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Ventilation Control of Volatile Organic Compounds in New U.S. Homes: Results of a Controlled Field Study in Nine Residential Units

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Environmental Energy Technologies Division

January 2013

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Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231, by the U.S. Dept. of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control through Interagency Agreement I-PHI-01070, by the U.S. Environmental Protection Agency Office of Air and Radiation through Interagency Agreement DW-89-92322201-0 and by the California Energy Commission through Contract 500-08-061.

We thank our colleagues who secured access and collected samples at several of the study sites. Kurt W. Roth and Peter Engelmann of Fraunhoffer Institute carried out the study protocol and collected samples in two study homes in Boston, MA. Ari Rapport of IBACOS provided access and managed sample collection at a study site in Pittsburgh, PA. Bud Offermann and Justin Offermann conducted the field study work at site H5 in California. We thank Doug Black and Doug Sullivan for providing inputs and resolving issues in the PFT calibration process, Elizabeth Heredia and Thuy Nguyen for assisting with PFT sample preparation and analysis, and Brennan Less for assisting with sample collections at several sites.

Abstract

In order to optimize strategies to remove airborne contaminants in residences, it is necessary to determine how contaminant concentrations respond to changes in the air exchange rate. The impact of air exchange rate on the indoor concentrations of 39 target volatile organic compounds (VOCs) was assessed by measuring air exchange rates and VOC concentrations at three ventilation settings in nine residences. Active sampling methods were used for VOC concentration measurements, and passive perfluorocarbon tracer gas emitters with active sampling were used to determine the overall air exchange rate corresponding to the VOC measurements at each ventilation setting. The concentration levels and emission rates of the target VOCs varied by as much as two orders of magnitude across sites. Aldehyde and terpene compounds were typically the chemical classes with highest concentrations, followed by alkanes, aromatics, and siloxanes. For each home, VOC concentrations tended to decrease as the air exchange rate was increased, however, measurement uncertainty was significant. The indoor concentration was inversely proportional to air exchange rate for most compounds. For a subset of compounds including formaldehyde, however, the indoor concentration exhibited a non-linear dependence on the timescale for air exchange.

Key Words

VOCs, residential, ventilation, formaldehyde

Implications

For VOCs with indoor sources, increasing air exchange rates reduces indoor concentrations. While the dependence of the concentration on the air exchange rate can be difficult to resolve using ventilation control in inhabited homes, it appears that this dependence does depend on the particular VOC. The reduction in concentration is proportional to the increase in ventilation for most target VOCs and less than proportional for other compounds such as formaldehyde.

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1. Introduction

Residential indoor air quality (IAQ) can be adversely affected by volatile organic compounds (VOCs) that are emitted by various sources in homes. The majority of existing homes do not currently meet health-based guidelines for formaldehyde chronic exposure levels and guidelines for other VOCs are exceeded in a non-negligible minority of homes (Logue et al. 2011). New homes typically have the highest concentrations of formaldehyde and other VOCs that are emitted from new building materials or new furnishings brought into the home (Dingle and Franklin 2002; Park and Ikeda 2006). Homes with lower outdoor air exchange rates, a condition that occurs when building envelopes are tightened to reduce uncontrolled infiltration, also typically have higher concentrations of VOCs from indoor sources (Salthammer et al. 1995).

Dilution and removal via ventilation is a straightforward and common approach to managing concentrations of pollutants from indoor sources. Historically, homes were leaky enough that the rate of infiltration of outdoor air (through cracks and other leakage pathways) was so large that there was no need to provide mechanical systems to ensure minimum air exchange rates. As envelopes have been tightened and sealed to reduce uncontrolled infiltration, the minimum outdoor air exchange rate has become a design element. Recent years have seen a substantial increase in airtight, energy-efficient homes. The typical energy efficiency rated home in California built since 2000 has about 3 air changes per hour measured at 50 Pa (ACH50), with the tightest homes having ACH50 values as low as 0.6 (Chan & Sherman 2011). During typical operation, the air exchange rates in these homes are 0.2 h^{-1} or less (assuming an indoor-outdoor pressure difference of 1 Pa, typical of observed conditions). These air exchange rates are regarded as too low. ASHRAE publishes a residential ventilation standard that aims to provide “acceptable” indoor air quality in residences. Standard 62.2 specifies overall mechanical ventilation rates as a function of the floor area and number of bedrooms (ASHRAE 2010). The calculation of the required mechanical ventilation rate in the 2010 standard includes an infiltration credit of 100 L/s per 100 m^2 (2 cfm per100 ft^2) of habitable space (equivalent to about 0.12-0.15 h^{-1}). This is significantly greater than the natural air exchange rate in tight homes (if air tightness is measured, a credit of up to half the measured infiltration can be used). The 2013 version of Standard 62.2, however, will follow Addendum R of the 2010 standard, which omits the automatic infiltration credit and requires higher fan flows, giving full credit for the measured infiltration rate (ASHRAE 2012). Typical homes have required mechanical ventilation rates equivalent to 0.1 to 0.2 air changes per hour. This mechanical ventilation requirement provides ventilation that is more consistent and often larger than the infiltration rate through modern building envelopes. Increasing the rate at which outdoor air is provided to a home can increase occupant exposure to contaminants with sources outside the home.

Managing VOC levels is an implicit objective of ventilation standards and it is commonly assumed that increasing the air exchange rate can be an effective measure to reduce in-home concentrations of VOCs that are emitted from materials already built into a home. The effect of ventilation on VOC concentrations in existing homes has been explored primarily through cross-sectional studies (Offermann 2009; Hun et al. 2010; Gilbert et al. 2008). The limitation to this approach is that large sample sizes are needed to identify an effect of ventilation since variations exist between homes in the emission rates resulting from homes having different mixes of materials and products. Emissions also vary with environmental factors including temperature, relative humidity and solar insolation. Gilbert et al. (2008) reported that ventilation effectively reduced formaldehyde concentrations based on individual measurements in 96 homes in Quebec City, Canada, but there was significant variability across homes. Field studies provide valuable information about exposure concentrations, but it is difficult to draw detailed conclusions regarding the emission mechanisms, given the range of factors that vary across sites.

To understand how formaldehyde emission depends on environmental factors, emissions from single materials have been measured under varied conditions in controlled, laboratory environments. Myers (1984) reviews a range of experimental studies that examined how formaldehyde concentration responds to changes in the air exchange rate of the chamber. However, homes contain a wide range of materials compared to chamber tests that evaluate only one material or a small collection of materials at a time. While lab experiments have been instrumental to understanding emission from a single material, it is very difficult to extrapolate from experimental studies what indoor VOC concentrations from building materials and furnishings are likely to be, due to the different varieties and quantities of VOC containing materials present in homes. There also can be substantial variations in how directly emitting materials are in contact with the mixing volume of air in the home. For example, materials contained within furniture or wall cavities may not have direct communication with indoor air.

A few studies have reported measurements of VOC concentrations in the same home operating at varied air exchange rates. Jewell (1980) sampled formaldehyde concentrations at 4 air exchange rates in a single mobile home. Moschandreas and Rector (1981) examined the impact of air exchange rate, temperature, and relative humidity on formaldehyde in one house. Singh et al. (1982) measured formaldehyde concentrations at two air exchange rates in each of 4 mobile homes. Hodgson et al. (2000) conducted a controlled study in which air exchange rates were varied in a single home and resulting VOC concentrations were measured. These limited data suggest that although increasing the air exchange rate generally reduces indoor VOC concentrations, the effectiveness of this strategy may depend on the compound. Specifically, the reduction in VOC concentrations may not be directly proportional to the increase in air exchange rate.

To understand the impacts of ventilation on indoor contaminant concentrations, mass balance models can be used to describe behavior under simplified conditions. The change in concentration, C, over time of an indoor contaminant in an enclosed space can be described:

$$\frac{dC}{dt} = \frac{EA}{V} + N_h \left(C_{out} - C \right) \tag{1}$$

where E is the emission rate in mass per unit floor area per unit time, A is the floor area, C_{out} is the concentration of the chemical in the outdoor air, V is the volume of the space and N_h is air exchange rate in air changes per hour. Assuming a static set of VOC sources over some period of time (e.g., unchanging set of materials and furnishings that emit the VOC) and that outdoor sources make a negligible contribution to indoor concentrations, the time-averaged indoor concentration should be inversely proportional to the time-averaged air exchange rate:

$$C = \frac{EA}{N_h V}, \tag{2}$$

Thus if the emission rate is constant, the reduction of the indoor concentration is proportional to the increase in air exchange rate from $N_{h,1}$ to $N_{h,2}$:

$$\frac{C_2}{C_1} = \frac{N_{h,1}}{N_{h,2}} . \tag{3}$$

This relationship is sometimes referred to as proportional reduction in concentration. For some compounds, however, it has been observed that the emission rate depends on the airborne concentration of the compound; this is due to sorptive partitioning of the compound between air and material surfaces within the space (Myers 1984; Sparks et al. 1996; Singer et al. 2004). In such cases, the relationship in Equation (3) does not hold. Because of possible dependence on the indoor concentration, the emission rates presented in this study calculated using Equation (2) or the analogous expression for the multi-zone case should be considered the effective emission rate.

This study, termed the Ventilation and Indoor Air Quality study (VIAQ), sought to examine the role of ventilation in controlling indoor pollutants by evaluating the impact of air exchange rate on chemicals concentrations and emission rates in relatively new U.S. homes. This study sought to answer the following research questions:

- To what extent does increasing the air exchange rate in new homes reduce pollutant concentrations in the short term, and thus help to mitigate residents' exposure?
- For which chemicals does increasing the air exchange rate result in proportional reductions of indoor chemical concentrations, and for which chemicals is the relationship not proportional?

The answers to these questions will allow us to address the basic research question: what are the optimal strategies for controlling VOC exposures in new or renovated homes? In this study, the impact of air exchange rate on indoor concentrations of VOCs was investigated in 9 residences. Using the installed ventilation systems as well as additional ventilation equipment where necessary, the protocol sought to establish three distinct air exchange rates with other environmental parameters consistent and measure the resulting indoor VOC concentrations in each one of a group of study homes. This controlled approach provides information about how VOC concentrations in real residences respond to changes in ventilation. Section 2 presents study protocols and methods, Section 3 discusses results, and Section 4 presents the conclusions. Tabulated data are provided in the Appendix.

2. Methods

The study was designed to assess the direct impact of varying ventilation on VOC concentrations in finished and furnished homes. The intent was to control other environmental variables to focus study on the effect of air exchange rate.

The study design required that we achieve and maintain three ventilation settings in each home. Air samples were collected for each ventilation setting after a pseudo-steady-state condition had been achieved. A pilot study was initially conducted to determine the time constant needed to achieve the steady state. During the pilot study, we also took samples at different times of day to check whether a diurnal pattern existed. Each site was visited at least four times. A few additional visits were needed for some study locations to enable installation of a supplemental ventilation system that met the operational requirements of our protocol. The study protocols and methods are outlined in Figure 1.

2.1. Study home recruitment

New homes with mechanical ventilation systems were targeted for this study. We conducted experiments on an opportunity-based sample (i.e., sites were selected based on availability) identified through several approaches. We conducted an initial set of pilot experiments at the Lawrence Berkeley National Laboratory (LBNL) guesthouse. Several teams in the Department of Energy's Building America program volunteered to identify suitable homes or test houses that could be used for the study. We also conducted outreach through professional networks and personal contacts of colleagues not directly involved in the research to identify homeowners that were interested and willing to have their homes used for this research project. Lastly, we contracted with the consulting firm Indoor Environmental Engineering (IEE-SF) to conduct additional outreach activities including placing flyers in newly constructed neighborhoods, and to contact participants of a previous study of indoor air quality in California new homes. Direct contacts were made only to homeowners that previously indicated willingness to be contacted about IAQ studies. Aside from the guesthouse experiments, only single-family detached homes were considered. A mix of occupied and unoccupied homes was sampled.

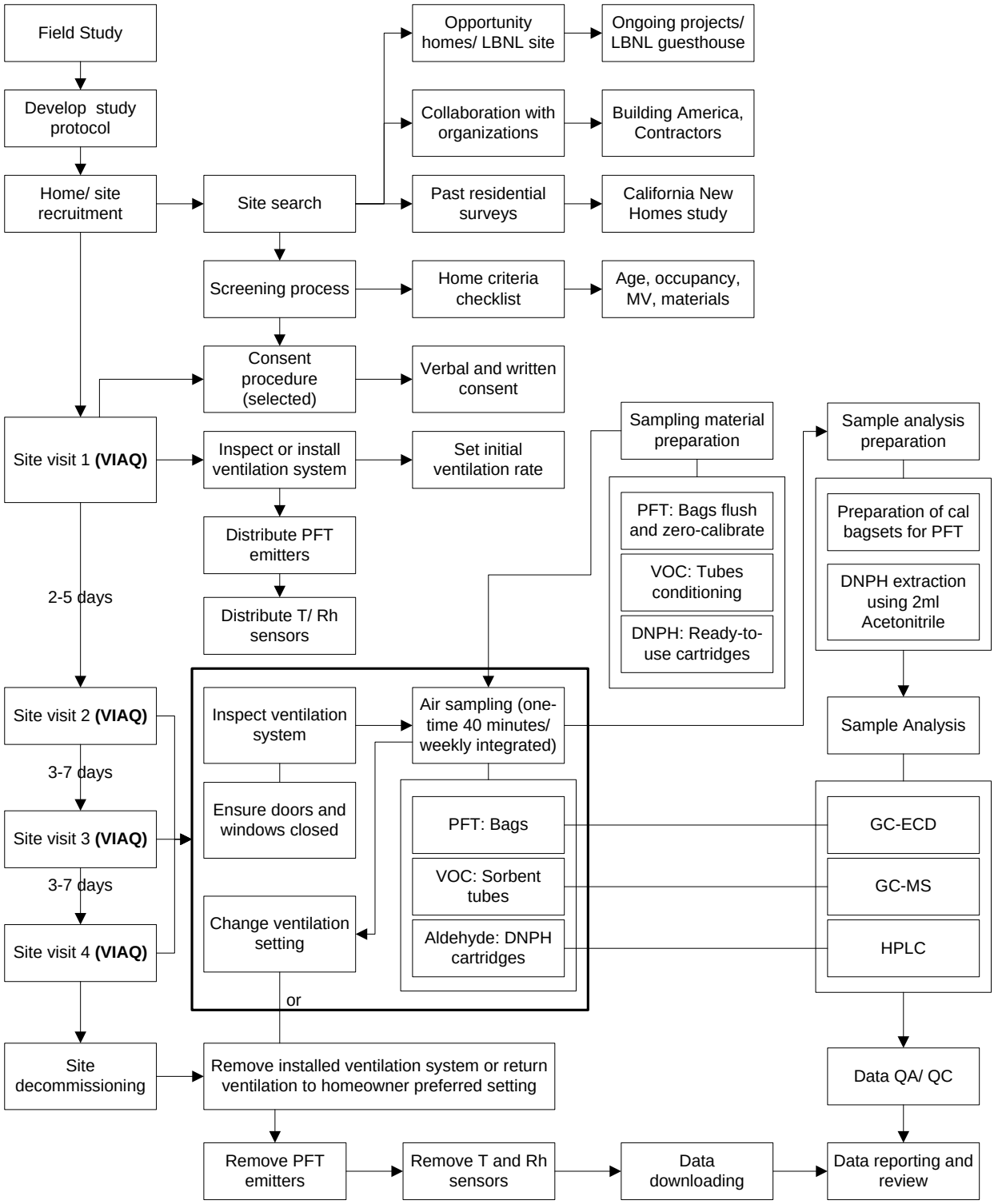

Figure 1 Flow chart of the protocols and methods for the field study.

VIAQ study homes were selected based on several target characteristics. The following basic criteria were used in the selection process:

- Age: 0.5 to 5.0 years, preferably 0.5 to 3.0 years.

- Airtightness: airtight, preferably with ACH_{50} of 5 or lower.
- Size: floor area of 80–300 m^2 (one selected home was slightly larger at 320 m^2).
- Furnishing: fully furnished at a level suitable for habitation.
- Mechanical ventilation: a central mechanical ventilation system and/or local exhausts for kitchen and bathroom that can provide ventilation corresponding to 0.8 air changes per hour preferred. (Alternatively, a window or other location to install a temporary, balanced ventilation system with homeowner's approval).
- Thermal control: thermostatically controlled with heating and/or cooling as needed for local climate.
- Location: at least 400 m away from major outdoor sources such as highways and industrial sites.
- Attached garage (if present): local exhaust or sealing treatments of shared surfaces between the living space and the garage.

2.2. Study homes

The general characteristics of the study locations are shown in Table 1. We selected six detached houses, hereafter labeled as H1, H4, and H6–H9. We also included two residential units, labeled as R2 and R3. R2 and R3 were identical, single-room guesthouse units, not typical full-scale homes. We ordered the study locations by whether they were generally inhabited (uninhabited to inhabited) followed by occupancy (unoccupied to occupied) during the measurement period. Another house, H5, which fulfilled all the selection criteria except for the home age, was included in the study because it was identified from a previous study as a home with high formaldehyde concentrations. All the study locations were located in California, Massachusetts, and Pennsylvania. Communications with the homeowners were initiated through professional contacts. The study protocols were described to homeowners and signed access agreements were obtained. Access was arranged on a schedule and with conditions agreeable to the homeowner. As a result, the study schedule varied somewhat from home to home. Special attention and flexibility in methods and schedules were applied for homes occupied during the study. Homeowners were provided with a small payment to recompense energy costs associated with operating our equipment and as a token of appreciation for their time and inconvenience in assisting the study. The guesthouse units were rented for a three-week period.

The houses were two-story except for H5, and one home (H7) had a finished basement and attic. Floor areas of the houses ranged from 140 to 320 m^2 and the guesthouse units were each 14 m^2. All study locations except H1 were generally being used for habitation; H1 was being used as a full-scale test house. The guesthouse is intermittently inhabited. Five study locations including H1 were not regularly occupied during the study and the other four were occupied during the study by the homeowners. All study locations were less than three years old when the study was conducted, except for H5, which was 7.5 years old. Given the home ages, the building and surface materials in the homes including the furniture and cabinetry were thought to be relatively new. Many of the homes were built using one or more categories of low-emitting materials.

Chronologically, we started the study in the two LBNL guesthouse units (R2 and R3). This was followed by two energy-efficient homes (H6 and H7) in the Boston, MA area. A recently rebuilt home in Berkeley, CA (H8) was subsequently recruited for the study. Then, we identified a study home (H1) in Pittsburgh, PA which was a full-scale test house made available as part of a collaboration with a Building America team. The rest of the study locations were in located in California, starting with a single-story home in Brentwood (H5), followed by a two-story home in Palo Alto (H4), and finally another two-story home with the largest floor area in our study in Dublin (H9).

Table 1 Summary of house characteristics and schedule.

ID	Generally in-use for habitation	Occupied during sampling	Age^ (yrs)	Floor area (m^2)	# of story	# of bedrooms / # of occupants	Air tight-ness (ACH_{50})	Low-emitting materials#	Ventilation system	Air distribution system	Study period
H1	No	No	2.0	195	2	4/ 0	1.2	1,3	ERV* with enthalpy wheel	Ducted exhaust	07-08/ 2011
R2	Yes	No	1.5	14	1	1/ 0	4.0	1,3,4	Added balanced system	Single supply & exhaust	12/2010
R3	Yes	No	1.5	14	1	1/ 0	4.0	1,3,4	Added balanced system	Single supply & exhaust	12/2010
H4	Yes	No	0.3	230	2	3/ 0	0.6	2,3,4	HRV**	Ducted supply	08/2011
H5	Yes	No	7.5	141	1	3/ 0	4.3	NA	Added balanced system	Ducted supply	07-08/ 2011
H6	Yes	Yes	0.8	146	2	3/ 4	1.0	2,3,4	ERV	Single supply	05/2011
H7	Yes	Yes	1.0	210	2	3/ 4	0.7	2,3,4	ERV	Ducted supply	05/2011
H8	Yes	Yes	2.5	150	2	3/ 3	1.0	3	ERV	Ducted supply	07/2011
H9	Yes	Yes	2.5	320	2	4/ 2	4.0	3	Added balanced system	Single supply & exhaust	09/ 2011

^Age of home when study was conducted; #1= Certified, low-emitting materials were used in construction, 2= Homeowners reported requesting that low-emitting materials were used in construction, however materials present were not confirmed, 3= Wet surface finishing product certified as low-emitting in accordance to CA Section 01350 requirements or equivalent low- or no-VOC standards, 4= Carpet materials and backing certified as low-emitting in accordance to CA Section 01350 requirements or CRI-certified low-emitting carpet and backing system; *ERV-Energy Recovery Ventilator; **HRV-Heat Recovery Ventilator

Additional details on the characteristics and ventilation systems in each home are provided below.

H1: This is a high performance home constructed with special features to improve energy efficiency that is instrumented and that was used by a Building America team for various energy-efficiency research studies. Air sampling was conducted between July and August 2011. It was fully furnished but not inhabited during the study period. All windows and external doors were closed. Internal doors were opened during air sampling. An ERV unit installed in the house was used to provide ventilation with a ducted air supply and return for each room.

R2 and R3: A pilot study was conducted at the LBNL guesthouse in December 2010. The facility is used as on-site accommodations for guest researchers. We conducted this experiment in two identical units of LBNL's guesthouse, R2 and R3, because they were accessible throughout the day over three weeks. The identical units had low-emitting materials and furnishings, and neither was inhabited during the sampling period. Baseline air sampling of aldehydes was carried out for both units prior to the study while an air leakage test was carried out in one unit. During the study, ventilation settings were achieved using two flow-calibrated, balanced ventilation systems designed and constructed specially for this study. Each unit had a window-installed system consisting of an intake fan and an exhaust fan with 15.2 cm diameter adjustable iris dampers for manual control of the ventilation rate.

H4: This home was the newest in the study, completed about four months prior to air sampling. It was constructed as an energy-efficient home with the intent to achieve the airtightness of a Passive House. Air sampling was conducted in August 2011 while the house was unoccupied. All windows were completely closed and all internal doors were opened. An HRV unit with smart control system provided ventilation.

H5: This home was first studied as part of the California New Homes Study (CNHS) (Offermann 2009). Offermann collected an air sample and found a formaldehyde concentration of 80 µg/m^3, twice the average concentration measured during the CNHS. Although this home was seven years old (i.e., older than the maximum target age of five years), it was selected because of the high formaldehyde concentration. There was no preference for low-emitting building materials in the construction of this home. The home has a direct outdoor air supply system. Since we were unsure of the system's performance in terms of providing sufficient outdoor air, we installed the temporary balanced ventilation system that was used in the guesthouse units. Experiments and measurements at this home were conducted by Indoor Environmental Engineering – the firm that conducted the CNHS – working as a subcontractor to LBNL. The study was conducted while the homeowner was away from the home on a pre-planned trip.

H6 and H7: Air sampling was conducted in both homes simultaneously for three weeks in May 2011. Both homes were occupied throughout the study period. To provide adequate ventilation, an ERV system was installed in each home at the time of construction. One of the homes, H7, had continuous ventilation and ducted outdoor air supply to each room, while H6 had intermittent ventilation and supply outdoor air ducted directly to the central floor and staircase. The owners of H6 did not routinely operate the system continuously, but agreed to have it operate in this manner for the duration of our study.

H8: This study location was a fully remodeled home. The home was built to meet stringent energy-efficiency requirements and was highly insulated and airtight. There was no preference for low-emitting materials in the house construction. A distinguishing feature of this newly remodeled home was that the bedrooms were located on the first floor, while the living room and kitchen were located on the second floor. The air sampling protocol was carried out at this site in July 2011. The home was occupied during the period of measurements. Ventilation was provided to each room of the house using fully ducted air supply from the ERV.

H9: Air sampling was conducted in this large, two-story home during August and September 2011. The home was occupied during the study. There was no dedicated outdoor air ventilation system in this house, but there was an exhaust fan in each bathroom. To achieve desired air exchange rates, we installed two balanced ventilation systems, one on each floor. There was no preference for low-emitting materials in the house construction.

2.3. Study protocols

The recruited study locations varied in terms of baseline air exchange rates and air tightness. To investigate the effect of ventilation on indoor VOC concentrations, the study was designed around the objective of varying outdoor air exchange rate while keeping constant or nearly constant all other parameters that impact indoor VOC emissions. The objective was to achieve three distinct air exchange rates in each home, targeted at roughly 0.2, 0.4 and 0.8 air changes per hour. In seeking to maintain the consistency of other influencing parameters, we recognized up front that external factors such as daily weather variations, windows opening, and residents' activities in the occupied homes would introduce some variance to the air exchange rates and air flow profiles. The building owners agreed not to open their windows from the night before through the scheduled air sampling session. Thermostatic control was set at 72±2°F during the study period. The indoor sources of chemical emissions and the number of people living in each home were the same throughout the experiment. The guesthouse units (R2 and R3) were studied in December 2010 and the houses (H1, H4-H9) were studied between May and September of 2011.

After getting verbal consent for access from the building owners or operators, a researcher would arrange for a site visit. The purpose of this visit was to:

- Obtain written consent for permission to be on premises and to use the building for research.

- Inspect the existing mechanical ventilation system or install a balanced ventilation system.
- Perform SF_6 tracer gas measurements to estimate the range of possible air exchange rates.
- Distribute the perfluorocarbon tracer emitters/vials in the house.

Before leaving, the researcher would set the ventilation setting and ensure that all windows and doors were tightly closed (in case of unoccupied homes) or request that the occupants close them the day before the scheduled air sampling session.

Table 2 Ventilation settings of nine study locations.

ID	Ventilation setting 1	Ventilation setting 2	Ventilation setting 3
	(day # from beginning of experiment/ number of days the setting was kept)		
H1	Medium (1/3)	Low (15/3)	High (43/3)
R2	Low (1/5)	Medium (6/6)	High (12/5)
R3	Low (1/8)	High (9/4)	Medium (13/5)
H4	Low (1/3)	Medium (4/2)	High (6/2)
H5	Low (1/5)	Medium (6/5)	High (11/5)
H6	High (1/7)	Low (8/7)	Medium (15/7)
H7	Medium (1/7)	Low (8/7)	High (15/7)
H8	Medium (1/5)	High (6/2)	Low (8/2)
H9	Low (1/4)	Medium (5/3)	High (8/3)

To achieve and maintain three ventilation levels, a sizeable mechanical ventilation system was required in each home. In homes with an existing ERV or HRV system, the ventilation settings were obtained by adjusting the flow rate to achieve medium and high ventilation settings, and by turning off the system to achieve the low ventilation setting. A balanced ventilation system was installed in homes or locations without a dedicated outdoor air mechanical ventilation system. Once the ventilation setting was established, the condition was maintained for a period of at least two days to establish a pseudo-steady-state condition and the indoor air quality measurements were carried out at the end of this period. Following these measurements, the ventilation setting was modified and again maintained for at least two days. We attempted to randomize the order of ventilation settings across the sample of homes. In homes to which the homeowners allowed only limited access, we started with the pre-existing setting; this was typically the low ventilation setting. Table 2 lists the ventilation settings in each home and the number of days each condition was maintained. The following discussion for each home was arranged in chronological order from the first to last VIAQ study locations.

During site visits 2-4, the researcher repeated the following steps:

- Check all windows and exteriors to note whether they were completely closed upon arrival.
- Inspect the ventilation setting of the whole-house ventilation system or the damper setting of the balanced ventilation system.
- Conduct air sampling for VOCs, aldehydes, and perfluorocarbon tracer gases (PFTs), according to the sampling methods and plan shown in Table 3.
- After sampling was completed, change the ventilation setting to the next setting by adjusting the supply and exhaust air dampers of the added ventilation system or by using the fan speed controller on the mechanical ventilation unit to obtain the desired flow setting.
- For the last visit (Visit 4), remove the added ventilation system, if any, or return the ventilation system to the pre-existing condition or other setting of the homeowner's choice. The researcher collected all air sampling equipment, PFT emitters/vials, and temperature and relative humidity (RH) sensors from the site.

Table 3 Air sampling methods and plan of nine study locations

ID	Air sampling method of the target samples					
	VOCs		Aldehydes		PFTs	
	Active 40 minutes	Active 24-hour	Active 40 minutes	Active 24-hour	Automated bag sampling	Syringe/ pump bag sampling
H1	✓	-	✓	-	-	✓
R2	✓	-	✓	-	✓	-
R3	✓	-	✓	-	✓	-
H4	✓	-	✓	-	-	✓
H5	-	✓	-	✓	-	✓
H6	✓	-	✓	-	✓	-
H7	✓	-	✓	-	✓	-
H8	✓	-	✓	-	-	✓
H9	✓	-	✓	-	-	✓

Details of the procedure specific to each site are provided below.

H1: This house was only accessible once every two weeks because of an ongoing energy monitoring study. Each ventilation setting was maintained for three consecutive days and the supply and return airflow rate through the ERV was monitored continuously. The ERV fan speed was adjusted two days before each sampling event and then the setting was returned to the initial setting (used for energy monitoring study) after each air sampling session. Ventilation settings and sample collection were conducted by IBACOS, the Building America team operated the house for energy monitoring.

R2 & R3: This study started with an intensive, three-week pilot in R2 and R3 to assess the response time of indoor contaminant concentrations following changes to the air exchange rate. A preliminary measurement of the air exchange rate using sulfur hexafluoride (SF_6) tracer decay method was carried out to determine the ventilation system settings required for the actual study. The ventilation settings were achieved using the balanced ventilation system designed and used as a supplemental system for several study sites. We collected air samples in both units at 6 AM, 4 PM, and 10 PM each day for the first week and thereafter at 4 PM and 10 PM each day for two consecutive weeks. Under all test conditions, a slight positive pressure differential between the room and outside was maintained in both units. All activities and measurements at this site were conducted by LBNL researchers.

H4: We used the minimum and maximum settings on the HRV under fresh air mode (no recirculation) to maintain medium and high ventilation settings. For the low ventilation setting, the system was turned off to get to the lowest possible ventilation settings. At this house, there was a one-week time frame to complete the study, so the higher ventilation settings were each maintained for two days rather than three. The air sampling session was carried out once at the end of each ventilation condition. Measurements at this site were conducted by LBNL researchers.

H5: A more intensive sampling study was conducted at H5. We installed a balanced ventilation system in this house to achieve medium and high ventilation settings. The low setting was achieved by turning off the ventilation system and keeping all the exterior doors and windows closed. Each ventilation setting was maintained for five consecutive days. A daily 24-hour air sampling protocol was used to collect air samples over days 3-5 during each ventilation setting. The study protocol at this site was carried out by Indoor Environmental Engineering (IEE).

H6 & H7: Air sampling in H6 and H7 was conducted once every week during the afternoon. In H6, the homeowner objected to the noise when the ventilation system was set to maximum. Therefore, the experimental protocol was modified to use three levels suitable for an occupied home with a field-sampling schedule that could be achieved by the research team. The ventilation setting was changed every Friday, and this setting was maintained for one week. In H7, we achieved three ventilation settings by adjusting the ERV fan speed each week. One of the Building America teams, Fraunhoffer Institute, carried out the study in both homes.

H8: In H8, the window of time provided by the homeowner to complete the study protocol was relatively short (nine days). Air sampling was carried out once at the end of each ventilation setting. We achieved three ventilation settings by adjusting the ERV fan speed. H8 was the only home for which windows were observed to be open when researchers arrived to collect samples. Measurements at this site were conducted by LBNL researchers.

H9: In H9, we repeated the same protocol used in H4. We used two of the balanced ventilation systems (one on each floor) to increase air exchange rates because there was no dedicated mechanical ventilation system in this home. Our initial measurements suggested it was difficult to maintain three distinct air exchange rates. Thus, for the lowest ventilation setting the ventilation systems were turned off, and external doors and windows were closed. We then turned on the systems and adjusted the supply air dampers to obtain both medium and high ventilation settings. Each ventilation setting was maintained for at least three consecutive days, and air sampling was conducted at the end of each setting. Measurements at this site were conducted by LBNL researchers.

2.4. Ventilation measurements

The air exchange rate was determined by measuring concentrations of PFTs released from passive emitters deployed throughout the homes. Emission rates were determined by measuring the change in mass of the emitters. Active sampling methods were used to collect air samples containing PFT tracers into sets of bags. The active methods included two key elements: distribution of emitters and collection of air samples. The emitters were 2-dram glass vials sealed with a polyvinyl chloride (PVC) cap and a septum layer on the top. Each vial was filled with either perfluorodimethylcyclobutane (PDCB) or perfluoromethylcyclohexane (PMCH). All vials were weighed daily over three to five days using a micro scale to determine the emission rate. Only vials with less than ±3% daily variation were selected for site deployment. Because the tracers were not emitted by other indoor sources, and concentrations in outdoor air were exceedingly low, air exchange rates could be determined from measured indoor concentrations and known emission rates of the vials. Selected vials were placed in transparent casings, which were opened at both ends. When in use, the vials (in their casings) were inverted (cap and septum facing downward) and suspended on the wall or secured on a vertical structure to ensure continuous and consistent emission.

2.4.1. PFT sampling

Table 4 shows the allocation of PFT emitters within the nine VIAQ study locations, by zone. The table also includes the measured emission rates by zone. Each zone represented a level in the house, where Zone 1 was the first level of the house and Zone 2 was the second level. In H7, Zone 1 included the first floor and the finished basement, and Zone 2 included the second level and the finished attic. All PFT emitters were deployed in the residential units at least two days before the sampling events. An emitter was placed every 30-50 m^2 of floor area or at least one emitter in each main room of the house. The area-specific emission rates were in the range of 19.4 - 37.3 $\mu g\ m^{-2}\ h^{-1}$ for the single-family homes. The emission rates per square meter were much higher in the two guesthouse units due to smaller floor area, despite only two vials used in each unit.

Table 4 PFT distributions, emission rates, and area-specific emission by zones

ID	Number of zones	Zone 1 PFT	Zone 2 PFT	Zone 1 volume (m^3)	Zone 2 volume (m^3)	PFT emission rate in Zone 1 ($\mu g\ h^{-1}$)	PFT emission rate in Zone 2 ($\mu g\ h^{-1}$)	Area-specific PFT emission rate in Zone 1 ($\mu g\ m^{-2}\ h^{-1}$)	Area-specific PFT emission rate in Zone 2 ($\mu g\ m^{-2}\ h^{-1}$)
H1	2	PDCB^	PMCH#	194	194	2044	1534	29.2	21.9
R2	1	PMCH		34		1016		72.6	
R3	1	PDCB		34		1335		95.4	
H4	2	PMCH	PDCB	292	269	1828	2677	27.0	19.6
H5	1	PDCB & PMCH		464		3625	2857	25.3	19.4
H6	2	PMCH	PDCB	180	180	2099	2551	30.0	36.4
	1	HB*		360		3458		23.7	
H7	2	PMCH	PDCB	260	260	2257	2613	32.2	37.3
	1	HB		520		3338		15.9	
H8	2	PDCB	PMCH	174	256	2203	1704	36.7	19.4
H9	2	PMCH	PDCB	512	395	2642	3462	21.1	24.0

^PDCB: perfluorodimethylcyclobutane (CAS: 2994-71-0) MW: 300 g mol^{-1}; #PMCH: perfluoromethylcyclohexane (CAS: 355-02-2) MW: 350 g mol^{-1}; *HB: hexafluorobenzene (CAS: 392-56-3) MW: 186 g mol^{-1}

Emitters were secured with zip ties or taped to interior walls, cabinet surfaces, handles, or table legs. Because temperature affected emission from the vial, we avoided placing the vials near any heat sources. Some emitters were suspended from smoke detectors, chandeliers, or other structures on the ceiling. Wall attachment was designed such that the emitters were at least 5 cm away from the surfaces, to avoid the influence of the wall boundary layer. Room temperature variation was minimized through thermostatic control in each residential unit. Two temperature sensors were placed in each zone of the residential units next to a PFT emitter to record air temperatures and the total emission rates were corrected for temperature variation, if any.

Several methods were used to collect air samples to determine PFT concentrations; all involved filling bags. The first method included a programmable and automated air sampling system consisting of a pump (ACI Medical 100 series, operating on 12 volts) connected to multichannel valves. The system was developed to collect air samples at a pre-determined time and duration and was capable of filling 15 0.3 liter Tedlar bags (15 channels) contiguously for each sampling cycle. In R2 and R3 as well as H6 and H7, the sampling system was used to collect air samples over a 40-minute period every two hours. Six air samples were collected each day, plus another empty bag as travel blank control, over the duration of the study. At these study locations, one sampling location near the center of a room was selected in each zone. Sets of seven bags were conditioned before each sampling day. The following steps were followed to condition each air bag. Leftover air inside the bag was removed. The bag was flushed twice by filling it with clean air then removing the air. The bag was filled with air for a third time, and this time it was left overnight. The next day, air was removed from the bag, and it was again flushed with clean air twice. As quality control, we randomly selected 25% of the conditioned air bags, filled them with clean air, and ran the PFT quantification method.

The air sampling in H1, H4, H8, and H9 was carried out manually. Samples were collected only one time when the indoor chemical samples were collected, or once for each ventilation setting. A manual pump sampling system was used in H4 and H9. The pump was connected to a controller and a single-channel valve. Air was immediately drawn into a bag by turning on the pump for several seconds until it was filled. In H1 and H8, the pump was replaced by a hand-operated syringe pump. About 8-10 draws were needed to fill a bag using this method. At these study locations, we collected air samples from three

locations in each zone, plus a travel blank. A 24-hour air sampling protocol was conducted in H5 using a low-flow air pump, in conjunction with the sampling protocol of the indoor chemicals. Air was drawn into 10 liter Tedlar bags at approximately 5 mL/min. Sampling was carried out for three consecutive days during each ventilation setting. We then transferred the air collected in the large Tedlar bag to 0.3 L bags in the laboratory prior to the analysis.

2.4.2. PFT sample analysis

Each set of PFT samples was analyzed using an Agilent 6890N dual-column; dual-detector gas chromatograph (GC) equipped with model G2397A electron capture detectors (ECD). A column and ECD pair was dedicated to the separation and detection of PDCB and PMCH. The GC was calibrated using 12 PFT standards, ranging from 0.79 to 15.1 ppb for PDCB and from 0.61 to 11.4 ppb for PMCH. These standards were clean Tedlar bags filled with a diluted gas mixture from a calibrated gas cylinder. A calibration curve was developed for each PFT and used to determine the PFT concentration. The calibration generally took place after the GC-ECD system was re-started for a new batch of bag analysis. Analysis of dilutions of calibration standards below 0.05 ppb was not shown to be reliable in the past. Thus, the value of 0.05 ppb has been considered as the quantitation limit. The total run time for each sample was 1.5 minutes. Sample introduction was done using a Valco valve equipped with a 0.25 mL sample loop. The PFT analyses were performed with the oven set isothermal at 180 °C and ECD temperature set at 300 °C, with P5 (5% methane / 95% argon) as carrier gas and makeup gas flow to the detectors. Chromatographic resolution of the analytes was achieved using a 30 m x 0.53 mm id megabore Alumina porous layer open tubular column (J&W Scientific).

2.5. VOC measurements

Volatile organic compounds were sampled onto Tenax TA (P/N 16251, Chrompack, The Netherlands). The media was compacted in glass tubes and capped with Teflon-lined PVC caps. Before use, the tubes were conditioned by helium purge at 275 °C for 60 minutes at a rate of 10 mL/min. A stainless steel thermal desorption (TD) tube (0.6 cm OD × 17.5 cm L) containing a sorbent bed consisting of two parts (v/v) CarboPack-B 60/80 mesh backed with one part CarboPack-X 60/80 (Supelco) was placed side-by-side with a Tenax Carbosieve tube during each sampling event. The tubes were conditioned prior to each use by helium purge (~ 30 cc/min) for one hour at 315 °C in batches of 10 tubes. Conditioned tubes (analytical blanks) are routinely analyzed to confirm background contamination below method quantification limits.

A peristaltic pump was used to draw the air through the sampling media with target sampling flow rate at approximately 100 mL/min for 40 minutes. Before the start of sampling, the airflow rates through each sampling line were measured and adjusted to the target flow rate. Actual airflow rates were recorded on a sampling record sheet once at the start of each sampling event and once towards the end of each sampling event.

Sampling locations are listed in Table 5. The frequency and the number of samples collected varied among the study locations. At the very least, there was one indoor sample, one outdoor (or representative) sample, and one travel blank for each study location at each ventilation setting. One of these three locations was randomly selected for duplicate sampling during each site visit. All samples were sealed using the Teflon-lined caps, transported to the laboratory, and kept in a sample storage refrigerator. These samples were analyzed within 48 hours of sampling.

Table 5 Air sampling locations and schedule

ID	1st sampling location	2nd sampling location	3rd sampling location	Sampling plan during each ventilation setting
H1	Living room	Main bedroom	Outdoor	One sampling on the last day of each setting
R2	Center of room	*No sample*	*No sample*[#]	Daily sampling for 18 consecutive days; sampling time: 6AM, 4PM, 10PM
R3	Center of room	*No sample*	*No sample*[#]	Daily sampling for 18 consecutive days; sampling time: 6AM, 4PM, 10PM
H4	Living room	Child bedroom	Outdoor	One sampling on the last day of each setting
H5	Hallway	Main bedroom	Outdoor	Daily sampling for 3 consecutive days after each ventilation setting was set, each sampling lasted 24 hours
H6	Living room	Hallway	Outdoor	One sampling on the last day of each setting
H7	Living room	Hallway	Outdoor	One sampling on the last day of each setting
H8	Bedroom 1	*No sample*	Outdoor	One sampling on the last day of each setting
H9	Multi-use room	Loft	Outdoor	One sampling on the last day of each setting

[#]Outdoor VOCs were removed from the incoming air, outdoor samples not required.

Thirty-nine target analytes (VOCs) were selected for analysis. These were representative of the major chemical classes of compounds found in indoor air, indicative of specific indoor sources, or of interest because they have been identified as health hazards. The list includes 25 target chemicals considered by the California Department of Public Health (CDPH) for evaluation of acceptable emissions from indoor materials (California Department of Public Health, 2010).

The analytical method for VOC samples has been described in various publications (Hodgson 2000; Singer et al. 2004; Singer et al. 2005). The following describes in detail the analytical methods and instrumentation for the TD tubes. Tubes were thermally desorbed and focused using a thermodesorption auto-sampler (Model TDSA2; Gerstel), a thermodesorption oven (Model TDS3, Gerstel), and a cooled injection system (Model CIS4; Gerstel). The cooled injection system was fitted with Tenax TA-filled glass liner. Tubes were desorbed at 20 mL/min (solvent vent mode) at a starting temperature of 25 ^{o}C with a 0.5-minute delay followed by a 60 ^{o}C/min ramp to 330 ^{o}C and a 1-minute hold time with the transfer line temperature at 275 ^{o}C. The cryogenic inlet was held at 1 ^{o}C throughout desorption, then heated within 0.1 minutes to 330 ^{o}C at a rate of 12 ^{o}C/s and held for two minutes. Injection flow was set to 1.2 mL/min from 0.0 (start of injection) to 2.25 minutes when the vent flow was returned to 20 mL/min. Compounds were resolved on a GC (Series 6890Plus; Agilent Technologies) equipped with a 30-meter-long by 0.25-mm-diameter J&W DB-1701 capillary column with 0.25 mm film thickness. The initial oven temperature was 1 ^{o}C, held for 2 minutes, then ramped to 40 ^{o}C at 5 ^{o}C/min, to 140 ^{o}C at 3 ^{o}C/min, then to 250 ^{o}C at 10 ^{o}C/min and held for 10 minutes. The helium flow through the column was constant at 1.2 mL/min (initial pressure 47.4 kPa, 39 cm/sec). The resolved analytes were detected using electron impact MS (5973; Agilent Technologies) operated in total ion current (TIC) with the target and qualifier ions specified for each target compound. The MS temperature settings were 240 ^{o}C, 230 ^{o}C, and 150 ^{o}C for the transfer line, MS source, and MS quad, respectively. A gaseous internal standard (ISTD) was added to each sample tube by syringe prior to analysis then an additional helium flow was passed through the tube for three minutes. The ISTD was 180 nanograms (ng) of 1-bromo-4-fluorobenzene (BFB) prepared continuously in a diffusion oven. The ISTD was used to check on the operation of the system, to provide a retention-time marker, and to enable quantitative analysis. Target compounds were quantified by a multi-point calibration prepared with pure standards and normalized to the ISTD. The TIC chromatogram for a sample was integrated over a retention time range using parameters that captured most of the chromatographic response. The mass of the compounds represented by the sum of the TIC area was calculated relative to the amount and area response of the internal standard.

2.6. Aldehyde measurements

Target aldehydes with low molecular weight - formaldehyde, and acetaldehyde - were actively sampled onto silica gel cartridges coated with 2,4-dinitrophenylhydrazine (DNPH XPoSure Aldehyde Sampler P/N WAT047205; Waters corporation) with ozone scrubbers installed upstream (P/N WAT054420; Waters). A peristaltic pump was used to draw the air through the sampling media with a target sampling flow rate of approximately 1000 mL/min. Before the start of sampling, the airflow rates through each sampling line were measured using a BIOS flow meter (S/N 118925) and adjusted to the target flow rate. Actual airflow rates were recorded on a sampling record sheet once at the start and once towards the end of each sampling period. Sampling was carried out for 40 minutes at three locations (two indoor and one outdoor). The sampling locations were the same as the VOC sampling locations (see Table 5). The frequency and the number of samples collected varied among the study locations. The following samplers were collected during each period: one indoor sample, one outdoor (or representative) sample, and one travel blank for each study location at each ventilation setting.

The DNPH-coated cartridges were analyzed for the target aldehydes following ASTM Method D5197-92. Each cartridge was eluted with 2 mL of high purity acetonitrile and analyzed by high-performance liquid chromatography (HPLC; 1200 Series; Agilent Technologies). The HPLC was fitted with a C18 reverse phase column and run with 65:35 H_2O: acetonitrile mobile phase at 0.35 mL/minute with UV detection at 360 nm. Multipoint calibration standards prepared from hydrazone derivatives of the target analytes were used for quantification.

2.7. Quality assurance

Travel blanks were transported, stored, and analyzed along with all other samples from the same sampling event. To avoid contamination, blanks and PFT samples were not transported and stored in the same shipment or storage location as the PFT emitters. We collected 10% additional samples as duplicates with at least one sample for each ventilation setting. Start and stop sampling flow rates and the total sampling duration were recorded for each sample and average sampling flow rates were used in the calculation of concentrations.

All samples were quantified with multipoint calibration curves prepared from pure chemicals. The quantitation limit for PFT samples was 0.05 ppb. The method detection limit (MDL) for the aldehydes was determined to be 0.3 µg m^{-3}. MDLs for target VOCs were in the range of 0.1 to 0.4 µg m^{-3}. Analytical blanks were included in all analysis runs. Analysis results were corrected for the travel blank for each batch of samples.

To evaluate the accuracy of air exchange rates determined by different PFTs, we introduced a known amount of PMCH and PDCB at constant emission rate into a test chamber with known volume and constant airflow rate. The analysis results of each PFT revealed different air exchange rates in the chamber, suggesting an error in the quantification process. Systematic investigation was conducted to determine the source of this error. It was determined that the concentrations of the PFTs in the primary calibration cylinder needed to be checked and calibrated. Bag sets with precise concentrations were obtained from Lagus Applied Technologies (Escondido, California, www.tracergas.com). The analysis results showed that the concentration of the PMCH in the calibration cylinder was correct; however, the concentration of PDCB was 77% of the concentration used in the generation of the calibration standards. All PDCB concentration data obtained using this primary calibration cylinder were corrected for this error. Estimates of uncertainty in the PFT emission rates and PFT concentrations are discussed in Section 2.11.

2.8. Data analysis

2.8.1. Determination of air exchange rates

The total emission rates from PFT emitters and the average measured concentrations of PFTs in the homes were used to determine the whole-house air exchange rates. Homes with one level were treated as a single well-mixed zone and only one PFT was used. For homes with two zones, two PFTs were used and the two-zone model was used to solve for the air exchange rates between zones and across the house envelope of each zone.

Equation (4) is derived from a single zone mass-balance model and is used to determine the hourly air exchange rate *(N_h)* under the pseudo-steady-state condition that is assumed to have occurred in the homes maintained at a consistent ventilation condition (at least on the day that measurements were made, with windows closed in all homes but H8).

$$N_h = \frac{E_{PFT}}{C_{PFT} V} \tag{4}$$

In this equation, E_{PFT} is the total PFT emission rate (µg h^{-1}), C_{PFT} is the average PFT concentration in the home (µg m^{-3}), and V is the effective house volume (m^3). For multi-story homes with two zones, a set of different equations, which can be found in previous references (Dietz & Cote 1982; Shinohara et al. 2010), was used to solve for the air exchange rates between zones and across the house envelope of each zone. This involves solving a set of 6 equations resulting from applying a mass balance with regard to the PFT mass and the total airflow for Zone 1, Zone 2 and the combined zones. The total air exchange rate was determined from the sum of the air infiltration rates calculated for both zones:

$$N_h = \frac{C_{1B}E_A - C_{2B}E_A - C_{1A}E_B + C_{2A}E_B}{C_{1B}C_{2A} - C_{1A}C_{2B}} \left(\frac{1}{V_1 + V_2} \right) \tag{5}$$

where 1 and 2 refer to levels 1 and 2, and A & B refer to the PFTs released. Due to uncertainty in the measured quantities and model assumptions, it is possible that the calculated inter-zone flows can be negative. If flows are not constrained to be greater than zero, non-physical flows can result, due to the terms in the PFT mass balance that include the product of PFT concentrations and inter-zone flow rates. I.e., if the term representing flow from Zone 1 to the outside is negative, then that term describes a flow of air with the concentration of Zone 1 flowing in from the outside, which is not physically possible if the concentration in Zone 1 is different than that outside. The equation above does not, however, constrain all inter-zone flows to be greater than zero as stated in Shinohara et al. (2010). By constraining flows to be greater than zero, all flows are physically realistic, but the set of 6 equations may then not have an exact solution, and the solution must be found by minimizing residuals from the system equations. With this approach, the resulting air exchange rates can be slightly different due to this assumption. Using this limitation of physically meaningful flows yielded total air exchange rates that were typically within 20% of the results obtained with Equation (5), as shown in Figure 2. If the ratio on the y-axis is 1, then the two approaches for calculating the air exchange rate in a two zone space are equivalent. The air exchange rates show throughout this report for two-zone homes are those calculated using Equation (5).

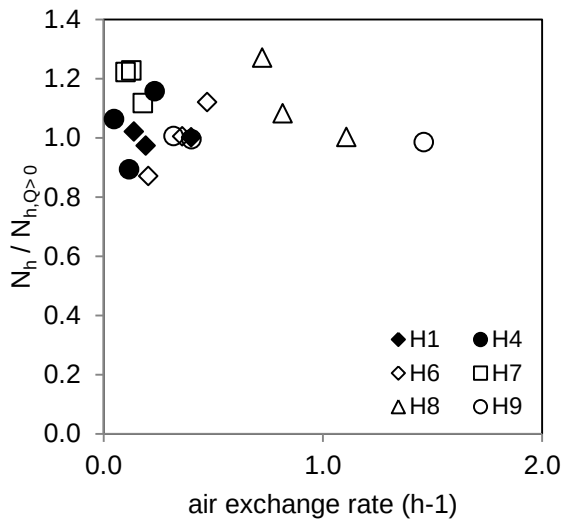

Figure 2 The ratio of the air exchange rate N_h for two-zone homes using Equation (5) to the air exchange rate from constraining inter-zone flows to be positive $N_{h,Q>0}$

PFT concentrations in H1, H4, H8, and H9 showed some locations with substantial deviation from the average concentration (±40%). These were mostly in occupied homes. On the other hand, time-resolved data from R2 and R3 and H6 and H7 showed less variation (±15%). To determine the air exchange rates, we used PFT concentrations sampled over 40 minutes, corresponding to the VOCs and aldehydes sampling.

2.8.2. Calculation of VOC emission rates

The emission rate of each target compound was calculated based on the total air infiltration rate or the whole-house air exchange rate determined using the method described in the previous subsection. We used the steady-state equation that assumes ideal well-mixed zone(s) to calculate the emission rates:

$$E = \frac{VN_h}{A}\left(C - C_{out}\right) \tag{6}$$

where E is the emission rate of target compound (µg m^{-2} h^{-1}); C is the average measured indoor concentration of the target chemical (µg m^{-3}); C_{out} is the measured outdoor concentration of the target chemical (µg m^{-3}); and A is the effective floor area of the house (m^2).

2.9. Uncertainty

In all of the measured quantities in this study, there is some degree of uncertainty. In order to estimate the uncertainty in the air exchange rates and emission rates introduced above, it is necessary to first discuss the uncertainty in the estimated PFT emission rate, measured PFT concentration values, measured VOC concentration values and the mixing volume in each zone and overall in each home:

- The relative uncertainty in the PFT emission rate $u(E_{PFT})/E_{PFT}$ is estimated to be approximately 15% for PFT emitters. In this study, the vial temperature was not controlled. The temperature at the emitter locations was recorded and emission rates were adjusted accordingly, but uncertainty in the temperature or local ventilation variation can alter emission rates further. Thus, there is bias error in the emission rate when comparing measurements at the same site, however there is also uncertainty because the emission rate may vary from the measured value. Here, we assume 10% bias error and 5% random error in the emission rate. PFT emission rates vary approximately 4%

for each degree change in temperature, and up to 6% when exposed directly to fans (Lunden et al. 2012). The PFT emission rate is measured only once at each site and corrected for any measured temperature fluctuations.

- $u(C_{PFT})/C_{PFT}$ is approximately 10%. This includes bias in the calibration and measurement uncertainty. Because calibration error can occur whenever the GC-ECD is recalibrated, this error cannot be assumed to have the same sign for all samples and thus is not treated as a bias error in the uncertainty analysis. When two different PFTs were emitted in the single zone of H5, the calculated air exchange rates from the two PFTs were 8% different.
- u(C)/C is approximately 27% for VOC measurements. The uncertainty resulting from the GC/MS process used is expected to be approximately 10% for values not near the detection limit. Comparison of replicate samples shows that concentrations of individual VOCs determined from one sample bag were offset by 15-30% when compared to the same VOCs determined from a replicate sample bag at the same location. Pairwise comparisons of individual VOCs in replicate bags varied around this offset. The offset could result from error in some parameter recorded or set for one or both samples, e.g., sampling flow rate or sample volume, leakage at connections during sampling, application of the general standard or mechanical problems during the GC/MS analysis. The relative uncertainty of 27% for VOC concentrations is based on the 68% quantile (σ) of the difference between replicate samples, using only replicates with concentration greater than 5 $\mu g\ m^{-3}$ (at least 10 times the detection limit). For replicate samples between 1 and 10 times the detection level, the relative uncertainty increases to 34%. For some calculations, the value of C used is an average of multiple measurements, which decreases the uncertainty slightly. For the low-weight aldehydes, however, the sampling procedure was less susceptible to error and the replicate samples agreed to within 4%, based on the 68% quantile for values at least 10 times the detection limit.
- u(V)/V is thought to be approximately 20%, due to irregularities in ceiling height. Partially connected spaces can also alter the effective volume. Similarly, the relative uncertainty in the floor area u(A)/A is also estimated to be 20%. The uncertainty in V and A are bias errors.

In addition to the calculated values, it is useful to have estimates of the uncertainty of these quantities. Assuming error contributions are uncorrelated, the total error in the air exchange rate for a single zone space is:

$$\frac{u(N_h)}{N_h} = \sqrt{\left(\frac{u(E_{PFT})}{E_{PFT}}\right)^2 + \left(\frac{u(C_{PFT})}{C_{PFT}}\right)^2 + \left(\frac{u(V)}{V}\right)^2}, \tag{7}$$

where the uncertainty of the terms on the right hand side are discussed above in Section 2.8. Assuming the uncertainty in the concentration measurements and emission rates is uncorrelated, the resulting total uncertainty is approximately 27%. For the two-zone case, the expression for the uncertainty in the air exchange rate is more complex, but the estimated uncertainty is similar (29%). The total uncertainty in the emission rate for a single zone is:

$$\frac{u(E)}{E} = \sqrt{\left(\frac{u(E_{PFT})}{E_{PFT}}\right)^2 + \left(\frac{u(C_{PFT})}{C_{PFT}}\right)^2 + \left(\frac{u(C)}{C}\right)^2 + \left(\frac{u(A)}{A}\right)^2}, \tag{8}$$

assuming the outdoor concentration is small relative to C. Thus, for the uncertainties estimated above, u(E)/E is approximately 38% for VOCs and 27% for low-weight aldehydes. In the following section, some results are presented in the form of ratios of concentration, air exchange rate, and emission rate in order to be able to compare data from different sites. Because the uncertainty associated with the floor

area and volume are bias errors, the resulting uncertainty in the ratio quantities do not include these errors. The uncertainty in the concentration ratio is approximately 38% for VOCs and 6% for low-weight aldehydes, the uncertainty in the ventilation ratio is 16% and the uncertainty in the emission rate ratio is 41% for VOCs and 17% for low-weight aldehydes.

3. Results

3.1. Air exchange rates

Table 6 shows the PFT concentration data and the calculated air exchange rates for the studied residences. Measured PFT concentrations were above the limit of quantitation (0.05 ppb) for all sampling events. The lowest PFT concentrations were measured for air exchange rates above 1 h^{-1}: 0.09 ppb for PDCB and 0.11 ppb for PMCH (both in H9 at 1.45 h^{-1}). The highest PFT concentrations were measured in the guesthouse units, which were in line with the small floor area of the units and the high PFT area-specific emission rates. Ventilation interventions led to distinct air exchange rates in most study locations, except for H7 and H8. For houses other than H7 and H8, the ratio of high-to-low air exchange rate was at least 2.5 and as high as 5.0. In H7, the air exchange rate rose by less than a factor of 2 from low to high. For H8, the lowest air exchange rate was not discernibly different than the medium rate and only about 30% lower than the high air exchange rate. Internal leakage of the ventilation system in H7 and opened windows during the low air exchange rate sampling day in H8 are plausible explanations for these results.

The ventilation measurement results indicated substantial variation of air exchange rates across study locations. Air exchange rates at low, medium, and high ventilation settings were 0.05-0.81 h^{-1} (median: 0.17), 0.11-0.85 h^{-1} (median: 0.31), and 0.25-1.45 h^{-1} (median: 0.65), respectively. The highest air exchange rates at the low and medium settings (i.e., 0.81 and 0.85 h^{-1}) were obtained from H8, and they were more than twice those of the second-highest settings (i.e., 0.32 and 0.40 h^{-1}). H8 was the only home where the windows were opened on the sampling day. For reference, the ASHRAE 62.2 recommended continuous mechanical ventilation rates for the houses in the study were equivalent to 0.10–0.16 air changes per hour.

Table 6 PFT concentrations and calculated air exchange rates

ID	Ventilation setting	PDCB concentration (ppb)		PMCH concentration (ppb)		Air exchange rate (h^{-1})
		Zone 1	Zone 2	Zone 1	Zone 2	
H1	Low	3.56	3.19	1.61	1.95	0.14
	Medium	2.53	1.94	0.97	1.79	0.19
	High	1.41	0.78	0.47	0.89	0.40
R2*	Low	N.A.		13.31		0.16
	Medium			6.37		0.34
	High			2.62		0.82
R3*	Low	19.80		N.A.		0.17
	Medium	11.63				0.28
	High	4.05				0.80
H4	Low	6.37	7.75	4.96	4.71	0.05
	Medium	2.67	2.78	1.79	1.42	0.11
	High	1.17	1.50	0.97	0.59	0.25
H5	Low	3.25		2.03		0.20/ 0.21#
	Medium	1.75		1.11		0.36/ 0.39#
	High	1.04		0.62		0.61/ 0.70#
H6	Low	2.97	2.97	1.36	1.25	0.19
	Medium	1.34	1.84	1.97	0.46	0.36
	High	1.78	2.14	0.98	1.08	0.50
H7	Low	5.29	5.56	1.67	1.49	0.11
	Medium	4.15	4.61	1.52	1.28	0.14
	High	2.79	3.42	0.99	0.39	0.19
H8	Low	1.06	0.74	0.13	0.25	0.81
	Medium	1.10	0.57	0.14	0.30	0.85
	High	0.83	0.17	0.12	0.31	1.11
H9	Low	0.50	1.02	2.21	0.50	0.32
	Medium	0.42	0.90	0.61	0.47	0.40
	High	0.09	0.22	0.54	0.11	1.45

*Data shown are average values of all measurements;
#Air exchange rates are three-day average values based on PDCB/ PMCH concentrations

In R2 and R3 – which are two rooms of the LBNL Guest House – we collected bi-hourly measurements of PFTs to understand the variation over time in an unoccupied multi-unit residential setting. In R2, the relative variation in PMCH concentration was similar at the low ventilation setting (C = 13.3 ± 1.2 ppb) and the high ventilation setting (C = 2.6 ± 0.3 ppb), as shown in Figure 3 during 12/5-12/9 and 12/17-12/22 respectively. The same trend was observed in R3, where the PDCB concentration at low ventilation was 19.0 ± 2.3 ppb and at high ventilation was 4.1 ± 0.6 ppb, as shown in Figure 4. The ventilation at the lower settings could have been more impacted by air infiltration through the building envelope that changes over time. Generally lower PFT concentrations (corresponding to higher air exchange rates) were observed in the early morning hours, when infiltration due to cold outdoor air was likely higher than it was later in the day on the first level of the building where these units were located. The observed variations were not related to temperature variation within the units, as they each had an air conditioning unit that was controlled by thermostat. Air temperature in R2 was 21.4 ± 0.3°C and in R3 was 21.6 ± 0.4°C. Relative humidity in R2 was 44.7 ± 4.3 % and in R3 43.9 ± 4.4 %.

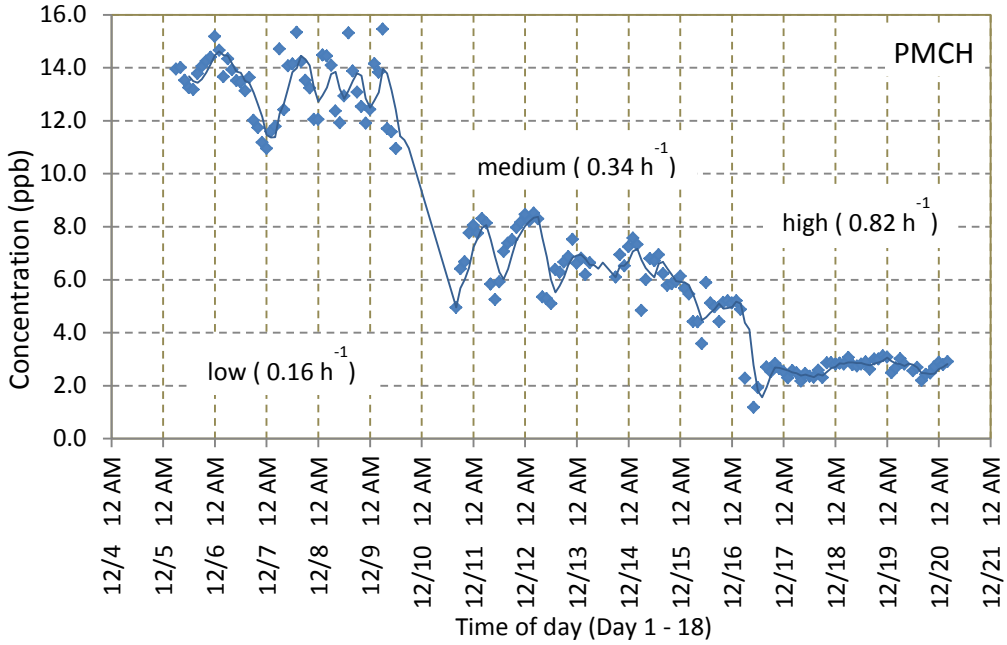

Figure 3 PMCH concentration profile in R2 where the line is a 4 point running average.

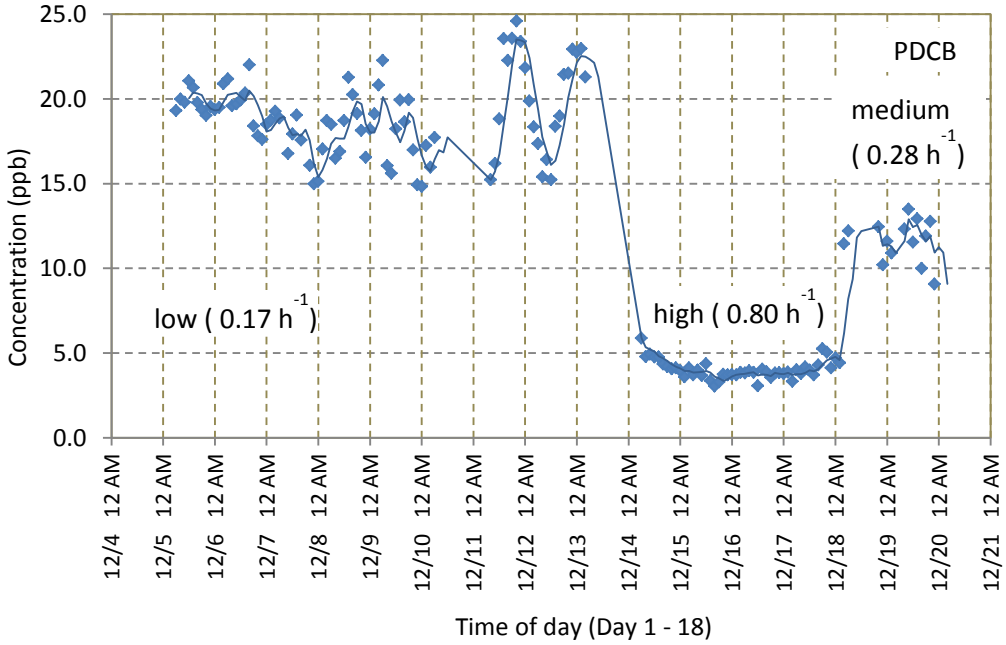

Figure 4 PDCB concentration profile in R3 where the line is a 4 point running average.

The PFT concentrations based on 24-hour integrated air sampling over three consecutive days in house H5 did not show any substantial variations. Figure 5 shows the concentrations of both PFTs. Air exchange rates over three consecutive days were almost constant with relative standard deviations of less than 2%. Diurnal variations of the type observed in the guesthouse units are not discernible from 24-h time-integrated samples. Because both PFTs were distributed at the same locations around the house, the estimated air exchange rates from both PFTs were expected to be approximately the same. The air exchange rates calculated based on the PDCB concentration were on average 8% lower than the PMCH-

based air exchange rates. The difference was considered small and the PMCH result was used in subsequent calculations for H5. Air exchange rates at low, medium, and high settings averaged 0.21, 0.39, and 0.70 h^{-1}, respectively. The air temperature in the home was controlled by a thermostat and remained constant at 23.5 ± 0.2 ^{o}C, while the relative humidity was kept at 48.4 ± 2.1%.

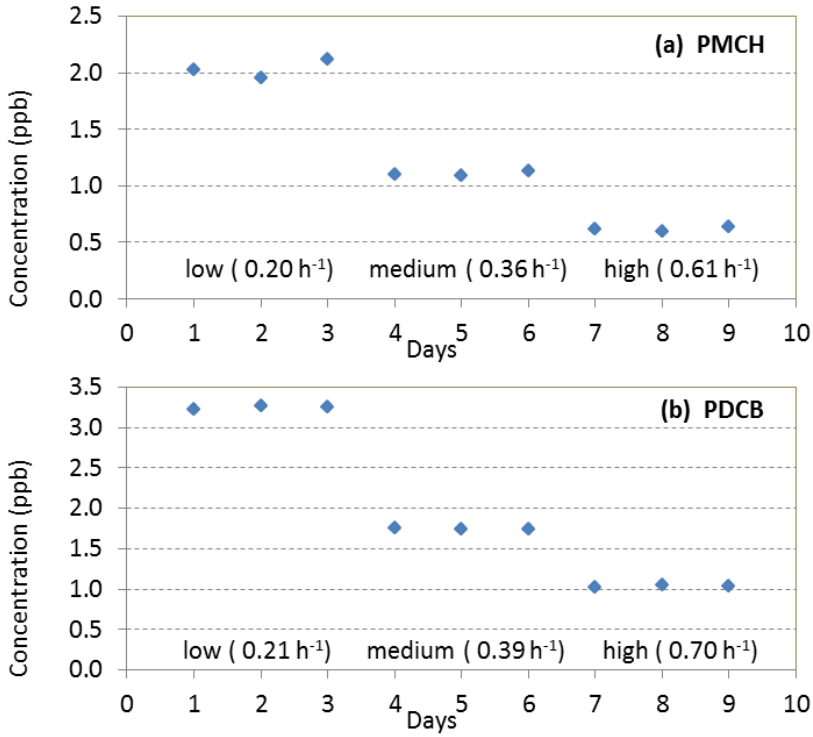

Figure 5 PMCH and PDCB concentrations profiles in H5

Air exchange rates within the occupied homes were sometimes difficult to control, and the variability in daily PFT measurements reflected this. Daily PFT bag samples were collected in H6 and H7. Unlike H5, these samples were not 24-hour integrated samples. Each sample was collected over 40 minutes to match the duration of the active VOC and aldehyde sampling in these homes. Air samples were collected once in the afternoon every day over three weeks. Both homes were occupied throughout the study period. The homeowners were asked to keep the external doors and windows closed at least from the night before the sampling day.

Despite efforts taken to control air exchange rates over the study period, daily PFT concentration measurements at H6 and H7 indicate that the air exchange rate did vary. At H6, substantial variation in the PFT concentrations was observed over time as shown in Figure 6. To determine the air exchange rate in this two-zone case, two different PFTs were emitted, one on each floor: PMCH was emitted on Level 1 and PDCB was emitted on Level 2 (see Table 4). Figure 6 shows that the concentration of each PFT was higher on the floor on which it was emitted, with a larger difference for PMCH. The arrows indicate the day of VOC and aldehyde air sampling. On the first two sampling days when external doors and windows were closed, the house air became better mixed, and the floor concentrations were closer. The trend, however, was not repeated on the last sampling day, when the PMCH concentrations diverged further. While the homeowners were reminded to keep windows closed from the evening prior to the sampling day and were interviewed to verify this, the window state was only observed directly during the sampling period. These results suggested that there may have been positive net airflow from the upper floor to the

lower floor and that PFT concentrations were more uniform when the exterior doors and windows were closed. A similar set of measurements is shown Figure 7 for H7.

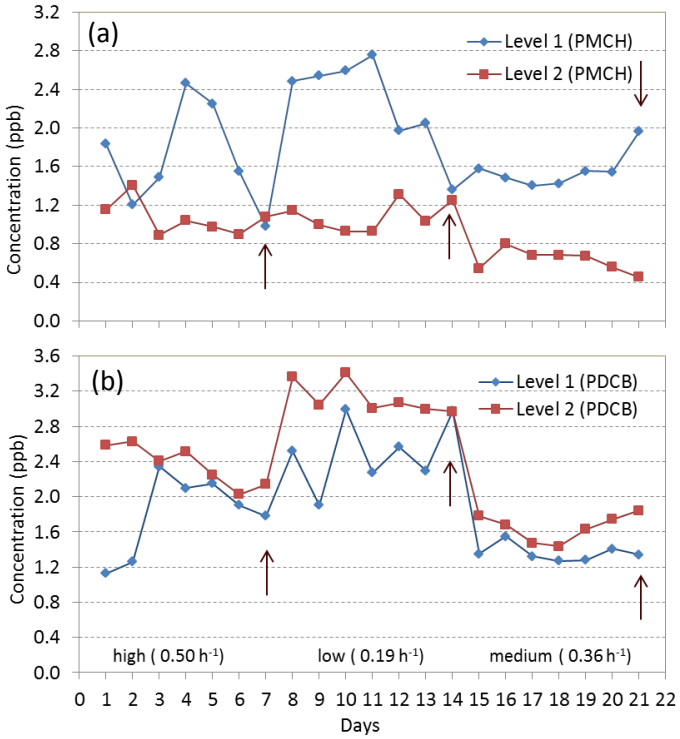

Figure 6 PMCH and PDCB concentration profiles in H6 with labeled ventilation settings

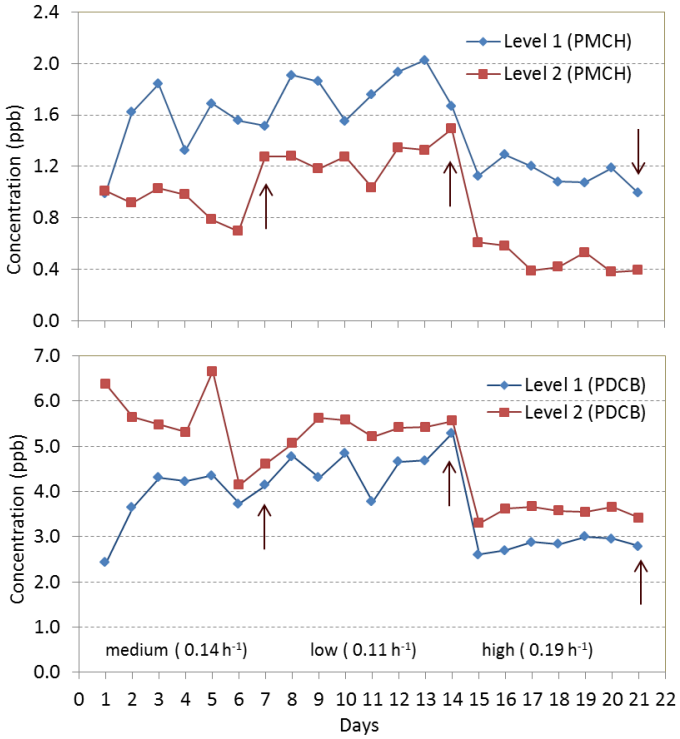

Figure 7 PMCH and PDCB concentration profiles in H7 with labeled ventilation settings

3.2. Low molecular weight aldehydes

As the air exchange rate was increased, the measured concentration of compounds with indoor sources was expected to decrease. Figure 8 and Table 7 show that for formaldehyde and acetaldehyde, higher air exchange rates did lead to lower indoor concentrations at all study locations. The concentration ratios for formaldehyde and acetaldehyde in Table 8 were all greater than 1 indicating a decrease in concentration with increased air exchange rate. If the emission rate were constant, the concentration ratio C_1/C_2 would be equal to the (inverse) ventilation ratio V_2/V_1 in Table 8. However, for formaldehyde, the concentration ratio was lower than the ventilation ratio in all cases, i.e., the reduction was less than proportional. For acetaldehyde, the reduction was proportional on average: the mean ratio of C_1/C_2 to V_2/V_1 is 0.99. This indicates that for formaldehyde, the emission rates may have been buffered by the elevated indoor concentrations of the compounds.

The range of formaldehyde concentrations measured across the residences is suggestive of different levels of formaldehyde emissions, which are presumed to come primarily from materials. The amount of resistance to formaldehyde transport from materials can also impact the measured concentrations. In homes with two zones, there was little variation between zones (i.e., less than 15%) with lower concentrations on the second story of the two story houses.

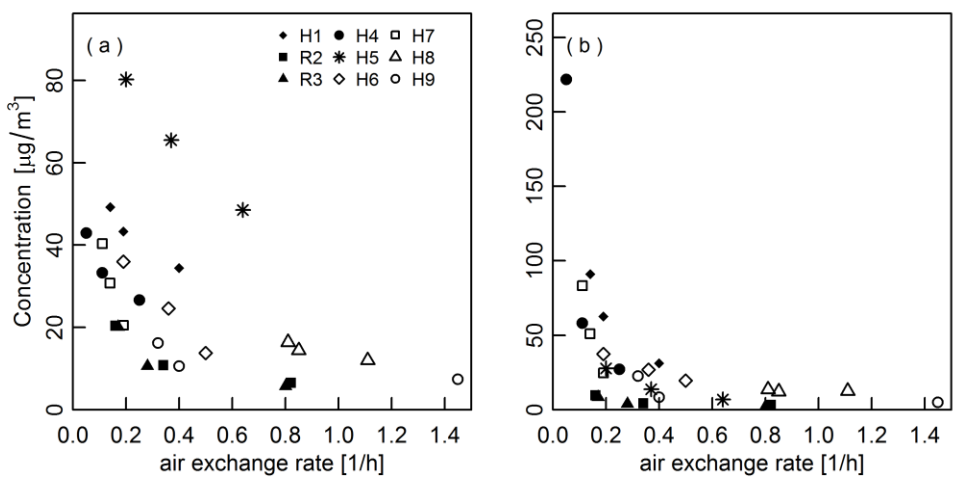

Figure 8 Concentration of formaldehyde (a) and acetaldehyde (b) for three air exchange rates at each of the nine site.

Table 7 Aldehyde concentration

VOC class	Volatile organic compounds		Indoor concentration minus outdoor concentration (μg m^{-3})													
			H1		R2	R3	H4		H5	H6		H7		H8	H9	
		Sampling zone (floor)	*1*	*2*	*1*	*1*	*1*	*2*	*1*	*1*	*2*	*1*	*2*	*1*	*1*	*2*
		Ventilation setting														
Aldehyde	Formaldehyde	*Low*	52.7	45.8	20.4	20.1	40.1	39.5	80.3	37.7	34.2	41.4	39.4	16.5	17.9	14.2
		Medium	44.7	41.9	10.8	10.6	29.6	29.7	65.6	26.1	23.1	31.4	30.1	14.5	10.8	10.4
		High	41.7	26.9	6.5	5.7	23.6	24.4	48.6	13.0	14.6	23.1	17.8	12.0	7.5	7.2
	Acetaldehyde	*Low*	96.1	85.9	9.6	8.3	218.3	221.9	27.8	38.4	36.4	84.8	81.8	13.5	25.0	20.3
		Medium	64.0	61.2	4.3	3.9	57.1	59.0	13.8	27.9	25.9	52.0	50.0	12.2	8.3	8.4
		High	38.1	24.3	3.1	2.1	26.5	27.5	6.9	20.1	18.8	26.2	23.2	12.6	4.8	4.8

Table 8 Aldehyde concentration ratio with reference to concentration at high air exchange rate

VOC class	Volatile organic compounds	Ratio of concentration at low (L) or medium (M) to high (H) ventilation setting																	
		H1		R2		R3		H4		H5		H6		H7		H8		H9	
Concentration ratio		*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*
Aldehyde	Formaldehyde	1.4	1.3	3.1	1.7	3.5	1.9	1.6	1.3	1.8	1.5	2.6	1.8	2.0	1.5	1.5	1.4	2.2	1.4
	Acetaldehyde	2.9	2.0	3.1	1.4	4.0	1.9	8.1	2.1	4.1	2.0	1.9	1.4	3.4	2.1	1.1	1.0	4.7	1.7
Ventilation ratio		*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*
		2.3	***1.8***	***5.1***	***2.4***	***4.7***	***2.9***	***3.2***	***1.6***	***3.2***	***1.7***	***2.1***	***1.5***	***2.5***	***1.5***	***1.7***	***1.3***	***4.1***	***2.5***

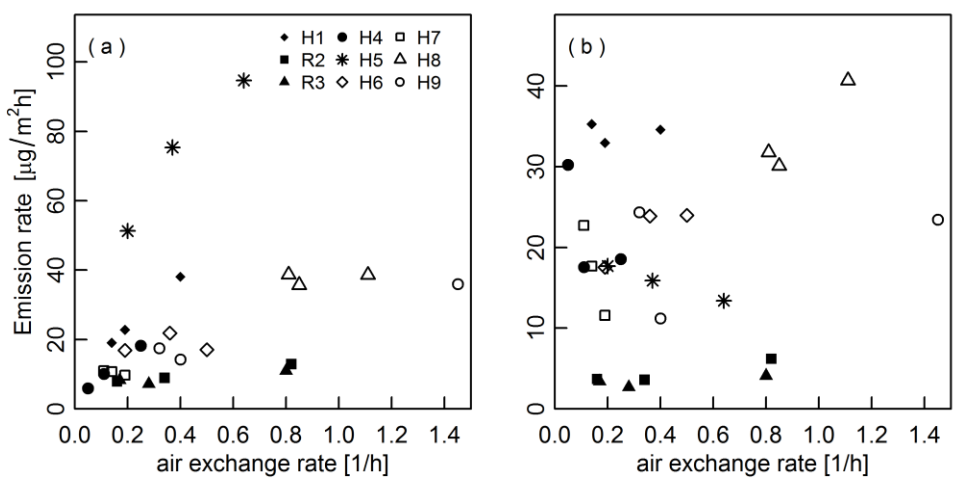

Figure 9 Calculated emission rate of formaldehyde (a) and acetaldehyde (b) for three air exchange rates at each site.

There was a range of baseline emission rates across the homes sampled. In general, low-weight aldehyde emission rates were lowest in R2 and R3, which were built with certified, low-emitting materials, and highest in H5, H8 and H9, which were built with standard construction materials. Intermediate levels were observed in H4, H6 and H7 where homeowners requested low-emitting construction materials but the materials used could not be confirmed.

The variability of formaldehyde emission rate with air exchange rate depended on the particular residence. As shown in Figure 9(a) and Table 9, the emission rate of formaldehyde appeared to increase slightly with the air exchange rate in most residences. An increase in emission rate with air exchange rate (or emission rate ratios of less than one in Table 10) indicates less than proportional reduction of concentration with air exchange rate. The ventilation interventions in H7 and H8 produced only small variations in air exchange rate (low, medium and high air exchange rates were 0.11, 0.14, 0.19 in H7 and 0.81, 0.85, 1.11 h^{-1} in H8) without clear variations in formaldehyde emission rate. The emission rate ratios

for formaldehyde across homes varied: the emission rate changed little in H2 and H6, but increased substantially in H1 and H4, which could have been due to different characteristics of formaldehyde emitting materials in the residences.

There is not a consistent relationship between the emission rate of acetaldehyde and the air exchange rate in Figure 9(b) and Table 9. This may result from a greater diversity of sources of acetaldehyde, including consumer products, and cooking. Intermittent acetaldehyde emission could confound the comparison between the observed acetaldehyde concentrations and theoretical models. For example, in H4, a recent application of kitchen table polish was thought to be a significant point source of acetaldehyde and other compounds. The emission decay over time was considered a confounding factor to the emission rates resulting from changes in air exchange rate.

Table 9 Aldehyde emission rate

VOC class	Volatile organic compounds		Emission rate (μg m^{-2} h^{-1})													
			H1		R2	R3	H4		H5	H6		H7		H8	H9	
		Sampling zone (floor)	*1*	*2*	*1*	*1*	*1*	*2*	*1*	*1*	*2*	*1*	*2*	*1*	*1*	*2*
		Ventilation setting														
Aldehyde	Formaldehyde	*Low*	20.4	17.8	7.9	8.3	6.0	5.9	51.3	17.7	16.0	11.3	10.7	38.7	19.3	15.6
		Medium	23.5	22.1	8.9	7.2	10.0	10.1	75.4	23.2	20.5	10.9	10.4	35.7	14.5	14.0
		High	46.3	29.9	12.9	11.0	18.0	18.5	94.7	16.1	18.0	10.9	8.4	38.6	36.7	35.2
	Acetaldehyde	*Low*	37.3	33.3	3.7	3.4	30.0	30.5	17.7	18.0	17.1	23.1	22.3	31.8	26.9	21.8
		Medium	33.7	32.2	3.6	2.7	17.3	17.8	15.9	24.8	23.0	18.0	17.3	30.1	11.1	11.3
		High	42.3	26.9	6.2	4.1	18.2	18.9	13.4	24.8	23.2	12.3	10.9	40.7	23.5	23.4

Table 10 Aldehyde emission rate ratio

VOC class	Volatile organic compounds	Ratio of emission rate at low (L) or medium (M) to high (H) ventilation setting																	
		H1		R2		R3		H4		H5		H6		H7		H8		H9	
Emission rate ratio		*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*
Aldehyde	Formaldehyde	0.5	0.6	0.6	0.7	0.8	0.7	0.3	0.6	0.5	0.8	1.0	1.3	1.1	1.1	1.0	0.9	0.5	0.4
	Acetaldehyde	1.0	1.0	0.6	0.6	0.8	0.7	1.6	0.9	1.3	1.2	0.7	1.0	2.0	1.5	0.8	0.7	1.0	0.5
Ventilation ratio		*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*
		2.3	1.8	5.1	2.4	4.7	2.9	3.2	1.6	3.2	1.7	2.1	1.5	2.5	1.5	1.7	1.3	4.1	2.5

3.3. Volatile organic compounds

Table 11 lists the concentrations of 39 target VOCs measured at the high ventilation setting in all study locations. In this and other tables, the VOCs were grouped by chemical class and then ordered by increasing boiling point. The complete results of measured concentrations can be found in the Appendix. The VOCs mass data were corrected for analytical and travel blanks. In subsequent calculations (e.g., for concentration ratios), we used the mass detection limit (MDL) concentrations for VOCs with concentrations below their MDLs. The VOCs that were not detected in the analysis are shown as blanks in the tables.

Table 11 VOC concentrations at high ventilation setting[a]

VOC class	Volatile organic compounds	Indoor concentration at high ventilation setting (µg m^{-3})													
		H1		R2	R3	H4		H5	H6		H7		H8	H9	
Air exchange rate (h^{-1})		*0.4*		*0.8*	*0.8*	*0.25*		*0.7*	*0.5*		*0.2*		*0.85*	*0.4*	
Sampling zone (floor)		*1*	*2*	*1*	*1*	*1*	*2*	*1*	*1*	*2*	*1*	*2*	*1*	*1*	*2*
Alcohol	2-Ethyl-1-hexanol	17.3	10.9	1.1	1.0	3.8	6.2	3.0	1.2	2.4	6.6	7.6	4.0	0.5	0.6
Aldehyde	Butanal	6.3	5.3			2.8	3.7	0.6						0.5	1.0
	Hexanal	187.4	128.6	13.3	7.9	50.3	68.2	10.0	6.9	29.1	79.8	86.7	11.5	8.2	18.0
	Heptanal	8.4	6.2			4.1	5.6	1.1	1.2	3.0	9.2	9.5	1.8	0.5	1.0
	Octanal	16.3	11.2	1.6	1.4	8.9	12.2	2.9	3.3	7.6	19.9	21.4	4.9	0.8	1.6
	Benzaldehyde	16.4	10.6	1.2	1.1	6.1	7.8	5.7	6.1	8.8	5.5	5.6	3.8	2.8	3.3
	Nonanal	13.4	10.5	2.7	3.1	13.2	18.6	9.3	6.3	16.4	36.5	36.4	16.9	1.1	2.0
	Decanal	3.7	2.7	4.4	3.4	3.9	4.6		2.2	5.8	12.4	13.4	6.9	0.7	1.3
Alkane	Heptane	1.5	1.0			1.9	2.3	1.9	1.0	2.0	2.2	2.3	4.8		
	Octane	1.1	0.7			1.8	2.4	0.5	0.6	1.2	1.8	1.9	0.6		0.3
	Decane	4.0	2.7			3.4	4.6	0.6	3.0	4.9	1.6	1.7	0.5		0.3
	Undecane	3.7	2.5			5.9	8.1	2.6	2.2	4.7	3.1	3.8	0.5		
	Dodecane	3.7	2.2			5.2	6.8	9.7		1.0	3.8	4.1	0.6		0.1
	Tetradecane	6.0	4.0		0.5	0.8	1.1	3.7	0.9	2.1	1.9	2.2	2.0	0.6	0.9
	Hexadecane	2.8	1.9		1.0	0.6	0.9	1.6	0.7	1.6	2.6	2.5	2.5		0.2
Aromatic	Benzene	2.2	3.5			0.3		1.2	1.8	2.0	0.7	0.8	2.7	1.7	0.7
	Toluene	5.2	3.2	0.5	2.1	3.1	4.3	2.4	2.8	4.9	4.5	9.0	3.9	0.9	1.3
	Ethylbenzene	6.1	3.4			0.6	0.8	0.4		0.7	0.5	0.6	0.4	0.1	0.2
	m/p-Xylene	17.9	9.4			1.2	1.8	1.2	1.0	1.9	1.3	1.6	1.3	0.3	0.4
	o-Xylene	9.4	5.8			2.2	3.2	0.6	0.6	1.1	2.0	2.2	0.8	0.6	0.7
	1,2,4-Trimethylbenzene	2.6	1.7			0.8	1.1	0.5		0.5	0.3	0.4	0.3		0.2
	1,2,3-Trimethylbenzene	1.9	1.1			0.2	0.3	0.1						0.8	
	Butylbenzene	0.4	0.3												
Chlor	Tetrachloroethylene	0.3	0.2					0.1				0.2			
Cyclic siloxane	Hexamethylcyclo-trisiloxane	2.6	6.2	17.8	27.7	8.3	8.8	2.5	0.7	4.0	3.5	3.5	6.7		3.7
	Octamethylcyclo-tetrasiloxane	2.8	2.3	0.4	0.7	1.9	2.2	0.4			0.5	0.5	1.4	0.8	1.0
	Decamethylcyclo-pentasiloxane	5.2	3.7	0.5	0.8	1.6	2.3	1.0	1.2	3.2	24.0	11.3		0.6	0.7
Ester	TXIB (mono-isomer)	3.5	2.8	1.9	2.2	7.4	10.7	11.0		2.0	2.3	2.4	1.1	0.3	1.0
	TXIB (di-isomer)	2.0	1.1		0.6	2.3	4.9	0.8		0.5	5.3	6.8	1.7	1.1	1.7
Glycol ether	2-Butoxyethanol	7.4	6.6			4.0	7.0	9.4		2.5	14.0	15.8	3.0		
Phthalate	Dimethyl phthalate		0.1												
	Diethyl phthalate		0.2		0.3			0.3					0.4		
	Dibutyl phthalate	0.1	0.4					0.3					0.1		
Terpene HC	a-Pinene	100.6	73.7	1.4	2.1	57.0	87.2	4.6	3.5	6.5	29.8	32.1	10.8	15.7	20.7
	3-Carene	165.9	105.2			19.7	29.7	0.1	1.8	4.6	7.4	7.8	4.6		0.4
	d-Limonene	47.8	34.9		1.4	15.1	25.7	2.2		1.9	6.7	7.6	4.1	0.8	1.0
	g-Terpinene	1.4	1.1			0.6	1.1								
	a-Terpineol	2.1	1.6		0.5	5.0	7.4	0.3			0.3	0.4	0.3		

[a] Empty cells represent values below the detection limit.

Aldehyde and terpene compounds were typically the chemicals with highest concentrations, followed by alkanes, aromatics, and siloxanes. H1, H4, and H7 were the homes with highest total VOCs. Not surprisingly, these three homes also had the lowest intervention air exchange rates. Hexanal, α-pinene, d-limonene, and 3-carene were the chemicals with highest concentrations in these homes. At the low ventilation setting, the concentrations were mostly above 100 µg m^{-3}, reaching a maximum of 335 µg m^{-3} for 3-carene and 310 µg m^{-3} for hexanal in H1. R2 and R3 had the least number of detected VOCs from the target list. The levels generally were less than 5 µg m^{-3} in both units at the low ventilation setting, and many of them were not detected at medium and high settings. Hexanal, hexamethylcyclotrisiloxane, and α-pinene had the highest concentrations of the VOCs detected in R2 and R3. The main sources of these chemicals in these premises were thought to be cleaning and laundry products, as well as pressed-wood

materials such as furniture. In homes with two measurement locations, there was a consistent trend of higher concentrations at one of the locations for the entire set of target VOCs. Concentrations were generally higher for the upper-level locations, except in H1, where concentrations from the lower level were consistently higher.

We selected several VOCs that represent the major classes with indoor sources to demonstrate the impact of air exchange rate changes. Hexanal is found in wood-based and surface treatment products. Decane is used as a solvent in paints and cleaning products. O-Xylene is commonly used in carpet and its adhesive backing, and as a solvent in paints, coatings, and other home-consumer products. Decamethylcyclopentasiloxane is used as a cleaning agent for textile materials and as a smoothing agent added to personal care products. TXIB, a plasticizer, is primarily emitted from water-based paints, whereas α-Pinene is emitted from wood-based products and some cleaning products.

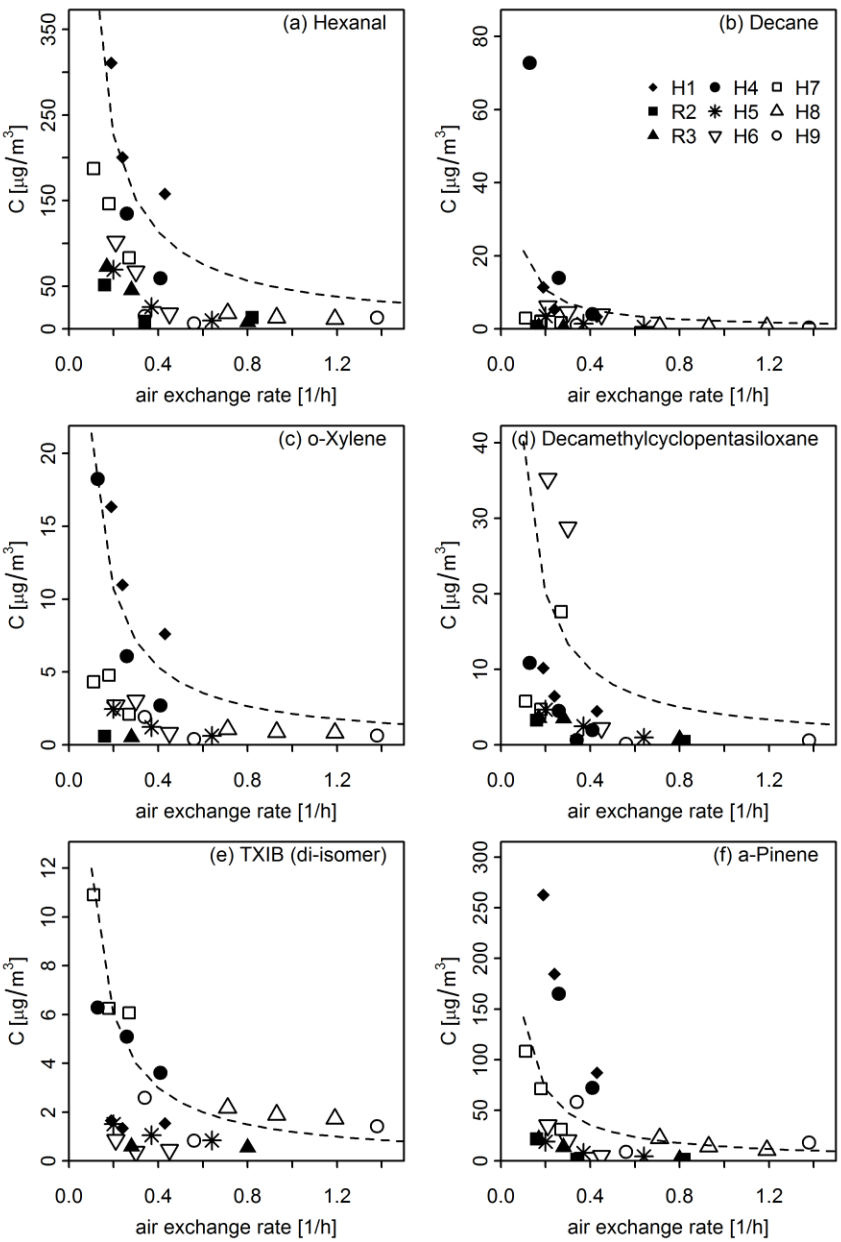

Figure 10 Concentration of 6 selected VOCs for three air exchange rates at each site, where the dashed line shows a linear relationship between C and the air exchange rate timescale $1/N_h$, for reference.

Figure 10 shows that the concentrations of six selected compounds decreased with increasing air exchange rates. The dashed line shown in each subplot shows for reference one relationship between concentration and the air exchange rate timescale $1/N_h$, as described in Equation (3). For the same increase in air exchange rate, there was a much larger reduction in indoor VOC concentration when the initial air exchange rate was low (i.e., lower than 0.5 h^{-1}). In general, the measured indoor concentrations of the selected VOCs presented in Figure 10 were low when the air exchange rate was higher than about 0.4 to 0.5 h^{-1}.

Table 12 VOC concentration ratio with reference to concentration at high ventilation setting

VOC class	Volatile organic compounds	Ratio of indoor concentration at low (L) or medium (M) to high (H) ventilation setting C_L/C_H or C_M/C_H																	
		H1		**R2**		**R3**		**H4**		**H5**		**H6**		**H7**		**H8**		**H9**	
	Concentration ratio	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*
Alcohol	2-Ethyl-1-hexanol	1.4	1.2	2.5	1.0	3.4	2.9	3.3	2.1	2.7	1.5	4.6	2.2	1.3	0.8	1.0	1.1	1.4	0.7
Aldehyde	Butanal	2.5	1.5					5.9	1.9	1.6	0.3							1.7	0.5
	Hexanal	2.0	1.3	3.8	0.7	9.2	5.7		2.3	6.9	2.6	5.7	3.7	2.3	1.8	1.6	1.2	1.2	0.5
	Heptanal	2.0	1.4					5.0	2.2	4.1	2.1	3.5	2.3	2.0	1.4	1.5	1.1	0.8	0.5
	Octanal	1.7	1.5	2.0	0.6	2.8	2.4	3.5	2.0	2.8	1.3	3.3	2.0	1.7	1.3	1.5	1.3	1.0	0.5
	Benzaldehyde	1.7	1.4	1.9	1.3	3.5	2.4	2.7	1.6	2.3	1.3	0.9	0.6	1.6	1.2	1.4	1.3	0.8	0.6
	Nonanal	1.5	1.3	2.1	0.8	2.6	2.6	1.3	1.6	1.5	0.7	1.8	1.2	1.2	0.9	1.3	1.2	0.9	0.6
	Decanal	1.4	1.1	1.2	0.5	1.6	1.5	0.8	0.9			1.3	1.0	0.9	0.9	1.2	1.2	0.9	0.5
Alkane	Heptane	3.5	1.9					10.5	2.7	3.9	1.8	6.2	5.1	2.7	2.0	1.0	0.9		
	Octane	3.7	2.0					10.5	2.7	1.4	1.0	1.6	1.6	1.9	1.3	1.5	1.2	0.9	0.7
	Decane	3.4	1.6					18.1	3.5	6.2	2.5	1.6	1.2	1.8	1.3	1.2	1.1	3.2	
	Undecane	2.4	1.3					9.5	2.7	4.7	2.0	1.9	1.1	2.4	1.7	1.3	1.2		
	Dodecane	2.1	1.1					5.7	2.3	3.9	1.8	1.8	1.1	2.3	1.5	0.9	0.9	1.5	
	Tetradecane	1.4	1.0			1.2	1.1	2.1	1.6	2.6	1.4	3.1	1.6	2.3	1.2	1.1	1.0	1.6	0.6
	Hexadecane	1.2	0.9			0.6	0.6	1.8	1.4	2.1	1.5	2.4	1.0	1.7	0.9	1.2	1.1	1.2	
Aromatic	Benzene	1.2	0.5					5.7		2.1	0.9	0.7	0.8	3.9	0.8		0.1	1.4	0.7
	Toluene	2.6	1.4	6.1	1.2	1.8	1.5	9.0	2.6	5.4	2.5	4.3	3.8	2.7	1.5	0.5	2.2	1.5	0.7
	Ethylbenzene	2.1	1.3					11.7	2.7	4.9	2.3	2.9	2.8	2.7	1.7	0.8	1.0	2.1	0.9
	m/p-Xylene	2.0	1.3					8.6	2.5	4.8	2.3	3.5	3.8	2.6	1.7	0.7	0.9	2.7	0.8
	o-Xylene	2.1	1.4					6.8	2.3	3.9	2.0	3.3	3.7	2.1	2.3	1.3	1.1	2.9	0.6
	1,2,4-Trimethylbenzene	2.1	1.1					10.3	2.9	3.2	1.6	3.1	2.5	3.4	2.3	0.8	0.9	4.7	0.8
	1,2,3-Trimethylbenzene	1.5	0.9					11.2	3.0	3.2	1.6							0.3	
	Butylbenzene	1.9	1.0							3.2	1.4								
Chlor	Tetrachloroethylene	1.7	1.0							2.3	1.2								
Cyclic siloxane	Hexamethylcyclo-trisiloxane	1.3	1.5	1.5	1.0	1.0	1.0	3.2	1.0	1.9	0.9	2.2	1.7	1.5	1.1	0.9	1.1	0.5	
	Octamethylcyclo-tetrasiloxane	1.7	1.9	2.1	0.9	1.5	1.4	5.2	1.7	2.7	1.5			2.3	1.2	1.2	1.2	0.7	
	Decamethylcyclo-pentasiloxane	2.3	1.4	7.1	1.1	4.5	4.5	5.5	2.3	4.8	2.6	15.8	12.9	0.3	0.3			1.0	0.3
Ester	TXIB (mono-isomer)	1.2	1.1	0.5	0.4	0.5	0.8	1.6	1.5	2.2	1.4	1.6	0.9	1.2	0.8	1.0	1.1	1.9	0.5
	TXIB (di-isomer)	1.1	0.9				1.1	1.7	1.4	1.8	1.3	1.9	0.8	1.8	1.0	1.3	1.1	1.8	0.6
Glycol ether	2-Butoxyethanol	1.3	1.0					4.3	2.3	3.0	1.8	2.7	1.7	1.6	1.2	0.9	0.8		
Phthalate	Dimethyl phthalate									1.4	1.3								
	Diethyl phthalate									1.0	1.0					1.0	0.9		
	Dibutyl phthalate	0.5								0.8	0.8						0.9		
Terpene HC	a-Pinene	3.0	2.1	15.1	1.0	10.4	6.5		2.3	4.2	1.7	7.1	4.1	3.5	2.3	2.1	1.3	3.2	0.5
	3-Carene	2.5	2.1						2.6	5.4	2.2	7.4	6.0	3.5	2.4	1.7	1.3	3.0	
	d-Limonene	2.5	1.6			2.0	1.6	7.3	2.2	7.2	2.7	41.0	9.3	12.6	2.3	9.1	1.0	4.2	0.6
	g-Terpinene	2.2	1.7					5.0	1.6										
	a-Terpineol	1.4	1.1					0.3	0.2	3.5	2.0			2.9	1.7	0.9	0.9		
Ventilation ratio		*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*
		2.3	***1.8***	***5.1***	***2.4***	***4.7***	***2.9***	***3.2***	***1.6***	***3.2***	***1.7***	***2.1***	***1.5***	***2.5***	***1.5***	***1.7***	***1.3***	***4.1***	***2.5***

As discussed for the aldehydes, the concentrations of compounds with indoor sources were expected to decrease as the air exchange rate was increased. The trends in the VOC concentrations are less consistent than those for the aldehydes, due to lower concentrations, higher measurement uncertainty, and more varied sources. Table 12 lists the ratios of VOC concentrations between low and high air exchange rates for each study location, as well as those between medium and high. Concentration ratios greater than one indicate lower VOC concentrations at higher air exchange rates. For the majority of cases (77%), the concentration ratio is greater than one. There are, however, a number of cases where the concentration

ratio is less than one. The main factors that could lead to this result are variations in outdoor concentrations or intermittent sources, and uncertainty in the measured VOC concentration. Sites H8 and H9 had concentration ratios much lower than expected. Both of these houses were occupied during the study, leading to higher potential variability in indoor sources and factors that affect the air exchange rate. For example, in H8, windows were open during the study, which can lead to spatial and temporal variability in the impact of both indoor and outdoor sources at any fixed indoor location.

For VOCs that come primarily from outdoors, the ratios of concentrations that occur at low and high ventilation settings – and medium to high – may depend more on the outdoor concentrations at that time than on the AER.

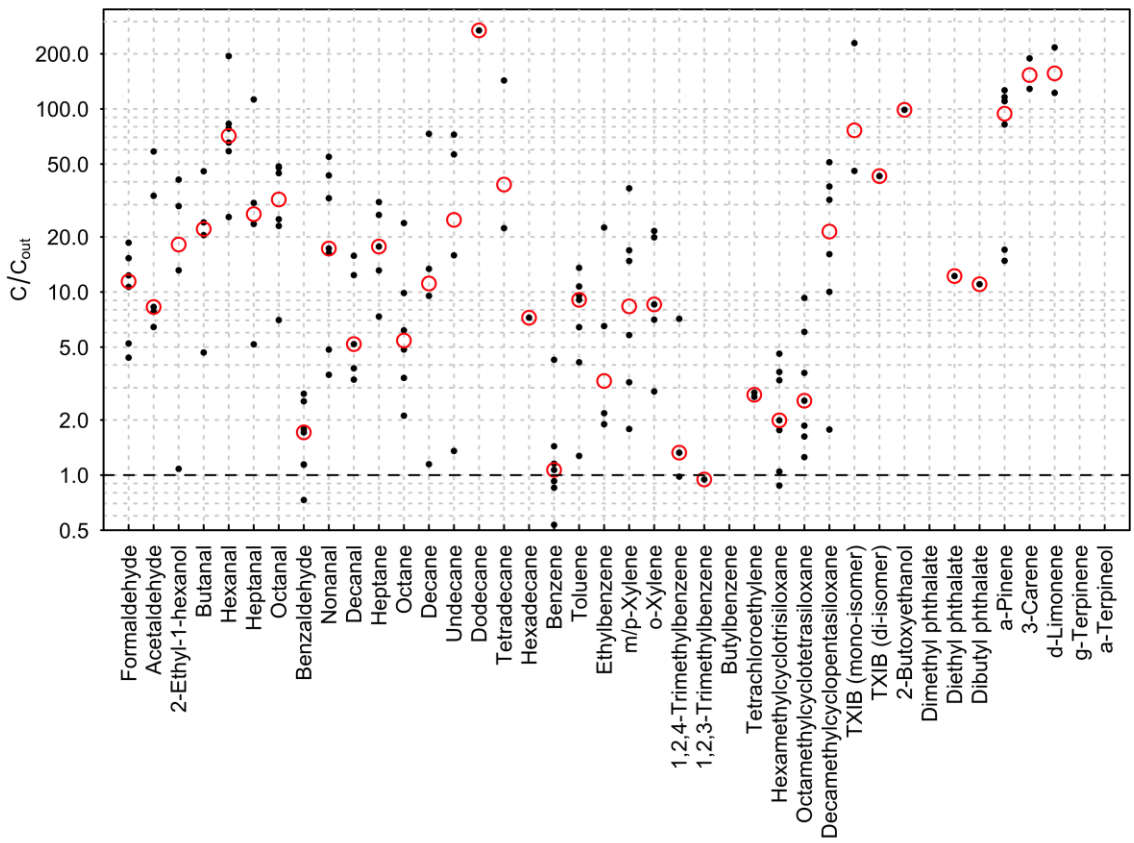

Figure 11 Ratio of indoor to outdoor VOC concentrations for all houses where (O) is the median value and (•) is the individual house value.

The ratio of the indoor to outdoor concentration of VOCs, shown in Figure 11, can be helpful in determining the source of the contaminant. The red circles are the median values and the black dots represent the value for each house. Outdoor concentrations were not measured routinely at R2 and R3 because supply air was directed through a VOC sorbent bed; In chamber tests, the VOC sorbent bed was effective at removing most target VOCs including formaldehyde. For long filtration times, the sorbent bed may become less effective. We assumed there were non-detectable levels of VOCs in the air supply to the room. The value C/C_{out} is calculated as the ratio of the mean of indoor concentrations measured at high, medium and low ventilation settings to the mean of outdoor concentrations, with 'not detected' values omitted. For a number of VOCs, no values of C_{out} above the detection limit were measured. For the majority of the VOCs listed here, indoor concentrations were more than 5 times higher indoors than

outdoors (this is a conservative estimate because 'non-detect' values were excluded from the mean outdoor concentration value). There are no VOCs in this set where the ratio of C/C_{out} is less than 0.5, indicating that the outdoor concentration is never significantly higher than the indoor concentration. The VOCs for which C/C_{out} was generally between 0.5 and 2 were benzaldehyde, benzene, trimethylbenzene, and hexamethylcyclopentasiloxane; the main source of these VOCs indoors likely was from outdoor air. We would not expect that the indoor concentration of compounds with only outdoor sources would show the same reduction with increased ventilation rates that is seen for compounds with indoor sources. Therefore it is not surprising that compounds with relatively high outdoor concentrations (benzene and hexamethylcyclopentasiloxane) had concentration ratios less than one or less than those of other VOCs at the same site.

Table 13 lists the area-specific emission rates for 39 target compounds at the nine study locations. Emission rates are shown for all the sampling zones at the high ventilation setting. Emission rates varied widely between study locations. For some compounds, the difference in emission rate across study locations reached two orders of magnitude. Emission rates by zone for the two-zone homes were comparable. Compounds with emission rates greater than 25 $\mu g\ m^{-2}\ h^{-1}$ at the high ventilation setting were hexanal (H1, R2, H4, H6, H7, H8, and H9), nonanal (H8), hexamethylcyclotrisiloxane (R2 and R3), α-pinene (H1, H4, H8, and H9), 3-carene (H1 and H4), and d-limonene (H1 and H4).

Table 13 VOC emission rates at high ventilation setting

VOC class	Volatile organic compounds	Emission rates at high ventilation setting (μg m^{-2} h^{-1})													
		H1		**R2**	**R3**	**H4**		**H5**	**H6**		**H7**		**H8**	**H9**	
Air exchange rate (h^{-1})		*0.4*		*0.8*	*0.8*	*0.25*		*0.7*	*0.5*		*0.2*		*0.85*	*0.4*	
Sampling zone (floor)		*1*	*2*	*1*	*1*	*1*	*2*	*1*	*1*	*2*	*1*	*2*	*1*	*1*	*2*
Alcohol	2-Ethyl-1-hexanol	14.4	9.0	2.2	2.0	4.6	7.6	6.2	1.3	2.7	4.4	5.1	12.7		0.5
Aldehyde	Butanal	5.2	4.3			3.4	4.5	1.3						1.4	3.4
	Hexanal	156.1	105.9	26.2	16.0	61.0	83.0	19.8	6.2	30.8	52.7	57.3	39.1	29.4	65.7
	Heptanal	6.9	5.0			5.0	6.9	2.0	1.4	3.3	6.2	6.4	6.1	1.4	3.3
	Octanal	13.4	9.0	3.1	2.9	10.6	14.7	5.9	3.7	8.4	12.8	13.8	16.8	2.6	5.7
	Benzaldehyde	4.6		2.3	2.2	1.5	3.6			1.1	0.4	0.4	9.1		
	Nonanal	10.7	8.3	5.3	6.3	15.3	21.9	18.9	5.4	16.6	23.7	23.6	57.6	2.5	6.0
	Decanal	2.7	1.9	8.5	6.9	4.6	5.4		2.4	6.4	7.5	8.2	23.6	1.6	1.9
Alkane	Heptane	1.3	0.9			2.0	2.5	3.6	1.1	2.2	1.5	1.5	15.0		
	Octane	0.9	0.6			1.7	2.5	0.7	0.6	1.3	1.2	1.3	0.9		1.3
	Decane	3.4	2.3			4.2	5.7	0.9	3.3	5.4	1.1	1.1	1.6		1.3
	Undecane	3.0	2.0			6.7	9.4	5.2	2.4	5.2	2.1	2.6	1.7		
	Dodecane	3.2	1.9			6.4	8.4	20.3		1.1	2.6	2.7	2.1		0.5
	Tetradecane	5.0	3.2		1.1	1.0	1.4	7.7	1.0	2.3	1.3	1.5	7.0	2.4	3.7
	Hexadecane	2.4	1.6		2.0	0.8	1.1	3.5	0.7	1.8	1.7	1.7	8.6		0.7
Aromatic	Benzene		1.0			0.3		1.8					5.2	1.3	
	Toluene	3.8	2.1	1.0	4.3	2.5	4.0	2.7	1.9	4.3	2.0	4.9	8.5		
	Ethylbenzene	5.1	2.8			0.7	1.0	0.3		0.7	0.3	0.4	0.6	0.6	0.8
	m/p-Xylene	14.8	7.5			1.0	1.7	0.7	1.1	2.1	0.9	1.1	1.5	0.7	1.0
	o-Xylene	7.7	4.6			2.3	3.5	0.6	0.6	1.2	1.3	1.5	1.7	2.2	2.9
	1,2,4-Trimethylbenzene	2.2	1.4			1.0	1.3	0.7		0.6	0.2	0.2	0.1		0.6
	1,2,3-Trimethylbenzene	1.6	1.0			0.3	0.3	0.3						3.0	
	Butylbenzene	0.3	0.2					0.1							
Chlor	Tetrachloroethylene	0.3	0.2									0.2			
Cyclic siloxane	Hexamethylcyclo-trisiloxane		3.0	34.9	56.1	8.4	9.1	4.3		3.2	1.1	1.1	3.1		10.4
	Octamethylcyclo-tetrasiloxane	1.9	1.5	0.8	1.4	1.9	2.3	0.6			0.3	0.3	2.4	0.2	0.9
	Decamethylcyclo-pentasiloxane	4.2	2.9	0.9	1.6	2.0	2.9	1.4	0.6	2.8	15.8	7.3		0.4	0.8
Ester	TXIB (mono-isomer)	3.0	2.4	3.7	4.4	9.1	13.1	23.0		2.2	1.5	1.6	3.8	1.3	3.8
	TXIB (di-isomer)	1.7	0.9		1.1	2.8	6.1	1.7		0.5	3.6	4.5	5.9	4.4	6.7
Glycol ether	2-Butoxyethanol	6.3	5.7			4.9	8.7	19.7		2.7	9.4	10.6	10.3		
Phthalate	Dimethyl phthalate		0.1					0.1							
	Diethyl phthalate		0.2					0.6					1.3		
	Dibutyl phthalate	0.1	0.4					0.7					0.3		
Terpene HC	a-Pinene	83.8	60.8	2.8	4.3	63.6	100.8	9.4	1.4	4.8	19.5	21.1	36.9	60.7	79.9
	3-Carene	138.9	87.1			24.3	36.6	0.3	1.9	5.1	5.0	5.2	15.8		1.4
	d-Limonene	40.3	29.3		2.7	18.6	31.7	4.6		2.1	4.5	5.1	13.9	3.2	3.9
	g-Terpinene	1.2	0.9			0.7	1.3								
	a-Terpineol	1.8	1.4		1.1	6.2	9.1	0.6			0.2	0.3	0.9		

The impact of the air exchange rate on the emission rate was less clear, as seen in Figure 12. In H4, emission rates decreased for most compounds (see time-varying effects discussed earlier), while in other locations, there were varied effects on emission rate with increasing air exchange rate. The variation in the calculated emission rate among different sites was high: for a given compound, the variation in emission rate of the same VOC across sites was 2 to 3 times larger than the variation in emission rate with air exchange rate. The VOC emission rate, however, was calculated using the PFT emission rate, the effective floor area and the PFT concentration in addition to the measured VOC concentration, as shown in Equations (4) and (6). Thus the uncertainty in the emission rate of the VOCs was relatively high (38%), which should be considered in the interpretation of the results.

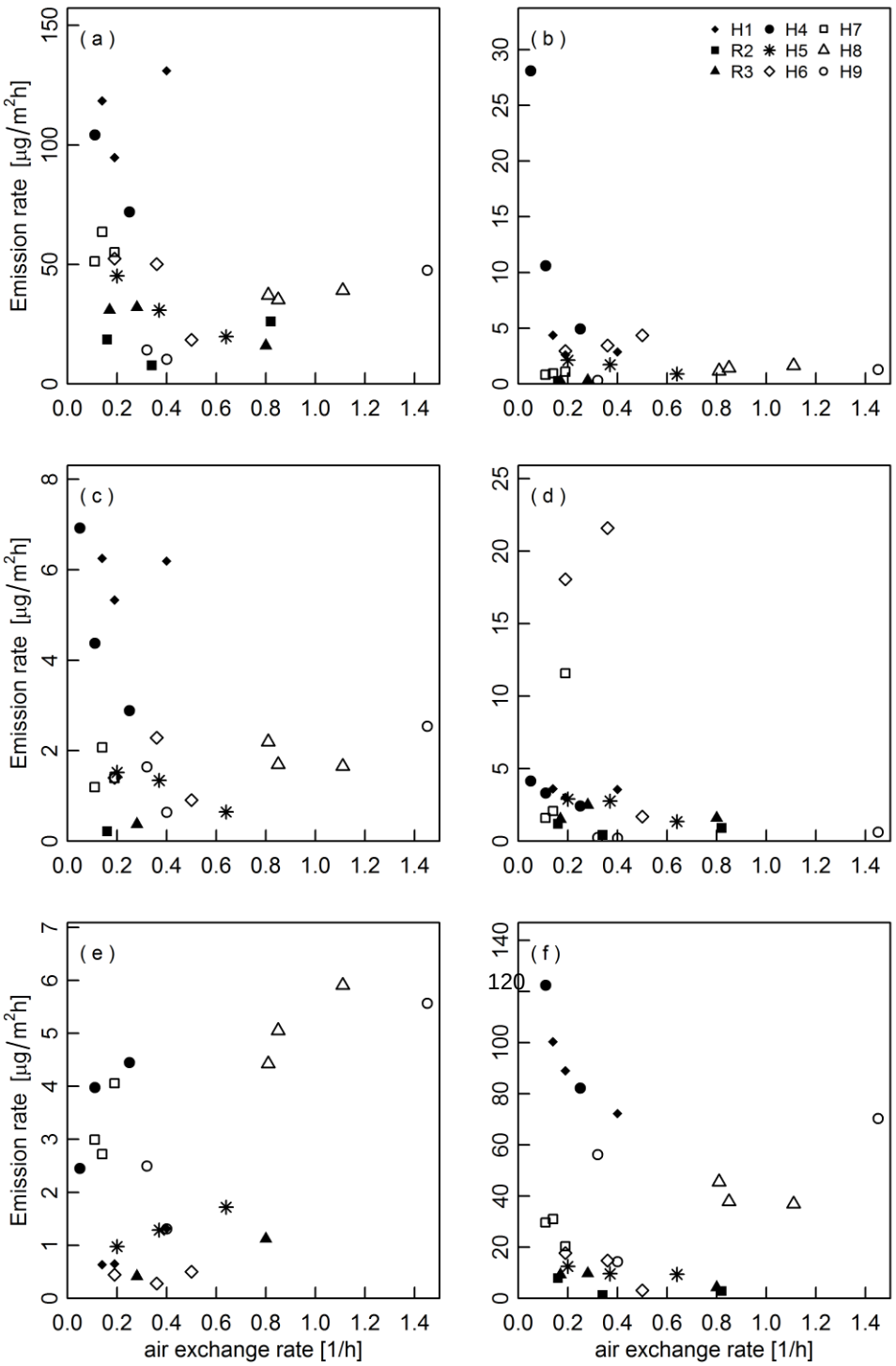

Figure 12 Emission rate of hexanal (a), decane (b), o-xylene (c), decamethylcyclopentasiloxane (d), TXIB (di-isomer) (e), and α-pinene (f) for three air exchange rates at each site.

Calculated emission rate ratios for the VOCs are shown in Table 14. An emission rate ratio of one is consistent with a constant emission rate, whereas emission rate ratios less than one indicate that there is less than proportional reduction in VOC concentrations to increases in ventilation. There are certain VOC classes where the emission rate tends to be less than one (ester and pthalate) as well as certain aldehydes

(nonanal, decanal), alkanes (tetradecane, hexadecane), and cyclic siloxanes (hexamethylcyclotrisiloxane and hexamethylcyclotetrasiloxane). On the other hand, the aromatic and terpene HC classes tended to have emission rate ratios of one or greater. The emission rate ratio also tends to vary by site, with consistently lower emission rate ratios at H9 and to a lesser extent at H2, H3 and H8. On the other hand, the emission rate ratios at H4 tended to be higher than average. This suggests that location specific factors including error in measurements (air exchange rate) could explain some of this variability. Within chemical classes of aldehyde, alkane, aromatic, cyclic siloxane, phthalate, and terpene, the ratio of the emission rates generally decreased with increasing boiling point (lower volatility).

One of the objectives of this study was to assess whether the reduction in indoor concentration was proportional to the increase in air exchange rate for different VOCs of interest. Figure 13 shows the emission rate ratio versus the ventilation ratio, where the dashed line shows the median value of the emission rate ratio for that compound. Proportional reduction is consistent with the assumption of constant emission rate in Equation (2), or an emission rate ratio of 1 in Figure 13 independent of the air exchange rate ratio. If the concentration were reduced by more than a proportional reduction for a given increase in the air exchange rate, points would fall above the line where emission rate ratio equals 1, and below the line if the decrease in concentration were less than proportional reduction. For most compounds shown in Figure 13, there is scatter but the median value of the emission rate ratio is close to one. The exceptions are TXIB (di-isomer) and formaldehyde, where the emission ratios are more tightly clustered. As discussed earlier, the estimated uncertainty in the emission rate ratio is 41% for VOCs and 18% for Aldehydes, which may account for some of the scatter. For TXIB (di-isomer) and formaldehyde, however, there tends to be less than proportional reduction in indoor concentration when the air exchange rate is increased. In general, clear trends are not apparent between emission rate and air exchange rate, as shown in Figure 13. The results for formaldehyde and TXIB (di-isomer) suggest that the emission rate ratio increased slightly with ventilation ratio for the range of conditions tested here.

Comparing the VOC levels measured in the nine residences with health benchmark data was not a primary objective of this report. Measured indoor concentrations in US residences across a range of studies in the literature compared with health standards and guidelines can be found in Logue et al. (2011). Of the 39 target VOCs studied here, 10 have available health benchmark data listed by Logue et al. Measured VOC concentrations in this study were low relative to acute standards, but some exceeded chronic cancer hazard levels. Ethylbenzene exceeded the CA EPA hazard level for cancer of 4 µg m^{-3} in 2 homes (H1 and H4 at low or medium settings). For benzene, the CA EPA chronic hazard level for cancer is 0.34 µg m^{-3}, which is approximately the detection limit for VOCs in this study. Many homes exceeded this level, but all measured benzene levels were below 6 µg m^{-3} and most below 3µg m^{-3}, well below the non-cancer chronic hazard levels for the CA and US EPA (60 and 30 µg m^{-3} respectively). Tetrachlorethylene levels exceeded the CA EPA hazard level for cancer level in only one home (H4 at the low ventilation setting).

The low-weight aldehyde concentration measurements regularly exceeded hazard levels. For formaldehyde, all homes exceeded the CA and US EPA hazard levels for cancer of 1.67 µg m^{-3} as well as the US EPA chronic non-cancer hazard level of 3 µg m^{-3}. Formaldehyde concentrations in all homes (except R2 and R3 at the high ventilation setting) also exceeded the CA EPA 8-h acute hazard level and the non-cancer chronic hazard level (both are 9 µg m^{-3}). The acute, 1-h hazard level of the CA EPA of 55µg m^{-3} was exceeded in H1 at the low setting and in H5 at low and medium ventilation settings.

Acetaldehyde levels were over 200 µg m^{-3} in H4, but in other homes were between 10 and 100 µg m^{-3} with lower levels in H2 and H3. Acetaldehyde concentrations exceeded chronic hazard guidelines depending on the standard used (140 µg m^{-3} is the CA EPA non-cancer hazard level and 3.7 the cancer level, whereas 9 µg m^{-3} is the US EPA non-cancer hazard level). Further discussion of these health guidelines as well as population impacts can be found in Logue et al. (2011, 2012).

Table 14 VOC emission rate ratio with reference to emission rate at high ventilation setting

VOC class	Volatile organic compounds	Ratio of emission rate at low (L) or medium (M) to high (H) ventilation setting																	
		H1		R2		R3		H4		H5		H6		H7		H8		H9	
	Emission rate ratio	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*	*L/H*	*M/H*
Alcohol	2-Ethyl-1-hexanol	0.7	0.7	0.5	0.5	0.7	1.0	1.1	1.3	0.9	0.9	2.1	1.5	0.6	0.5	0.7	0.9	1.5	1.2
Aldehyde	Butanal	1.1	0.9					1.9	1.1	0.5	0.1							0.5	0.3
	Hexanal	0.9	0.7	0.7	0.3	1.9	2.0		1.4	2.3	1.6	2.8	2.7	0.9	1.2	1.0	0.9		0.2
	Heptanal	0.9	0.7					1.6	1.4	1.3	1.3	1.6	1.6	0.8	0.9	0.9	0.9	0.3	0.3
	Octanal	0.8	0.8	0.4	0.3	0.6	0.9	1.1	1.3	0.9	0.8	1.5	1.3	0.7	0.8	0.9	1.0	0.3	0.3
	Benzaldehyde	1.4	1.8	0.3	0.6	0.7	0.8	2.0	2.1			0.5	1.4	6.4	5.2	0.0			
	Nonanal	0.5	0.6	0.4	0.4	0.6	0.9	0.4	1.0	0.5	0.4	0.9	0.9	0.5	0.6	0.7	0.9	0.3	0.3
	Decanal	0.5	0.6	0.2	0.2	0.3	0.5	0.2	0.5			0.6	0.6	0.4	0.7	0.7	0.9	0.5	0.5
Alkane	Heptane	1.3	1.0					3.9	1.9	1.3	1.1	2.7	3.5	1.1	1.3	0.6	0.7		
	Octane	1.1	0.9					4.0	1.9	0.5	0.7	0.6	1.1	0.7	0.8	1.0	1.3	0.2	0.3
	Decane	1.5	0.9					5.7	2.1	2.4	1.9	0.7	0.8	0.7	0.8	0.7	0.9	0.2	
	Undecane	1.2	0.8					3.2	1.8	1.5	1.2	0.9	0.7	1.0	1.1	0.8	0.9		
	Dodecane	0.9	0.6					1.8	1.5	1.2	1.0	0.8	0.7	0.9	0.9	0.6	0.7	0.4	
	Tetradecane	0.7	0.5			0.3	0.4	0.7	1.0	0.8	0.8	1.5	1.1	0.9	0.8	0.7	0.8	0.4	0.2
	Hexadecane	0.6	0.4			0.1	0.2	0.6	0.9	0.7	0.9	1.1	0.7	0.7	0.6	0.7	0.9	0.3	
Aromatic	Benzene	0.1	0.6							0.7	0.5							0.7	0.4
	Toluene	1.2	0.9	1.1	0.6	0.4	0.5	3.9	2.0	2.9	2.4	2.4	3.5	1.4	1.2	0.3	2.3		
	Ethylbenzene	1.0	0.8					3.7	1.7	3.9	3.2	1.3	1.9	1.1	1.1	1.2	1.0	0.3	0.3
	m/p-Xylene	0.9	0.8					3.7	1.9	5.0	4.2	1.6	2.6	1.1	1.1	0.8	1.0	0.8	0.6
	o-Xylene	1.0	0.9					2.4	1.5	2.4	2.1	1.5	2.5	0.9	1.5	1.3	1.0	0.6	0.3
	1,2,4-Trimethylbenzene	0.9	0.7					3.3	1.8	1.6	1.5	1.4	1.7	1.4	1.5	3.9	2.1	0.1	0.3
	1,2,3-Trimethylbenzene	0.7	0.5					3.6	1.9	1.0	0.9								0.0
	Butylbenzene	0.9	0.6							1.0	0.8								
Chlor	Tetrachloroethylene	0.7	0.6							2.5	2.8								
Cyclic siloxane	Hexamethylcyclo-trisiloxane		0.9	0.3	0.4	0.2	0.4	1.0	0.4	0.4	0.5	0.2	0.7	0.3	0.9		0.0	0.2	
	Octamethylcyclo-tetrasiloxane	0.5	1.2	0.4	0.4	0.3	0.5	1.8	1.0	0.9	0.9			0.4	0.8	0.5	0.7	0.4	
	Decamethylcyclo-pentasiloxane	1.0	0.8	1.3	0.5	0.9	1.6	1.7	1.4	2.1	2.0	10.6	12.7	0.1	0.2			0.4	0.3
Ester	TXIB (mono-isomer)	0.6	0.6	0.1	0.2	0.1	0.3	0.5	0.9	0.7	0.8	0.7	0.6	0.5	0.5	0.6	0.8	0.5	0.2
	TXIB (di-isomer)	0.5	0.5				0.4	0.6	0.9	0.6	0.7	0.9	0.6	0.7	0.7	0.7	0.9	0.4	0.2
Glycol ether	2-Butoxyethanol	0.6	0.6					1.4	1.5	1.0	1.0	1.2	1.2	0.7	0.8	0.5	0.6		
Phthalate	Dimethyl phthalate									0.4	0.8								
	Diethyl phthalate									0.3	0.6					0.6	0.7		
	Dibutyl phthalate	0.2								0.2	0.5						0.7		
Terpene HC	a-Pinene	1.4	1.2	2.8	0.5	2.2	2.3		1.5	1.3	1.0	5.7	4.8	1.5	1.5	1.2	1.0	0.8	0.2
	3-Carene	1.1	1.2						1.7	1.7	1.3	3.4	4.1	1.4	1.6	1.0	1.1	0.7	
	d-Limonene	1.1	0.9			0.4	0.6	2.3	1.4	2.2	1.5	19.2	6.3	5.2	1.5	5.4	0.8	1.0	0.3
	g-Terpinene	1.0	1.0					1.6	1.0										
	a-Terpineol	0.6	0.6					0.1	0.1	1.1	1.1			1.2	1.1	0.6	0.7		
Ventilation ratio		*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*	*H/L*	*H/M*
		2.3	***1.8***	***5.1***	***2.4***	***4.7***	***2.9***	***3.2***	***1.6***	***3.2***	***1.7***	***2.1***	***1.5***	***2.5***	***1.5***	***1.7***	***1.3***	***4.1***	***2.5***

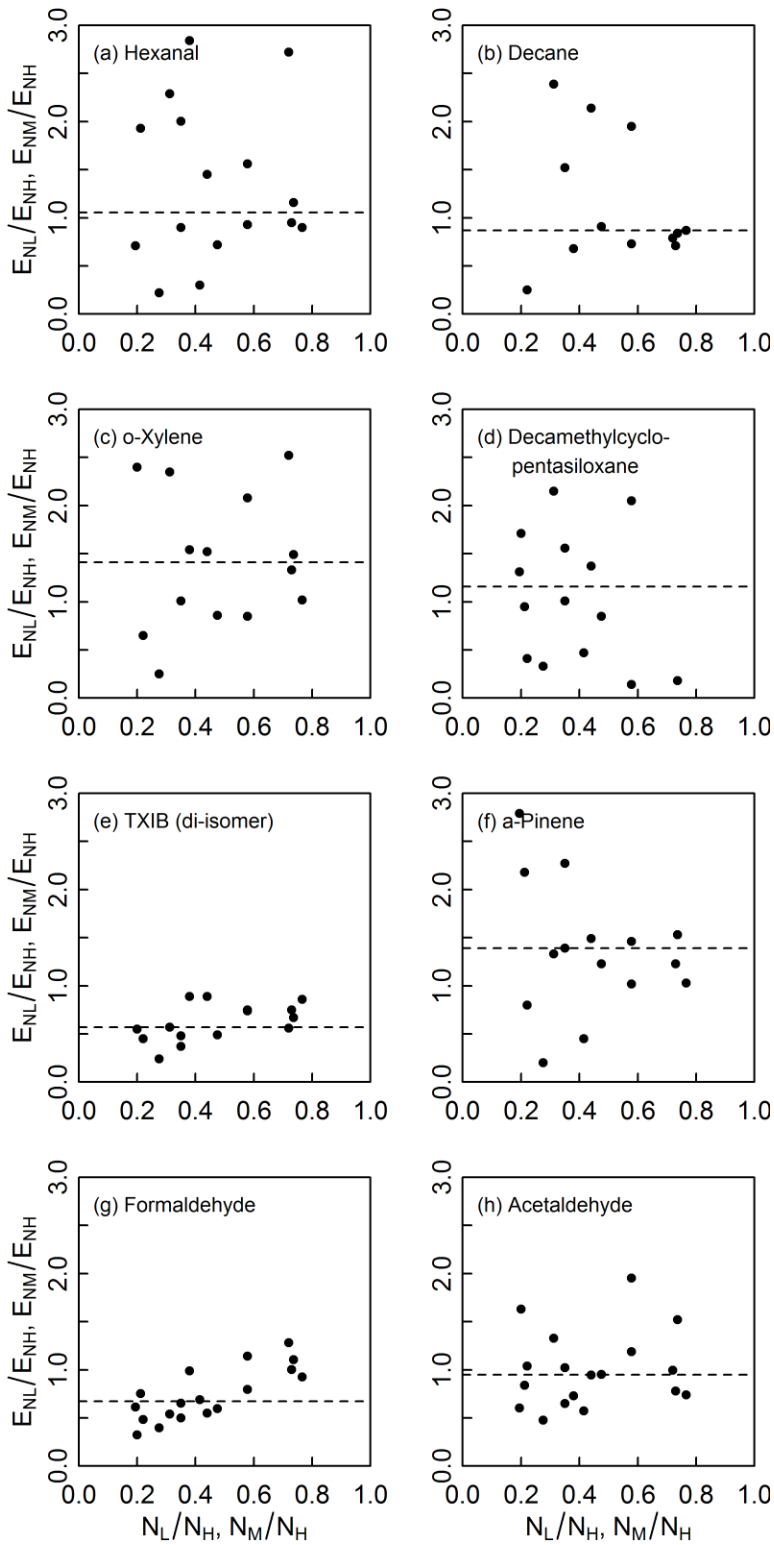

Figure 13 Emission ratio (E_{NL}/E_{NH} or E_{NM}/E_{NH}) versus ventilation ratio (N_H/N_L or N_M/N_H) for 8 highlighted VOCs where the dashed line shows the median value of the emission ratio

4. Summary

This study examined the impact of air exchange rate on indoor concentrations of 39 target VOCs using active air-sampling methods at three air exchange rate settings in each of nine study residences. PFT sampling was used to determine the overall air exchange rate for each ventilation setting. From the measured air exchange rates and the VOC concentrations, the main conclusions from this study were:

- The concentration levels and emission rates of the target VOCs varied widely between sites. For a given VOC, the measured concentration at the lowest ventilation setting varied by up to two orders of magnitude at the different sites.
- Aldehyde and terpene compounds were typically the chemicals with highest indoor concentrations, followed by alkanes, aromatics, and siloxanes.
- Low-weight aldehydes and VOC concentrations tended to decrease as the air exchange rate was increased. Generally, concentrations were reduced significantly when the air exchange rate was above about 0.4 ACH.
- The dependence of indoor concentration on the air exchange rate timescale was linear for most compounds with concentration proportional to $1/N_h$. For a subset of compounds including formaldehyde, however, the indoor concentration exhibited a non-linear dependence on air exchange rate, consistent with a concentration-dependent emission rate.
- The experimental approach of measuring VOC concentrations and air exchange rates at discrete times, rather than over longer, integrated time periods was suitable for unoccupied homes but not for the occupied homes. In occupied homes, the ventilation rates varied substantially from day to day even when measured at the same time every day. Opening of windows and other occupant-driven ventilation caused ventilation conditions in at least two of the occupied homes to vary substantially from the experimental design. Conducting experiments in occupied homes also likely brought variability in VOC emissions related to activities (e.g., cooking) and consumer product use that confound results.
- The uncertainty in measured quantities was considerable relative to the impacts of processes of interest (e.g., whether storage buffering leads to less than proportional reduction in concentration).

This report is intended as a first-cut description of data and major results. Additional analysis of these data may appear in future reports.

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Appendix A: Measured VOC concentrations

Table A.1 House 1 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin						Cout		
		L		M		H		L	M	H
	AER (/h)	0.19		0.24	0.24	0.43	0.43	0.19	0.24	0.43
H1	Sampling Zone	1	2	1	2	1	2	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	21	19	17	16	17	11		0.61	0.44
Aldehyde	Butanal	13	17	8.8	8.9	6.3	5.3	0.57	0.42	0.22
	Hexanal		**311**	**202**	**199**	**187**	**129**	**1.6**	**5.4**	**4.4**
	Heptanal	15	14	9.6	10	8.4	6.2	0.49	0.61	0.26
	Octanal	24	24	20	22	16	11	0.66	1.3	0.57
	Benzaldehyde	25	22	21	17	16	11	6.6	2.5	11
	Nonanal	15	20	14	16	13	11	5.3	3.1	0.85
	Decanal	4.3	4.4	3.5	3.7	3.7	2.7	1.4	0.97	0.51
Alkane	Heptane	4.7	4.1	2.4	2.4	1.5	1.0	0.63	0.29	
	Octane	3.5	3.1	1.8	1.9	1.1	0.73	1.1	0.38	
	Decane	**12**	**11**	**5.2**	**5.5**	**4.0**	**2.7**			
	Undecane	7.6	7.4	3.9	3.9	3.7	2.5			0.19
	Dodecane	6.5	5.8	3.5	3.1	3.7	2.2			
	Tetradecane	7.6	6.8	4.8	4.8	6.0	4.0		0.25	0.19
	Hexadecane	3.1	2.7	2.1	2.1	2.8	1.9		0.29	
Aromatic	Benzene	1.4	5.2		1.4	2.2	3.5	5.0		2.3
	Toluene	11	10	6.1	6.0	5.2	3.2	1.9	0.60	0.74
	Ethylbenzene	11	9.1	6.6	6.2	6.1	3.4			0.21
	m/p-Xylene	30	24	19	16	18	9.4	0.54		0.56
	o-Xylene	**16**	**17**	**11**	**11**	**9.4**	**5.8**			**0.35**
	1,2,4-Trimethylbenzene	4.8	4.0	2.4	2.4	2.6	1.7			
	1,2,3-Trimethylbenzene	2.4	2.2	1.4	1.3	1.9	1.1			
	Butylbenzene	0.71	0.60	0.35	0.35	0.39	0.29			
Chlor	Tetrachloroethylene	0.50	0.44	0.30	0.29	0.34	0.22			
	Hexamethylcyclotrisiloxane	6.0	5.6	5.9	7.7	2.6	6.2	13	4.0	2.6
	Octamethylcyclotetrasiloxane	4.5	3.9	4.6	5.0	2.8	2.3	2.0	0.66	0.49
	Decamethylcyclopentasiloxane	**12**	**8.3**	**6.3**	**6.6**	**5.2**	**3.7**	**0.77**	**0.25**	**0.29**
Ester	TXIB (mono-isomer)	3.9	3.8	3.1	3.8	3.5	2.8			
	TXIB (di-isomer)	**2.1**	**1.2**	**1.6**	**1.1**	**2.0**	**1.1**			
Glycol ether	2-Butoxyethanol	7.7	11	6.7	7.9	7.4	6.6			
Phthalate	Dimethyl phthalate						0.12			
	Diethyl phthalate						0.18			
	Dibutyl phthalate	0.12				0.12	0.43			
Terpene HC	**a-Pinene**	**226**	**299**	**190**	**179**	**101**	**74**	**0.54**	**1.3**	**2.4**
	3-Carene		335		278	166	105	0.43	0.46	3.1
	d-Limonene	106	98	62	66	48	35		0.31	0.55
	g-Terpinene	2.8	2.6	2.2	2.0	1.4	1.1			
	a-Terpineol	2.9	2.5	2.0	2.2	2.1	1.6			

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.2 House 2 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin			Cout		
		L	M	H	L	M	H
	AER (/h)						
R2	Sampling Zone	1	1	1			
Alcohol	2-Ethyl-1-hexanol	2.8	1.2	1.1	No sample collected, outdoor VOCs were removed from outdoor air stream		
Aldehyde	Butanal						
	Hexanal	**51**	**8.8**	**13**			
	Heptanal	1.4	0.45				
	Octanal	3.1	1.0	1.6			
	Benzaldehyde	2.2	1.5	1.2			
	Nonanal	5.7	2.2	2.7			
	Decanal	5.1	2.0	4.4			
Alkane	Heptane	2.1					
	Octane	0.68					
	Decane	**0.70**					
	Undecane	0.87					
	Dodecane	0.50					
	Tetradecane	0.55					
	Hexadecane	0.61	0.70				
Aromatic	Benzene						
	Toluene	3.2	0.65	0.52			
	Ethylbenzene	0.46					
	m/p-Xylene	1.1					
	o-Xylene	**0.60**					
	1,2,4-Trimethylbenzene						
	1,2,3-Trimethylbenzene	0.94					
	Butylbenzene						
Chlor	Tetrachloroethylene						
	Hexamethylcyclotrisiloxane	27	17	18			
	Octamethylcyclotetrasiloxane	0.86	0.37	0.41			
	Decamethylcyclopentasiloxane	**3.3**	**0.49**	**0.46**			
Ester	TXIB (mono-isomer)	1.0	0.69	1.9			
	TXIB (di-isomer)						
Glycol ether	2-Butoxyethanol						
Phthalate	Dimethyl phthalate						
	Diethyl phthalate						
	Dibutyl phthalate						
Terpene HC	**a-Pinene**	**22**	**1.5**	**1.4**			
	3-Carene						
	d-Limonene	2.8					
	g-Terpinene						
	a-Terpineol	0.84					

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.3 House 3 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin			Cout		
		L	M	H	L	M	H
	AER (/h)						
R3	Sampling Zone	1	1	1			
Alcohol	2-Ethyl-1-hexanol	3.4	2.9	0.99	No sample collected, outdoor VOCs were removed from outdoor air stream		
Aldehyde	Butanal						
	Hexanal	**73**	**45**	**7.9**			
	Heptanal	1.7	1.5				
	Octanal	3.9	3.5	1.4			
	Benzaldehyde	3.9	2.7	1.1			
	Nonanal	8.1	7.9	3.1			
	Decanal	5.4	5.0	3.4			
Alkane	Heptane	1.8	1.4				
	Octane	0.77	0.70				
	Decane	**0.60**	**0.46**				
	Undecane	0.56	0.48				
	Dodecane	0.53	0.19				
	Tetradecane	0.67	0.61	0.55			
	Hexadecane	0.59	0.58	0.98			
Aromatic	Benzene						
	Toluene	3.8	3.1	2.1			
	Ethylbenzene	0.52	0.45				
	m/p-Xylene	1.3	1.0				
	o-Xylene		**0.53**				
	1,2,4-Trimethylbenzene						
	1,2,3-Trimethylbenzene						
	Butylbenzene						
Chlor	Tetrachloroethylene						
	Hexamethylcyclotrisiloxane	29	28	28			
	Octamethylcyclotetrasiloxane	1.00	0.95	0.68			
	Decamethylcyclopentasiloxane	**3.6**	**3.5**	**0.79**			
Ester	TXIB (mono-isomer)	1.1	1.8	2.2			
	TXIB (di-isomer)		**0.59**	**0.55**			
Glycol ether	2-Butoxyethanol						
Phthalate	Dimethyl phthalate						
	Diethyl phthalate			0.35			
	Dibutyl phthalate						
Terpene HC	**a-Pinene**	**22**	**14**	**2.1**			
	3-Carene	0.64	0.57				
	d-Limonene	2.7	2.2	1.4			
	g-Terpinene						
	a-Terpineol			0.55			

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.4 House 4 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin						Cout		
		L		M		H		L	M	H
	AER (/h)	0.13	0.13	0.26	0.26	0.41	0.41	0.13	0.26	0.41
H4	Sampling Zone	1	2	1	2	1	2	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	Sample lost due to instrument breakdown	17	10	10	3.8	6.2			
Aldehyde	Butanal		19	6.5	5.8	2.8	3.7	0.25	0.30	
	Hexanal			**133**	**137**	**50**	**68**	**1.3**	**1.4**	**0.78**
	Heptanal		25	11	11	4.1	5.6	0.22		
	Octanal		37	22	21	8.9	12	0.64	0.54	0.26
	Benzaldehyde		19	11	12	6.1	7.8	5.4	4.3	4.9
	Nonanal		20	27	25	13	19	1.7	1.3	0.78
	Decanal		3.3	5.1	2.9	3.9	4.6	1.2	0.86	0.18
Alkane	Heptane		22	5.9	5.9	1.9	2.3	0.33	0.34	0.32
	Octane		22	5.6	5.8	1.8	2.4	0.42	0.46	0.38
	Decane		**73**	**15**	**13**	**3.4**	**4.6**	**0.82**	**0.37**	
	Undecane		66	19	19	5.9	8.1	0.44	0.43	0.40
	Dodecane		34	14	14	5.2	6.8			
	Tetradecane		2.1	1.7	1.6	0.83	1.1			
	Hexadecane		1.4	1.3	0.86	0.64	0.88			
Aromatic	Benzene		1.5			0.25		2.5	2.9	
	Toluene		33	9.5	9.6	3.1	4.3	1.1	1.2	1.1
	Ethylbenzene		8.0	1.9	1.9	0.56	0.81			
	m/p-Xylene		13	3.8	3.8	1.2	1.8	0.33	0.48	0.41
	o-Xylene		**18**	**6.1**	**6.1**	**2.2**	**3.2**	**0.52**	**0.48**	**0.36**
	1,2,4-Trimethylbenzene		9.4	2.7	2.5	0.77	1.1			
	1,2,3-Trimethylbenzene		2.9	0.76	0.77	0.24	0.27			
	Butylbenzene		0.89							
Chlor	Tetrachloroethylene		2.2	0.42	0.45					
	Hexamethylcyclotrisiloxane		27	10	6.8	8.3	8.8	4.6	3.6	1.4
	Octamethylcyclotetrasiloxane		11	3.6	3.2	1.9	2.2	0.75	0.68	0.32
	Decamethylcyclopentasiloxane		**11**	**4.4**	**4.6**	**1.6**	**2.3**	**0.22**	**0.26**	
Ester	TXIB (mono-isomer)		15	13	14	7.4	11	0.31	0.31	
	TXIB (di-isomer)		**6.3**	**4.2**	**6.0**	**2.3**	**4.9**			
Glycol ether	2-Butoxyethanol		24	12	14	4.0	7.0			
Phthalate	Dimethyl phthalate									
	Diethyl phthalate			0.17	0.16					
	Dibutyl phthalate			0.26	0.12					
Terpene HC	**a-Pinene**			**165**	**165**	**57**	**87**	**10**	**8.3**	**5.4**
	3-Carene			64	66	20	30	0.61	0.41	
	d-Limonene		150	44	47	15	26	0.50	0.40	
	g-Terpinene		4.2	1.4	1.3	0.57	1.1			
	a-Terpineol		1.7	1.3	1.4	5.0	7.4			

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.5 House 5 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin			Cout		
		L	M	H	L	M	H
	AER (/h)	0.20	0.37	0.64	0.20	0.37	0.64
H5	Sampling Zone	1	1	1	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	8.2	4.6	3.0			0.07
Aldehyde	Butanal	0.94	0.15	0.60			
	Hexanal	**69**	**26**	**10.0**	**0.62**	**0.38**	**0.60**
	Heptanal	4.3	2.2	1.1	0.09		0.08
	Octanal	8.2	3.9	2.9	0.14		0.11
	Benzaldehyde	13	7.4	5.7	4.6	4.4	5.7
	Nonanal	14	7.0	9.3	0.37	0.24	0.31
	Decanal				0.31	0.22	0.27
Alkane	Heptane	7.4	3.4	1.9	0.14	0.11	0.23
	Octane	0.69	0.50	0.48	0.07	0.07	0.13
	Decane	**3.5**	**1.4**	**0.57**	**0.28**		**0.14**
	Undecane	12	5.3	2.6	0.18	0.06	0.11
	Dodecane	38	17	9.7	0.10	0.07	0.07
	Tetradecane	9.6	5.3	3.7	0.05		0.04
	Hexadecane	3.5	2.4	1.6			
Aromatic	Benzene	2.5	1.0	1.2	0.50	0.31	0.29
	Toluene	13	5.9	2.4	0.72	0.52	1.1
	Ethylbenzene	1.8	0.84	0.37	0.13	0.09	0.23
	m/p-Xylene	5.6	2.6	1.2	0.47	0.31	0.83
	o-Xylene	**2.5**	**1.2**	**0.63**	**0.17**	**0.13**	**0.32**
	1,2,4-Trimethylbenzene	1.7	0.89	0.54	0.13	0.08	0.23
	1,2,3-Trimethylbenzene	0.47	0.24	0.15			
	Butylbenzene	0.12	0.06	0.04			
Chlor	Tetrachloroethylene	0.19	0.10	0.08	0.04		0.06
	Hexamethylcyclotrisiloxane	4.8	2.4	2.5	1.9	0.55	0.52
	Octamethylcyclotetrasiloxane	1.0	0.56	0.37	0.17	0.07	0.07
	Decamethylcyclopentasiloxane	**4.7**	**2.5**	**0.97**	**0.28**	**0.21**	**0.33**
Ester	TXIB (mono-isomer)	24	15	11	0.07	0.06	0.09
	TXIB (di-isomer)	**1.5**	**1.1**	**0.84**	**0.03**		**0.03**
Glycol ether	2-Butoxyethanol	29	17	9.4			0.10
Phthalate	Dimethyl phthalate	0.05	0.05	0.04			
	Diethyl phthalate	0.31	0.30	0.31	0.02		0.03
	Dibutyl phthalate	0.26	0.25	0.31	0.02		
Terpene HC	**a-Pinene**	**19**	**8.0**	**4.6**	**0.09**	**0.08**	**0.12**
	3-Carene	0.76	0.31	0.14			
	d-Limonene	15	5.8	2.2			
	g-Terpinene	0.35	0.12				
	a-Terpineol	1.1	0.61	0.31			

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.6 House 6 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin						Cout		
		L		M		H		L	M	H
	AER (/h)	0.21	0.21	0.30	0.30	0.45	0.45	0.21	0.30	0.45
H6	Sampling Zone	1	2	1	2	1	2	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	9.0	7.8	4.6	3.4	1.2	2.4			
Aldehyde	Butanal	5.4	5.5	5.1	4.4			0.27		
	Hexanal	**102**	**102**	**75**	**59**	**6.9**	**29**	**0.69**	**0.41**	**1.3**
	Heptanal	7.7	7.1	5.5	4.3	1.2	3.0			
	Octanal	19	17	13	9.5	3.3	7.6	0.28	0.32	
	Benzaldehyde	7.1	5.7	5.0	4.1	6.1	8.8	6.0	2.4	7.8
	Nonanal	21	21	15	12	6.3	16	0.73	0.48	1.4
	Decanal	5.1	5.6	4.6	3.2	2.2	5.8	0.42	0.32	
Alkane	Heptane	9.7	8.6	8.6	6.5	0.95	2.0	0.51		
	Octane	1.5	1.5	1.6	1.3	0.58	1.2	0.30		
	Decane	**6.4**	**6.0**	**5.1**	**4.1**	**3.0**	**4.9**	**0.46**		
	Undecane	7.0	6.1	4.3	3.1	2.2	4.7			
	Dodecane	1.9	1.7	1.3	0.89		1.0			
	Tetradecane	4.8	4.5	2.7	2.1	0.94	2.1			
	Hexadecane	2.6	2.8	1.2	1.0	0.68	1.6			
Aromatic	Benzene	1.9	0.82	1.6	1.4	1.8	2.0	1.9	0.51	2.1
	Toluene	17	16	17	12	2.8	4.9	2.3	0.25	1.1
	Ethylbenzene	2.0	1.8	2.1	1.5		0.66			
	m/p-Xylene	5.3	4.8	6.4	4.5	1.0	1.9	0.30		
	o-Xylene	**2.8**	**2.6**	**3.5**	**2.6**	**0.57**	**1.1**			
	1,2,4-Trimethylbenzene	1.8	1.6	1.6	1.2		0.55			
	1,2,3-Trimethylbenzene	0.48	0.41	0.41	0.30					
	Butylbenzene									
Chlor	Tetrachloroethylene	0.78	0.71	0.86	0.69			0.26		
	Hexamethylcyclotrisiloxane	4.4	5.9	3.6	4.3	0.71	4.0	3.7	0.96	1.0
	Octamethylcyclotetrasiloxane	1.3	1.6	0.78	0.78			0.56		
	Decamethylcyclopentasiloxane	**33**	**37**	**31**	**27**	**1.2**	**3.2**	**0.30**		**0.70**
Ester	TXIB (mono-isomer)	3.4	3.0	2.2	1.5		2.0			
	TXIB (di-isomer)	**0.91**	**0.81**	**0.40**	**0.35**		**0.45**			
Glycol ether	2-Butoxyethanol	6.7	6.4	4.9	3.5		2.5			
Phthalate	Dimethyl phthalate									
	Diethyl phthalate									
	Dibutyl phthalate									
Terpene HC	**a-Pinene**	**38**	**33**	**23**	**18**	**3.5**	**6.5**	**0.80**	**0.56**	**2.2**
	3-Carene	24	22	22	16	1.8	4.6			
	d-Limonene	99	58	21	15		1.9			
	g-Terpinene	13	6.2	0.40						
	a-Terpineol	0.53	0.35	0.23	0.15					

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.7 House 1 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin						Cout		
		L		M		H		L	M	H
	AER (/h)	0.11	0.11	0.18	0.18	0.27	0.27	0.11	0.18	0.27
H7	Sampling Zone	1	2	1	2	1	2	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	9.2	10.0	6.1	5.8	6.6	7.6			
Aldehyde	Butanal	7.4	9.0	7.3	7.7					
	Hexanal	**172**	**204**	**148**	**145**	**80**	**87**	**0.72**	**0.43**	**1.00**
	Heptanal	17	20	14	13	9.2	9.5			
	Octanal	31	37	26	26	20	21			0.83
	Benzaldehyde	8.6	9.1	6.9	6.6	5.5	5.6		2.2	5.0
	Nonanal	40	47	34	32	37	36	0.76		1.1
	Decanal	9.2	13	12	12	12	13	0.35		1.2
Alkane	Heptane	5.7	6.5	4.5	4.3	2.2	2.3			
	Octane	3.5	3.7	2.4	2.4	1.8	1.9	0.36		
	Decane	**2.8**	**3.1**	**2.2**	**2.1**	**1.6**	**1.7**			
	Undecane	7.6	8.9	5.8	5.9	3.1	3.8			
	Dodecane	8.6	9.4	5.8	5.7	3.8	4.1			
	Tetradecane	4.6	4.8	2.6	2.5	1.9	2.2			
	Hexadecane	4.2	4.6	2.3	2.2	2.6	2.5			
Aromatic	Benzene	2.7	3.0	0.55	0.60	0.71	0.79	1.1	0.60	1.2
	Toluene	18	18	9.9	9.7	4.5	9.0	0.98	0.67	1.6
	Ethylbenzene	1.5	1.6	1.0	0.97	0.52	0.63			
	m/p-Xylene	3.6	4.0	2.6	2.5	1.3	1.6			
	o-Xylene	**4.0**	**4.6**	**4.8**	**4.7**	**2.0**	**2.2**			
	1,2,4-Trimethylbenzene	1.2	1.3	0.82	0.79	0.34	0.37			
	1,2,3-Trimethylbenzene	0.47	0.53	0.32	0.31					
	Butylbenzene									
Chlor	Tetrachloroethylene						0.24			
	Hexamethylcyclotrisiloxane	5.8	4.5	3.2	4.2	3.5	3.5	3.8	1.4	1.8
	Octamethylcyclotetrasiloxane	1.2	1.0	0.56	0.58	0.46	0.50	0.59		
	Decamethylcyclopentasiloxane	**6.0**	**5.6**	**4.7**	**4.7**	**24**	**11**			**0.34**
Ester	TXIB (mono-isomer)	2.9	2.8	2.1	1.8	2.3	2.4			
	TXIB (di-isomer)	**12**	**9.7**	**6.3**	**6.2**	**5.3**	**6.8**			
Glycol ether	2-Butoxyethanol	22	26	18	17	14	16			
Phthalate	Dimethyl phthalate									
	Diethyl phthalate									
	Dibutyl phthalate									
Terpene HC	**a-Pinene**	**101**	**115**	**70**	**73**	**30**	**32**	**0.57**		**0.63**
	3-Carene	26	28	19	18	7.4	7.8			
	d-Limonene	85	96	17	17	6.7	7.6			
	g-Terpinene	0.72	0.81	0.50	0.48					
	a-Terpineol	1.0	1.1	0.64	0.63	0.32	0.41			

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.8 House 8 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin			Cout		
		L	M	H	L	M	H
	AER (/h)	0.71	0.93	1.19	0.71	0.93	1.19
H8	Sampling Zone	1	1	1	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	4.2	4.5	4.0			0.31
Aldehyde	Butanal						
	Hexanal	**18**	**13**	**11**			
	Heptanal	2.7	2.0	1.8			
	Octanal	7.6	6.3	4.9			
	Benzaldehyde	5.2	4.8	3.8	5.1	5.8	1.1
	Nonanal	22	20	17	0.46	0.31	
	Decanal	8.0	8.0	6.9			
Alkane	Heptane	4.7	4.5	4.8	0.29	0.34	0.44
	Octane	0.94	0.75	0.62	0.48	0.27	0.34
	Decane	**0.57**	**0.53**	**0.48**			
	Undecane	0.67	0.60	0.50			
	Dodecane	0.57	0.57	0.61			
	Tetradecane	2.3	2.1	2.0			
	Hexadecane	3.0	2.8	2.5			
Aromatic	Benzene		0.23	2.7		2.0	1.2
	Toluene	2.0	8.4	3.9	0.89	1.2	1.4
	Ethylbenzene	0.34	0.43	0.44		0.20	0.27
	m/p-Xylene	0.99	1.2	1.3	0.44	0.63	0.90
	o-Xylene	**1.1**	**0.89**	**0.84**		**0.25**	**0.35**
	1,2,4-Trimethylbenzene	0.28	0.31	0.34		0.19	0.30
	1,2,3-Trimethylbenzene						
	Butylbenzene						
Chlor	Tetrachloroethylene		0.11				
	Hexamethylcyclotrisiloxane	6.2	7.4	6.7	6.3	7.3	5.8
	Octamethylcyclotetrasiloxane	1.7	1.7	1.4	1.1	1.1	0.74
	Decamethylcyclopentasiloxane				**0.43**	**0.47**	**0.31**
Ester	TXIB (mono-isomer)	1.1	1.2	1.1			
	TXIB (di-isomer)	**2.2**	**1.9**	**1.7**			
Glycol ether	2-Butoxyethanol	2.8	2.4	3.0			
Phthalate	Dimethyl phthalate						
	Diethyl phthalate	0.36	0.32	0.37			
	Dibutyl phthalate		0.08	0.09			
Terpene HC	**a-Pinene**	**22**	**14**	**11**			
	3-Carene	7.9	6.2	4.6			
	d-Limonene	37	4.2	4.1			
	g-Terpinene	2.3					
	a-Terpineol	0.24	0.24	0.25			

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Table A.9 House 9 measured indoor and outdoor concentrations [µg m^{-3}] at three ventilation rates (L,M,H) sorted by chemical classes

		Cin						Cout		
		L		M		H		L	M	H
	AER (/h)	0.34	0.34	0.56	0.56	1.38	1.38	0.34	0.56	1.38
H9	Sampling Zone	1	2	1	2	1	2	Out	Out	Out
Alcohol	2-Ethyl-1-hexanol	0.96	0.62	0.54	0.22	0.47	0.64			0.52
Aldehyde	Butanal	1.3	1.3	0.43	0.36	0.52	1.0			0.17
	Hexanal	**12**	**19**	**6.2**	**6.9**	**8.2**	**18**	**0.36**		**0.74**
	Heptanal	0.54	0.72	0.41	0.37	0.51	0.98			0.14
	Octanal	1.1	1.4	0.76	0.59	0.84	1.6			0.18
	Benzaldehyde	2.1	3.0	1.3	2.2	2.8	3.3	4.3	1.4	4.3
	Nonanal	1.1	1.6	0.95	0.77	1.1	2.0			0.43
	Decanal	0.73	1.1	0.56	0.49	0.69	1.3			0.29
Alkane	Heptane	0.23	0.24							
	Octane	0.24	0.34	0.22			0.34			
	Decane	**0.86**	**1.3**				**0.33**	**0.93**		
	Undecane	0.43	0.59					0.60		0.16
	Dodecane		0.20				0.14			
	Tetradecane	1.1	1.5	0.49	0.44	0.63	0.95			
	Hexadecane	0.17	0.24				0.18			
Aromatic	Benzene	2.3	1.1	0.92		1.7	0.73	1.3	0.60	1.4
	Toluene	1.5	1.7	0.78	0.71	0.87	1.3	0.82	0.48	1.4
	Ethylbenzene	0.33	0.42	0.16	0.14	0.15	0.21	0.17		
	m/p-Xylene	0.88	1.1	0.32	0.31	0.33	0.41	0.28		0.14
	o-Xylene	**1.8**	**2.0**	**0.44**	**0.37**	**0.56**	**0.74**	**0.22**		
	1,2,4-Trimethylbenzene	0.61	0.83		0.12		0.15	0.74		
	1,2,3-Trimethylbenzene	0.20	0.28			0.77		0.26		
	Butylbenzene									
Chlor	Tetrachloroethylene		0.11							
	Hexamethylcyclotrisiloxane		1.7				3.7			1.00
	Octamethylcyclotetrasiloxane	0.57	0.77			0.81	0.99	0.49		0.77
	Decamethylcyclopentasiloxane	**0.53**	**0.76**	**0.17**	**0.14**	**0.56**	**0.67**	**0.31**	**0.04**	**0.45**
Ester	TXIB (mono-isomer)	0.69	1.7	0.25	0.38	0.33	0.97			
	TXIB (di-isomer)	**2.0**	**3.1**	**0.91**	**0.75**	**1.1**	**1.7**			
Glycol ether	2-Butoxyethanol									
Phthalate	Dimethyl phthalate									
	Diethyl phthalate									
	Dibutyl phthalate									
Terpene HC	**a-Pinene**	**56**	**60**	**10**	**7.7**	**16**	**21**			**0.22**
	3-Carene	0.95	1.1				0.36			
	d-Limonene	3.7	3.8	0.77	0.38	0.81	0.99			
	g-Terpinene	0.24	0.25							
	a-Terpineol									

	Blue	Yellow	Orange	Red
Cin, Cout	0-1	1.1-10	10.1-50	>50

Appendix B: Emission Rates and Concentration Ratios

Table B.1 House 1 concentration ratios, area-specific emission rates [µg/m^{2}h], and emission rate ratios

		Cin/Cout						ER						ERratio	
		L		M		H		L		M		H		L/H	M/H
	AER (/h)	0.19	0.19	0.24	0.24	0.43	0.43	0.19	0.19	0.24	0.24	0.43	0.43		
H1	Sampling Zone	1	2	1	2	1	2	1	2	1	2	1	2		
Alcohol	2-Ethyl-1-hexanol			28	26	40	25	8.0	7.3	8.0	7.5	14	9.0	0.65	0.66
Aldehyde	Butanal	22	29	21	21	28	24	4.6	6.2	4.0	4.1	5.2	4.3	1.1	0.86
	Hexanal		**193**	**38**	**37**	**42**	**29**		**118**	**95**	**94**	**156**	**106**	**0.90**	**0.72**
	Heptanal	31	29	16	17	33	24	5.6	5.3	4.4	4.6	6.9	5.0	0.91	0.75
	Octanal	35	36	15	17	28	19	8.8	9.0	8.9	10	13	9.0	0.79	0.84
	Benzaldehyde	3.8	3.3	8.4	6.9	1.5	0.96	7.1	5.7	9.0	7.2	4.6		1.4	1.8
	Nonanal	2.9	3.9	4.5	5.1	16	12	3.9	5.8	5.3	6.2	11	8.3	0.51	0.61
	Decanal	3.0	3.1	3.6	3.9	7.2	5.3	1.1	1.1	1.2	1.3	2.7	1.9	0.49	0.57
Alkane	Heptane	7.4	6.5	8.3	8.1			1.5	1.3	1.0	1.0	1.3	0.89	1.3	0.95
	Octane	3.1	2.7	4.6	5.0			0.90	0.74	0.67	0.73	0.90	0.62	1.1	0.92
	Decane							**4.7**	**4.0**	**2.5**	**2.7**	**3.4**	**2.3**	**1.5**	**0.91**
	Undecane					19	13	2.9	2.8	1.9	1.9	3.0	2.0	1.2	0.76
	Dodecane							2.5	2.2	1.7	1.5	3.2	1.9	0.93	0.63
	Tetradecane			19	19	32	21	2.9	2.6	2.2	2.2	5.0	3.2	0.67	0.54
	Hexadecane			7.3	7.2			1.2	1.0	0.89	0.87	2.4	1.6	0.55	0.44
Aromatic	Benzene	0.28	1.1			0.97	1.5		0.11		0.67		1.0	0.11	0.64
	Toluene	5.9	5.3	10	10	7.0	4.3	3.6	3.2	2.7	2.6	3.8	2.1	1.2	0.90
	Ethylbenzene					29	16	4.2	3.5	3.2	3.0	5.1	2.8	0.99	0.79
	m/p-Xylene	55	44			32	17	11	8.8	9.0	8.0	15	7.5	0.90	0.76
	o-Xylene					**27**	**16**	**6.0**	**6.5**	**5.6**	**5.1**	**7.7**	**4.6**	**1.0**	**0.86**
	1,2,4-Trimethylbenzene							1.8	1.5	1.2	1.2	2.2	1.4	0.93	0.65
	1,2,3-Trimethylbenzene							0.91	0.82	0.67	0.65	1.6	0.96	0.68	0.52
	Butylbenzene							0.27	0.23	0.17	0.17	0.34	0.25	0.86	0.58
Chlor	Tetrachloroethylene							0.19	0.17	0.14	0.14	0.29	0.19	0.75	0.59
	Hexamethylcyclotrisiloxane	0.47	0.44	1.5	1.9	1.0	2.3			0.92	1.8	0.00	3.0		0.89
	Octamethylcyclotetrasiloxane	2.2	1.9	7.0	7.5	5.6	4.6	0.93	0.72	1.9	2.1	1.9	1.5	0.48	1.2
	Decamethylcyclopentasiloxane	**16**	**11**	**25**	**27**	**18**	**13**	**4.3**	**2.9**	**2.9**	**3.1**	**4.2**	**2.9**	**1.0**	**0.85**
Ester	TXIB (mono-isomer)							1.5	1.5	1.5	1.8	3.0	2.4	0.55	0.63
	TXIB (di-isomer)							**0.79**	**0.48**	**0.78**	**0.52**	**1.7**	**0.91**	**0.48**	**0.49**
Glycol ether	2-Butoxyethanol							3.0	4.3	3.3	3.8	6.3	5.7	0.60	0.59
Phthalate	Dimethyl phthalate												0.10		
	Diethyl phthalate												0.15		
	Dibutyl phthalate							0.05				0.10	0.36	0.20	
Terpene HC	**a-Pinene**	**417**	**550**	**147**	**139**	**42**	**31**	**86**	**114**	**92**	**86**	**84**	**61**	**1.4**	**1.2**
	3-Carene		782		601	54	34		128		135	139	87	1.1	1.2
	d-Limonene			200	211	87	63	41	38	30	32	40	29	1.1	0.89
	g-Terpinene							1.1	0.99	1.1	0.99	1.2	0.92	1.00	0.98
	a-Terpineol							1.1	0.96	0.97	1.1	1.8	1.4	0.65	0.64

Emission Ratio	0-1	>1

Table B.2 House 2 concentration ratios, area-specific emission rates [μg/m²h], and emission rate ratios

		Cin/Cout			ER			ERratio	
		L	M	H	L	M	H	L/H	M/H
	AER (/h)								
R2	Sampling Zone				1	1	1		
Alcohol	2-Ethyl-1-hexanol	Outdoor VOCs data not collected			1.0	1.0	2.2	0.47	0.46
Aldehyde	Butanal								
	Hexanal				**19**	**7.7**	**26**	**0.71**	**0.30**
	Heptanal				0.52	0.40			
	Octanal				1.1	0.89	3.1	0.36	0.29
	Benzaldehyde				0.79	1.3	2.3	0.34	0.57
	Nonanal				2.1	2.0	5.3	0.39	0.37
	Decanal				1.9	1.7	8.5	0.22	0.20
Alkane	Heptane				0.75				
	Octane				0.25				
	Decane				**0.25**				
	Undecane				0.31				
	Dodecane				0.18				
	Tetradecane				0.20				
	Hexadecane				0.22	0.61			
Aromatic	Benzene								
	Toluene				1.2	0.57	1.0	1.1	0.56
	Ethylbenzene				0.17				
	m/p-Xylene				0.39				
	o-Xylene				**0.22**				
	1,2,4-Trimethylbenzene								
	1,2,3-Trimethylbenzene				0.34				
	Butylbenzene								
Chlor	Tetrachloroethylene								
	Hexamethylcyclotrisiloxane				9.8	15	35	0.28	0.44
	Octamethylcyclotetrasiloxane				0.31	0.33	0.81	0.39	0.40
	Decamethylcyclopentasiloxane				**1.2**	**0.43**	**0.91**	**1.3**	**0.47**
Ester	TXIB (mono-isomer)				0.37	0.61	3.7	0.10	0.17
	TXIB (di-isomer)								
Glycol ether	2-Butoxyethanol								
Phthalate	Dimethyl phthalate								
	Diethyl phthalate								
	Dibutyl phthalate								
Terpene HC	**a-Pinene**				**7.9**	**1.3**	**2.8**	**2.8**	**0.45**
	3-Carene				0.19				
	d-Limonene				1.0				
	g-Terpinene								
	a-Terpineol				0.30				

Emission Ratio	0-1	>1

Table B.3 House 3 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout			ER			ERratio	
		L	M	H	L	M	H	L/H	M/H
	AER (/h)								
R3	Sampling Zone				1	1	1		
Alcohol	2-Ethyl-1-hexanol	Outdoor VOCs data not collected			1.4	2.1	2.0	0.72	1.0
Aldehyde	Butanal								
	Hexanal				**31**	**32**	**16**	**1.9**	**2.0**
	Heptanal				0.73	1.0			
	Octanal				1.7	2.5	2.9	0.58	0.85
	Benzaldehyde				1.7	1.9	2.2	0.74	0.85
	Nonanal				3.5	5.6	6.3	0.55	0.89
	Decanal				2.3	3.5	6.9	0.33	0.52
Alkane	Heptane				0.76	1.0			
	Octane				0.33	0.49			
	Decane				**0.26**	**0.32**			
	Undecane				0.24	0.34			
	Dodecane				0.23	0.14			
	Tetradecane				0.29	0.43	1.1	0.26	0.39
	Hexadecane				0.25	0.41	2.0	0.13	0.21
Aromatic	Benzene								
	Toluene				1.6	2.2	4.3	0.38	0.52
	Ethylbenzene				0.22	0.32			
	m/p-Xylene				0.55	0.71			
	o-Xylene					**0.37**			
	1,2,4-Trimethylbenzene								
	1,2,3-Trimethylbenzene								
	Butylbenzene								
Chlor	Tetrachloroethylene								
	Hexamethylcyclotrisiloxane				12	20	56	0.22	0.35
	Octamethylcyclotetrasiloxane				0.42	0.67	1.4	0.31	0.49
	Decamethylcyclopentasiloxane				**1.5**	**2.5**	**1.6**	**0.95**	**1.6**
Ester	TXIB (mono-isomer)				0.48	1.3	4.4	0.11	0.29
	TXIB (di-isomer)					**0.42**	**1.1**		**0.37**
Glycol ether	2-Butoxyethanol								
Phthalate	Dimethyl phthalate								
	Diethyl phthalate								
	Dibutyl phthalate								
Terpene HC	**a-Pinene**				**9.3**	**9.7**	**4.3**	**2.2**	**2.3**
	3-Carene								
	d-Limonene				1.2	1.6	2.7	0.42	0.57
	g-Terpinene								
	a-Terpineol						1.1		

Emission Ratio	0-1	>1

Table B.4 House 4 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout						ER						ERratio	
		L		M		H		L		M		H		L/H	M/H
	AER (/h)	0.13	0.13	0.26	0.26	0.41	0.41	0.13	0.13	0.26	0.26	0.41	0.41		
H4	Sampling Zone	1	2	1	2	1	2	1	2	1	2	1	2		
Alcohol	2-Ethyl-1-hexanol								6.4	7.9	8.1	4.6	7.6	1.1	1.3
Aldehyde	Butanal		76	21	19				7.4	4.8	4.3	3.4	4.5	1.9	1.1
	Hexanal			**93**	**96**	**64**	**87**			**103**	**106**	**61**	**83**		**1.4**
	Heptanal		113						9.5	8.5	8.3	5.0	6.9	1.6	1.4
	Octanal		58	40	39	34	47		14	17	16	11	15	1.1	1.3
	Benzaldehyde		3.5	2.4	2.8	1.2	1.6		5.2	4.9	6.0	1.5	3.6	2.0	2.1
	Nonanal		12	20	19	17	24		7.2	20	19	15	22	0.39	1.0
	Decanal		2.8	5.9	3.3	22	26		0.83	3.3	1.6	4.6	5.4	0.17	0.49
Alkane	Heptane		68	17	17	6.1	7.4		8.7	4.3	4.3	2.0	2.5	3.9	1.9
	Octane		52	12	13	4.7	6.4		8.5	4.0	4.2	1.7	2.5	4.0	1.9
	Decane		**89**	**41**	**35**				**28**	**11**	**9.7**	**4.2**	**5.7**	**5.7**	**2.1**
	Undecane		150	44	43	15	20		26	15	14	6.7	9.4	3.2	1.8
	Dodecane								13	11	11	6.4	8.4	1.8	1.5
	Tetradecane								0.81	1.3	1.2	1.0	1.4	0.66	1.0
	Hexadecane								0.54	0.99	0.67	0.78	1.1	0.58	0.89
Aromatic	Benzene		0.58									0.31			
	Toluene		30	7.6	7.7	2.8	4.0		13	6.4	6.5	2.5	4.0	3.9	2.0
	Ethylbenzene								3.1	1.5	1.5	0.69	1.00	3.7	1.7
	m/p-Xylene		38	7.9	7.9	3.0	4.3		4.9	2.6	2.6	1.0	1.7	3.7	1.9
	o-Xylene		**35**	**13**	**13**	**6.1**	**8.9**		**6.9**	**4.4**	**4.4**	**2.3**	**3.5**	**2.4**	**1.5**
	1,2,4-Trimethylbenzene								3.7	2.1	2.0	0.95	1.3	3.3	1.8
	1,2,3-Trimethylbenzene								1.1	0.59	0.60	0.30	0.33	3.6	1.9
	Butylbenzene								0.35						
Chlor	Tetrachloroethylene								0.86	0.33	0.35				
	Hexamethylcyclotrisiloxane		5.9	2.8	1.9	5.9	6.3		8.9	5.2	2.5	8.4	9.1	1.0	0.44
	Octamethylcyclotetrasiloxane		14	5.4	4.8	6.0	7.0		3.9	2.3	2.0	1.9	2.3	1.8	1.0
	Decamethylcyclopentasiloxane		**49**	**17**	**18**				**4.2**	**3.3**	**3.4**	**2.0**	**2.9**	**1.7**	**1.4**
Ester	TXIB (mono-isomer)		47	44	45				5.6	10	11	9.1	13	0.50	0.94
	TXIB (di-isomer)								**2.5**	**3.3**	**4.7**	**2.8**	**6.1**	**0.55**	**0.89**
Glycol ether	2-Butoxyethanol								9.3	9.1	11	4.9	8.7	1.4	1.5
Phthalate	Dimethyl phthalate														
	Diethyl phthalate									0.13	0.13				
	Dibutyl phthalate									0.20	0.09				
Terpene HC	**a-Pinene**			**20**	**20**	**11**	**16**			**123**	**122**	**64**	**101**		**1.5**
	3-Carene			158	163					50	51	24	37		1.7
	d-Limonene		301	110	117				58	34	36	19	32	2.3	1.4
	g-Terpinene								1.6	1.1	0.98	0.71	1.3	1.6	1.00
	a-Terpineol								0.68	0.98	1.1	6.2	9.1	0.09	0.14

Emission Ratio	0-1	>1

Table B.5 House 5 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout			ER			ERratio	
		L	M	H	L	M	H	L/H	M/H
	AER (/h)	**0.20**	**0.37**	**0.64**	**0.20**	**0.37**	**0.64**		
H5	**Sampling Zone**	**1**	**1**	**1**	**1**	**1**	**1**		
Alcohol	2-Ethyl-1-hexanol			41	5.4	5.6	6.2	0.88	0.90
Aldehyde	Butanal				0.62	0.19	1.3	0.49	0.15
	Hexanal	**112**	**68**	**17**	**45**	**31**	**20**	**2.3**	**1.6**
	Heptanal	47		13	2.7	2.7	2.0	1.3	1.3
	Octanal	60		26	5.3	4.7	5.9	0.90	0.80
	Benzaldehyde	2.9	1.7	1.00	5.7	3.6			
	Nonanal	37	29	30	8.8	8.2	19	0.46	0.43
	Decanal								
Alkane	Heptane	53	29	8.4	4.8	3.9	3.6	1.3	1.1
	Octane	9.8	7.3	3.7	0.41	0.52	0.74	0.55	0.70
	Decane	**12**		**3.9**	**2.1**	**1.7**	**0.89**	**2.4**	**1.9**
	Undecane	67	90	22	7.9	6.4	5.2	1.5	1.2
	Dodecane	369	264	133	25	21	20	1.2	1.0
	Tetradecane	186		89	6.3	6.5	7.7	0.82	0.84
	Hexadecane				2.3	3.0	3.5	0.67	0.86
Aromatic	Benzene	5.0	3.4	3.9	1.3	0.90	1.8	0.71	0.49
	Toluene	18	11	2.2	8.0	6.6	2.7	2.9	2.4
	Ethylbenzene	14	9.0	1.6	1.1	0.91	0.28	3.9	3.2
	m/p-Xylene	12	8.4	1.4	3.4	2.8	0.68	5.0	4.2
	o-Xylene	**15**	**9.7**	**2.0**	**1.5**	**1.3**	**0.65**	**2.4**	**2.1**
	1,2,4-Trimethylbenzene	13	11	2.4	1.0	0.98	0.67	1.6	1.5
	1,2,3-Trimethylbenzene				0.31	0.29	0.31	0.99	0.93
	Butylbenzene				0.08	0.07	0.08	0.99	0.83
Chlor	Tetrachloroethylene	4.8		1.3	0.10	0.12	0.04	2.5	2.8
	Hexamethylcyclotrisiloxane	2.5	4.3	4.9	1.9	2.2	4.3	0.45	0.53
	Octamethylcyclotetrasiloxane	5.8	7.8	5.0	0.54	0.59	0.63	0.86	0.93
	Decamethylcyclopentasiloxane	**17**	**12**	**3.0**	**2.9**	**2.8**	**1.4**	**2.1**	**2.0**
Ester	TXIB (mono-isomer)	338	270	120	16	19	23	0.68	0.82
	TXIB (di-isomer)	**56**		**30**	**0.98**	**1.3**	**1.7**	**0.57**	**0.75**
Glycol ether	2-Butoxyethanol			99	19	21	20	0.96	1.0
Phthalate	Dimethyl phthalate				0.03	0.06	0.07	0.43	0.76
	Diethyl phthalate	13		12	0.19	0.37	0.60	0.31	0.61
	Dibutyl phthalate	11			0.15	0.31	0.65	0.24	0.47
Terpene HC	**a-Pinene**	**217**	**99**	**39**	**12**	**9.6**	**9.4**	**1.3**	**1.0**
	3-Carene				0.50	0.38	0.30	1.7	1.3
	d-Limonene				10	7.0	4.6	2.2	1.5
	g-Terpinene				0.23	0.15			
	a-Terpineol				0.71	0.74	0.65	1.1	1.1

Emission Ratio	0-1	>1

Table B.6 House 6 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout						ER						ERratio	
		L		M		H		L		M		H		L/H	M/H
	AER (/h)	0.21	0.21	0.30	0.30	0.45	0.45	0.21	0.21	0.30	0.30	0.45	0.45		
H6	Sampling Zone	1	2	1	2	1	2	1	2	1	2	1	2		
Alcohol	2-Ethyl-1-hexanol							4.6	4.0	3.4	2.6	1.3	2.7	2.1	1.5
Aldehyde	Butanal	20	21					2.7	2.7	3.8	3.3				
	Hexanal	**149**	**149**	**182**	**144**	**5.3**	**22**	**52**	**52**	**56**	**44**	**6.2**	**31**	**2.8**	**2.7**
	Heptanal							4.0	3.7	4.1	3.2	1.4	3.3	1.6	1.6
	Octanal	66	61	40	30			9.5	8.8	9.2	6.9	3.7	8.4	1.5	1.3
	Benzaldehyde	1.2	0.95	2.1	1.7	0.79	1.1	0.58		2.0	1.3		1.1	0.51	1.4
	Nonanal	28	29	30	24	4.5	12	10	10	11	8.4	5.4	17	0.94	0.86
	Decanal	12	13	14	9.8			2.4	2.7	3.2	2.1	2.4	6.4	0.58	0.61
Alkane	Heptane	19	17					4.7	4.2	6.5	4.9	1.1	2.2	2.7	3.5
	Octane	4.8	4.9					0.60	0.60	1.2	0.94	0.64	1.3	0.61	1.1
	Decane	**14**	**13**					**3.1**	**2.9**	**3.8**	**3.1**	**3.3**	**5.4**	**0.68**	**0.79**
	Undecane							3.6	3.1	3.2	2.3	2.4	5.2	0.89	0.73
	Dodecane							1.00	0.89	0.97	0.67		1.1	0.84	0.72
	Tetradecane							2.5	2.3	2.0	1.6	1.0	2.3	1.5	1.1
	Hexadecane							1.3	1.4	0.91	0.75	0.75	1.8	1.1	0.66
Aromatic	Benzene	0.97	0.42	3.2	2.7	0.90	0.99			0.85	0.66				
	Toluene	7.4	6.7	69	49	2.6	4.6	7.8	6.8	13	9.0	1.9	4.3	2.4	3.5
	Ethylbenzene							1.0	0.95	1.6	1.2		0.74	1.3	1.9
	m/p-Xylene	18	16					2.6	2.4	4.8	3.4	1.1	2.1	1.6	2.6
	o-Xylene							**1.5**	**1.3**	**2.6**	**2.0**	**0.63**	**1.2**	**1.5**	**2.5**
	1,2,4-Trimethylbenzene							0.92	0.82	1.2	0.89		0.61	1.4	1.7
	1,2,3-Trimethylbenzene							0.25	0.21	0.30	0.22				
	Butylbenzene														
Chlor	Tetrachloroethylene	2.9	2.7					0.27	0.23	0.64	0.52				
	Hexamethylcyclotrisiloxane	1.2	1.6	3.7	4.5	0.68	3.8	0.32	1.1	2.0	2.5		3.2	0.23	0.70
	Octamethylcyclotetrasiloxane	2.3	2.8					0.38	0.52	0.59	0.58				
	Decamethylcyclopentasiloxane	**111**	**125**			**1.8**	**4.7**	**17**	**19**	**23**	**20**	**0.58**	**2.8**	**10.6**	**12.7**
Ester	TXIB (mono-isomer)							1.8	1.5	1.6	1.1		2.2	0.75	0.63
	TXIB (di-isomer)							**0.47**	**0.42**	**0.30**	**0.26**		**0.50**	**0.89**	**0.56**
Glycol ether	2-Butoxyethanol							3.5	3.3	3.7	2.6		2.7	1.2	1.2
Phthalate	Dimethyl phthalate														
	Diethyl phthalate														
	Dibutyl phthalate														
Terpene HC	**a-Pinene**	**47**	**40**	**41**	**31**	**1.6**	**3.0**	**19**	**16**	**17**	**13**	**1.4**	**4.8**	**5.7**	**4.8**
	3-Carene							13	12	16	12	1.9	5.1	3.4	4.1
	d-Limonene							51	30	16	11		2.1	19.2	6.3
	g-Terpinene							6.9	3.2	0.30					
	a-Terpineol							0.27	0.18	0.17	0.11				

Emission Ratio	0-1	>1

Table B.7 House 7 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout						ER						ERratio	
		L		M		H		L		M		H		L/H	M/H
	AER (/h)	0.11	0.11	0.18	0.18	0.27	0.27	0.11	0.11	0.18	0.18	0.27	0.27		
H7	Sampling Zone	1	2	1	2	1	2	1	2	1	2	1	2		
Alcohol	2-Ethyl-1-hexanol							2.5	2.7	2.7	2.5	4.4	5.1	0.55	0.55
Aldehyde	Butanal							2.0	2.5	3.2	3.3				
	Hexanal	**239**	**283**	**345**	**340**	**80**	**87**	**47**	**56**	**64**	**63**	**53**	**57**	**0.93**	**1.2**
	Heptanal							4.6	5.5	5.9	5.8	6.2	6.4	0.81	0.94
	Octanal					24	26	8.6	10	11	11	13	14	0.71	0.85
	Benzaldehyde			3.2	3.0	1.1	1.1	2.4	2.5	2.0	1.9	0.37	0.39	6.4	5.2
	Nonanal	52	62			34	34	11	13	15	14	24	24	0.50	0.61
	Decanal	26	37			11	11	2.4	3.5	5.2	5.2	7.5	8.2	0.38	0.66
Alkane	Heptane							1.6	1.8	2.0	1.9	1.5	1.5	1.1	1.3
	Octane	9.7	10					0.86	0.91	1.0	1.0	1.2	1.3	0.71	0.84
	Decane							**0.76**	**0.86**	**0.94**	**0.92**	**1.1**	**1.1**	**0.73**	**0.84**
	Undecane							2.1	2.4	2.5	2.6	2.1	2.6	0.97	1.1
	Dodecane							2.4	2.6	2.5	2.5	2.6	2.7	0.93	0.95
	Tetradecane							1.3	1.3	1.1	1.1	1.3	1.5	0.93	0.81
	Hexadecane							1.2	1.3	1.0	0.96	1.7	1.7	0.71	0.58
Aromatic	Benzene	2.4	2.7	0.91	0.99	0.59	0.65	0.45	0.53						
	Toluene	18	19	15	15	2.9	5.7	4.7	4.7	4.0	3.9	2.0	4.9	1.4	1.2
	Ethylbenzene							0.40	0.44	0.44	0.42	0.35	0.42	1.1	1.1
	m/p-Xylene							0.99	1.1	1.1	1.1	0.89	1.1	1.1	1.1
	o-Xylene							**1.1**	**1.3**	**2.1**	**2.1**	**1.3**	**1.5**	**0.85**	**1.5**
	1,2,4-Trimethylbenzene							0.32	0.35	0.36	0.34	0.23	0.25	1.4	1.5
	1,2,3-Trimethylbenzene							0.13	0.14	0.14	0.13				
	Butylbenzene														
Chlor	Tetrachloroethylene												0.16		
	Hexamethylcyclotrisiloxane	1.5	1.2	2.3	3.1	1.9	1.9	0.54	0.19	0.80	1.2	1.1	1.1	0.32	0.90
	Octamethylcyclotetrasiloxane	2.0	1.7					0.16	0.12	0.24	0.25	0.31	0.34	0.44	0.77
	Decamethylcyclopentasiloxane					**70**	**33**	**1.6**	**1.5**	**2.0**	**2.1**	**16**	**7.3**	**0.14**	**0.18**
Ester	TXIB (mono-isomer)							0.81	0.76	0.90	0.77	1.5	1.6	0.50	0.53
	TXIB (di-isomer)							**3.3**	**2.7**	**2.8**	**2.7**	**3.6**	**4.5**	**0.74**	**0.67**
Glycol ether	2-Butoxyethanol							6.1	7.2	7.6	7.5	9.4	11	0.67	0.76
Phthalate	Dimethyl phthalate														
	Diethyl phthalate														
	Dibutyl phthalate														
Terpene HC	**a-Pinene**	**178**	**204**			**47**	**51**	**28**	**32**	**31**	**32**	**19**	**21**	**1.5**	**1.5**
	3-Carene							7.1	7.7	8.1	8.0	5.0	5.2	1.4	1.6
	d-Limonene							23	26	7.3	7.3	4.5	5.1	5.2	1.5
	g-Terpinene							0.20	0.22	0.22	0.21				
	a-Terpineol							0.28	0.30	0.28	0.28	0.21	0.27	1.2	1.1

Emission Ratio	0-1	>1

Table B.8 House 8 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout			ER			ERratio	
		L	M	H	L	M	H	L/H	M/H
	AER (/h)	**0.71**	**0.93**	**1.19**	**0.71**	**0.93**	**1.19**		
H8	**Sampling Zone**	**1**	**1**	**1**	**1**	**1**	**1**		
Alcohol	2-Ethyl-1-hexanol			13	8.5	12	13	0.67	0.93
Aldehyde	Butanal								
	Hexanal				**37**	**35**	**39**	**0.95**	**0.90**
	Heptanal				5.5	5.4	6.1	0.90	0.89
	Octanal				15	17	17	0.92	1.0
	Benzaldehyde	1.0	0.82	3.5	0.23		9.1	0.03	
	Nonanal	47	66		43	53	58	0.75	0.92
	Decanal				16	21	24	0.69	0.90
Alkane	Heptane	16	13	11	8.9	11	15	0.59	0.73
	Octane	2.0	2.7	1.8	0.94	1.3	0.95	0.99	1.3
	Decane				**1.2**	**1.4**	**1.6**	**0.71**	**0.87**
	Undecane				1.4	1.6	1.7	0.80	0.93
	Dodecane				1.2	1.5	2.1	0.56	0.74
	Tetradecane				4.8	5.6	7.0	0.68	0.80
	Hexadecane				6.1	7.6	8.6	0.71	0.88
Aromatic	Benzene		0.12	2.3			5.2		
	Toluene	2.3	7.2	2.8	2.3	19	8.5	0.26	2.3
	Ethylbenzene		2.2	1.7	0.70	0.63	0.61	1.2	1.0
	m/p-Xylene	2.3	1.9	1.5	1.1	1.5	1.5	0.76	1.0
	o-Xylene		**3.5**	**2.4**	**2.2**	**1.7**	**1.7**	**1.3**	**1.0**
	1,2,4-Trimethylbenzene		1.6	1.1	0.57	0.31	0.15	3.9	2.1
	1,2,3-Trimethylbenzene								
	Butylbenzene								
Chlor	Tetrachloroethylene					0.28			
	Hexamethylcyclotrisiloxane	0.99	1.0	1.2		0.07	3.1		0.02
	Octamethylcyclotetrasiloxane	1.5	1.5	1.9	1.2	1.6	2.4	0.50	0.66
	Decamethylcyclopentasiloxane								
Ester	TXIB (mono-isomer)				2.2	3.2	3.8	0.58	0.84
	TXIB (di-isomer)				**4.4**	**5.1**	**5.9**	**0.75**	**0.86**
Glycol ether	2-Butoxyethanol				5.6	6.5	10	0.55	0.63
Phthalate	Dimethyl phthalate								
	Diethyl phthalate				0.73	0.86	1.3	0.58	0.69
	Dibutyl phthalate					0.21	0.30		0.69
Terpene HC	**a-Pinene**				**46**	**38**	**37**	**1.2**	**1.0**
	3-Carene				16	17	16	1.0	1.1
	d-Limonene				75	11	14	5.4	0.80
	g-Terpinene				4.6				
	a-Terpineol				0.49	0.63	0.87	0.56	0.73

Emission Ratio	0-1	>1

Table B.9 House 9 concentration ratios, area-specific emission rates [µg/m²h], and emission rate ratios

		Cin/Cout						ER						ERratio	
		L		M		H		L		M		H		L/H	M/H
	AER (/h)	0.34	0.34	0.56	0.56	1.38	1.38	0.34	0.34	0.56	0.56	1.38	1.38		
H9	Sampling Zone	1	2	1	2	1	2	1	2	1	2	1	2		
Alcohol	2-Ethyl-1-hexanol					0.92	1.2	0.92	0.59	0.86	0.34		0.49	1.5	1.2
Aldehyde	Butanal					3.1	6.2	1.2	1.3	0.68	0.57	1.4	3.4	0.52	0.26
	Hexanal	**32**	**64**			**11**	**15**	**11**	**18**	**9.8**	**11**	**29**	**66**		**0.22**
	Heptanal					3.6	6.8	0.52	0.69	0.65	0.58	1.4	3.3	0.26	0.26
	Octanal					4.8	9.3	1.0	1.3	1.2	0.94	2.6	5.7	0.28	0.26
	Benzaldehyde	0.49	0.81	0.93	0.93	0.64	0.75								
	Nonanal					2.5	4.6	1.0	1.5	1.5	1.2	2.5	6.0	0.30	0.32
	Decanal					2.4	1.6	0.70	1.0	0.89	0.77	1.6	1.9	0.50	0.48
Alkane	Heptane							0.22	0.24						
	Octane							0.24	0.33	0.35			1.3	0.21	0.27
	Decane	**0.92**	**1.4**						**0.32**				**1.3**	**0.25**	
	Undecane	0.72	0.87												
	Dodecane								0.20				0.53	0.37	
	Tetradecane							1.0	1.4	0.78	0.69	2.4	3.7	0.39	0.24
	Hexadecane							0.16	0.24				0.69	0.29	
Aromatic	Benzene	1.7	0.87	1.5		1.2	0.39	0.93		0.51		1.3		0.72	0.39
	Toluene	1.8	2.5	1.6	1.5	0.64	0.95	0.63	0.95	0.47	0.36				
	Ethylbenzene	1.9	3.0					0.15	0.27	0.25	0.22	0.57	0.81	0.30	0.35
	m/p-Xylene	3.1	4.9			2.3	2.9	0.58	0.86	0.50	0.50	0.74	1.0	0.81	0.56
	o-Xylene	**8.3**	**11**					**1.6**	**1.7**	**0.70**	**0.58**	**2.2**	**2.9**	**0.65**	**0.25**
	1,2,4-Trimethylbenzene	0.84	1.1						0.04		0.18		0.60	0.07	0.30
	1,2,3-Trimethylbenzene	0.80	0.70									3.0			0.00
	Butylbenzene														
Chlor	Tetrachloroethylene								0.10						
	Hexamethylcyclotrisiloxane						3.7		1.6				10	0.15	
	Octamethylcyclotetrasiloxane	1.2	2.0			1.1	1.3	0.08	0.36			0.18	0.87	0.42	
	Decamethylcyclopentasiloxane	**1.7**	**1.7**	**4.1**	**0.14**	**1.2**	**1.5**	**0.22**	**0.31**	**0.21**		**0.42**	**0.84**	**0.41**	**0.33**
Ester	TXIB (mono-isomer)							0.66	1.6	0.39	0.60	1.3	3.8	0.46	0.20
	TXIB (di-isomer)							**2.0**	**3.0**	**1.4**	**1.2**	**4.4**	**6.7**	**0.45**	**0.24**
Glycol ether	2-Butoxyethanol														
Phthalate	Dimethyl phthalate														
	Diethyl phthalate														
	Dibutyl phthalate														
Terpene HC	**a-Pinene**					**71**	**93**	**54**	**58**	**16**	**12**	**61**	**80**	**0.80**	**0.20**
	3-Carene							0.92	1.1				1.4	0.73	
	d-Limonene							3.6	3.7	1.2	0.60	3.2	3.9	1.0	0.26
	g-Terpinene							0.23	0.24						
	a-Terpineol														

Emission Ratio	0-1	>1