldehydes in Indoor Air using Solid Adsorbent Cartridge-Method IP-6A*. Compendium of Methods for the Determination of Air. Cincinnati, OH. EPA-600/4-90-010.

———. 1999a. *Compendium Method TO-11A: Determination of Formaldehyde in Ambient Air Using Adsorbent Cartridge Followed by High-Performance Liquid Chromatography (HPLC) [Active Sampling Methodology]*. Compendium of Methods for Determining Toxic Organic Compounds in Ambient Air. Cincinnati, OH. EPA/625/R-96/010b.

———. 1999b. *Compendium Method TO-17: Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling Onto Sorbent Tubes*. Compendium of Methods for Determining Toxic Organic Compounds in Ambient Air. Cincinnati, OH. EPA/625/R 96/010b.

—. 2009a. "A Citizen's Guide to Radon." IE Division (ed.), Washington D.C. http://www.epa.gov/radon/pubs/citguide.html.

———. 2012. *An Introduction to Indoor Air Quality: Volatile Organic Compounds*. Cincinnati, Ohio. Last updated July 29, 2012. http://www.epa.gov/iaq/voc.html.

———. 2013. *Energy Star Qualified Homes, Version 3 (Rev. 07): National Program Requirements*. Cincinnati, OHL U.S. Environmental Protection Agency. http://www.energystar.gov/ia/partners/bldrs_lenders_raters/downloads/National_Program_Requirements.pdf?5fae-d76b.

Hult, E. L., H Willem, P. N. Price, T. Hotchi, M. L. Russell, and B. C. Singer. 2014. "Formaldehyde and Acetaldehyde Exposure Mitigation in US Residences: In-Home Measurements of Ventilation Control and Source Control." *Indoor Air* (5 November 2014):n/a-n/a. doi:10.1111/ina.12160. http://dx.doi.org/10.1111/ina.12160.

Hun, D., M. Jackson, and S. Shrestha. 2014. "Optimization of Ventilation Energy Demands and Indoor Air Quality in High-Performance Homes." *2014 ACEEE Summer Study on Energy Efficiency in Buildings*. August 2014, Pacific Grove, CA. American Council for an Energy Efficient Economy, Washington, D.C.

Kerrigan, P. 2014. *Evaluation of the Performance of Houses With and Without Supplemental Dehumidification in a Hot-Humid Climate*. Golden, CO: National Renewable Energy Laboratory. NREL/SR-5500-62531. http://www.nrel.gov/docs/fy15osti/62531.pdf.

Kuhlman, C., and N. Zovack. 2013. "Validation of Nitrogen Dioxide Using the SKC UMEx 200 Passive Sampler Cat. No. 500-200." SKC Inc., Eighty Four, Pennsylvania. http://www.skcinc.com/instructions/1789.pdf.

Lajoie, P., D. Aubin, V. Gingras, P. Daigneault, F. Ducharme, D. Gauvin, D. Fugler, J.-M. Leclerc, D. Won, M. Courteau, S. Gingras, M.-È Héroux, W. Yang, and H. Schleibinger. 2015. "The Ivaire Project: A Randomized Controlled Study of the Impact of Ventilation on Indoor Air Quality and the Respiratory Symptoms of Asthmatic Children in Single Family Homes." *Indoor Air* (21 January 2015):n/a-n/a. doi:10.1111/ina.12181. http://dx.doi.org/10.1111/ina.12181

Logue J.M., T.E. Mckone, M. H. Sherman, and B.C. Singer. 2010. Hazard Assessment of Chemical Air Contaminants Measured in Residences. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-3650-E. http://eetd.lbl.gov/sites/all/files/publications/hazard-assessment-lbnl3650e.pdf.

Martin, E. for Building Science Corporation, Florida Solar Energy Center/BA-PIRC, and IBACOS. 2014. *Impact of Residential Mechanical Ventilation on Energy Cost and Humidity Control*. Golden, CO. National Renewable Energy Laboratory. NREL/SR-5500-60675. http://www.nrel.gov/docs/fy14osti/60675.pdf.

OSHA (Occupational Safety and Health Administration). 2016. *Occupational Safety and Health Standards, Toxic and Hazardous Substances: Formaldehyde*. Code of Federal Regulations. 29 CFR 1910.1048.

Offermann, F. 2009. *Ventilation and Indoor Air Quality in New Homes*. Public Interest Energy Research (PIER), California Energy Commission. CEC-500-2009-085. http://www.arb.ca.gov/research/apr/past/04-310.pdf.

OEHHA (Office of Environmental Health Hazard Assessment). 2014. *Air Toxicology and Epidemiology: Table of 8-hour and Chronic Reference Exposure Levels (chRELs)*. California Environmental Protection Agency. http://oehha.ca.gov/air/allrels.html.

Prichard, H., and K. Marien. 1985. "A Passive Diffusion 222~n Sampler Based on Activated Charcoal Adsorption." *Health Physics* 48:797–803.

Rudd, A., and D. Bergey. 2014. *Ventilation Systems Effectiveness and Tested Indoor Air Quality Impacts*. Golden, CO: National Renewable Energy Laboratory. NREL/SR-5500-61128. http://www.nrel.gov/docs/fy14osti/61128.pdf.

Rudd, A., and J. Lstiburek, J. 2008. "Systems Research on Residential Ventilation." *Proceedings of the 2008 ACEEE Summer Study on Energy Efficiency in Buildings*. August 2008, Pacific Grove, CA. American Council for an Energy Efficient Economy, Washington, D.C.

Salthammer T, S. Mentese, and R. Marutzky. 2010. "Formaldehyde in the Indoor Environment." *Chemical Reviews* 110(4):2536–2572.

Spengler, JD, and K Sexton. 1983. "Indoor Air Pollution: A Public Health Perspective." *Science* 221:9–17.

Tsongas G. 2009. "Case Studies of Moisture Problems in Residences," Chapter 13 in *Moisture Control in Buildings: The Key Factor if Mold Prevention*. 2nd Edition, HR Trechsel and MT Bomberg (eds.), ASTM International, Baltimore, Maryland.

Weisel, C. P.; J. Zhang, B. J. Turpin, M. T. Morandi, S. Colome, T. H. Stock, D. M. Spektor, L. Korn, A. Winer, S. Alimokhtari, J. Kwon, K. Mohan, R. Harrington, R. Giovanetti, W. Cui, M. Afshar, S. Maberti, and D. Shendell. (2005). "Relationship of Indoor, Outdoor and Personal Air (RIOPA) Study." *Journal of Exposure Analysis and Environmental Epidemiology* 15(2):123–37. Environmental and Occupational Health Sciences Institute, Piscataway, NJ.

Weschler C. J., and W. W. Nazaroff. 2008. "Semivolatile Organic Compounds in Indoor Environments." *Atmospheric Environment* 42:9018–9040.

WHO (World Health Organization. 2010. *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Copenhagen, Denmark: World Health Organization.

Wray C, I. Walker, and M. Sherman. 2002. *Accuracy of Flow Hoods in Residential Applications*. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL 49697. http://epb.lbl.gov/publications/pdf/lbnl-49697.pdf.

Appendix A. Sampling Protocol

Pre-Sampling Activities:

- Weigh PFT Emitters
    1. Calibrate the scale by weighing the 5-g, 10-g, and 20-g weights three times each and recording the weights. (Just record this; no zeroing is necessary if it is off.)
    2. Weigh the PFT emitters using calibrated scale and record weight on field data form and/or spreadsheet.
- Sampler prep
    1. Vary the home that receives the duplicate sampler for each sampler type.
    2. Gather samplers for each home as specified in the IAQ_samplerlist.xls file, including field blanks (to be carried around with other samplers) and lab blank/QC samplers (to be sent with collected samplers to the lab).
    3. Store the lab blank/QC samplers in the freezer until they are ready to ship collected samplers. Store all other samplers in a cooler with ice or cool packs so they stay cool in the warm car during deployment. Be sure to include the field blanks in this cooler that will go to the field with you.

To Deploy Samplers at Each Home/Outdoor Sampling Location:

- **PFT Emitters**
    1. Retrieve the bag with appropriate house number on it.
    2. Remove the PFT emitters from the bag and replace the solid cap with the perforated cap.
    3. Attach all emitters at pre-defined locations as indicated on previous sampling sheet or the sampler spreadsheet (IAQ_samplerlist.xlsx). In general:
        a. H#.1 goes near the thermostat.
        b. H#.2 goes above the door near the passive return in the main bedroom.
        c. H#.3 goes above the door near the passive return in the back bedroom.
    4. Record the start time of measurement.
    - **Samplers**
    1. Take all samplers out of metal pouch and record relevant information (time, date, ID# = House # and 1, 2, 3 if multiple samplers of the same type) on the samplers. **Be sure to keep any caps or accessories in the appropriate pouch for resealing and sending**. See the table below for the sampler type, a visual description, the "make and model" information, the pouch description, where the sampler is located, and information to record.
    2. Remove the end caps or slide open from one each of the PFT (2 per home), VOC, HCHO (two types), and NO_2 (in some homes) passive samplers.
    3. Hang the VOC, HCHO (both), H#.1 PFT sampler, and NO_2 sampler (if applicable) in the provided indoor or outdoor sampler housing. If there are duplicates of any of the

above, also place them on the indoor sample stand. Place the indoor sample stand on top of the refrigerator in most homes (refer to previous IAQ data sheet).

4. Place the second PFT sampler (H#.2) on a passive return in back bedroom or other location as indicated on previous IAQ data sheet.

Wait seven days, or until the IAQ sample period has concluded.

To Retrieve Samplers at Each Home/Outdoor Location:

- **PFT Emitters**
  1. Retrieve the three PFT emitters from their respective locations.
  2. Remove the perforated caps from the bag for that house number and replace with the solid caps.
  3. Place the emitters in a spare metal bag and then place the metal bag in the sealed plastic bag.
- **Samplers**
  1. Retrieve the samplers from the indoor/outdoor sampling stand.
  2. Cap each sampler as follows:
     a. For the blue VOC sampler, the black and green HCHO sampler, and the black and yellow NO_2 sampler, slide the door over the perforated section.
     b. For the LBNL HCHO white sampler, place the small twist cap (left in the bag) on the open end of the sampler.
     c. For the white circle PFT samplers, place the O-ring on the sampler and then place the white cap and closure on top and snap it into place.
     d. LEAVE the radon sampler in place.
  3. Record the end time on the data sheet.
  4. Place each sampler in appropriate metal bag and seal the bag. You can tell the appropriate bag by matching the color/type of sampler with the label, as noted in the following table.

Post-Sampling Activities:

- **PFT Emitters**
  1. Retrieve the emitters from the metal bags and re-weigh them using the same calibrated balance. Record the weights.
  2. Place the emitters back in the metal bags and store the metal bags in the refrigerator or freezer until their next use.
- **Samplers**
  1. For the SKC samplers:
     a. Place the all the VOC, HCHO, NO_2, and PFT samplers retrieved from the field, as well as the field blank samplers and the lab blank/QC samplers in the pre-addressed and pre-paid express mailbox going to ALS DataChem Laboratories. If

all the samplers do not fit in one box, use a second box. If they do fit, save the second box for subsequent sampling events.

b. Record the time and date of mailing on the field metering data form.

c. Take the box to the post office to mail and notify the contact when the package ships.

2. For the LBNL HCHO samplers (small bags):

   a. Place all samplers from the field, as well as field blank and any unused samplers in the pre-addressed and pre-paid express mail envelope. If space allows, include a cool pack, bubble wrap, or both.

   b. Record the mailing time and data on sample form and include in the envelope.

   c. Seal the envelope and take it to the post office to ship. Notify the contact that the package has been shipped.

After Six Months:

- **Radon Samplers**

1. Retrieve the radon sampler from each home (usually above the refrigerator; refer to the first IAQ data sheet).
2. Record the end time and date.
3. Fill out the Radon Data Card with the necessary information.
4. Place the completed Radon Data Card and sampler in pre-addressed mailer envelope.
5. Mail the card and notify the contact that the samplers have been sent.

Table A-1. Sampler Summary

Sampler	Make and Model Information	Physical Description	Sampler Location	Information To Record
VOC	SKC Ultra III Passive Sampler	Blue “band-aid” style sampler	indoor sample stand on top of refrigerator (for most homes)	- on metal pouch record start date, time, and “ID” which will be “Season (SUM/FALL/WIN/SPRG) + 1/2 + H#” - on data sheet record start time and location
HCHO	SKC UMEx 100 Passive Sampler for Formaldehyde (500-100)	Black with green “band-aid” style sampler	on indoor sample stand on top of refrigerator (for most homes)	- on metal pouch record Name (“PNNL GVS”), Start date and time, and ID (“H#”) - on sampler record same information as pouch. - on data sheet record start time and location and sampler #
LBNL HCHO	Water Formaldehyde sampler	White pedestal sampler; small metal bag has no labeling except small white sticker with two numbers on it.	indoor sample stand on top of refrigerator (for most homes)	- on metal pouch record house number - on data sheet record start time and location and sampler lot number (i.e., numbers on bag)
PFT Samplers	SKC Passive (Diffusive) Samplers (575-002)	White circular badge	H#.1: on indoor sample stand on top of refrigerator for most homes H#.2: clipped on a passive return on far bedroom in most homes (see pictures)	- on sampler record start time and date and ID (“H#.1” for main and “H#.2” for other return - on data sheet record start time and location
PM 2.5	DustTrak	Large active blue equipment	main (various, see pictures)	- on data sheet record DT # and start time and location
NO2	SKC UMEx 200 Passive Sampler for Sulfur Dioxide and Nitrogen Dioxide (500-200)	Black with yellow “band-aid” style sampler	on indoor sample stand on top of refrigerator (for most homes)	- on metal pouch record Name (“PNNL GVS”), Start date and time, and ID (“H#”) - on sampler record same information as pouch. - on data sheet record start time and location and sampler #
Radon	Pro Lab Long-term Radon Gas Test Kit	Black circular device with no openings and numbers on top	indoor sample stand on top of refrigerator (for most homes)	- on data sheet, radon sampler # and time and location

Appendix B. Field Data Sheet

Sampling Date: ______________________ Sampling Location: ________________

Weather Conditions: Temp: ________________ RH: ________________________

PFT Emitter Weights

Sample Description	Sample Location (note if different)	Pre-Weight	Start Date/Time	Post-Weight	End Date/Time	Notes
PFT Emitter	H#.1 = main near thermostat					
PFT Emitter	H#.2 = near passive return over master bedroom					
PFT Emitter	H#.3 = near passive return over back bedroom					

IAQ Sampler Data

Sample Description	Sampler Location (note if different)	Sampling Start Time	Sampling End Date	Sampling End Time	Notes
VOC	Main = indoor sample stand on refrigerator				
HCHO	Main = indoor sample stand on refrigerator				Sampler ID =
LBNL HCHO	Main = indoor sample stand on refrigerator				Sampler Lot # =
PFT Sampler	H#.1 = Main = indoor sample stand on refrigerator				
PFT Sampler	H#.2 = Passive return elsewhere in house, not directly near emitter				
NO_2	Main = indoor sample stand on refrigerator				Sampler ID =
Radon	Main = indoor sample stand on refrigerator	LEAVE FOR 6 MONTHS			

Mailing Information

Mail Date: ____________________ Mail Time: ______________________________

Mailed By: ____

Appendix C. Quality Assurance and Quality Control

The following is a brief discussion of quality assurance and quality control (QA/QC) procedures to be followed during each sampling event.

Field Procedures

Field QA/QC procedures will include the following:

- TVOC, HCHO, NO_2, and CO_2 data will be taken indoors and outdoors to ensure environmental factors are not confounding results.
- A blank sample (remains capped) of each constituent will be collected at each site for comparison.
- At least one duplicate sample of each constituent will be collected for each IAQ sampling event.
- Analysis will include a unique analysis blank and spike for each constituent and each analysis period. See Laboratory Analysis Summary [Appendix F] for details on analysis QA/QC methods.

Field Logbook

Relevant field data will be recorded on a field metering data sheet [Appendix B] for each sampling site (each home and outdoors). These data will include, at a minimum:

- Date of sample collection
- Location of sample collection
- Times and dates corresponding to the start of sampling and the end of sampling; weather conditions.

Appendix D. List of IAQ Samplers and Relevant Standards

Item Number	Model/Title	Description	Pollutant	Type of Sampling	Sensitivity	Range	Accuracy	Sampling Rate	Standard Level	Standard Referenc	Expected Concentr
IAQ Equipment											
1.1	Ultra III Sorbent Badges-VOC	Ultra II badges, fillable. Must purchase sorbant seperately (see 1.2)	VOC	point	various (0.027 - 0	various	various	see http://www.skcinc.com/pdf/18		various	
2.1	Indoor Air Formaldehyde Passive Sar	Disk treated with sodium hydrogen sulfite	HCOH	point	0.01 ppm ± 30%	0.01 to 3 ppm	0.025 to 1 ppm ±	5-7 days	0.02 ppm (NIOSH REL) 0.75 ppm (OSHA PEL)	noted in level	
3.1	UMEx200 Sorbent Badges-No2 and So	Tape treated with triethanolamine [TEA], accuarte to 0.4 ppm. Collects Sox and Nox informtaion. To be sent back to DataChem for analysis (see 6)	Nox/Sox	point	0.1 ppm (8 hours	0.4 and 8 ppm	± 30%	17.5 ml/min with	ST1 ppm (NIOSH) 5 ppm (OSHA) ACGIH 3 ppm	noted in level	
4.1	Radon Test Strips	Passive long-term test strips for Radon gas in air	Radon	point	0.1 pCi/L	0.1 pCi/L to ...	± 10%	7 days	4 pCi/L	EPA	<4 pCi/L
5.1	HOBO U12-011 T/RH meters	To measure T/RH 4 locations in each home	T/RH	continuous		-4 to 158 ppm; 5 to 95%	±0.35 ºF ; 0.3%	15 minutes	N/A	N/A	5-95% RH; 32-115 F
5.2	EXTECH T/RH/CO2 meters	To measure T/RH/CO2 in at least on location in each home	T/RH/CO2	continuous		0-9999 ppm	±5% of the readi	15 minutes	380 ppm	global mean CO2	380 to 800 ppm
Ventilation Equipment											
6.3	Tracer Gas Test	To quantify natural air changes and ventilation effective	Ventilation Rat	point	6.7 ppb	TBD	TBD	TBD	N/A	N/A	
Other Equipment/Materials											
7.1	14 channel eMonitor (including CT)			continuous				hourly	N/A	N/A	N/A
	Lacrosse T/RH sensor			continuous	9 to 12 bits	-10 to 85C	± 0.5C	hourly	N/A	N/A	N/A

Appendix E. Homeowner Questionnaire

The answers to the following questions can be filled out by the homeowner in paper copy, or they can be provided verbally on the phone or in person.

Initial Questions Regarding HVAC System and Home Operation (to be asked one time)

In a typical week:

When do you use your ceiling fans (all the time, while sleeping, when you feel uncomfortable)?

____

Please describe typical frequency and duration (e.g., about three times per week, for about an hour each time):

____

____

How frequently do you use your bath fans (e.g., number of times per day, week, or month) and for how long each time (number of minutes)?________________________________

How frequently do you use your range hood and for how long each time?_______________

How often do you change your return air filter(s)?______________________________

If your home has a whole-house ventilation system, how often do you change its filter?________

How often do you turn off the heating/cooling system and open windows (check all that apply)?

	Never	Sometimes during the day	Sometimes at night	As much as I can during the day	As much as I can at night
Winter					
Spring					
Summer					
Fall					

Considering typical conditions, please respond “yes” or “no” to the following statements. If “no,” please describe the discomfort or dissatisfaction in terms of hot, cold, humid, dry, stuffy, clammy, drafty, unusual odors, mold, etc.

	Y/N	If “no”, please describe
My home is generally comfortable.	___	____________________
All rooms in my home are equally comfortable.	___	____________________

I am satisfied with the overall comfort of my home. ___ ________________________________
The indoor air quality in my home is generally good. ___ ________________________________

Follow-Up Questions Regarding HVAC System and Home Operation (to be asked during each change in ventilation rate)

Was there any change in the number or schedule of occupants in the past two weeks (e.g., occupant traveling or home from college, switch to night shift)?

____

____

Considering only the *past two weeks,* please indicate "yes" or "no" for the following statements. If "no," please describe the discomfort or dissatisfaction in terms of hot, cold, humid, dry, stuffy, clammy, drafty, unusual odors, mold, etc.

	Y/N	If "no", please describe
My home has been comfortable for the past two weeks.	____	______________________________
All rooms in my home are equally comfortable.	____	______________________________
I am satisfied with the overall comfort of my home.	____	______________________________
The indoor air quality in my home was good.	____	______________________________
All indoor surfaces were free of condensation.	____	______________________________

Have there been other changes in comfort? ____ If yes, please describe: _________

____

The next questions relate to changes in fans and windows operation compared to typical operation in your home. For "yes" responses, describe the change—typical frequency and typical duration. Indicate whether occupancy changes indicated in the first question were a factor. In the past two weeks, have you noticed or made any changes in the operation of:

	Y/N	**Change**	**Frequency**	**Duration**	**Related to Q1 answer?**
Ceiling fans					
HVAC system?					
Master Bath fan*					
Bath 2 Fan*					
Bath 3 Fan*					
Kitchen exhaust fan					

	Y/N	Change	Frequency	Duration	Related to Q1 answer?
Dryer					
Windows					

*excluding continuously operating fans

In the past two weeks, was there a continuously operating exhaust fan(s) in your home?____
If yes, was the fan turned off? __________If yes, please describe frequency, duration, and conditions or events.

____

Indoor Air Quality Supplement
(only to be asked at beginning and end of IAQ Sample Events)

In the past week, did any occupants have variable work hours? If yes, please describe.

____
____
____

In the past week, were there any unusual events that took place (e.g., parties, larger-than-usual cooking events)? If yes, please describe.

____
____
____

Did you clean your home using chemicals in the past week?

____

Did you acquire or remove any furniture, carpets or rugs, cabinetry, window treatments, appliances, or other interior finishes or furnishings during the past week?

Were the indoor air quality samplers moved or displaced during the past weeks?

Homeowner Comments (Is there anything else you would like to add that has not been addressed?):

____
____
____

Appendix F. Laboratory Analysis Summary

Objectives

This document [appendix] discusses methods and procedures for analyzing field samples for various contaminants in residential buildings. Contaminants of interest include volatile organic compounds (VOCs), formaldehyde, acetaldehyde, and nitrogen dioxide. This document addresses relevant procedures needed to analyze individual analytes so that all performance criteria can be strictly managed during the entire period of the analysis under quality assurance/quality control (QA/QC) managements.

Scope

The main works that the operator of the analysis are as follows:

- Treatments of passive samplers to be analyzed
- Verification of various performance criteria and maintenance of QA program
- Preparation of laboratory supplies such as constant temperature refrigerator, dry oven, gas chromatography (GC) columns, carrier gas, standards, and chemicals
- Calibration of instruments such as GC, mass spectrometry (MS), gas chromatograph with electron capture detectors (GC-ECD) system, ion chromatography (IC), and high-performance liquid chromatography (HPLC)
- Sample analysis by using relevant instruments
- Provision of a report demonstrating standard operating procedure (SOP) of the analysis and the results of the target contaminants described below.

General Considerations

Field Sampling

- A number of SKC passive samplers will be used: Ultra III passive sampler with Carbograph 5 TD (Cat. No. 690-102), UMEx 100 (Cat. No. 500-100), and UMEx200 passive sampler (Cat. No. 500-200).
- Field sampling may begin as early as the first week of June, and the earliest analysis date may be the second week of the month.
- Contaminants of interest will be sampled for one full week for a single sampling period.
- A total of eight sampling periods will occur, and two sampling periods will take place each season.
- The total numbers of samples for each sampling period may be different for each individual contaminant.

Laboratory Analysis

- The laboratory is responsible for inspecting samples shipped immediately when they arrive, and report condition of samples, especially visible signs of damage or contamination.

- The laboratory may reject sample analysis if samples are damaged, unlabeled, or any relevant reasons identified during visual inspection.
- All procedures are to be strictly followed by standard methods such as EPA Compendium Methods and SKC operating instructions referred in each section below.
- Samples are to be analyzed as soon as they arrive at the laboratory, and the duration of entire analysis procedures should not exceed two weeks for each analysis cycle.
- No special treatments should be made to particular samples known as blanks.
- The performance criteria analysis can be performed once at the beginning of the sampling period. If any of the performance criteria is unmet, another attempt to such particular criterion or criteria can be followed by using duplicate samples available.
- All passive samplers delivered are supposed to be stored immediately in a refrigerator maintaining a constant temperature below 4°C and a clean environment, unless they are transferred on the same day upon arrival.
- All reusable samples in the forms to be analyzed such as solutions and sample extracts for NO_2 analysis are supposed to be stored in the constant temperature refrigerator until data validity is verified.
- All efforts should be made to avoid possible interferences over all different types of samples being stored.

VOC Analysis

Sample Treatment

- Individual samples transferred must be labeled as indicated on the original samples.
- Duplicate samples may not be transferred, but they are to be stored in the same manner as original samples are treated. They may be transferred later if some samples fail to pass performance criteria or leak test during analyzing processes.
- No physical pressure should be applied when sorbents from individual samplers are transferred.
- Once transferred, all samples in a thermal desorption tube should be rewrapped with uncoated aluminum foil unless they are analyzed on the same day.
- A set of samples collected on a single sampling cycle are supposed to be treated on the same day, if possible. If not possible, at least individual processes, such as sorbent transfer, should occur on the same day.
- Thermal desorption tubes are to be immediately sealed and wrapped individually with uncoated aluminum foil after individual sorbent transfer from passive samplers.
- All tubes including blank ones should be stored in the refrigerator unless they are analyzed on the same day.

Calculation of Concentration

- An average room temperature during sampling duration will be provided by PNNL for each sampler.

- Sampling site atmospheric pressure in mm Hg can be assumed to be atmospheric pressure at the time of sampling.
- Desorption efficiency is assumed to be 1.0.
- Pre-defined sampling rates in ml/min provided by the manufacturer can be used.

Sample Analysis

- All procedures for laboratory analysis such as thermal desorption tube conditioning, pre-desorption system checks, and interferences should be carefully followed by the guidance of TO-17 method.
- Portions of descriptions regarding active sampling such as sampling apparatus, calibration, and sampling rate in the method TO-17 document may not be considered.
- Among the four performance criteria listed in the document, the precision for the distributed volume pair may not be considered as it is not applicable to a passive sampling method.
- Two laboratory blanks should be analyzed every analysis cycle.
- At least one field blank should be taken from the blank/correction sorbent every analysis cycle.
- Samples should be removed from refrigerated storage at least two hours prior to analysis to equilibrate with the ambient air temperature. The duration of the sample placement before analysis can be determined by the operator of the analysis.
- Individual VOCs listed in Table 1 in the method TO-14 should be identified, and the TVOC should include both non-list VOCs and unidentified VOCs.

Formaldehyde Analysis

- Analytes of interest are formaldehyde and acetaldehyde, and other aldehydes may be analyzed if detection of other aldehydes does not need modifications to the standard analysis procedure or additional treatments.
- The analysis procedure should follow the Analysis Instructions in the document of the SKC Operating Instructions for UMEx 100 passive sampler for formaldehyde, which summarizes EPA IP-6C for diffusive sampler.
- The TO-11A method can be referred to for HPLC analysis and calibration, performance criteria, and QA/QC.
- Sample analysis including sample extraction and HPLC analysis is recommended to be performed on the same day.
- The DNPH-formaldehyde solution should be stored in the constant temperature refrigerator at blow 4°C if HPLC analysis is scheduled another day. The stored solution must be analyzed within three days.
- The calibration process should be verified to meet all processes demonstrated in the TO-11A method.

- Method detection limits (MDLs) may not be evaluated if they have been validated within five months and no instrument change has been made in the period.
- Remaining solutions should be stored up to three days in a constant temperature refrigerator until the data validity of the analysis has been verified.

Nitrogen Dioxide Analysis

- All analysis procedures are to be strictly followed by the operating instructions for SKC UMEx 200.
- The remaining sample extracts originally for analyzing sulfur dioxide should be stored in the constant temperature refrigerator at below 4°C as duplicate extracts.

PFT Sample Analysis

- The tracer gas to be used is perfluoromethylcyclohexane (PMCH), and it is analyzed by GC-ECD system.
- The detection limit would be considered as 0.05 ppb, or as determined by the laboratory.
- Due to lack of a standard procedure for the analysis, the laboratory may refer specific methods associated with the analysis.

Laboratory Test Report

The laboratory report should include the following information:

- Laboratory identification
- Specifications of sample transfer elements, instruments, and laboratory supplies
- Analysis methods and conditions
- Data validity depending on the performance criteria and blank tests including data analysis procedures
- Test results: Concentration of compounds of interest in $\mu g/m^3$, ppm, or equivalent including individual VOC compounds listed in Table 1 in EPA Compendium Method TO-14, TVOC, HCHO, and acetaldehyde
- Photographs ensuring individual analysis processes
- Certification of the report
- Additional information that would be relevant to reporting analysis procedure.

Appendix G. Weather Conditions in Gainesville, Florida, During the Monitoring Period

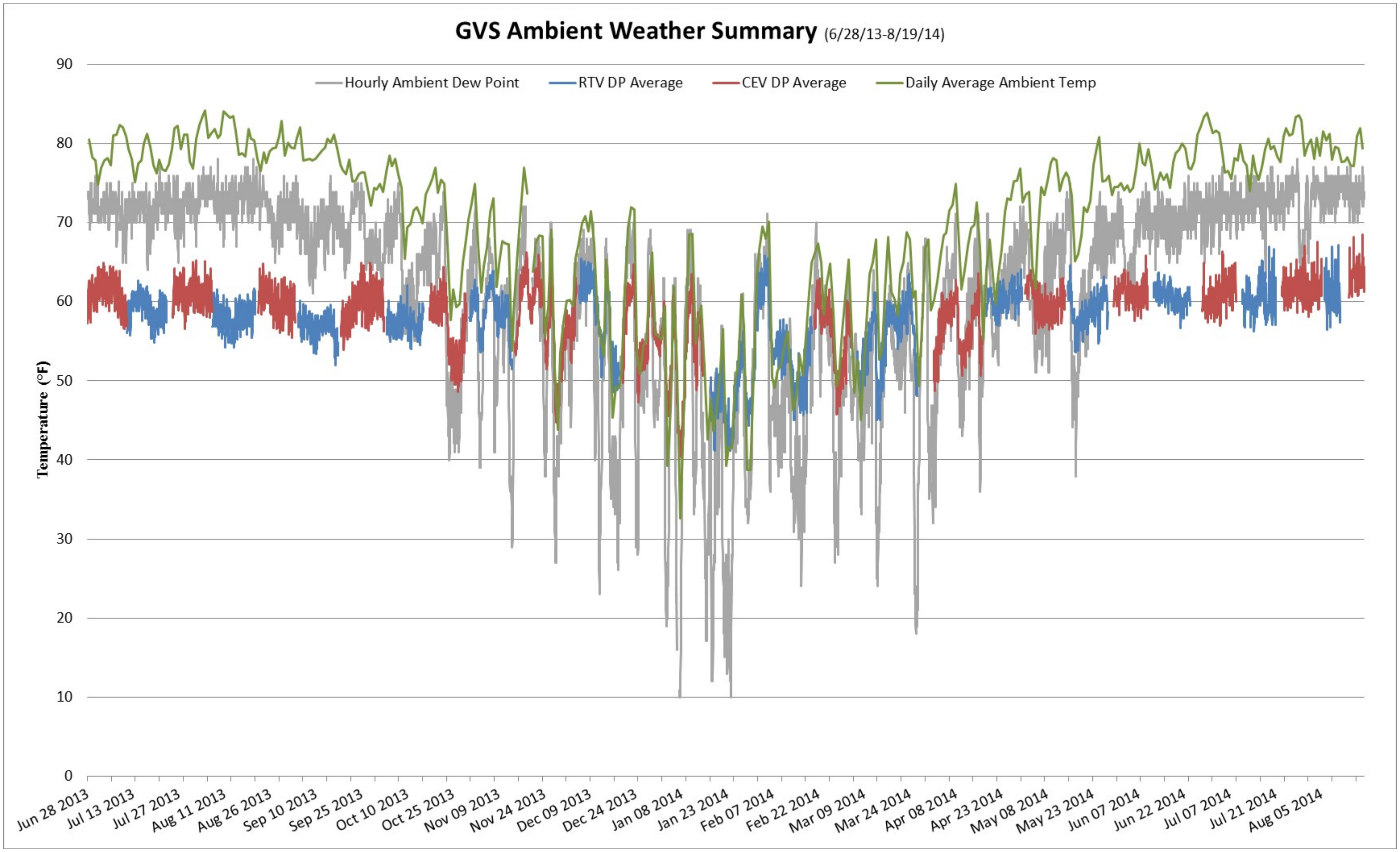


Figure G-1. Full year plot of average hourly indoor dew point temperature for six flip-flop homes plus hourly outdoor dew point and average daily dry bulb temperatures from 6/28/2013 to 8/19/2014

Appendix H. Indoor Home Plots

Figure H-1 through Figure H-10 plot the hourly indoor temperature, relative humidity, and carbon dioxide for each home for the complete study period: 6/28/2013 to 8/04/2014.

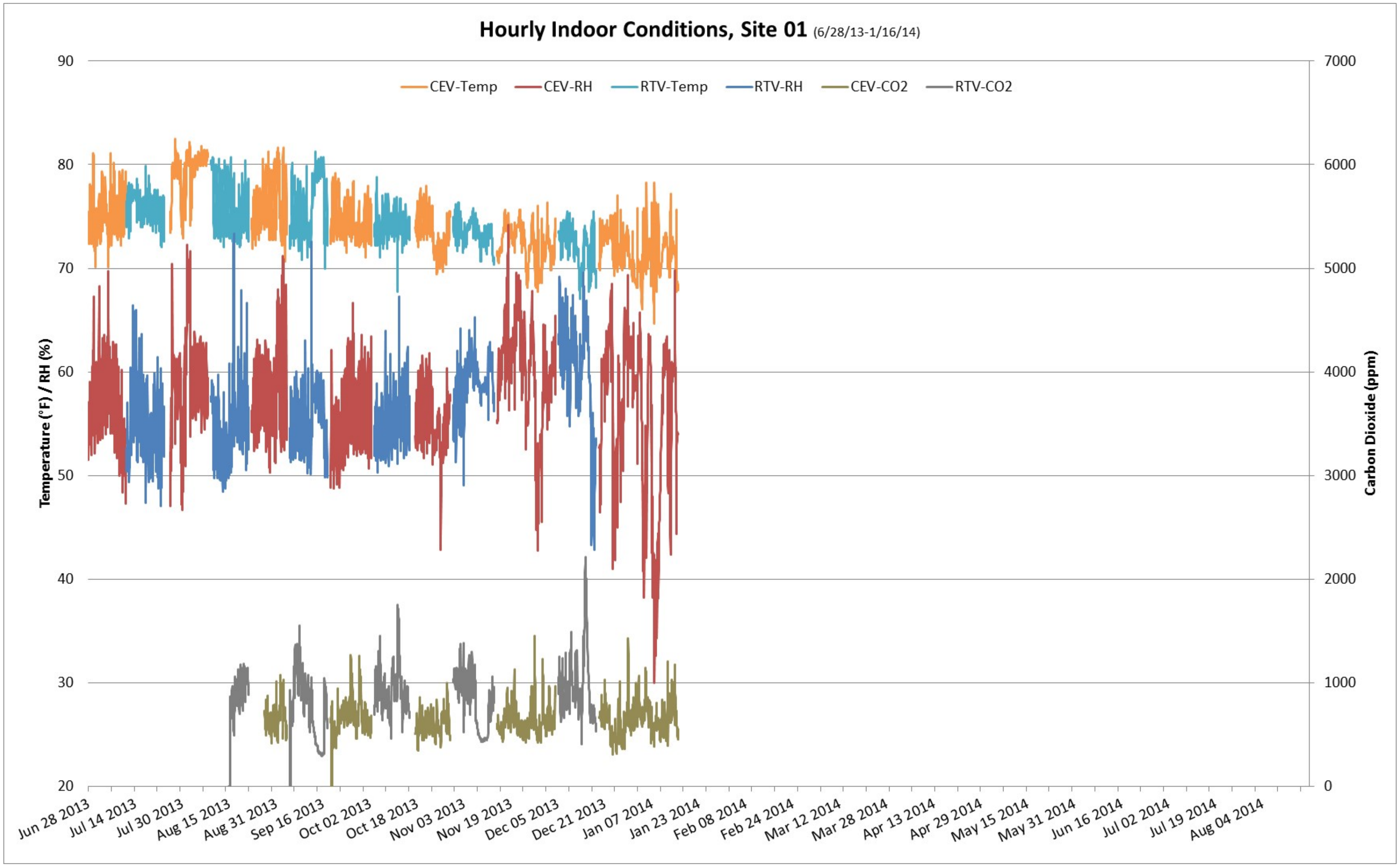


Figure H-1. Hourly indoor conditions for Home 1

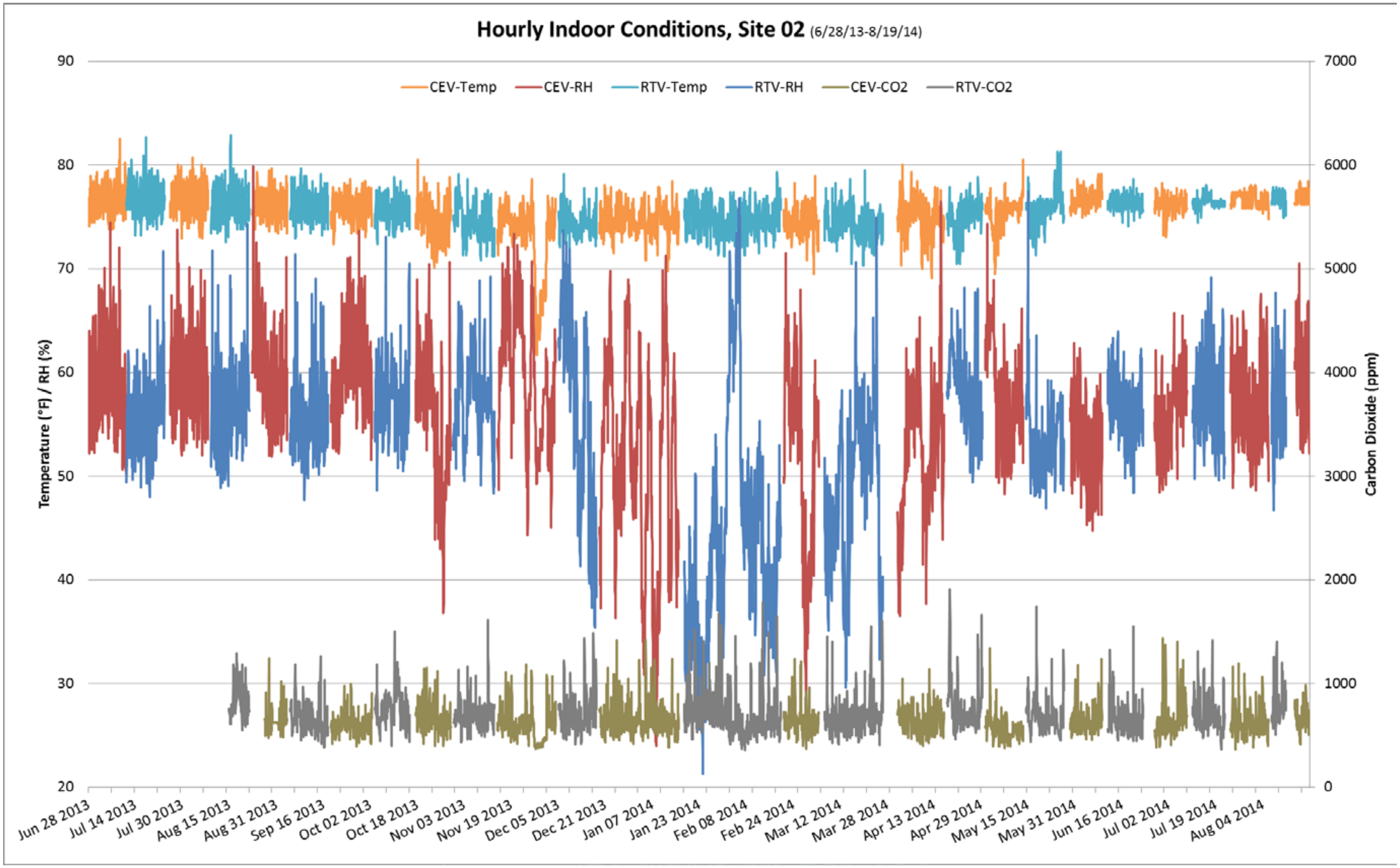


Figure H-2. Hourly indoor conditions for Home 2

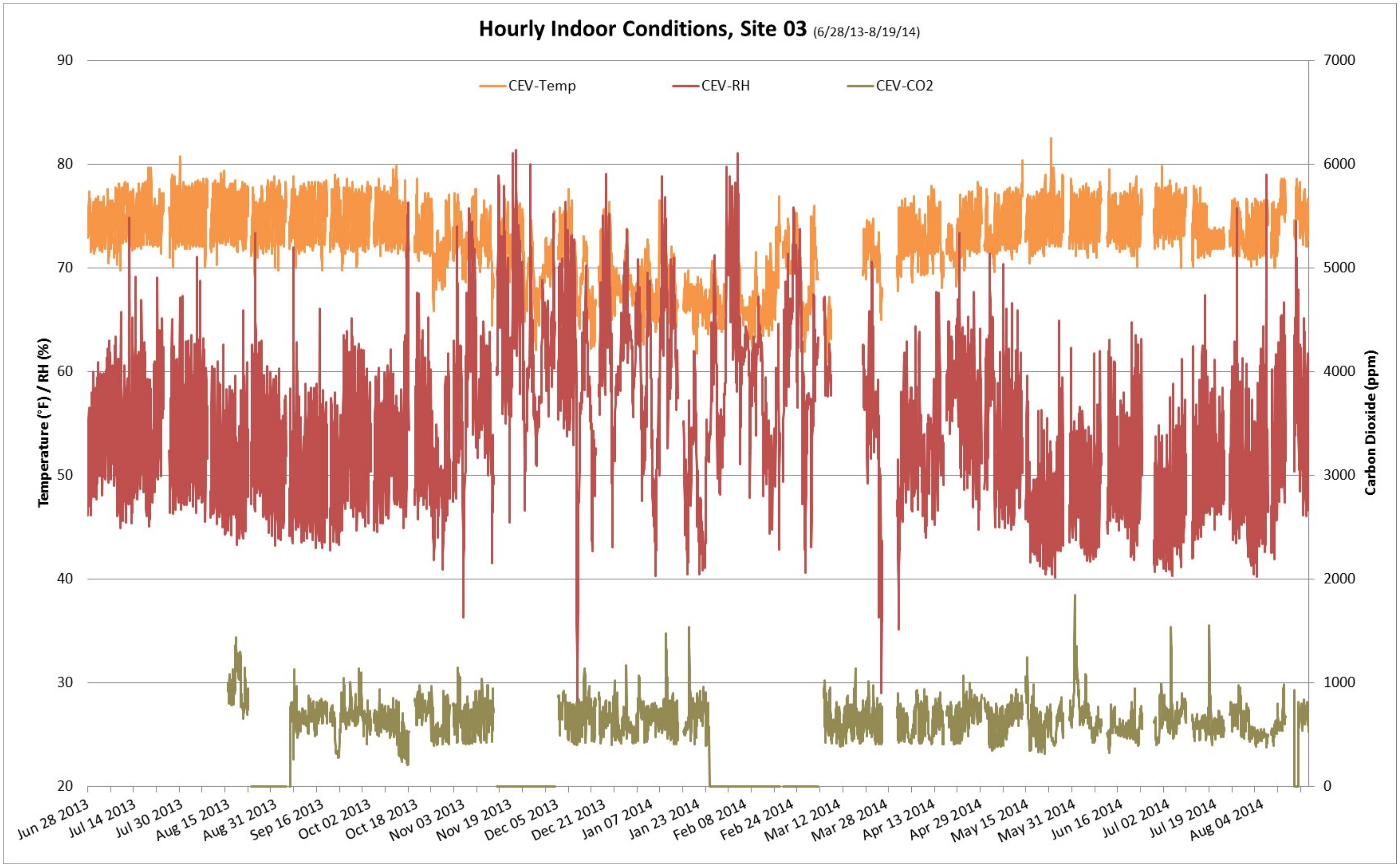


Figure H-3. Hourly indoor conditions for Home 3

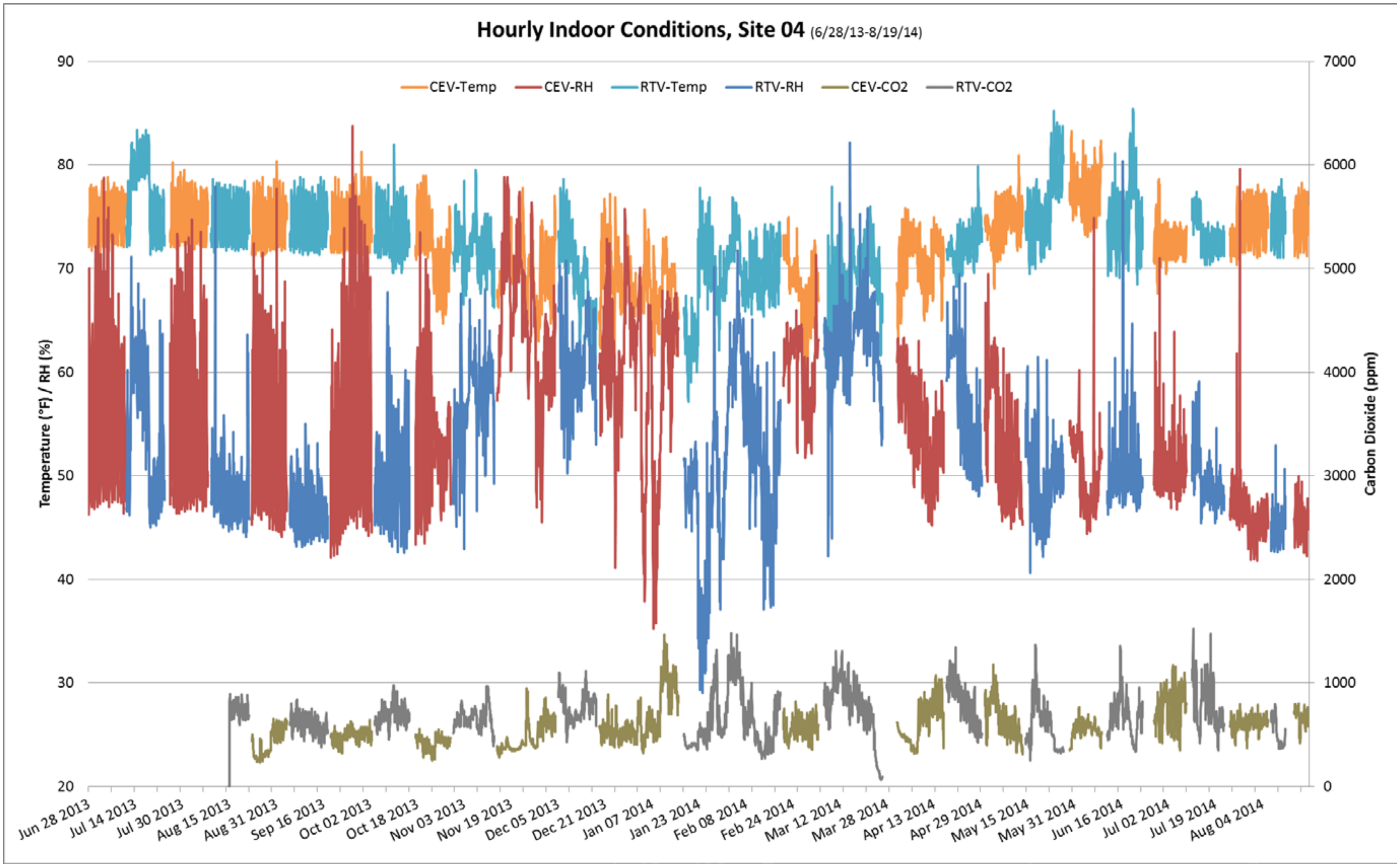


Figure H-4. Hourly indoor conditions for Home 4

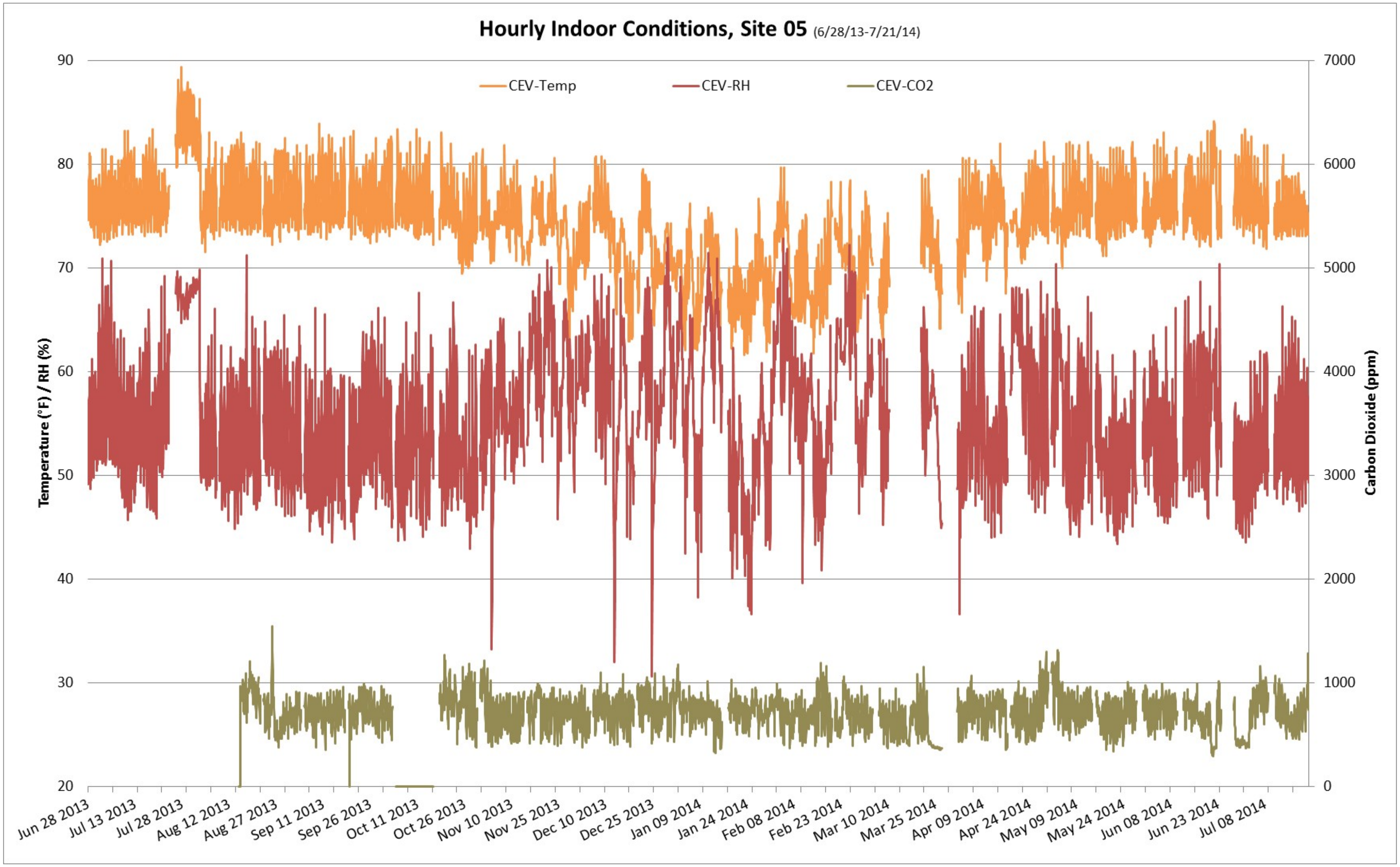


Figure H-5. Hourly indoor conditions for Home 5

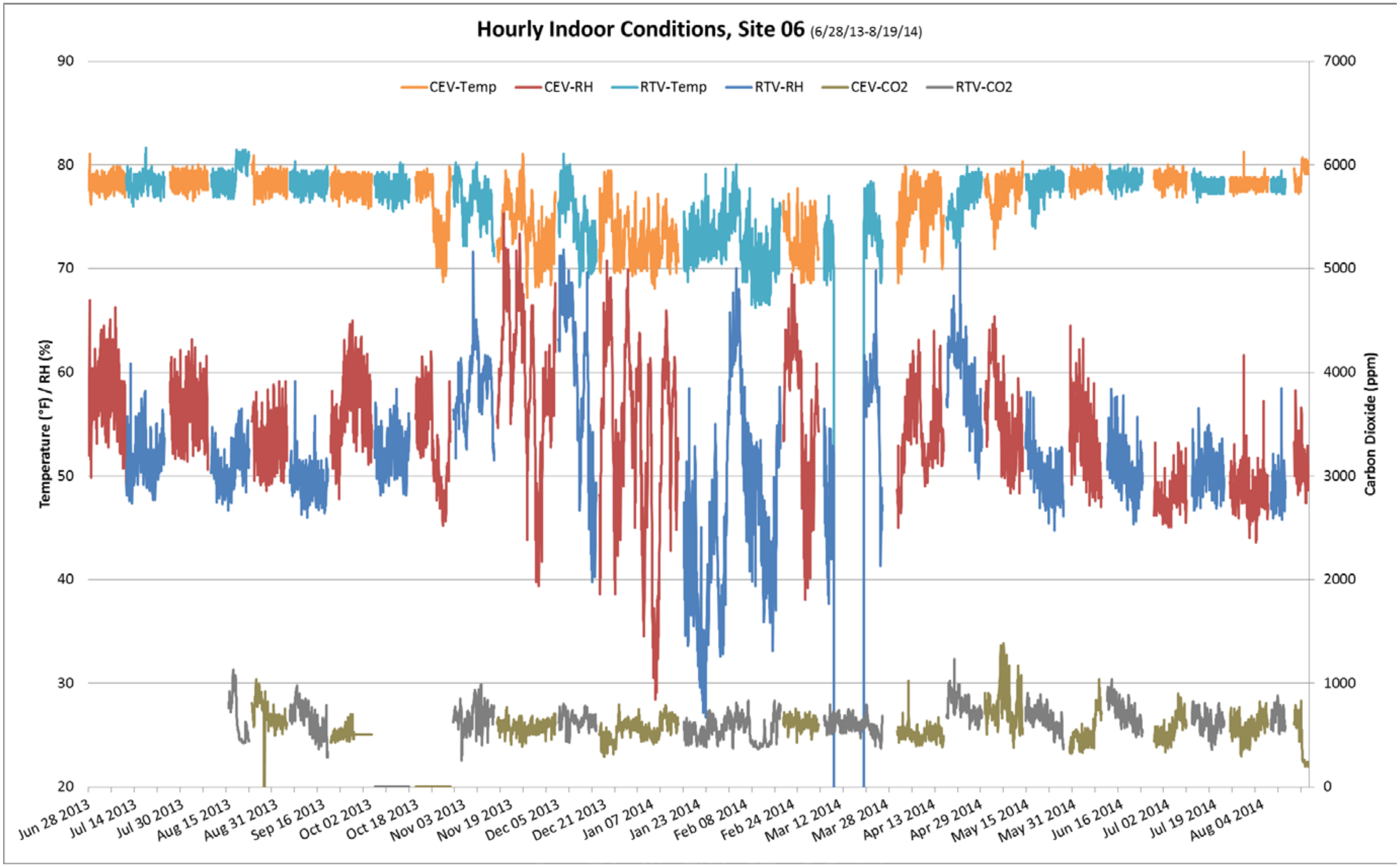


Figure H-6. Hourly indoor conditions for Home 6

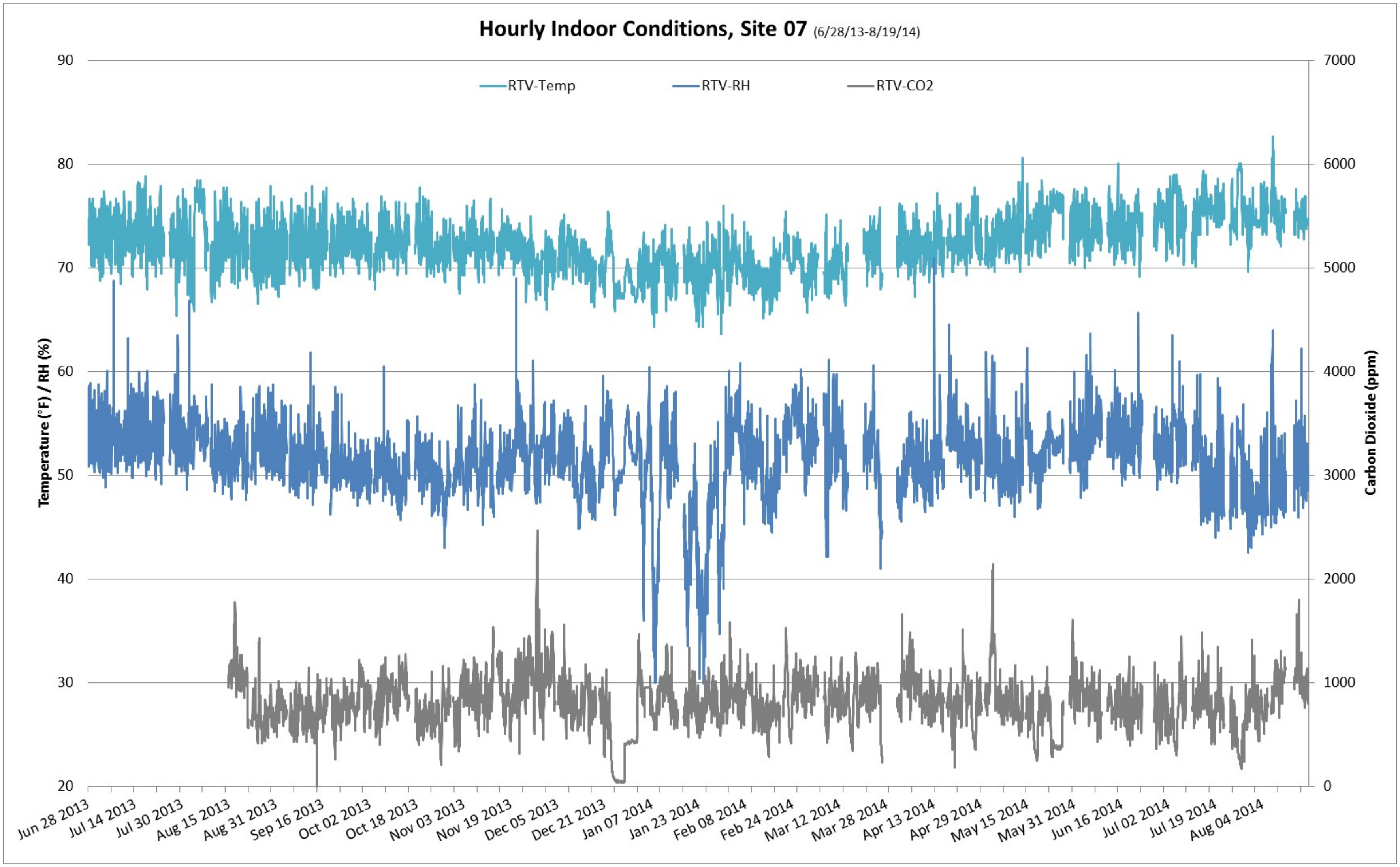


Figure H-7. Hourly indoor conditions for Home 7

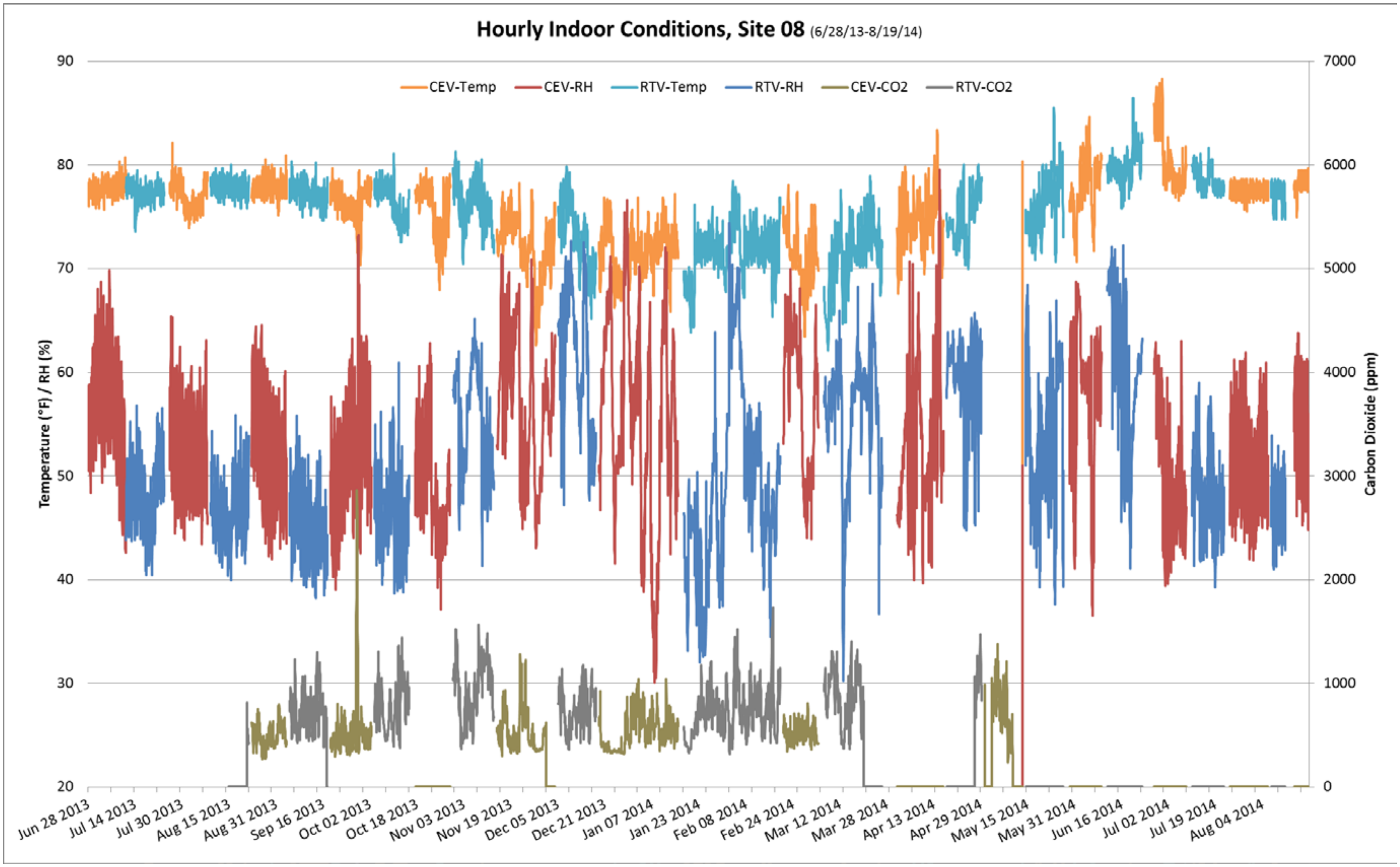


Figure H-8. Hourly indoor conditions for Home 8

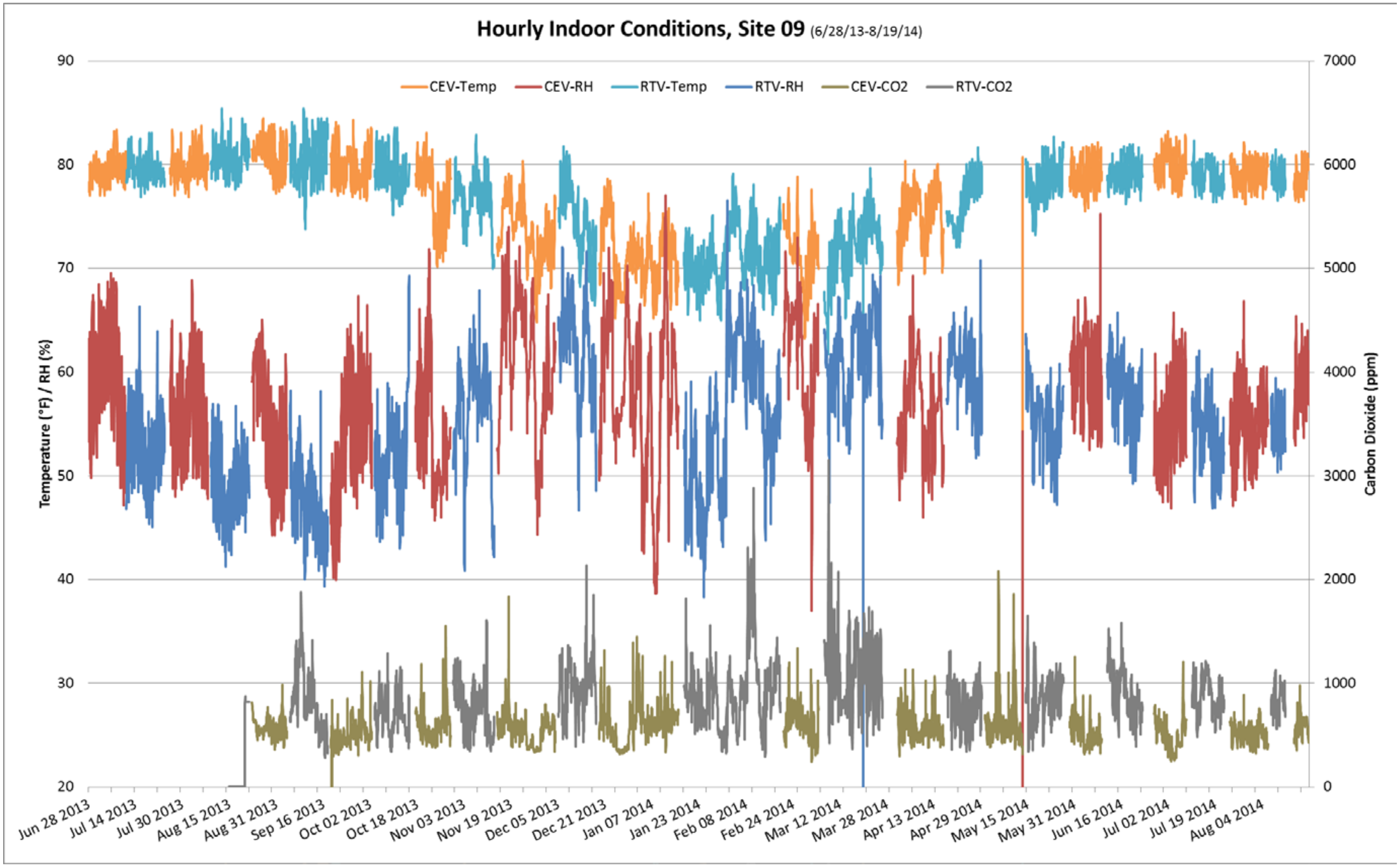


Figure H-9. Hourly indoor conditions for Home 9

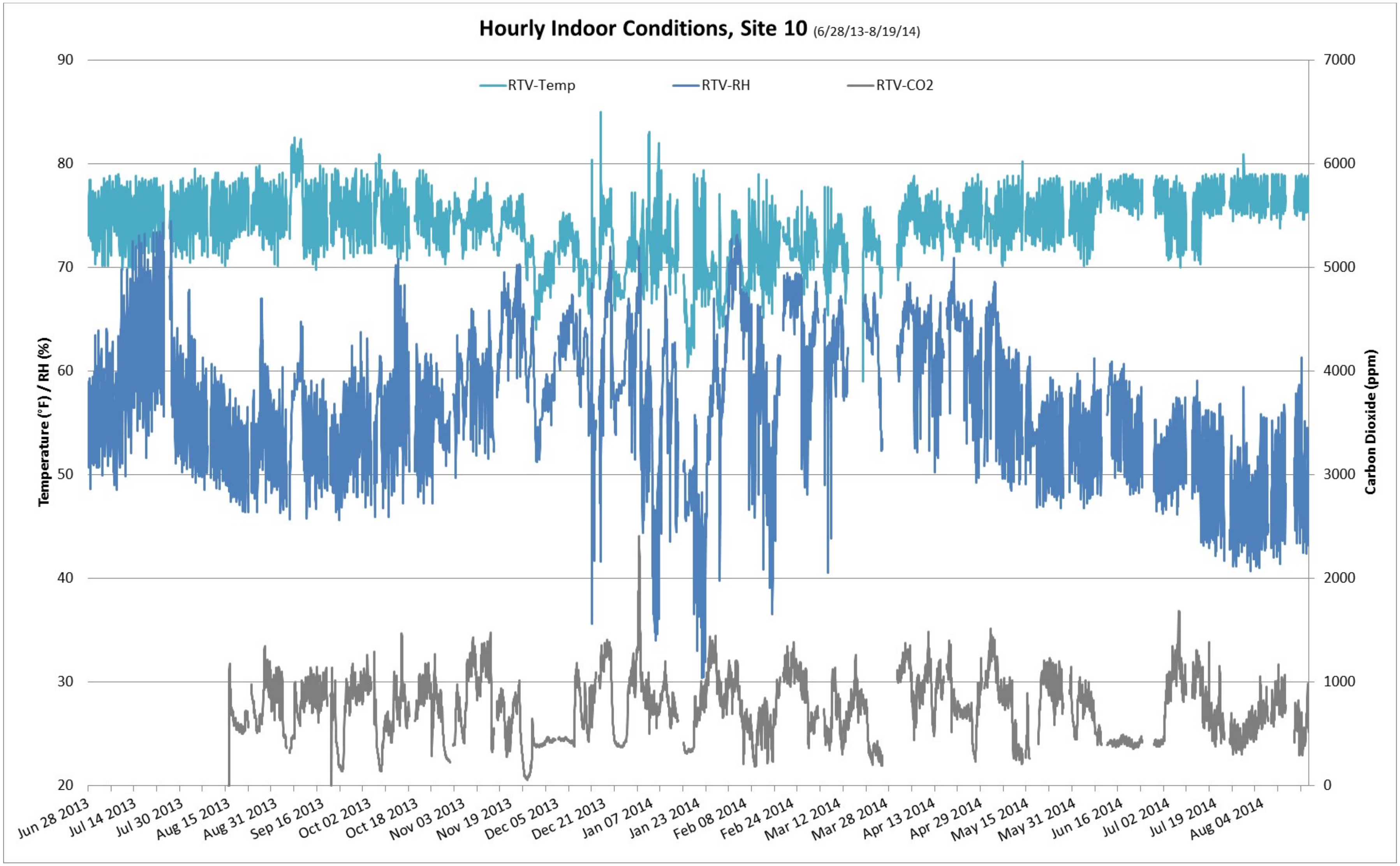
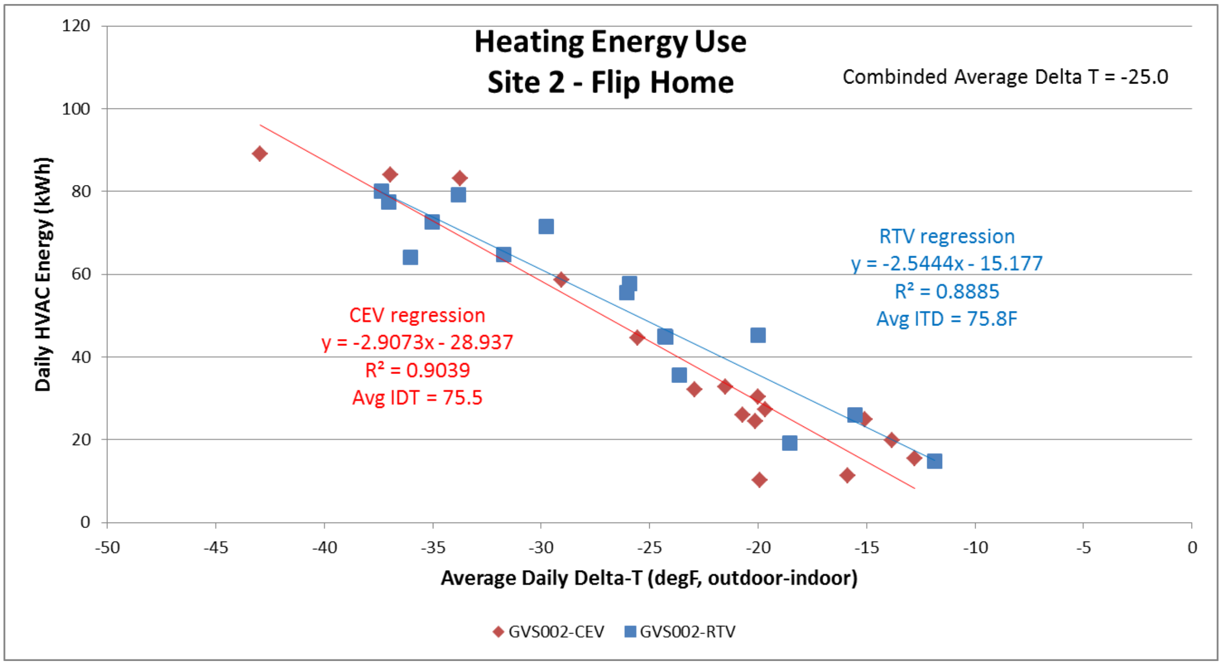
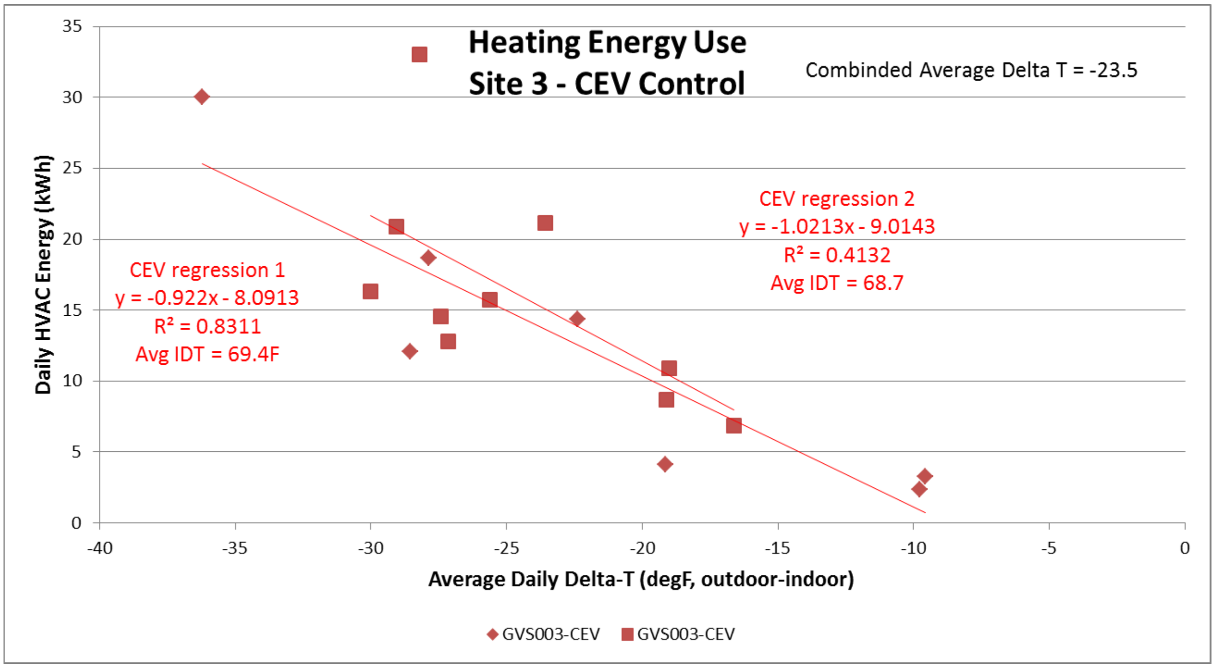


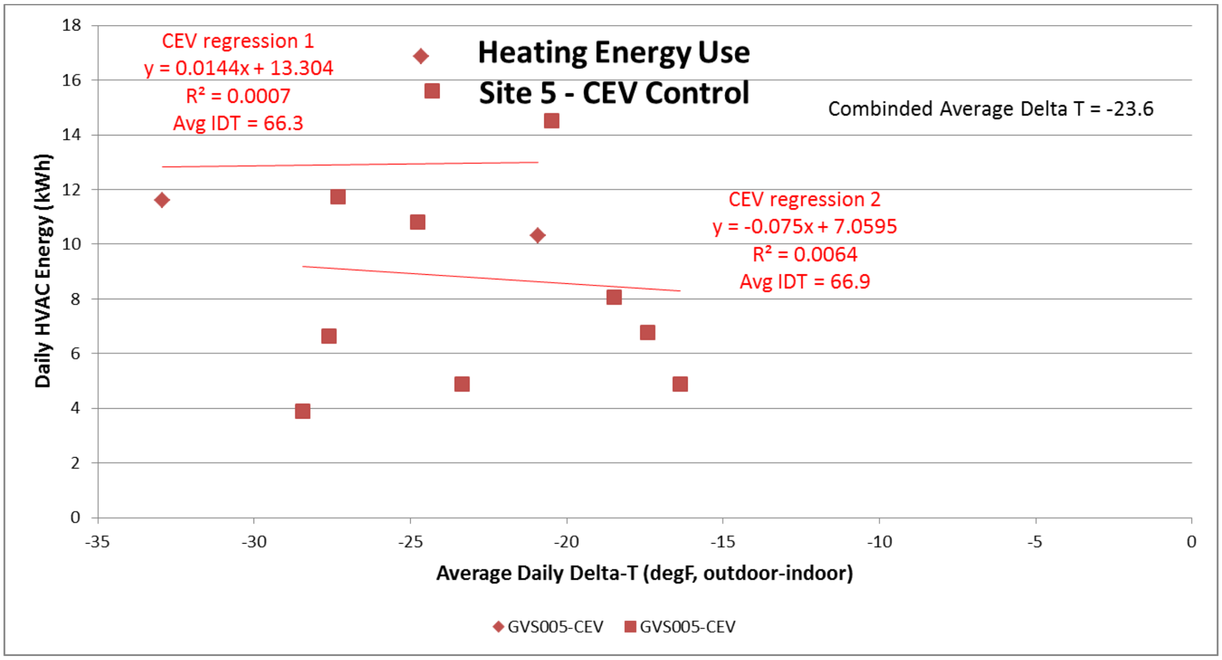
Figure H-10. Hourly indoor conditions for Home 10

Appendix I. Space-Heating Analysis, Linear Regressions

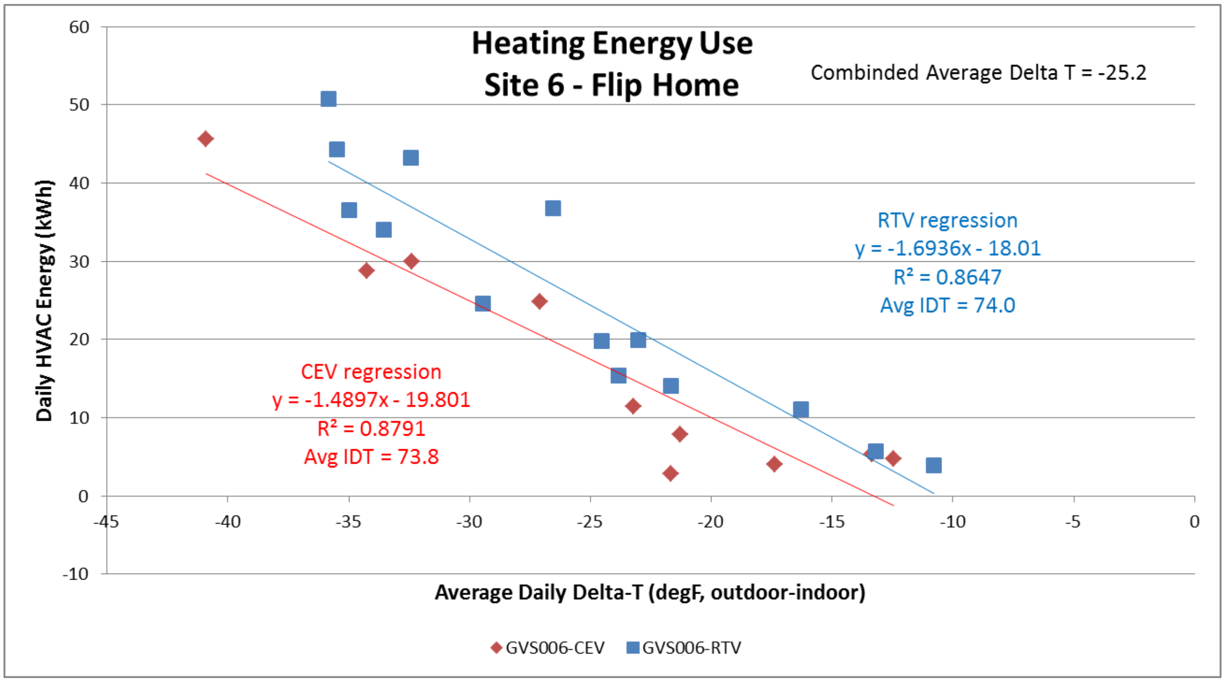
Figure I-1 through Figure I-6.



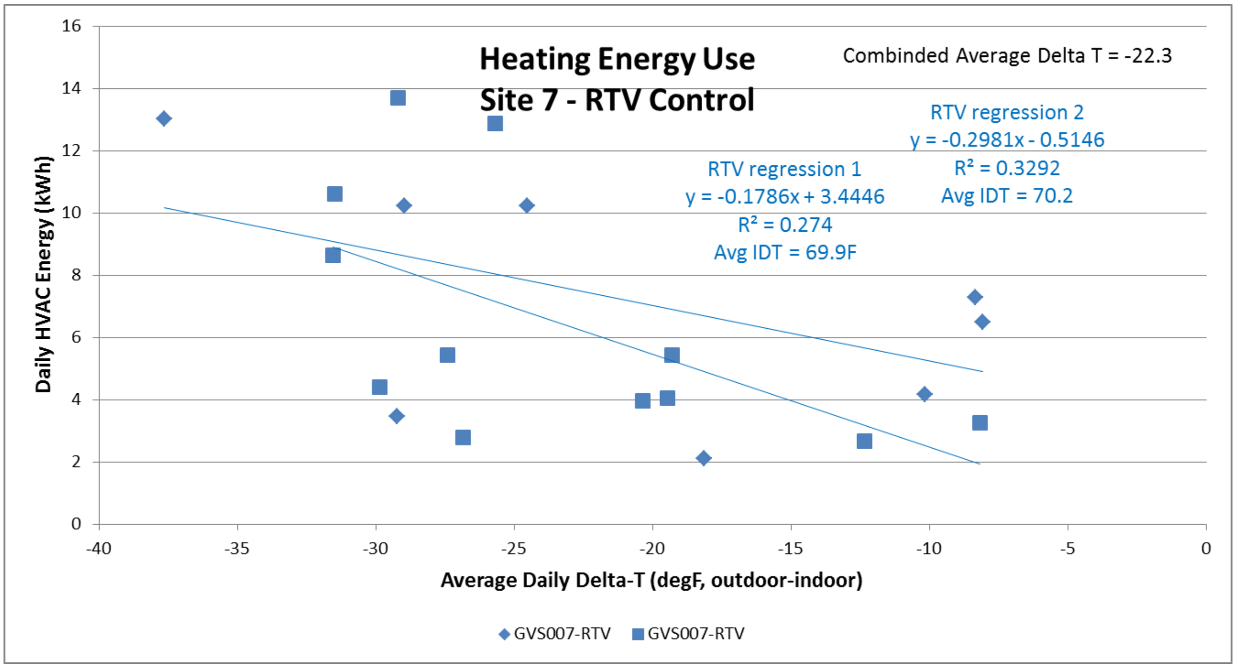


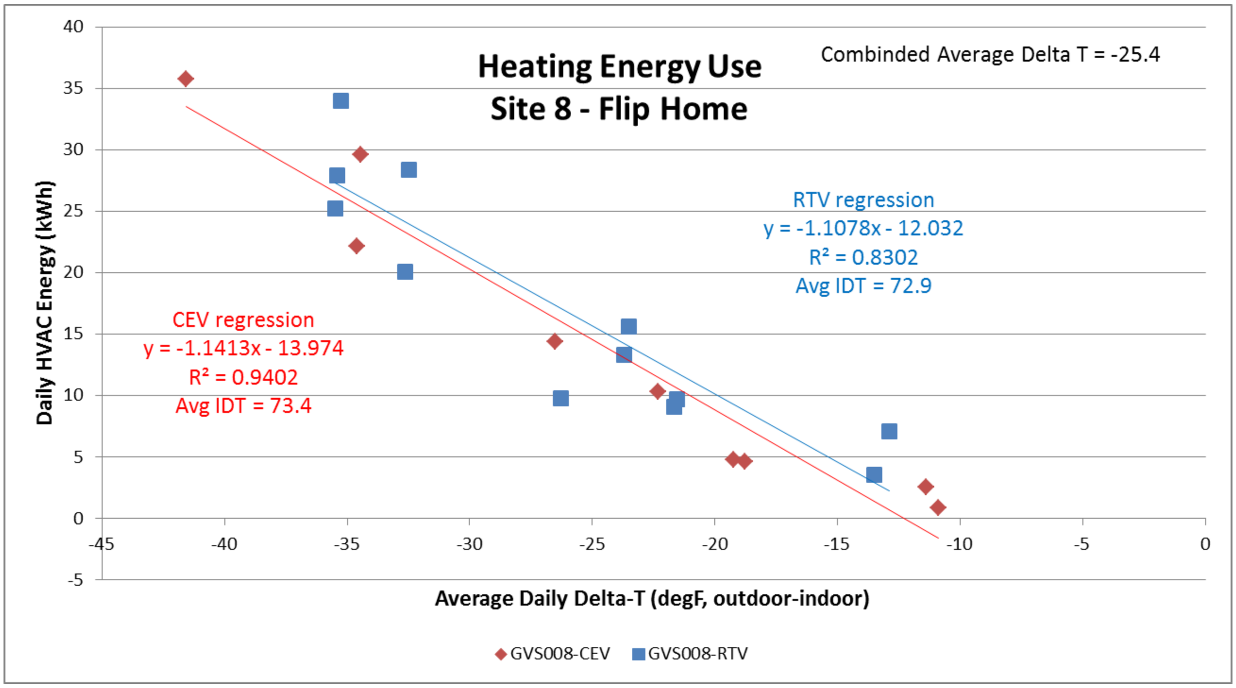


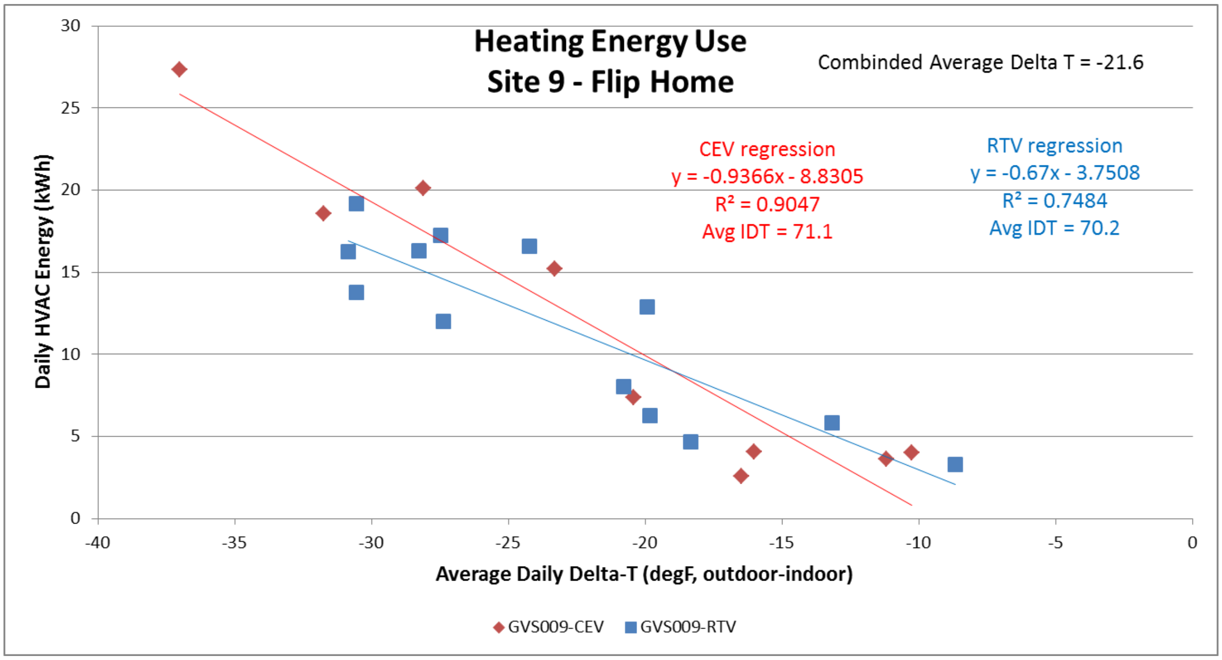
Heating Energy Use
Site 5 - CEV Control
Combinded Average Delta T = -23.6
CEV regression 1
y = 0.0144x + 13.304
R² = 0.0007
Avg IDT = 66.3
CEV regression 2
y = -0.075x + 7.0595
R² = 0.0064
Avg IDT = 66.9
Daily HVAC Energy (kWh)
Average Daily Delta-T (degF, outdoor-indoor)
GVS005-CEV
GVS005-CEV

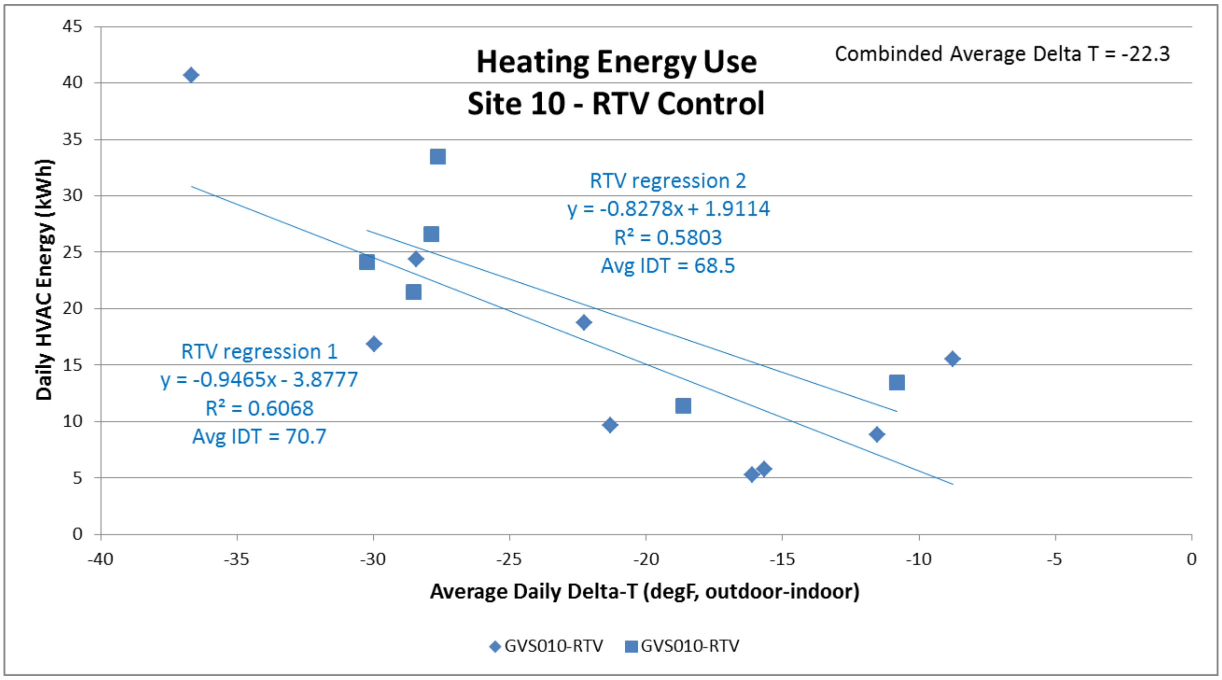


Heating Energy Use
Site 6 - Flip Home
Combinded Average Delta T = -25.2
RTV regression
y = -1.6936x - 18.01
R² = 0.8647
Avg IDT = 74.0
CEV regression
y = -1.4897x - 19.801
R² = 0.8791
Avg IDT = 73.8
Daily HVAC Energy (kWh)
Average Daily Delta-T (degF, outdoor-indoor)
GVS006-CEV
GVS006-RTV


Heating Energy Use
Site 7 - RTV Control
Combinded Average Delta T = -22.3
RTV regression 2
y = -0.2981x - 0.5146
R² = 0.3292
Avg IDT = 70.2
RTV regression 1
y = -0.1786x + 3.4446
R² = 0.274
Avg IDT = 69.9F
Daily HVAC Energy (kWh)
Average Daily Delta-T (degF, outdoor-indoor)
GVS007-RTV
GVS007-RTV


Heating Energy Use
Site 8 - Flip Home
Combinded Average Delta T = -25.4
RTV regression
y = -1.1078x - 12.032
R² = 0.8302
Avg IDT = 72.9
CEV regression
y = -1.1413x - 13.974
R² = 0.9402
Avg IDT = 73.4
Daily HVAC Energy (kWh)
Average Daily Delta-T (degF, outdoor-indoor)
GVS008-CEV
GVS008-RTV


Heating Energy Use
Site 9 - Flip Home
Combinded Average Delta T = -21.6
CEV regression
y = -0.9366x - 8.8305
R² = 0.9047
Avg IDT = 71.1
RTV regression
y = -0.67x - 3.7508
R² = 0.7484
Avg IDT = 70.2
Daily HVAC Energy (kWh)
Average Daily Delta-T (degF, outdoor-indoor)
GVS009-CEV
GVS009-RTV


Heating Energy Use
Site 10 - RTV Control
Combinded Average Delta T = -22.3
RTV regression 2
y = -0.8278x + 1.9114
R² = 0.5803
Avg IDT = 68.5
RTV regression 1
y = -0.9465x - 3.8777
R² = 0.6068
Avg IDT = 70.7
Daily HVAC Energy (kWh)
Average Daily Delta-T (degF, outdoor-indoor)
GVS010-RTV
GVS010-RTV

Appendix J. IAQ Sampling Schedule

Table J-1.

Key		
62.2	**Unmodified**	**IAQ = week IAQ test is occurring**

Season	Round #	Flip Days Begin	Flip Days End	Length	Flip To	Control Homes - CEV	Control Homes - RTV	Flip-Flop Homes
Summer	1.1	06/21/13	06/27/13	6	Fan on			
	1.2	06/28/13	07/11/13	13	RTV			
	2.1	07/12/13	08/07/13	26	Fan on			
	2.2	08/08/13	08/13/13	5	RTV			
	2.2 (IAQ)	08/14/13	08/20/13	6	no change	IAQ	IAQ	IAQ
	3.1	08/21/13	09/03/13	13	Fan on			
	3.2	09/04/13	09/17/13	13	RTV			
	4.1 (IAQ)	09/18/13	09/26/13	8	Fan on	IAQ	IAQ	IAQ
	4.1 (continued)	09/27/13	10/02/13	5	no change			
Fall	4.2	10/03/13	10/16/13	13	RTV			
	5.1	10/17/13	10/30/13	13	Fan on			
	5.2	10/31/13	11/13/13	13	RTV			
	6.1	11/14/13	12/04/13	20	Fan on			

Key		
62.2	Unmodified	IAQ = week IAQ test is occurring

Season	Round #	Flip Days Begin	Flip Days End	Length	Flip To	Control Homes - CEV	Control Homes - RTV	Flip-Flop Homes
Winter/ Mixed	6.2	12/05/13	12/18/13	13	RTV			
	7.1	12/19/13	01/01/14	13	Fan on			
	7.2	01/02/14	02/18/14	47	RTV			
	8.1	02/19/14	03/05/14	14	Fan on			
	8.2	03/06/14	03/19/14	13	RTV			
	8.2 (IAQ)	03/20/14	03/26/14	6	RTV	IAQ	IAQ	IAQ
	9.1	03/27/14	04/16/14	20	Fan on			
	9.1 (IAQ)	04/10/14	04/16/14	6	no change	IAQ	IAQ	IAQ
	10.1	04/17/14	04/30/14	13	RTV			
	10.2	05/01/14	05/14/14	13	Fan on			
Summer	11.1	05/15/14	05/28/14	13	RTV			
	11.2	05/29/14	06/11/14	13	Fan on			
	12.1	06/12/14	06/25/14	13	RTV			
	12.2	06/26/14	07/09/14	13	Fan on			
	13.1	07/10/14	07/16/14	6	RTV			
	13.1 (IAQ)	07/16/14	07/22/14	6	no change	IAQ	IAQ	IAQ
	13.2	07/23/14	08/11/14	19	Fan on			
	13.2 (IAQ)	08/12/14	08/18/14	10	no change	IAQ	IAQ	IAQ
	14.1	08/18/14	08/18/14	6	REMOVE			

Appendix K. Air Exchange Rate and Indoor Air Quality Data Tables

The following data tables present the full outdoor and field blank-corrected ppb concentrations (except as otherwise noted) of the seasonally sampling IAQ parameters, including measured and calculated AER, formaldehyde, VOCs, and NO_2 not otherwise presented in the report.

Air Exchange Rate

Table K-1 presents the calculated air exchange rate and related infiltration and mechanical ventilation-related flow rates calculated based on theoretical relationships and combined in quadrature in accordance with the methods described in the ASHRAE Fundamentals Handbook (ASHRAE 2013a).

Table K-1

House	Configuration	Qinf (CFM)	Runtime Fraction	Qunbalanced (CFM)	Qtot (CFM)	ACHn (hr^{-1})	Runtime Fraction	Qunbalanced (CFM)	Qtot (CFM)	ACHn (hr^{-1})
First Summer Sampling Period										
			SUM1.1 (RTV)				**SUM1.2 (CEV)**			
H1	FF	72.32	0.31	12.44	73.38	0.20	0.24	57.50	92.39	0.26
H2	FF	43.33	0.41	14.01	45.54	0.18	0.41	55.00	70.02	0.28
H4	FF	44.44	0.60	15.62	47.10	0.14	0.54	56.00	71.49	0.22
H6	FF	38.34	0.36	15.13	41.21	0.15	0.30	56.00	67.87	0.24
H8	FF	28.59	0.43	16.61	33.07	0.13	0.44	77.50	82.61	0.33
H9	FF	48.36	0.27	6.41	48.78	0.19	0.34	64.50	80.61	0.31
H3	CEV	30.49	0.57	54.50	62.45	0.24	0.46	54.50	62.45	0.24
H5	CEV	38.97	0.39	59.50	71.13	0.22	0.31	59.50	71.13	0.22
H7	RTV	44.63	0.57	18.23	48.21	0.15	0.47	14.95	47.07	0.14
H10	RTV	42.73	0.26	9.68	43.81	0.11	0.24	8.83	43.63	0.11

House	Configuration	Qinf (CFM)	Runtime Fraction	Qunbalanced (CFM)	Qtot (CFM)	ACHn (hr^{-1})	Runtime Fraction	Qunbalanced (CFM)	Qtot (CFM)	ACHn (hr^{-1})
Winter/Mixed Sampling Period										
			WIN1 (RTV)				**WIN2 (CEV)**			
H1	FF	72.32								
H2	FF	43.33	0.13	4.51	43.56	0.17	0.07	55.00	70.02	0.28
H4	FF	44.44	0.04	1.12	44.45	0.13	0.29	56.00	71.49	0.22
H6	FF	38.34	0.01	0.41	38.34	0.14	0.11	56.00	67.87	0.24
H8	FF	28.59	0.02	0.68	28.60	0.11	0.46	77.50	82.61	0.33
H9	FF	48.36	0.00	0.00	48.36	0.19	0.08	64.50	80.61	0.31
H3	CEV	30.49	0.12	54.50	62.45	0.24	0.19	54.50	62.45	0.24
H5	CEV	38.97	0.05	59.50	71.13	0.22	0.12	59.50	71.13	0.22
H7	RTV	44.63	0.12	3.71	44.79	0.14	0.21	6.84	45.15	0.14
H10	RTV	42.73	0.00	0.00	42.73	0.10	0.08	3.13	42.85	0.10
Second Summer Sampling Period										
			SUM2.1 (RTV)				**SUM2.2 (CEV)**			
H1	FF	72.32								
H2	FF	43.33	0.44	14.98	45.84	0.18	0.43	55.00	70.02	0.28
H4	FF	44.44	0.58	14.96	46.89	0.14				
H6	FF	38.34	0.35	14.69	41.05	0.15	0.29	56.00	67.87	0.24
H8	FF	28.59	0.41	16.05	32.79	0.13	0.42	77.50	82.61	0.33
H9	FF	48.36	0.38	9.06	49.20	0.19	0.47	64.50	80.61	0.31
H3	CEV	30.49	0.62	54.50	62.45	0.24	0.63	54.50	62.45	0.24
H5	CEV	38.97								
H7	RTV	44.63	0.64	20.50	49.12	0.15	0.54	17.25	47.85	0.14
H10	RTV	42.73	0.32	11.86	44.35	0.11	0.33	12.24	44.45	0.11

Formaldehyde

Table K-2 shows concentrations in of formaldehyde (ppb), corrected for the outdoor concentration and field blank.

Table K-2

Ventilation Configuration	Homes	SUM1 (ppb)	SUM2 (ppb)	SUM1 Diff (ppb)	SUM1 Perc. Diff (%)	WIN1 (ppb)	WIN2 (ppb)	WIN Diff (ppb)	WIN Perc. Diff (%)	SUM2.1 (ppb)	SUM2.2 (ppb)	SUM2 Diff (ppb)	SUM2 Perc. Diff (%)
FF	H1	24.50	29.86	5.36	17.95								
FF	H2	16.50	17.86	1.36	7.61	13.01	12.50	-0.51	-4.08	17.60	16.70	-0.90	-5.39
FF	H4	16.50	19.86	3.36	16.92								
FF	H6	38.50	33.86	-4.64	-13.70	38.01	31.50	-6.51	-20.67	29.60		-29.60	
FF	H8	22.50	28.86	6.36	22.04	21.01	17.50	-3.51	-20.06	24.60	15.70	-8.90	-56.69
FF	H9	53.96	37.86	-16.10	-42.53	31.01	34.50	3.49	10.12	32.60	32.70	0.10	0.31
FF	AVG	28.74	28.03	-0.72	1.38	25.76	24.00	-1.76	-8.67	26.10	21.70	-9.83	-20.59
	STDEV	14.75	7.81	8.49	25.05	11.00	10.66	4.27	14.69	6.56	9.54	13.78	31.39
	N	6.00	6.00	6.00	6.00	4.00	4.00	4.00	4.00	4.00	3.00	4.00	3.00
	95% CI	15.48	8.19	8.91	26.29	17.50	16.96	6.80	23.38	10.43	23.70	21.93	77.98
CEV	H3	20.50	24.86	4.36	17.54	17.01	17.00	-0.01	-0.06	19.60	19.70	0.10	0.51
CEV	H5	24.50	25.86	1.36	5.26	14.01	19.50	5.49	28.15	26.60		-26.60	
CEV	AVG	22.50	25.36	2.86	11.40	15.51	18.25	2.74	14.05	23.10	19.70	-13.25	0.51
	STDEV	2.83	0.71	2.12	8.68	2.12	1.77	3.89	19.95	4.95		18.88	
	N	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00	2.00	1.00
	95% CI	25.41	6.35	19.06	78.01	19.06	15.88	34.94	179.24	44.47		169.63	
RTV	H7	12.50	13.86	1.36	9.81	12.01	14.50	2.49	17.17	12.10	10.70	-1.40	-13.08
RTV	H10	43.50	23.86	-19.64	-82.31	42.01	33.50	-8.51	-25.40	24.60	22.70	-1.90	-8.37

Ventilation Configuration	Homes	SUM1 (ppb)	SUM2 (ppb)	SUM1 Diff (ppb)	SUM1 Perc. Diff (%)	WIN1 (ppb)	WIN2 (ppb)	WIN Diff (ppb)	WIN Perc. Diff (%)	SUM2.1 (ppb)	SUM2.2 (ppb)	SUM2 Diff (ppb)	SUM2 Perc. Diff (%)
RTV	AVG	28.00	18.86	-9.14	-36.25	27.01	24.00	-3.01	-4.12	18.35	16.70	-1.65	-10.73
	STDEV	21.92	7.07	14.85	65.14	21.21	13.44	7.78	30.11	8.84	8.49	0.35	3.33
	N	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	95% CI	196.95	63.53	133.42	585.29	190.59	120.71	69.88	270.49	79.41	76.24	3.18	29.95

Table K-3 shows concentrations in of acetaldehyde (ppb), corrected for the outdoor concentration and field blank.

Table K-3

Ventilation Configuration	Homes	SUM1 (ppb)	SUM2 (ppb)	SUM1 Diff (ppb)	SUM1 Perc. Diff (%)	WIN1 (ppb)	WIN2 (ppb)	WIN Diff (ppb)	WIN Perc. Diff (%)	SUM2.1 (ppb)	SUM2.2 (ppb)	SUM2 Diff (ppb)	SUM2 Perc. Diff (%)
FF	H1	4.76	2.28	-2.48	-108.77			0.00				0.00	
FF	H2	1.16	0.79	-0.37	-46.84	1.35	0.79	-0.56	-70.89	0.70	0.37	-0.33	-89.19
FF	H4	3.76	2.48	-1.28	-51.61			0.00				0.00	
FF	H6	2.76	2.58	-0.18	-6.98	2.35	2.34	-0.01	-0.43	4.30		-4.30	
FF	H8	5.96	4.38	-1.58	-36.07	3.55	1.14	-2.41	-211.40	4.90	0.88	-4.02	-456.82
FF	H9	-0.14	1.88	2.02	107.45	2.75	3.54	0.79	22.32	3.20	0.65	-2.55	-392.31
FF	AVG	3.04	2.40	-0.65	-23.80	2.50	1.95	-0.37	-65.10	3.28	0.63	-1.87	-312.77
	STDEV	2.27	1.17	1.55	72.37	0.91	1.25	1.09	105.30	1.86	0.26	2.02	196.30
	N	6.00	6.00	6.00	6.00	4.00	4.00	6.00	4.00	4.00	3.00	6.00	3.00
	95% CI	2.38	1.23	1.63	75.94	1.46	1.99	1.14	167.55	2.95	0.63	2.12	487.63
CEV	H3	3.66	3.28	-0.38	-11.59	1.75	2.59	0.84	32.43	1.80	1.28	-0.52	-40.63
CEV	H5	4.86	3.88	-0.98	-25.26	0.35	1.44	1.09	75.69	1.70			

Ventilation Configuration	Homes	SUM1 (ppb)	SUM2 (ppb)	SUM1 Diff (ppb)	SUM1 Perc. Diff (%)	WIN1 (ppb)	WIN2 (ppb)	WIN Diff (ppb)	WIN Perc. Diff (%)	SUM2.1 (ppb)	SUM2.2 (ppb)	SUM2 Diff (ppb)	SUM2 Perc. Diff (%)
CEV	AVG	4.26	3.58	-0.68	-18.42	1.05	2.02	0.97	54.06	1.75	1.28		
	STDEV	0.85	0.42	0.42	9.67	0.99	0.81	0.18	30.59	0.07			
	N	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00		
	95% CI	7.62	3.81	3.81	86.86	8.89	7.31	1.59	274.85	0.64			
RTV	H7	4.16	2.98	-1.18	-39.60	2.35	3.74	1.39	37.17	2.10	1.88	-0.22	-11.70
RTV	H10	3.96	4.08	0.12	2.94	2.55	3.14	0.59	18.79	3.20	2.18	-1.02	-46.79
RTV	AVG	4.06	3.53	-0.53	-18.33	2.45	3.44	0.99	27.98	2.65	2.03	-0.62	-29.25
	STDEV	0.14	0.78	0.92	30.08	0.14	0.42	0.57	12.99	0.78	0.21	0.57	24.81
	N	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	95% CI	1.27	6.99	8.26	270.25	1.27	3.81	5.08	116.74	6.99	1.91	5.08	222.91

Volatile Organic Compounds

Table K-4 shows raw concentrations for all resolved compounds (ppb) for each home, including the outdoor and field blank measurements.

Table K-4

		Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
Sampling Period	**Analyte Name**	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H6D**	**H7**	**H8**	**H9**	**H10**	**FB**	**OUT**
SUM1	1,1,1-Trichloroethane	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,1,2,2-Tetrachloroethane	0	0	0	0	0	0	0	0	0	0	0.16	0	0
SUM1	1,1,2-Trichloroethane	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,1-Dichloroethane	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,1-Dichloroethene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,2,4-Trichlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,2,4-Trimethylbenzene	0.12	0	0	0	0	0	0	0	0	0	0.23	0	0
SUM1	1,2-Dibromoethane	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,2-Dichlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,2-Dichloroethane	3.8	0	0.14	0.23	0.14	0	0	0.2	0.75	2.9	0.96	0	0
SUM1	1,2-Dichloropropane	0	0	0	0	0	0	0	0	0	0	0.087	0	0
SUM1	1,3,5-Trimethylbenzene	0.15	0	0	0	0	0	0	0	0	0	0.2	0	0
SUM1	1,3-Butadiene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,3-Dichlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	1,4-Dichlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	2-Hexanone	0.19	0.1	0.23	0.11	0.17	0	0	0.16	0	0.21	0.57	0	0
SUM1	4-Ethyl toluene	0.2	0	0	0	0	0	0	0	0	0	0.37	0	0
SUM1	Acetone	15	3.8	9.9	7.6	8.3	12	11	12	5.3	34	5.6	3.7	0
SUM1	Benzene	1.9	0.23	0.25	0.44	1.1	0.15	0.21	0.73	0.44	1.1	2.7	0	0.11
SUM1	Benzyl chloride	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Bromodichloromethane	0.25	0.072	0.12	0	0.062	0.069	0.091	0.14	0.11	0	0.33	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM1	Bromoform	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Bromomethane	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Carbon disulfide	2.8	0.99	3.3	2.4	2.9	3.5	4.1	2.2	2.5	6.6	1.7	1.3	2.4
SUM1	Carbon tetrachloride	0	0	0	0	0	0.037	0.057	0.044	0.05	0.15	0.096	0	0
SUM1	Chlorobenzene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Chloroform	0.5	0.28	0.53	1.3	0.21	0	0	0.63	0.83	1.3	0.27	0	0
SUM1	cis-1,2-Dichloroethene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	cis-1,3-Dichloropropene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Cyclohexane	0.86	0.12	0.65	0.58	0.51	0.11	0.1	0.49	0.13	0.55	1.6	0	0
SUM1	Dibromochloromethane	0	0	0	0	0	0.019	0.025	0	0	0	0	0	0
SUM1	Dichlorodifluoromethane	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Ethanol	11	3.9	14	11	8.1	14	15	8.1	7.8	22	2.5	14	0
SUM1	Ethyl acetate	2.1	1.1	10	6.8	3.1	50	49	4	5.4	24	1.4	0.3	0.087
SUM1	Ethyl benzene	0.97	0	0.085	0.11	0.26	0.093	0.078	0.15	0	0	11	0	0
SUM1	Ethyl chloride	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Freon 11	0.047	0.078	0.085	0.11	0.057	0.099	0.083	0.05	0.065	0.085	0	0	0.17
SUM1	Freon 113	0	0.043	0.085	0.11	0.061	0.3	0.31	0.054	0.11	0.17	0.023	0	0.11
SUM1	Freon 114	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Heptane	1.2	0.11	0.33	1.7	0.41	0.23	0.28	0.74	0.58	0.25	2.5	0	0
SUM1	Hexachloro-1,3-butadiene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Isopropyl alcohol	3.8	2	4.8	5.1	3.5	9.1	8.1	7.6	6.1	59	6.1	1.8	0
SUM1	m,p-Xylene	0.97	0	0.056	0.063	0.23	0.099	0.066	0.14	0	0	6.2	0	0
SUM1	Methyl chloride	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Methyl ethyl ketone	6.7	4.1	9.2	5.5	3.6	24	25	4.7	4.6	20	6.5	0.21	0
SUM1	Methyl isobutyl ketone	0	0.29	0.55	1.1	0.33	0.48	0.6	0.18	0.47	0.7	2.4	0	0
SUM1	Methyl t-butyl ether	0	0	0	0	0	0	0	0	0	0	0	0	0

		Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
Sampling Period	**Analyte Name**	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H6D**	**H7**	**H8**	**H9**	**H10**	**FB**	**OUT**
SUM1	Methylene chloride	4.7	6.8	8.1	12	5.4	37	28	11	12	41	8.6	2.9	14
SUM1	n-Hexane	2.8	0.39	0	0	1.2	0.27	0.36	0.9	0.3	0.72	3.7	0.2	0.22
SUM1	o-Xylene	0.78	0	0	0	0.16	0.084	0.055	0.097	0	0	7.9	0	0
SUM1	Propene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Styrene	0.11	0	0.061	0	0	0.19	0.13	0.1	0	0	1.4	0	0
SUM1	Tetrachloroethene	0.16	0	0.039	0.56	0	0	0	0.059	0	0	0.044	0	0
SUM1	Tetrahydrofuran	1.3	0.63	2	1.4	0.75	4.9	4.9	1.3	0.79	2.8	1.4	0.19	0
SUM1	Toluene	4.9	1.5	1.6	1.9	3.4	0.88	0.84	2	1.3	3	5.7	0.14	0.4
SUM1	Total Volatile Organics	52	18	35	35	39	44	39	43	32	51	160	5.3	4.7
SUM1	trans-1,2-Dichloroethene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	trans-1,3-Dichloropropene	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Trichloroethene	0.8	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Vinyl acetate	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM1	Vinyl chloride	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM2	1,1,1-Trichloroethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,1,2,2-Tetrachloroethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,1,2-Trichloroethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,1-Dichloroethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,1-Dichloroethene	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,2,4-Trichlorobenzene	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,2,4-Trimethylbenzene	0.18	0	0	0.068	0	0.076		0	0	0	0.1		0
SUM2	1,2-Dibromoethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,2-Dichlorobenzene	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,2-Dichloroethane	4.3	0	0.093	0	0.17	0		0.41	0.35	0.6	0.92		0
SUM2	1,2-Dichloropropane	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,3,5-Trimethylbenzene	0.12	0	0	0	0	0.058		0	0	0	0.079		0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM2	1,3-Butadiene	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,3-Dichlorobenzene	0	0	0	0	0	0		0	0	0	0		0
SUM2	1,4-Dichlorobenzene	0	0	0	0	0	0		0	0	0	0		0
SUM2	2-Hexanone	0	0.12	0	0.24	0.11	0.2		0.17	0.17	0.19	0.61		0
SUM2	4-Ethyl toluene	0.2	0	0	0	0	0		0	0	0	0.17		0
SUM2	Acetone	6.7	5.9	11	6	14	12		7.4	13	7	18		1.7
SUM2	Benzene	3.1	0.28	0.24	2.3	1.1	0.5		0.62	0.48	0.93	1.7		0
SUM2	Benzyl chloride	0	0	0	0	0	0		0	0	0	0		0
SUM2	Bromodichloromethane	0	0.075	0.069	0	0.11	0.082		0.16	0.086	0.074	0.21		0
SUM2	Bromoform	0	0	0	0	0	0		0	0	0	0		0
SUM2	Bromomethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	Carbon disulfide	2.2	0.72	1.8	1.3	1.3	1.1		1.1	2	1.5	1.2		0.11
SUM2	Carbon tetrachloride	0.044	0.043	0.045	0.038	0	0.057		0.075	0.077	0.087	0.047		0
SUM2	Chlorobenzene	0	0	0	0	0	0		0	0	0	0		0
SUM2	Chloroform	0.25	0.25	0.29	1.1	0.27	0.32		0.57	0.4	0.2	0.63		0
SUM2	cis-1,2-Dichloroethene	0	0	0	0	0	0		0	0	0	0		0
SUM2	cis-1,3-Dichloropropene	0	0	0	0	0	0		0	0	0	0		0
SUM2	Cyclohexane	1.2	0.13	0.32	0.96	0.49	0.13		0.4	0.13	0.3	0.75		0
SUM2	Dibromochloromethane	0	0	0	0	0	0		0.045	0	0	0.039		0
SUM2	Dichlorodifluoromethane	0	0	0	0	0	0		0	0	0	0		0
SUM2	Ethanol	13	3.7	21	11	10	13		9.6	12	6	6.3		4
SUM2	Ethyl acetate	3.4	3.3	6	2	2.9	9		2.9	8.5	5	2.5		0
SUM2	Ethyl benzene	1.4	0.1	0.081	0.43	0.088	0.12		0.29	0.061	0.22	5.9		0
SUM2	Ethyl chloride	0	0	0	0	0	0		0	0	0	0		0
SUM2	Freon 11	0.036	0.068	0.053	0.026	0.07	0.088		0	0.047	0.075	0.06		0.075
SUM2	Freon 113	0	0.028	0.045	0	0.034	0.062		0.02	0.056	0.039	0		0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM2	Freon 114	0	0	0	0	0	0		0	0	0	0		0
SUM2	Heptane	2	0.13	0.34	2.3	0.13	0.2		0.43	0.72	0.32	1.5		0
SUM2	Hexachloro-1,3-butadiene	0	0	0	0	0	0		0	0	0	0		0
SUM2	Isopropyl alcohol	2.8	1.5	1.8	3	8.9	5.7		8.2	5.2	5.4	6.2		0.78
SUM2	m,p-Xylene	1.4	0.076	0.061	0.36	0.075	0.13		0.25	0.046	0.22	4.9		0.04
SUM2	Methyl chloride	0	0	0	0	0	0		0	0	0	0		0
SUM2	Methyl ethyl ketone	7.5	4.4	4.5	4.5	4	7.4		6	5.3	6.6	6.1		0.14
SUM2	Methyl isobutyl ketone	0.13	0.27	0.28	0.98	0.47	0.34		0.3	0.74	0.53	1.4		0
SUM2	Methyl t-butyl ether	0	0	0	0	0	0		0	0	0	0		0
SUM2	Methylene chloride	9.4	5.4	4.4	6.3	7.5	9.9		7	9	10	7.7		11
SUM2	n-Hexane	5.8	0.59	0.61	5.4	1.6	0.61		1.2	0.59	1.2	3.7		0
SUM2	o-Xylene	1.1	0	0	0.28	0	0.11		0.2	0	0.15	5.5		0
SUM2	Propene	0	0	0	0	0	0		0	0	0	0		0
SUM2	Styrene	0.27	0.11	0.082	0.16	0	0.12		0.29	0	0.16	0.75		0
SUM2	Tetrachloroethene	0.21	0.041	0.037	0.5	0	0		0.072	0.11	0	0.055		0
SUM2	Tetrahydrofuran	1.7	1	1.1	1.1	0.97	2		1.5	1.1	0.36	1.4		0
SUM2	Toluene	6.3	2	1.9	4	4.2	2		0.82	2.2	3	5.4		0
SUM2	Total Volatile Organics	93	30	49	110	60	82		99	59	79	93		5
SUM2	trans-1,2-Dichloroethene	0	0	0	0	0	0		0	0	0	0		0
SUM2	trans-1,3-Dichloropropene	0	0	0	0	0	0		0	0	0	0		0
SUM2	Trichloroethene	0.23	0	0	0	0	0		0	0	0	0		0
SUM2	Vinyl acetate	0	0	0	0	0	0		0	0	0	0		0
SUM2	Vinyl chloride	0	0	0	0	0	0		0	0	0	0		0
SUM2.1	1,1,1-Trichloroethane		0	0		0	0			0	0	0	0	0
SUM2.1	1,1,2,2-Tetrachloroethane		0	0		0	0			0	0	0	0	0
SUM2.1	1,1,2-Trichloroethane		0	0		0	0			0	0	0.075	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM2.1	1,1-Dichloroethane		0	0		0	0			0	0	0	0	0
SUM2.1	1,1-Dichloroethene		0	0		0	0			0	0	0	0	0
SUM2.1	1,2,4-Trichlorobenzene		0	0		0	0			0	0	0	0	0
SUM2.1	1,2,4-Trimethylbenzene		0	0		0	0			0	0	0	0	0
SUM2.1	1,2-Dibromoethane		0	0		0	0			0	0	0	0	0
SUM2.1	1,2-Dichlorobenzene		0	0		0	0			0	0	0	0	0
SUM2.1	1,2-Dichloroethane		0	0		0.2	0.071			1.2	2.1	0.97	0	0
SUM2.1	1,2-Dichloropropane		0	0		0	0			0	0	0.05	0	0
SUM2.1	1,3,5-Trimethylbenzene		0	0		0	0			0	0	0	0	0
SUM2.1	1,3-Butadiene		0	0		0	0			0	0	0	0	0
SUM2.1	1,3-Dichlorobenzene		0	0		0	0			0	0	0	0	0
SUM2.1	1,4-Dichlorobenzene		0	0		0	0			0	0	0	0	0
SUM2.1	2-Hexanone		0	0		0	0			0	0	0	0	0
SUM2.1	4-Ethyl toluene		0	0		0	0			0	0	0	0	0
SUM2.1	Acetone		22	59		27	14			24	16	15	0	1.8
SUM2.1	Benzene		0.4	1.2		0.66	1.2			0.26	0.46	1.4	0	0
SUM2.1	Benzyl chloride		0	0		0	0			0	0	0	0	0
SUM2.1	Bromodichloromethane		0	0		0	0.06			0	0.1	0	0	0
SUM2.1	Bromoform		0	0		0	0			0	0	0	0	0
SUM2.1	Bromomethane		0	0		0	0			0	0	0	0	0
SUM2.1	Carbon disulfide		1.4	3.5		1.6	0.85			0.79	1.1	0.81	0	0.099
SUM2.1	Carbon tetrachloride		0	0		0	0			0	0.079	0	0	0
SUM2.1	Chlorobenzene		0	0		0	0			0	0	0	0	0
SUM2.1	Chloroform		0	0.32		0.11	0.5			0.28	1.1	0.32	0	0
SUM2.1	cis-1,2-Dichloroethene		0	0		0	0			0	0	0	0	0
SUM2.1	cis-1,3-Dichloropropene		0	0		0	0			0	0	0	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM2.1	Cyclohexane		0.22	0.78		2.6	0.5			0.35	0.41	1.4	0	0
SUM2.1	Dibromochloromethane		0	0		0	0			0	0	0	0	0
SUM2.1	Dichlorodifluoromethane		0	0		0	0			0	0	0	0	0
SUM2.1	Ethanol		17	170		22	21			9.5	14	6.4	0	13
SUM2.1	Ethyl acetate		1.8	0		2.6	18			3.9	17	0	0	0
SUM2.1	Ethyl benzene		0	0		0	0			0	0.12	0.71	0	0
SUM2.1	Ethyl chloride		0	0		0	0			0	0	0	0	0
SUM2.1	Freon 11		0.36	1		0.26	0.15			0.04	0.15	0.12	0	0.086
SUM2.1	Freon 113		0.12	0.32		0.11	0.073			0	0.093	0.023	0	0
SUM2.1	Freon 114		0	0		0	0			0	0	0.21	0	0
SUM2.1	Heptane		0	0		0	0			0	0.18	0.76	0	0
SUM2.1	Hexachloro-1,3-butadiene		0	0		0	0			0	0	0	0	0
SUM2.1	Isopropyl alcohol		12	79		25	15			310	15	11	0	3.1
SUM2.1	m,p-Xylene		0	0		0.042	0			0.082	0.16	0.98	0	0
SUM2.1	Methyl chloride		0	0		0	0			0.38	0	0	0	0
SUM2.1	Methyl ethyl ketone		1.7	6.2		2.6	9.1			2	1.1	3.1	0	0
SUM2.1	Methyl isobutyl ketone		0	0		0.33	0			0.15	0.58	0	0	0
SUM2.1	Methyl t-butyl ether		0	0		0	0			0	0	0	0	0
SUM2.1	Methylene chloride		110	410		99	47			39	49	66	0	33
SUM2.1	n-Hexane		1.1	3.5		1.6	0			0.86	0	4.1	0	0.51
SUM2.1	o-Xylene		0	0		0	0			0	0.1	0.83	0	0
SUM2.1	Propene		0	0		0	0			0	0	0	0	0
SUM2.1	Styrene		0	0		0	0			0	0.12	0.095	0	0
SUM2.1	Tetrachloroethene		0	0.2		0	0			0.087	0.053	0.52	0	0
SUM2.1	Tetrahydrofuran		2.7	4.4		0.73	3.7			0.61	1.9	2.3	0	0.18
SUM2.1	Toluene		0.4	0.69		3.1	0.73			0.44	1.9	3.4	0	0

		Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
Sampling Period	**Analyte Name**	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H6D**	**H7**	**H8**	**H9**	**H10**	**FB**	**OUT**
SUM2.1	Total Volatile Organics		19	37		27	31			78	54	57	0	11
SUM2.1	trans-1,2-Dichloroethene		0	0		0	0			0	0	0	0	0
SUM2.1	trans-1,3-Dichloropropene		0	0		0	0			0	0	0	0	0
SUM2.1	Trichloroethene		0	0		0	0			0	0	0	0	0
SUM2.1	Vinyl acetate		0	0		0	0			0	0	0	0	0
SUM2.1	Vinyl chloride		0	0		0	0			0	0	0	0	0
SUM2.2	1,1,1-Trichloroethane		0	0					0	0	0	0	0	0
SUM2.2	1,1,2,2-Tetrachloroethane		0	0					0	0	0	0	0	0
SUM2.2	1,1,2-Trichloroethane		0	0					0	0	0	0	0	0
SUM2.2	1,1-Dichloroethane		0	0					0	0	0	0	0	0
SUM2.2	1,1-Dichloroethene		0	0					0	0	0	0	0	0
SUM2.2	1,2,4-Trichlorobenzene		0	0					0	0	0	0	0	0
SUM2.2	1,2,4-Trimethylbenzene		0	0					0	0	0	0	0	0
SUM2.2	1,2-Dibromoethane		0	0					0	0	0	0	0	0
SUM2.2	1,2-Dichlorobenzene		0	0					0	0	0	0	0	0
SUM2.2	1,2-Dichloroethane		0	0					1	1.8	1.1	0.83	0	0
SUM2.2	1,2-Dichloropropane		0	0					0	0	0	0	0	0
SUM2.2	1,3,5-Trimethylbenzene		0	0					0	0	0	0	0	0
SUM2.2	1,3-Butadiene		0	0					0	0	0	0	0	0
SUM2.2	1,3-Dichlorobenzene		0	0					0	0	0	0	0	0
SUM2.2	1,4-Dichlorobenzene		0	0					0	0	0	0	0	0
SUM2.2	2-Hexanone		0	0					0	0	0	0.7	0	0
SUM2.2	4-Ethyl toluene		0	0					0	0	0	0	0	0
SUM2.2	Acetone		14	12					24	37	51	16	0	0
SUM2.2	Benzene		0.5	2					1.2	0.31	3.2	1.5	0	0
SUM2.2	Benzyl chloride		0	0					0	0	0	0	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM2.2	Bromodichloromethane		0	0					0	0	0	0.2	0	0
SUM2.2	Bromoform		0	0					0	0	0	0	0	0
SUM2.2	Bromomethane		0	0					0	0	0	0	0	0
SUM2.2	Carbon disulfide		0.95	0.82					0.83	0.36	4.6	0.93	0	0
SUM2.2	Carbon tetrachloride		0	0					0	0.041	0.047	0	0	0
SUM2.2	Chlorobenzene		0	0					0	0	0	0	0	0
SUM2.2	Chloroform		0.069	0.13					0.49	0.1	0.49	0.68	0	0
SUM2.2	cis-1,2-Dichloroethene		0	0					0	0	0	0	0	0
SUM2.2	cis-1,3-Dichloropropene		0	0					0	0	0	0	0	0
SUM2.2	Cyclohexane		0.32	1.2					1.8	0.28	3.1	1	0	0
SUM2.2	Dibromochloromethane		0	0					0	0	0	0	0	0
SUM2.2	Dichlorodifluoromethane		0	0					0	0	0	0	0	0
SUM2.2	Ethanol		15	19					0	6.1	42	16	0	0
SUM2.2	Ethyl acetate		3.8	5					5.1	4.6	11	4.7	0	0
SUM2.2	Ethyl benzene		0	0.17					0.091	0	0	0.35	0	0
SUM2.2	Ethyl chloride		0	0					0	0	0	0	0	0
SUM2.2	Freon 11		0.16	0.14					0.12	0.094	0.15	0.12	0	0
SUM2.2	Freon 113		0.074	0.033					0.05	0	0.059	0.05	0	0
SUM2.2	Freon 114		0	0					0	0	0	0	0	0
SUM2.2	Heptane		0	0.43					0.3	0	0.68	0.4	0	0
SUM2.2	Hexachloro-1,3-butadiene		0	0					0	0	0	0	0	0
SUM2.2	Isopropyl alcohol		7.1	9					79	1200	66	9.9	0	0
SUM2.2	m,p-Xylene		0.039	0.18					0.091	0	0.061	0.47	0	0
SUM2.2	Methyl chloride		0	0					0	0	0	0	0	0
SUM2.2	Methyl ethyl ketone		0.98	1.9					1.9	2.1	5.7	3.7	0	0
SUM2.2	Methyl isobutyl ketone		0.29	0					0.47	0.23	1	1.2	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
SUM2.2	Methyl t-butyl ether		0	0					0	0	0	0	0	0
SUM2.2	Methylene chloride		46	42					44	26	100	35	0	15
SUM2.2	n-Hexane		0.7	3					2.4	0.47	6.7	2.6	0	0
SUM2.2	o-Xylene		0	0.12					0.076	0	0	0.36	0	0
SUM2.2	Propene		0	0					0	0	0	0	0	0
SUM2.2	Styrene		0	0					0	0	0	0	0	0
SUM2.2	Tetrachloroethene		0	0.22					0	0.083	0	0.12	0	0
SUM2.2	Tetrahydrofuran		1.9	1.3					2	0.17	1.4	2	0	0
SUM2.2	Toluene		1.1	2.2					2.4	0.69	2.1	2.8	0	0.081
SUM2.2	Total Volatile Organics		20	42					40	58	54	54	0	0.39
SUM2.2	trans-1,2-Dichloroethene		0	0					0	0	0	0	0	0
SUM2.2	trans-1,3-Dichloropropene		0	0					0	0	0	0	0	0
SUM2.2	Trichloroethene		0	0					0	0.067	0	0	0	0
SUM2.2	Vinyl acetate		0	0					0	0	0	0	0	0
SUM2.2	Vinyl chloride		0	0					0	0	0	0	0	0
WIN1	1,1,1-Trichloroethane		0	0		0	0		0	0	0	0	0	0
WIN1	1,1,2,2-Tetrachloroethane		0	0		0	0		0	0	0	0	0	0
WIN1	1,1,2-Trichloroethane		0	0		0	0		0	0	0	0	0	0
WIN1	1,1-Dichloroethane		0	0		0	0		0	0	0	0	0	0
WIN1	1,1-Dichloroethene		0	0		0	0		0	0	0	0	0	0
WIN1	1,2,4-Trichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN1	1,2,4-Trimethylbenzene		0	0		0	0		0	0	0	0.068	0	0
WIN1	1,2-Dibromoethane		0	0		0	0		0	0	0	0	0	0
WIN1	1,2-Dichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN1	1,2-Dichloroethane		0	0.18		0.094	0		1.7	0.11	3	1	0	0
WIN1	1,2-Dichloropropane		0	0		0	0		0	0	0	0.052	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
WIN1	1,3,5-Trimethylbenzene		0	0		0	0		0	0	0	0	0	0
WIN1	1,3-Butadiene		0	0		0	0		0	0	0	0	0	0
WIN1	1,3-Dichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN1	1,4-Dichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN1	2-Hexanone		0	0		0.12	0.091		0.12	0	0	0.33	0	0
WIN1	4-Ethyl toluene		0	0		0	0		0	0	0	0	0	0
WIN1	Acetone		17	36		8.6	14		12	28	300	20	0.59	3.4
WIN1	Benzene		0.28	0.22		0.34	0.5		1.4	0.54	0.43	1.3	0	0.27
WIN1	Benzyl chloride		0	0		0	0		0	0	0	0	0	0
WIN1	Bromodichloromethane		0	0		0	0		0.11	0	0.078	0.13	0	0
WIN1	Bromoform		0	0		0	0		0	0	0	0	0	0
WIN1	Bromomethane		0	0		0	0		0	0	0	0	0	0
WIN1	Carbon disulfide		0.47	1.9		0.59	0.94		0.4	1.1	2	0.66	0.026	1.1
WIN1	Carbon tetrachloride		0	0		0	0		0.035	0	0.066	0	0	0
WIN1	Chlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN1	Chloroform		0	0		0.25	0.2		0.36	0.6	0	0.53	0	0
WIN1	cis-1,2-Dichloroethene		0	0		0	0		0	0	0	0	0	0
WIN1	cis-1,3-Dichloropropene		0	0		0	0		0	0	0	0	0	0
WIN1	Cyclohexane		0.11	0.1		0.1	0.12		0.8	0.097	0.41	0.93	0	0
WIN1	Dibromochloromethane		0	0		0	0		0	0	0	0	0	0
WIN1	Dichlorodifluoromethane		0	0		0	0		0	0	0	0	0	0
WIN1	Ethanol		10	140		4.7	34		7.2	19	68	16	13	9.1
WIN1	Ethyl acetate		2.3	78		2.2	8.3		1.8	7.5	97	3.6	0	0.17
WIN1	Ethyl benzene		0	0		0.098	0		0.13	0	0.047	1.6	0	0
WIN1	Ethyl chloride		0	0		0	0		0	0	0	0	0	0
WIN1	Freon 11		0.071	0.2		0.041	0.067		0.017	0.066	0	0.076	0	0.097

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
WIN1	Freon 113		0.056	0.18		0.041	0.058		0	0.051	0.041	0.025	0	0.036
WIN1	Freon 114		0	0		0	0		0	0	0	0	0	0
WIN1	Heptane		0	0		0.13	0.098		0.33	0	0.11	0.54	0	0
WIN1	Hexachloro-1,3-butadiene		0	0		0	0		0	0	0	0	0	0
WIN1	Isopropyl alcohol		4.3	8.3		4.3	3.9		8.6	3.4	45	5.5	0.22	1.4
WIN1	m,p-Xylene		0.054	0		0.1	0.036		0.11	0	0.038	2.1	0.026	0.068
WIN1	Methyl chloride		0	0		0	0		0	0	0	0	0	0
WIN1	Methyl ethyl ketone		1.2	3.6		3.2	3.4		4.8	2.5	4.2	2.5	0	0.14
WIN1	Methyl isobutyl ketone		0.082	0		0.31	0.21		0.48	0.12	0.39	1.7	0	0
WIN1	Methyl t-butyl ether		0	0		0	0		0	0	0	0	0	0
WIN1	Methylene chloride		1	5.1		0.98	1.9		0.74	2	2.3	0.66	0.062	1
WIN1	n-Hexane		0.3	0.24		0.35	0.34		2.3	0.29	1.6	2.2	0.065	0.26
WIN1	o-Xylene		0	0		0.073	0		0.081	0	0	1.9	0	0
WIN1	Propene		0	0		0	0		0	0	0	0	0	0
WIN1	Styrene		0	0		0.039	0		0.043	0	0	0.18	0	0
WIN1	Tetrachloroethene		0.035	0		0	0		0.072	0.041	0	0.06	0	0
WIN1	Tetrahydrofuran		0.66	2.1		0.49	1.9		1.4	0.8	4.1	2.4	0	0.17
WIN1	Toluene		0.54	0.32		1.7	1.2		2.3	0.69	1.7	3.4	0.11	0.37
WIN1	Total Volatile Organics		22	36		40	46		59	37	71	98	7.2	16
WIN1	trans-1,2-Dichloroethene		0	0		0	0		0	0	0	0	0	0
WIN1	trans-1,3-Dichloropropene		0	0		0	0		0	0	0	0	0	0
WIN1	Trichloroethene		0	0		0	0		0.027	0	0	0	0	0
WIN1	Vinyl acetate		0	0		0	0		0	0	0	0	0	0
WIN1	Vinyl chloride		0	0		0	0		0.037	0	0	0	0	0
WIN2	1,1,1-Trichloroethane		0	0		0	0		0	0	0	0	0	0
WIN2	1,1,2,2-Tetrachloroethane		0	0		0	0		0	0	0	0	0	0

Sampling Period	Analyte Name	Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
		H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
WIN2	1,1,2-Trichloroethane		0	0		0	0		0	0	0	0	0	0
WIN2	1,1-Dichloroethane		0	0		0	0		0	0	0	0	0	0
WIN2	1,1-Dichloroethene		0	0		0	0		0	0	0	0	0	0
WIN2	1,2,4-Trichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN2	1,2,4-Trimethylbenzene		0	0		0	0		0	0	0	0	0	0
WIN2	1,2-Dibromoethane		0	0		0	0		0	0	0	0	0	0
WIN2	1,2-Dichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN2	1,2-Dichloroethane		0	0.054		0.13	0		1.7	0.11	0.65	1.2	0	0
WIN2	1,2-Dichloropropane		0	0		0	0		0	0	0	0	0	0
WIN2	1,3,5-Trimethylbenzene		0	0		0	0		0	0	0	0	0	0
WIN2	1,3-Butadiene		0	0		0	0		0	0	0	0	0	0
WIN2	1,3-Dichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN2	1,4-Dichlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN2	2-Hexanone		0	0		0	0		0	0	0	0.13	0	0
WIN2	4-Ethyl toluene		0	0		0	0		0	0	0	0	0	0
WIN2	Acetone		12	2.2		4.9	5.6		6.7	7.2	51	8.5	0.36	0.73
WIN2	Benzene		0.23	0.23		0.35	0.43		1.6	0.72	0.71	1.1	0	0.14
WIN2	Benzyl chloride		0	0		0	0		0	0	0	0	0	0
WIN2	Bromodichloromethane		0	0		0	0		0	0	0	0	0	0
WIN2	Bromoform		0	0		0	0		0	0	0	0	0	0
WIN2	Bromomethane		0	0		0	0		0	0	0	0	0	0
WIN2	Carbon disulfide		0.5	0.4		0.49	0.63		0.42	0.81	1.7	1.1	0.06	0.64
WIN2	Carbon tetrachloride		0	0		0	0		0	0	0	0	0	0
WIN2	Chlorobenzene		0	0		0	0		0	0	0	0	0	0
WIN2	Chloroform		0	0		0.065	0.085		0.24	0.081	0.36	0.53	0	0
WIN2	cis-1,2-Dichloroethene		0	0		0	0		0	0	0	0	0	0

		Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
Sampling Period	**Analyte Name**	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H6D**	**H7**	**H8**	**H9**	**H10**	**FB**	**OUT**
WIN2	cis-1,3-Dichloropropene		0	0		0	0		0	0	0	0	0	0
WIN2	Cyclohexane		0.13	0.18		0.17	0.14		1	0.14	0.35	0.68	0	0
WIN2	Dibromochloromethane		0	0		0	0		0	0	0	0	0	0
WIN2	Dichlorodifluoromethane		0	0		0	0		0	0	0	0	0	0
WIN2	Ethanol		3.1	13		7.4	19		7.1	5.3	26	11	4.2	2.3
WIN2	Ethyl acetate		1.1	4.6		5.7	6.9		2.6	2.1	19	4.3	0	0
WIN2	Ethyl benzene		0	0		0	0		0	0	0	0.41	0	0
WIN2	Ethyl chloride		0	0		0	0		0	0	0	0	0	0
WIN2	Freon 11		0.1	0.12		0.056	0.14		0.042	0.11	0.15	0.05	0	0.17
WIN2	Freon 113		0.056	0.066		0.051	0.079		0	0.064	0.1	0.032	0	0.057
WIN2	Freon 114		0	0		0	0		0	0	0	0	0	0
WIN2	Heptane		0	0		0	0		0.26	0	0	0.23	0	0
WIN2	Hexachloro-1,3-butadiene		0	0		0	0		0	0	0	0	0	0
WIN2	Isopropyl alcohol		5.8	3.6		16	5.9		22	2.8	12	6.2	1	2.4
WIN2	m,p-Xylene		0	0		0	0		0.055	0	0	0.48	0	0
WIN2	Methyl chloride		0	0		0	0		0	0	0	0	0	0
WIN2	Methyl ethyl ketone		1.1	1		2.9	2.2		4.4	1.3	5.1	6.3	0	0
WIN2	Methyl isobutyl ketone		0	0		0.2	0		0.19	0.098	0.14	1.3	0	0
WIN2	Methyl t-butyl ether		0	0		0	0		0	0	0	0	0	0
WIN2	Methylene chloride		5.4	3.9		4.1	4.5		3.4	4.1	7	4.2	3.7	4.9
WIN2	n-Hexane		0.6	0.37		0.58	0.49		2.9	0.42	0.88	2.3	0.3	0.37
WIN2	o-Xylene		0	0		0	0		0	0	0	0.36	0	0
WIN2	Propene		0	0		0	0		0	0	0	0	0	0
WIN2	Styrene		0	0		0	0		0	0	0	0	0	0
WIN2	Tetrachloroethene		0	0		0	0		0.04	0	0	0	0	0
WIN2	Tetrahydrofuran		0.7	0.23		0.28	0.4		0.37	0.21	0.61	0.89	0.082	0

		Concentrations in Each House Corrected for Outdoor and Field Blank (ppb)												
Sampling Period	Analyte Name	H1	H2	H3	H4	H5	H6	H6D	H7	H8	H9	H10	FB	OUT
WIN2	Toluene		0.4	0.2		1.3	0.54		2.5	0.37	0.93	2.4	0	0
WIN2	Total Volatile Organics		11	13		24	17		37	14	27	48	4.6	3.5
WIN2	trans-1,2-Dichloroethene		0	0		0	0		0	0	0	0	0	0
WIN2	trans-1,3-Dichloropropene		0	0		0	0		0	0	0	0	0	0
WIN2	Trichloroethene		0	0		0	0		0	0	0	0	0	0
WIN2	Vinyl acetate		0	0		0	0		0	0	0	0	0	0
WIN2	Vinyl chloride		0	0		0	0		0	0	0	0	0	0

Nitrogen Dioxide

NO_2 was only sampled in one home with gas and one home without gas during each sampling period. Samples have been corrected for outdoor concentrations and the field blank as shown in Table K-5.

Table K-5

	Concentration (ppb)				Concentration Difference (ppb)			
Season	**GAS**		**NONE**		**Concentration Difference (ppb)**		**Percent Difference (%)**	
Status	**RTV**	**CEV**	**RTV**	**CEV**	**GAS**	**NONE**	**GAS**	**NONE**
N	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
	2.900	1.280	1.300	0.910	1.62	0.39	56%	30%
	8.100	7.000	5.600	8.400	1.10	-2.80	14%	-50%
	6.800	1.300	0.700	0.000	5.50	0.70	81%	100%
MIN	**2.900**	**1.280**	**0.700**	**0.000**	**1.10**	**-2.80**	**0.14**	**-0.50**
QUARTILE 1	**4.850**	**1.290**	**1.925**	**0.455**	**1.36**	**-1.21**	**0.35**	**-0.10**
MEDIAN	**6.800**	**1.300**	**3.150**	**0.910**	**1.62**	**0.39**	**0.56**	**0.30**
QUARTILE 3	**7.450**	**4.150**	**4.375**	**4.655**	**3.56**	**0.55**	**0.68**	**0.65**
MAX	**8.100**	**7.000**	**5.600**	**8.400**	**5.50**	**0.70**	**0.81**	**1.00**

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