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Experiments to Evaluate and Implement Passive Tracer Gas Methods to Measure Ventilation Rates in Homes

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October 2012

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Acknowledgment:
Funding was provided by the U.S. Dept. of Energy Building Technologies Program, Office of Energy Efficiency and Renewable Energy under DOE 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.

Executive Summary

This report documents a series of intensive experiments to investigate the performance of a common approach to measuring air exchange rate and airflow in residences using continuous passive emitters of perfluorocarbon tracers (PFT). The experiments were designed to identify optimal implementation procedures and limitations in the use of the method in residences and other multizone building environments.

Tracer techniques are the only methods that are capable of measuring the actual airflow between building zones and the outdoors. The measurement of airflows is crucial to understanding the convective transport of air, heat and contaminants for both energy and indoor air quality studies. Airflow through a home requires energy for thermal conditioning, helps dilute the concentrations of pollutants emitted by indoor sources and brings in pollutants from the outdoors. The air exchange rate is required in order to calculate the emission rate of indoor pollutants from measured indoor concentrations.

The direct measurement of the air exchange rate in homes is most often accomplished with tracer gas techniques. One method involves either real-time injections of tracer gases or real-time monitoring of tracer concentrations. These techniques often require expensive in-field instrumentation and highly trained personnel to use the equipment, making the method impractical for larger, more cost-constrained studies. Another common method to measure air exchange rate is called the passive tracer method, often referred to as the "PFT" method. It involves using passive emitters to continuously release a tracer gas (often at a rate that is temperature dependent) that is not released by any common indoor sources and either passive or active collection of air samples that are later analyzed to determine the concentration of tracer in air and thus the air exchange rate. The PFT technique can be implemented using small, relatively inexpensive, and relatively easy to use tracer sources and samplers. Sampling can occur over shorter periods for greater resolution or over longer periods to determine a time-weighted average air exchange rate. The PFT technique is particularly attractive for use in occupied homes as it can be implemented with unobtrusive equipment. Perfluorocarbons are the most commonly used tracer gases (and the ones we use herein); however, the results should be applicable to any appropriate tracer gas.

This report documents experiments performed in three homes to assess the methodology used to determine air exchange rates using passive tracer techniques. The experiments used four different tracer gases emitted simultaneously but implemented with different spatial coverage in the home. Two different tracer gas sampling methods were used. The results characterize the factors of the execution and analysis of the passive tracer technique that affect the uncertainty in the calculated air exchange rates. These factors include uncertainties in tracer gas emission rates, differences in measured concentrations for different tracer gases, temporal and spatial variability of the concentrations, the comparison between different gas sampling methods, and the effect of different ventilation conditions.

The results show that tracer gas emission rates from different emitters vary from 2 to 11 percent, and individual emitters show day-to-day variations of between 1.6 to 4.5 percent.

The primary reason for this variability in emission rates is variability in the temperature of the emitter, and indicate that careful control and measurement of emitter temperatures are necessary to reduce the uncertainty in tracer gas emission rates.

The spatial variabilities of measured tracer gas concentrations were affected by differences in the number and placement of emitters as well as the ventilation conditions in the home. The spatial variability of tracer gas concentrations was minimized when a central ventilation system fan, reflecting more effective mixing of the tracer gas throughout the home. With the central system fan operating continuously, the average relative standard deviation of the spatially resolved tracer gas concentrations had values of approximately 10 percent.

The experiments documented in this report resulted in much more data - both spatially and temporally - than is normally collected using the common PFT methods. Furthermore, multiple tracer gases were used in the same home in order to provide redundant measures of tracer concentrations and the resulting air exchange rates. To our knowledge no such data set has ever been collected before. Subsequent analyses of this data set will be used to recommend best practices for measurements of air exchange rate using the constant injection method as well as to assess the overall capability of passive tracer gas techniques to determine air change rates. These analyses are not part of this report.

Introduction

Individuals spend a significant portion of time in indoor environments like homes, schools, and workplaces [Klepeis et al, 2001]. Thus, exposure to air pollutants in the indoors is an important part of our overall exposure to pollutants. The ventilation of buildings with outdoor air is the primary process that is used to remove pollutants from indoor sources, thus reducing pollutant concentrations in indoor spaces. Much building ventilation currently occurs by the uncontrolled infiltration of air through the building envelope. National efforts to improve building energy efficiency have focused on reducing this uncontrolled air infiltration by making homes more airtight. In the absence of mechanical ventilation, this reduced infiltration can lead indoor exposures in excess of health standards. Thus, it is important to characterize building ventilation rates to understand indoor exposures as well as to devise ventilation schemes to provide acceptable indoor air quality.

Ventilation is often measured as an air exchange rate, or the rate at which air in the building is replaced. Air exchange rate varies as a function of HVAC operation, meteorological conditions, and changes in the configuration of the building envelope (e.g. windows open or closed). The most common approach to directly measure the air exchange rate in homes is to use tracer gas techniques. The two most common tracer gas methods are constant injection rate and decay rate methods [Basset et al, 1981; Condon et al, 1981; Dietz et al, 1982; Grot, 1980; Harrje and Grot, 1977]. The decay rate method entails the injection of a tracer gas and measuring the decay in real time over a few hours [Basset et al, 1981]. The method provides a good measurement of the air exchange rate, but requires trained technicians to be onsite and only allows for the air exchange rate to be

determined over short time-scales. Such techniques are well suited to research-grade investigations or very small sample sizes, but are often impractical for larger, more cost-constrained studies. The constant injection method involves placing a number of emission sources of one or more tracer gases in a house together with samplers to measure the concentration of the gas over a period of time that can range from hours to days [Condon et al, 1980]. The time-averaged air exchange rate is determined from the volume of gas tracer emitted into the house and the concentration of that tracer measured by the sampler. This method, often termed the *passive tracer method*, was pioneered by Brookhaven National Laboratory, and consists of small relatively inexpensive tracer sources and samplers that can be used to measure gas concentration either passively or actively and that require limited time and training to use [Dietz and Cote, 1982].

The small size of the sources and samplers, the ability to use passive samplers, and the ability to sample over a wide range to times from hours to weeks has led to the constant injection technique to be used in field projects that require the measurement of the air exchange rate in large numbers of homes [e.g. Clayton et al., 1993; Ozkaynak et al., 1996; Weisel et al., 2005; Offermann, 2009]. There is general guidance regarding the number of gas sources that should be placed based on the total area of the space [ASTM 2000]. Sources and samplers are placed in a specific home based on the convenience for occupants and engineering judgment. There is little analysis of the uncertainty of the air exchange rate determined by using this method [D'Ottavio et al, 1988; Sherman, 1988]. The factors that affect measurement uncertainty include uncertainties in the tracer emission rate, the measured tracer concentration, the time rate of change in the tracer concentration, and the spatial variability of tracer concentration within the house. Some of the early papers investigate some of these uncertainties [Dietz and Cole, 1982; Leaderer et al, 1985], but do not explicitly discuss the implications for the resulting air exchange rate.

To explore this issue, extensive measurements were carried out in three homes. The measurements varied the tracer gasses used, the number of and locations of emitters and samplers, and the operation of ventilation and central forced air systems. The objectives of the study were to determine best practices for measurements of air exchange rate using the constant injection method with regards to tracer gas selection, placement of samplers and emitters, and the use of fans for air mixing, and to assess the overall capability of passive tracer gas techniques to determine air change rates. This report provides details on the methods, experimental plan, and an initial presentation of the results. Future manuscripts will report on more detailed analyses of the results.

Methods

Tracer Gases

There are a number of perfluorocarbon (PFT) gases that can be used as tracer gas sources for airflow studies (Dietz and Cote, 1982; Fisk et al, 1993). The gases that we have either used or investigated for use in homes are listed in Table 1. The PFTs range in molecular weight (MW) from 186 to 350. The lighter PFTs, HB, OT, CPB, and OB, can be measured using a gas chromatograph with a mass spectrometer as a detector (GC-MS). This analysis method is useful when measuring both airflow and volatile organic compounds because both gases can be collected and analyzed using a single sampling media. All of the PFTs can

be analyzed using a gas chromatograph with an electron capture detector (GC-ECD). The GC-ECD at LBNL, however, is currently configured to analyze the heavier PFTs; PDCB, PMCH, and mPDCH.

Table 1: PFTs used or investigated as tracer gases for airflow studies

Tracer Label	Formula	MW	Chemical Name
PDCB	C_6F_{12}	300	perfluorodimethylcyclobutane
PMCH	C_7F_{14}	350	perfluoromethylcyclohexane
mPDCH	C_8F_{16}	400	perfluoro-1,3-dimethylcyclohexane
HB	C_6F_6	186	hexafluorobenzene
OT	C_7F_8	236	octafluorotoluene
CPB[1]	C_6ClF_5	202.5	chloro-pentafluorobenzene
PB	C_6HF_5	168	pentafluorobenzene

PFT tracers are liquid at room temperature. PDCB, PMCH, and mPDCH have been used extensively in ventilation and airflow experiments, and have established methods for their release and measurement. The four lighter PFT gases in Table 1 were identified and investigated to provide a selection of tracers that can be analyzed using the GC-MS. While characterizing these PFTs, both CPB and PB were identified to have chemical properties that make them too dangerous to use as tracer gases. Subsequent development of sampling and analysis methods detailed in this report focused on HB, which was the tracer selected for use in experiments that required GC-MS anallysis.

Emission Methods and Characterization

All tracer sources were prepared by placing an amount of an individual tracer into a glass vial. Three different sizes of vials, 4-dram, 2-dram, and ½-dram were used. These vials are standard sizes and commercially available. Each vial was topped with a screw cap that had a large hole in the top. For the heavier PFTs gases, a silicon rubber septa approximately 2 mm thick was sandwiched between the vial and the cap, forming a seal through which the tracer gas diffuses. An example of a vial is show in Figure 1. The vials containing the lighter PFTs needed a silicone septa with a Teflon lining instead of the silicon rubber septa as the latter resulted in emission rates that were too large. The emission rate of the tracer gas from the vial depends upon the temperature of the vial, the diameter of the septa end cap, the septa material and thickness, the vial orientation (cap up or down), and the type of tracer. The average emission rates of PDCH, PMCH, and mPDCH characterized during ventilation experiments previously performed by LBNL in commercial buildings are shown in Table 2 (Fisk et al, 1993). The data clearly show the emission rate increasing with septa diameter, which increases with vial size.

[1] Strictly speaking CPB and PB are not PFTs, as they contain elements other than carbon and fluorine.

Figure 1: Emission vial for PFT sources. The photo on the left shows the vial cap and rubber septa insert separated. The photo on the right shows the assembled vial with septa inserted into the vial cap.

Emission rates are determined by the weight loss of the vials over time. Vial weights are measured at the start and end of an experiment, and periodically during the experiment if possible. The quantity of tracer necessary for any individual experiment depends upon the emission rate from the vial. It is important to ensure that the concentration of PFT in the home is comfortably above the detection limit of the analysis method. More than one vial may be necessary to achieve sufficient concentrations. For a specific vial size and septa material, temperature and vial orientation are the most important factors that influence the emission rate. Temperature is particularly important, as experimental conditions may not allow for temperature control of the vial. Thus characterizing the effect of temperature on the emission rate of the tracer is necessary to quantify the amount of tracer released during any individual experiment.

Table 2: Average room temperature emission rates of PDCB, PMCH, and mPDCH in μg/hr.

	Septa Diameter	PDCB	PMCH	mPDCH
	mm	μg/hr	μg/hr	μg/hr
½ dram	8	333	250	125
2 dram	13	833	833	333
4 dram	22	2450	1667	833

The effect of temperature on the emission rate of PFTs was investigated in the laboratory for most of the gases listed in Table 1. The emission rate of the four lighter PFTs, HB, OT, CPB, and PB, were measured at four temperatures ranging from 15 to 30 °C (covering the range of expected indoor temperatures likely encountered in homes). Three ½ dram vials with each of the lighter PFTs were placed in a small glass chamber kept at a constant temperature using a water bath. Each vial was weighed once a day over a 5 to 7 day period.

The results are shown in Figure 2. The emission rate of two of the heavier PFTs, PDCB and PMCH, were measured at temperatures between 39 and 45 °C. (These elevated temperatures can be necessary to achieve stable vial temperatures under experimental conditions where the ambient temperatures are high.) Two 4 dram vials of both PFTs were placed in a holder kept at a constant temperature using a block heater. The change in the weight of the vial was weighed 6 times over an approximately 3-week period. The results are shown in Figure 3. The emission rates in both Figure 2 and Figure 3 show an exponential dependence on temperature. The fitted exponentials for each PFT are noted next to the curve for that PFT. The emission rate of heavier PFTs, PDCB and PMCH, show a greater temperature dependence than the lighter PFTs.

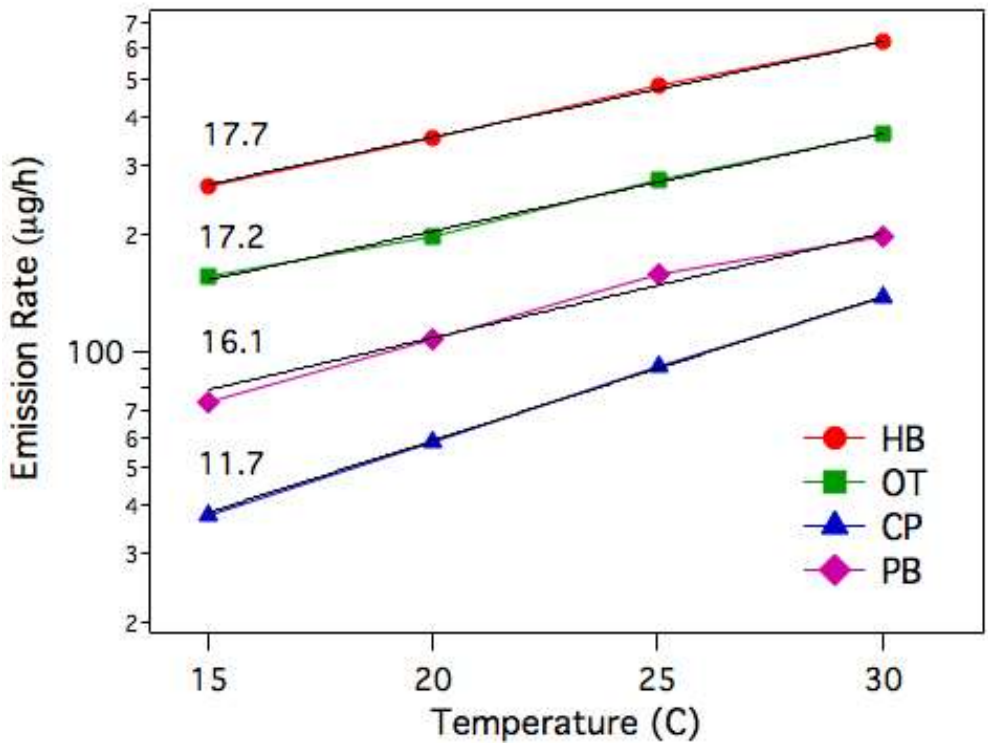

Figure 2: Emission rate of HB, OT, CP, and PB in µg/h as a function of temperature. The data were fitted using the exponential form, ER = A exp(B/Temp in °C). Only the resulting fitted exponential constants, B, are listed for each PFT.

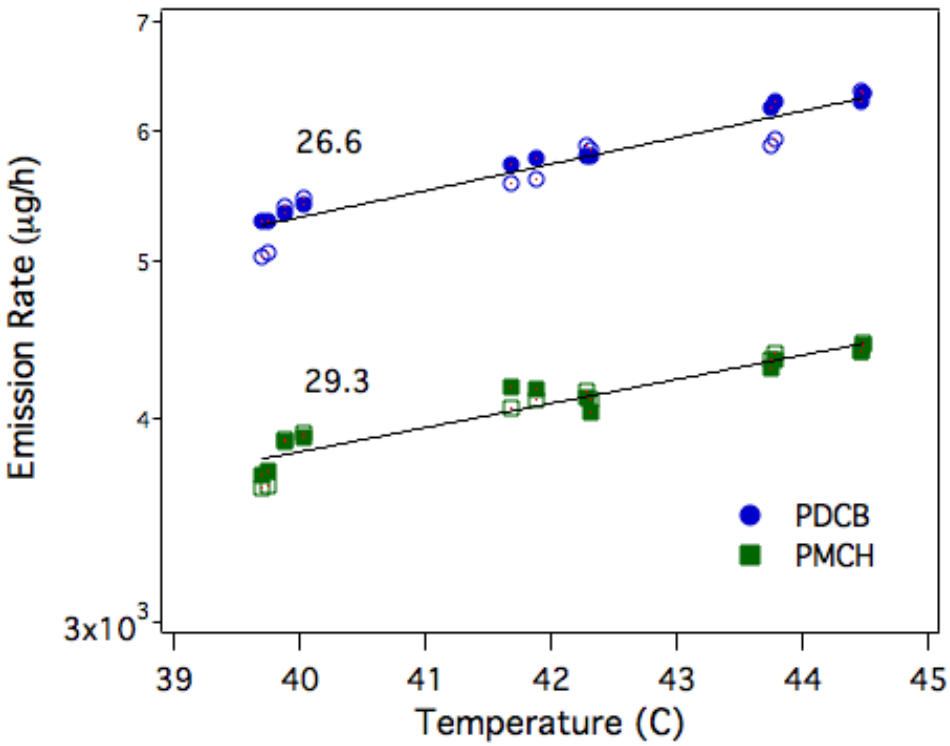

Figure 3: Emission rate of PDCB and PMCH in µg/h as a function of temperature. The data were fitted using the exponential form, ER = A exp(B/Temp in °C). Only the resulting fitted exponential constants, B, are listed for each PFT.

There have been concerns that emission rates can be significantly altered when emitters are placed in imperfect locations that can impede or alter flow from the emitter. To examine this issue, emission rates were measured for emitters configured in non-ideal ways. 4 dram vials of PDCB were placed in block heaters with a set point of 38 °C, and the actual temperature of the heating block was measured. All vials were placed in a fume hood at the same time. The vials were either covered with foil, left uncovered but with a fan blowing over the heater, or left in the normal, uncovered configuration. All vials were placed with the septa facing down. Each vial was weighed once a day over an approximately 2-week period. The emission rates from two unheated vials were measured at the same time. The results are shown in Figure 4. The PDCB emission rates shown in Figure 3 are re-plotted as well and are denoted as "uncovered, higher temps." The emission rates show an exponential dependence on temperature for temperatures ranging from room temperature to 45 °C. The fitted exponent constant of 24.5 is close to the value of 26.6 that resulted from the fit to the PDCB concentrations over the smaller range of temperatures shown in Figure 3, and equates to a change in emission rate of ~ 4 percent for a 1°C change in temperature. Note that the temperatures for the vials that had fans blowing air over them were approximately 6 degrees lower than the set point of 38 °C, the uncovered vials were approximately 3 degrees below the set point, and the vials covered with foil were at the set point. The covered vials have emission rates that are ~3 percent higher than the fitted exponential temperature dependence while the vials with the fan blowing over them had emission rates that were ~6 percent lower, showing that the physical conditions of the emitters do affect emission rates. These variations in the emission rates over those predicted by the temperature dependence are on the same order

of magnitude of the change in emission rate for a 1°C change in temperature. Thus, while temperature control is of primary importance to accurately characterize experimental tracer gas emission rates, unsuitable emitter placement can result in similar variability in emission rates.

Limited experiments were performed to investigate the differences in emission rates between vials oriented with the septa upward versus septa downward. The results showed that the emission rates are higher when the septa are facing downward. The emission rate of HB at room temperature was approximately 6% higher when the septa placed downward, while the emission rate of PMCH and PDCB at an average of 41 °C were approximately 30% higher when placed downward. The variability in emission rates was also higher for upward orientation. Thus, it is important to maintain a consistent emitter orientation in the test environment.

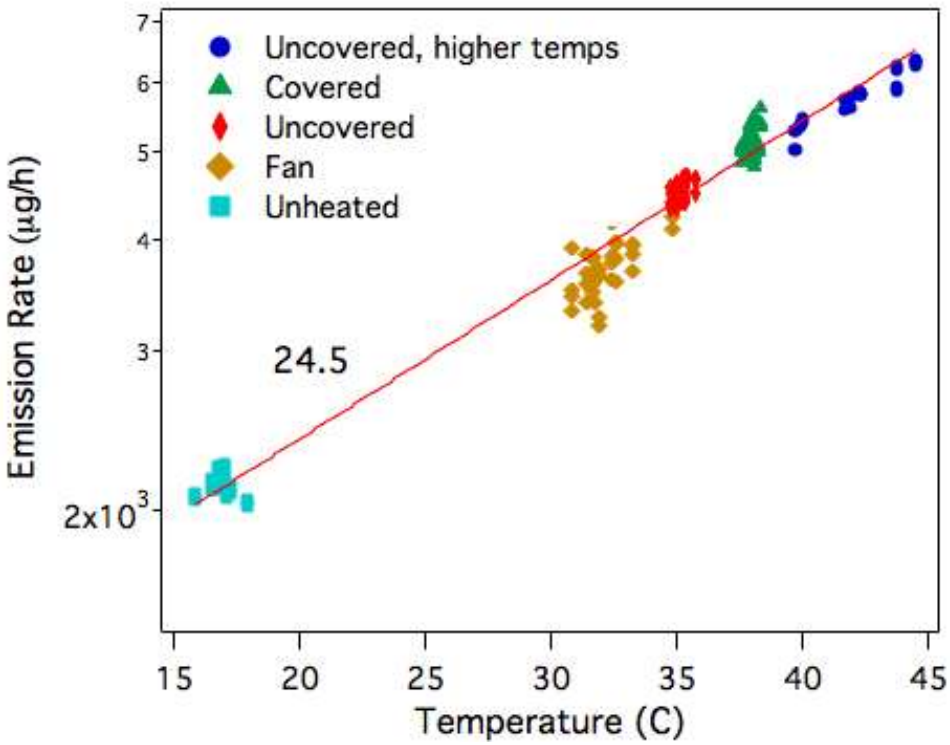

Figure 4: Emission rate of PDCB in µg/h as a function of temperature. All vials were uncovered in a fume hood with the exception of those marked covered, which were covered with foil, and fan, which has a fan blowing over vials. The data were fitted using the exponential form, ER = A exp(B/Temp), and the resulting fitted constant B is shown.

Tracer gas sampling

The method used to measure the concentration of the different tracer gases depends upon the specific compound. PDCB, PMCH, and mPDCH concentrations are measured using a gas chromatograph with an electron capture detector (GC-ECD). The other, HB, is measured using a gas chromatograph with a mass spectrometer as a detector (GC-MS). These two instruments require different sampling media. The GC-ECD is configured to accept samples from gas filled bags while the GC-MS is configured to extract samples from sorbent filled

stainless steel tubes. Detailed descriptions of the measurement techniques for the different sampling media are outlined below.

The bag samples require active sampling, collected either manually or using programmable grab sample collectors. The samples were collected in 750 ml polyethylene-lined bags (Cali-5-Bond™ Sampling Bags; Calibrated Instruments, Inc.; Hawthorne, NY), which are chemically inert. The bags allow for a sample of approximately 200 cubic centimeters. Previous tests conducted at LBNL have shown that the PFT tracers are stable in the bags over a period of several months, with reanalysis of the same bag resulting in the same concentration (D.Black, 2012, personal communication).

Passive samples were collected on stainless steel thermal desorption (TD) tubes (0.6 cm OD × 17.5 cm L, Supelco) containing approximately 180 mg of Tenax®-TA 60/80 mesh adsorbent. The TD tubes were stored in capped transport cylinders. Sampling started by removing the tube from the cylinder, capping one end, and placing a protective cover over the inlet. This protective cover is open to gas diffusion but has a stainless steel mesh that ensures that nothing else (e.g. dust or insects) can get into the tube. The sampling rate for the tubes was determined at room temperature (23 °C ± 2 °C) in a continuous stirred, flow through chamber with a constant source of target chemicals where concentration measurements were collected simultaneously using both active and passive sampling. The sampling rate was determined by comparing the mass on the passive tube to the measured concentration determined by active sampling. The samplers have been calibrated for durations of between 2 and 10 days. Temperature effects are expected to be minor for indoor applications. The TD tubes were conditioned prior to each use under a helium purge (~ 30 cc/min) for 30 minutes at 315 °C in batches of 10 tubes. Conditioned tubes (analytical blanks) were routinely analyzed to confirm target PFTs were below method quantification limits.

Trace Gas Analysis

Gas sample bags for the tracers PDCB, PMCH, and mPDCH were analyzed using an Agilent 6890N dual column, dual detector gas chromatograph (GC) equipped with model G2397A electron capture detectors (ECDs). The GC was configured with an external oven and two different columns. One of these columns was paired with an ECD and dedicated to separation and detection of the PFTs. The total run time for each sample was 1.5 minutes. Sample introduction was done using a VICI/Valco valve equipped with a 0.25 ml sample loop. The PFT analyses were performed with the oven at 180° C and ECD temperature set at 300° C, with P5 (5% methane/95% argon) as carrier gas and make-up gas flow to the detectors. Chromatographic resolution of the analytes was achieved using a 30 m x 0.53 mm i.d. megabore Alumina porous layer open tubular (PLOT) column (J & W Scientific).

The GC was calibrated at the beginning of each sample analysis day using 11 PFT standards ranging in concentration from 0.8 to 15.1 ppb (PDCB), 0.61 to 11.64 ppb (PMCH), and 0.71 to 12.7 ppb (mPMCH) and a standard containing zero air. These standards were produced by performing careful dilutions from a gas mixture in a calibrated gas cylinder. A calibration curve was constructed for each tracer. Analysis of dilutions of the lowest calibration standards has shown that the values of PFT concentrations below 0.05 ppb are considered below the limit of detection. The precision of the measurements is 5 percent.

The results of some ventilation experiments in the current study led to concerns regarding the calibration of the GC for PDCB and PMCH. Experiments where both tracers were released in the same space resulted in different ventilation rates, and the ratio of the rates calculated using the two tracer gases was constant over a range of ventilation rates. The calibration gases used for the last several years have not been certified to a significant degree of precision by the vendor. Their concentrations had been independently verified by carefully conducted tests using know emission rates into carefully measured volumes of air. However, there was no experimental verification of the verified concentration of PDCB in the primary calibration cylinder. New verifications of the concentrations of PDCB, PMCH, and mPDCH were performed using know tracer gas concentrations in calibration bags provided by Lagus Applied Technologies (Escondido, CA, www.tracergas.com). The results showed that, while the concentration of the PMCH and mPDCH in the calibration cylinder were correct, the concentration of PDCB was a multiple of 0.77 less than the value that we had been using. This result emphasizes the importance of instrument calibration and the difficulties obtaining and creating standards. All concentration data measured using the GC-ECD system has been corrected to reflect this error in the calibration of PDCB.

HB was quantitatively analyzed by thermal-desorption gas chromatography/mass spectrometry (TD-GC/MS) generally following U.S. EPA Method TO-17, "Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes" (U.S. EPA 1999). The main difference is that for the HB tracer, a selected ion method (SIM) was used to target the specific chemical and improve instrument sensitivity. Prior to analysis, a gaseous internal standard (ISTD) was added to each sampler by syringe then the tube was purged with helium flow (25 mL/min) in the sampling direction for three minutes. The ISTD was 120 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.

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 a Tenax-TA filled glass liner. Tubes were desorbed at 20 mL/min (solvent vent mode) at a starting temperature of 25 °C with a 0.5 minute delay followed by a 60 °C/min ramp to 330 °C and a 1 minute hold time with the transfer line temperature at 275 °C. The cryogenic inlet was held at 1 °C throughout desorption then heated within 0.1 minutes to 250 °C at a rate of 12 °C/s and held for 2 minutes. Injection flow was splitless (column flow) from 0.0 (start of injection) to 2.25 minutes. After injection, the vent flow was returned to 20 mL/min.

The tracer gas concentration was determined using 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 °C held for 2 minutes then ramped to 70 °C at 10 °C/min then to 250 °C at 20 °C/min holding 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 analyte was detected using electron impact MS (5973; Agilent Technologies) operated in selected ion mode using mass 117 as the target ion for

hexafluorobenzene, HB, and 186 as confirmation ion. Masses 174, 176 were scanned for the BFB internal standard. The MS temperature settings were 240 °C, 230 °C and 150 °C for the transfer line, MS source and MS quad, respectively. The target compound was quantified by multi-point calibrations prepared with pure standard using BFB as an internal standard.

Experimental Details

Tracer gas experiments were conducted under controlled ventilation conditions in three different homes. The house ventilation was primarily controlled by the adjusting the operation of the central forced air system. Four different perfluorocarbon tracer gases were used. Emitters for the different gases were placed in different configurations within each home to investigate the effect of tracer placement on the resulting measured ventilation rates, as well as to investigate different placement strategies. The use of a large number of samplers in the home enabled the measurement of the variability of tracer concentrations in the house, and the effect of that variability on the ventilation rate. The intent of the experiments was to investigate ventilation rates for the whole house treated as a single zone rather than measuring flows between zones within the home. The differences in the concentrations measured in different zones was used to suggest processes that influence the measurement of the air exchange rate such as inadequate mixing and flow directionalities. The objectives are to provide guidance on the best way to configure and locate sources and samplers to measure ventilation rates, to determine how the configuration of the house influences the measurements, and to assess the uncertainty in the resulting measured air exchange rate.

The tracer gas concentrations in the homes were sampled using both passive and active methods. The active method collected bag samples using programmable samplers. The instrument pulls the ambient gas through a manifold that directs the sample into one of 15 individual bags. The program allows for each bag to collect a sample over a specified number of minutes, and moves through the bags in order. A picture of the inside of the sampler showing the sample manifold and bags is shown in Figure 5. The instrument samples at a constant flow rate of 200 cc/min. The program directs the instrument to sample from this inlet stream into a specified bag at short intervals of a few seconds. As a result, the total sample in any individual bag is not an integrated sample over the entire sampling period specified for that bag. Instead, it consists of a series of shorter samples, or "grab" samples, that were collected at regular time intervals over the sampling period. While this technique does not take continuous samples over the sampling period, when gas concentrations are changing slowly in time, i.e. several times longer than the time interval of the sample, the resulting sample will adequately characterize the average concentration of the tracer over the sampling period.

Figure 5: The programmable active tracer gas sampling device. The picture on the left side shows detail of the sampling manifold and installed sample bags. The installed sampler is shown on the right, with the inlet to the instrument mounted to the top.

During these experiments, the gas sample was drawn through approximately 0.6 m of 1.7 mm inside diameter copper tubing, seen at the top of the sampler in Figure 5, resulting in a sampling inlet located approximately one meter above floor level. The samplers were programmed to collect a contiguous series of 15-bag samples over a 22.5-hour sample period. Each bag sample consisted of 1-second samples collected at approximate 10-minute intervals over a 90-minute time period, for a total sample volume of approximately 200 cubic centimeters.

The passive samplers used in the experiment were the stainless steel desorption tubes described above. One of these samplers, as installed, is shown in Figure 6. The passive samples required multi-day sampling times to ensure that the resulting sampled tracer mass was well above the detection limit of the GC-MS method. This requirement dictated the length of the experiment for a given ventilation configuration. We conducted experiments over a three-day period. Over three days, the integrated volume sampled by the desorption tubes was 0.89 L. The average concentration of the tracer gas over the three-day time period was determined by dividing the mass of the tracer measured by the GC-MS divided by this sample volume. Three sets of 15 active bag samples were obtained during each period, one set per day. The tracer emitters were placed in each home at least two days before sampling began in order for the concentrations in the house to reach a steady concentration.

Figure 6: A stainless steel desorption tube passive tracer gas sampler as installed. The sampler is attached to the end of the copper tubing inlet to the active sampler, which is directly behind the desorption tube in the image. The cap is attached to the lower left side of the tube and the protective cap is on the upper right side.

Dry block heaters (VWR Heatblock I) were used to keep the PFT emitter vials at a constant temperature to reduce the variability in emissions due to variations in temperature. The active part of the heater was a recessed rectangular area into which an aluminum block was placed, shown in Figure 7. We used blocks that had four cylindrical wells that were 35 mm in diameter. The tracer vials were placed upside down inside these wells. The aluminum block provides a large heated volume surrounding the tracer liquid. The aluminum blocks also had a small hole in the center into which we placed a temperature probe to verify the temperature of each heater. A Hobo temperature logger was used (Onset Computer Corp., model HOBO pro series) to record the temperature of the aluminum block. The block heaters had a precision of +/- 1°C. (The majority of the block heaters had a digital temperature set point. One of the block heaters had an analog set point that had a precision of +/- 2°C.) The earlier discussion of the effect of temperature on emission rates indicates that a precision of +/- 1°C results in an uncertainty in the emission rate of PDCB of ~8 percent. PMCH and mPDCH should have similar uncertainties, with a slightly smaller uncertainty in the emission rate of HB.

Figure 7: A dry block heater used to keep the PFT sources at a constant temperature. The tracer vials can be seen placed upside down in the blue-colored aluminum block. The temperature logger is to the right of the heater.

Experimental House Descriptions

Experimental House 1 is a 92.9 m^2, single-story home constructed in 1943 and located in Berkeley, CA. A floor plan of the house is shown in Figure 8 as well as the zones defined for the experiment. The structure is wood-frame construction over a crawl space. It has a mixed wood siding and stucco exterior, sliding aluminum frame double-pane windows with shades, 2.4 m ceiling height, and a forced air heating system with ducts located in the crawl space and registers in the floors. The house was determined to have an envelope leakage of 13 ACH50. The measured fan flow of the heating system was 924 cfm. The leakage characteristics of the ducts were measured at 78 and 87 cfm for the supply and return, respectively. The house is located in a residential neighborhood surrounded by mature trees and homes of similar height and age. The terrain in the neighborhood was flat, with moderate level of sheltering.

Eight heated emitter blocks were used in this house. All eight of the heater blocks had PMCH and HB, four heater blocks had PDCB, and two heaters had mPDCH. The different emitter locations are shown in Figure 8 and indicate which PFTs were placed in each location. The emitters containing all four PFTs were placed in the areas that were judged to be the best locations to provide house coverage, i.e., central, open locations with good communication to other parts of the house. One of these locations, the hallway adjacent to the heating system return, was hypothesized to result in good mixing of the PFTs emitted at that location throughout the house when the system fan is running.

The experiment used 10 active samplers and 10 passive samplers, with locations shown in Figure 8. In this house, the living, dining, and kitchen spaces were essentially one open contiguous space with no doorways and minimal partitions. The active samplers were placed with at least one sampler in every room of the house. The three samplers located in the living room that were closest to the kitchen had the sampling inlets at different heights to measure a vertical distribution of gas concentrations, with inlets at approximately 0.3, 1 and 2 meters above the floor. The passive samplers were placed with some co-located with active samplers, some at locations that are often used for ventilation experiments (i.e., using locations that do not interfere with normal household activities), and some were affixed to horizontal surfaces. The passive samplers located in the dining room, hallway, and half bath were secured to overhead locations; on a light fixture in the dining room and half bath, and on the attic access handle in the hallway. The passive samplers in the master bedroom, office, hallway, and the middle elevation of the living room locations were co-located with active samplers.

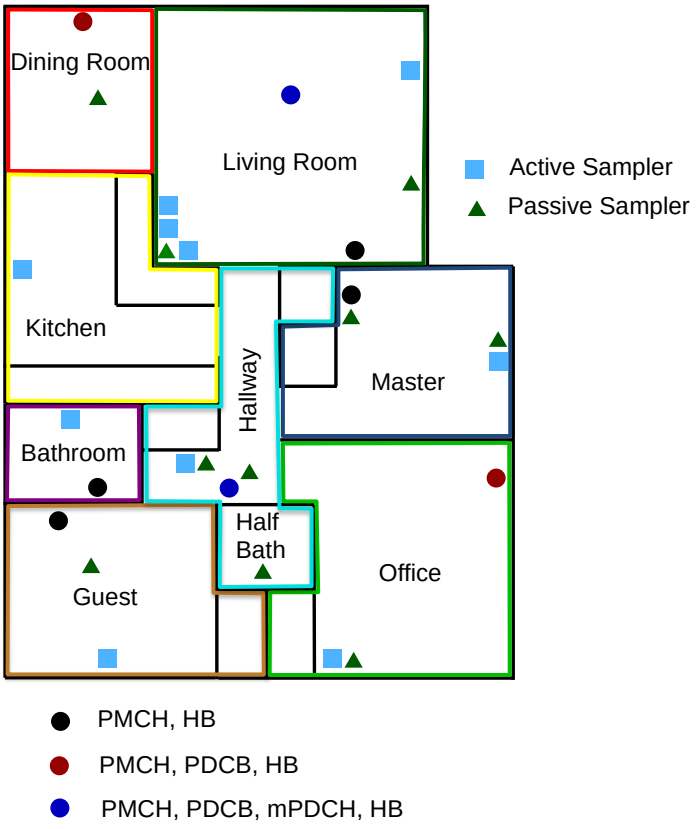

Figure 8: Floor plan of House 1 showing the locations of PFT emitters denoted by circles and tracer sampling locations denoted by squares and triangles for active and passive samplers, respectively. Different colors surround the zones defined for the house.

Experimental House 2 is a 325 m^2, single-story home constructed around 1960 located in Moraga, CA. A floor plan of the house is shown in Figure 9 as well as the zones defined for this experiment. The structure is wood-frame construction over a crawl space. It has a

wood siding exterior and sliding, vinyl framed, double-paned windows. The house has two different HVAC systems. The primary system services the majority of the house and a secondary system services the wing containing the master bedroom that begins at the doorway between the family room and the master hallway. The primary system has an economizer. The HVAC air supply registers are located in the floors. The returns for the primary systems are located in the ceiling of the front and back of the main hallway as well as in the kitchen above the door to the dining room. The return for the secondary system is in the master bedroom hallway. The ceiling heights in most of the home are 2.5 m, with the exception being the vaulted ceiling in the kitchen and family room with a peak height of 3.5 m. The house was measured to have an envelope leakage of 9.2 ACH50. The measured fan flow of the primary HVAC system was 1322 cfm. The leakage of the ducts in this system was measured at 94 and 149 cfm for the supply and return, respectively. The measured fan flow of the secondary HVAC system was 637 cfm. The leakage of the ducts in this system was measured at 147 and 212 cfm for the supply and return, respectively.

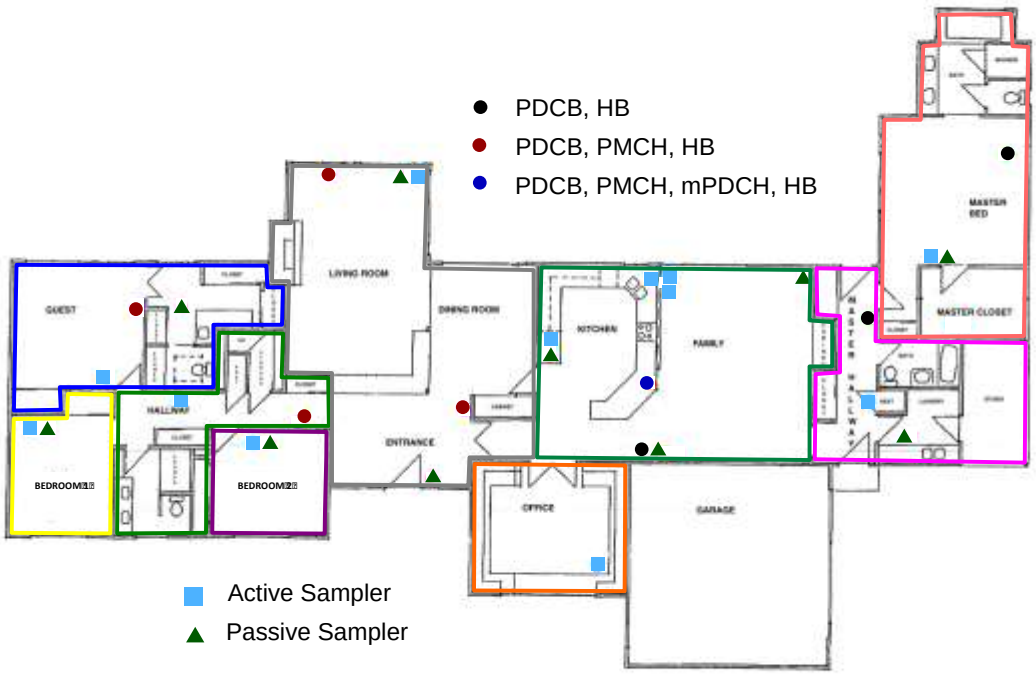

Figure 9: Floor plan of House 2 showing the locations of PFT emitters denoted by circles and tracer sampling locations denoted by squares and triangles for active and passive samplers, respectively. Different colors surround the zones in the house.

Eight heated emitter blocks were used in the house. Their locations are shown in Figure 9 labeled by the PFTs emitted in by location. Only one heater block had emitter vials for all three PFTs: PMCH, PDCB, and mPDCH. Four blocks had emitters for PMCH and PDCB and three blocks had only PDCB. This emitter was located next to the stovetop. As in House 1, all heater blocks had vials for HB. The PDCB emitters were placed throughout the house. PMCH emitters, however, were only placed in the half of the house with the living room and bedrooms.

Twelve active and 10 passive samplers were used in House 2, with placement locations shown in Figure 9. The active samplers were placed to ensure one sampler in each zone of the house. The samplers in the house hallway and master hallway were placed near the two HVAC returns. As in House 1, the three active samplers located on the wall between the kitchen and family room had their inlets modified to measure the vertical distribution of tracer concentration. The heights of these inlets were approximately 1, 2, and 3.5 meters above the floor. The passive samplers in the bedroom 1, bedroom 2, living room, kitchen, and master bedroom were co-located with active samplers. The other samplers were placed at positions that were of interest either on their own or by comparison with a nearby active sampler. For example, one passive sampler was placed near the laundry room exhaust fan.

Experimental House 3 is a 237 m^2, three-story home constructed in 2007 and located in Sausalito, CA. Figure 10 gives a floor plan of the house as well as outlines of the zones defined for each floor. The structure is wood-frame construction on a concrete slab. It has a wood sided exterior, sliding aluminum frame windows, 3 m ceiling heights, and a forced air heating system. The heating system supplies were located in the floors. The return was on the first floor on the wall above the entrance to the guest bedroom. The study, laundry room, and closet on the third floor were serviced by the HVAC system. The measured envelope leakage of the house was 8.8 ACH50. The measured fan flow of the heating system was 1133 cfm.

The experiments in this house used 9 heated emitter blocks with three located on each floor. The heater blocks on the first floor contained emitter vials for PMCH, those on the second had PDCB and the third floor had mPDCH. As in the previous experiments, all of the heater blocs had vials for HB. The heated emitter blocks were placed in the primary zones on each floor. The zones that represent the stair and stair landings did not have emitters.

Twelve active and passive samplers were used in this experiment, with locations shown in Figure 10. The active samplers were placed to ensure one sampler in each zone of the house, with four on each floor. The inlets for all of the active samplers were at the standard height of 1 m. For this experiment all of the passive and active samplers were co-located. The co-located passive sampler was attached to the inlet of the active sampler, ensuring that both sampled the same air space.

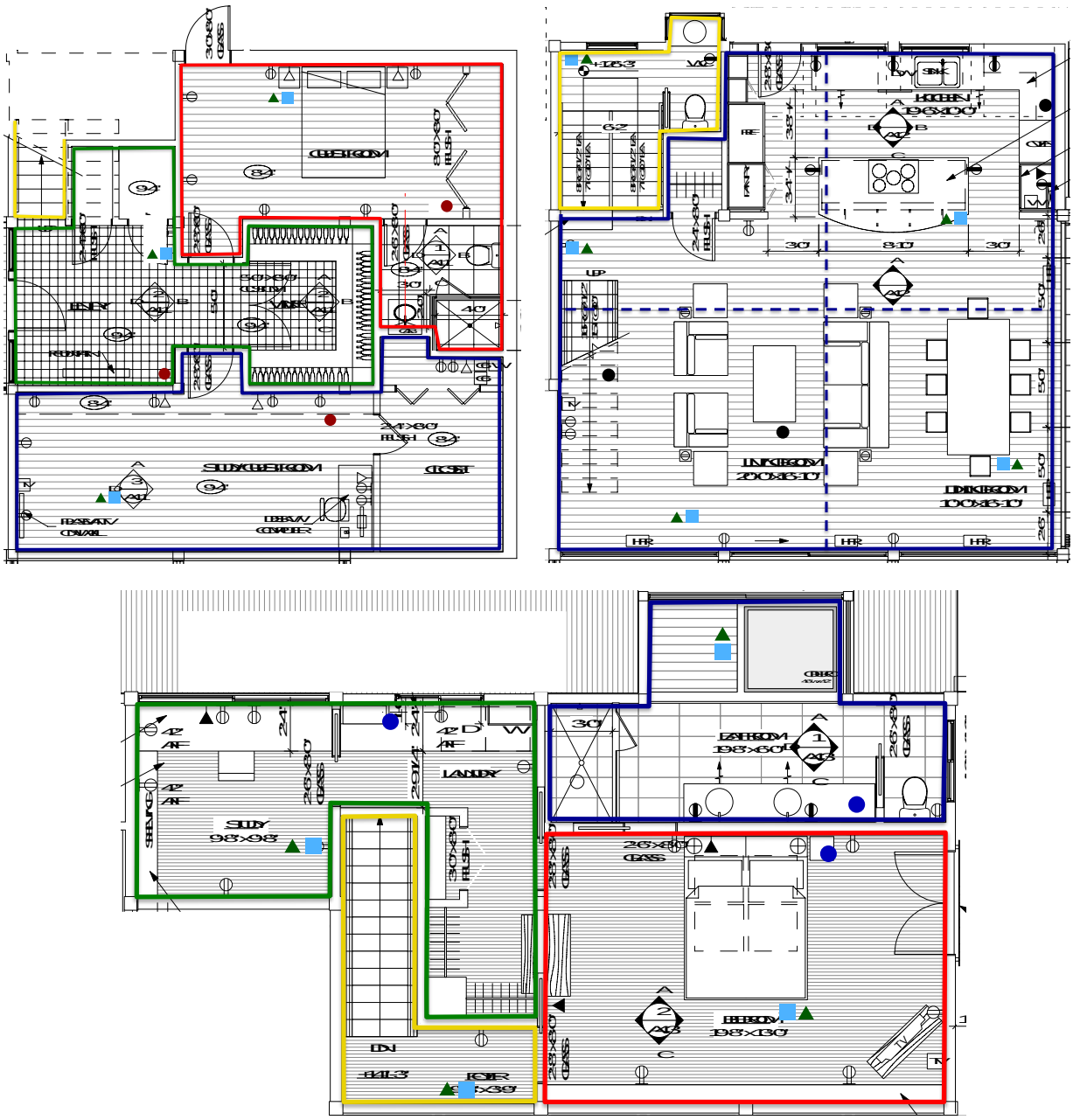

Figure 10: Floor plan of House 3 showing the locations of PFT emitters denoted by circles and tracer sampling locations denoted by squares and triangles for active and passive samplers, respectively. The large zone on the second floor was divided evenly into four separate zones corresponding to the four sampler locations but does not have any physical zone separation.

Experimental Test Plans

The experiments conducted in each house were designed to investigate a series of ventilation conditions. The experiments in House 1 were conducted from June 20th to June 26th, 2011. Two different ventilation conditions were investigated; one with no operation of the forced air heating system and one with the system fan operating continuously. In House 2, the experiments were conducted over the July 10th to July 21st, 2011 time period. In these experiments, three different ventilation conditions were examined; one with normal operation of the HVAC system, one with the HVAC system fan running constantly, and one with normal HVAC operation but with the economizer turned on. The experiments in House 3 were conducted over the November 14th to November 29th time period. Four different ventilation conditions were investigated during these experiments. Two had no heating system operation and two had continuous system fan operation. During one of each of these conditions, i.e. no fan and continuous fan, the kitchen exhaust fan was continuously operated at the medium speed setting. The flow rate of the kitchen exhaust fan was measured to be 242 cfm. While the kitchen exhaust fan was running, the internal room doors of the house were kept closed. A summary of these experimental conditions and dates is shown in Table 3.

Table 3: Experimental Ventilation conditions performed at the three houses.

	Date	Ventilation Condition
House 1	June 20th to June 23rd	No forced air system operation
	June 23rd to June 26th	Constant forced air system fan
House 2	July 10th to July 13th	Normal operation of air conditioner
	July 13th to July 16th	Air conditioner use with constant fan operation
	July 18th to July 21st	Normal operation of air conditioner with economizer
House 3	Nov. 14th to Nov. 17th	No forced air system operation
	Nov. 17th to Nov. 20th	No forced air system operation but with constant kitchen exhaust fan. Internal doors closed.
	Nov. 20th to Nov. 23rd	Constant forced air system fan and kitchen exhaust fan use. Internal doors closed.
	Nov. 26th to Nov. 29th	Constant forced air system fan

Notes were taken during each experiment regarding householder actions that would affect the ventilation rate in the home. In particular, the opening and closing times of specific windows in the house was recorded if possible. In addition, the status of internal doors was noted when routinely left closed for long periods of time.

Results

House 1

Figure 11 shows the PFT concentrations measured by the active bag samplers for both experimental conditions. The figure shows concentrations measured at each of the 10 locations as well as the volume-weighted average house concentration. The volume-weighted average house concentration $C_{g,t}$ for each sample is calculated as follows:

$$C_{g,t} = \frac{\sum_z V_z C_{z,g,t}}{\sum_z V_z} \qquad 1$$

where $C_{z,g,t}$ is the average concentration for zone z of gas g for time period t, and V_z is the volume of the zone. The standard deviation of the time-resolved, volume-weighted average house concentration was also calculated by weighting each term by the zone volume. The vertical lines on the figure indicate the time periods when some windows were open in the house. These open windows were most often in the master bedroom and the bathroom. The door to the half bathroom was closed during the entire experiment. A visual inspection of Figure 11 shows significantly greater variability in the measured concentrations both spatially and temporally during the experiment with no central forced air system fan running than during the time when the system fan was operating. The use of the forced air fan appears to improve mixing within the house, resulting in less zone-to-zone variability in tracer concentrations. The time resolved behavior of the concentrations of all three tracers is similar. There is a gradual decrease in mPDCH concentrations when the forced air system fan was running that is not reflected in the other two PFTs. There is no current explanation for this behavior.

In order to compare concentrations measured by the active samplers with the passive samplers, the time resolved data were averaged over each three-day ventilation condition:

$$C_{g,z} = \frac{\sum_t C_{z,g,t}}{\sum_t \Delta t} \qquad 2$$

These average and standard deviation of the concentration of all three PFTs in each zone, $C_{g,z}$, as well as the volume weighted house average concentration, C_g, are listed in Table 4. The volume weighted house average concentration, was calculated as follows:

$$C_g = \frac{\sum_t C_{g,t}}{\sum_t \Delta t} \qquad 3$$

The standard deviation of the time resolved data reflects the temporal variability in tracer concentrations. A spatial standard deviation of the volume weighted average house concentration was also calculated from the average concentration in each zone by weighing each term by the zone volume:

$$\sigma_g = \frac{\sqrt{\sum_z V_z (C_g - C_{g,z})^2}}{(n_z - 1) \sum_z V_z / n_z} \qquad 4$$

where n_z is the total number of zones. The magnitude of this standard deviation indicates the degree to which tracer concentrations vary spatially throughout the house. The measured concentrations of mPDCH during the experiment were low due to the use of only 2 emitters and a lower emission rate for this tracer gas. The concentrations of HB measured by the passive sampler for each ventilation condition are shown in Table 5.

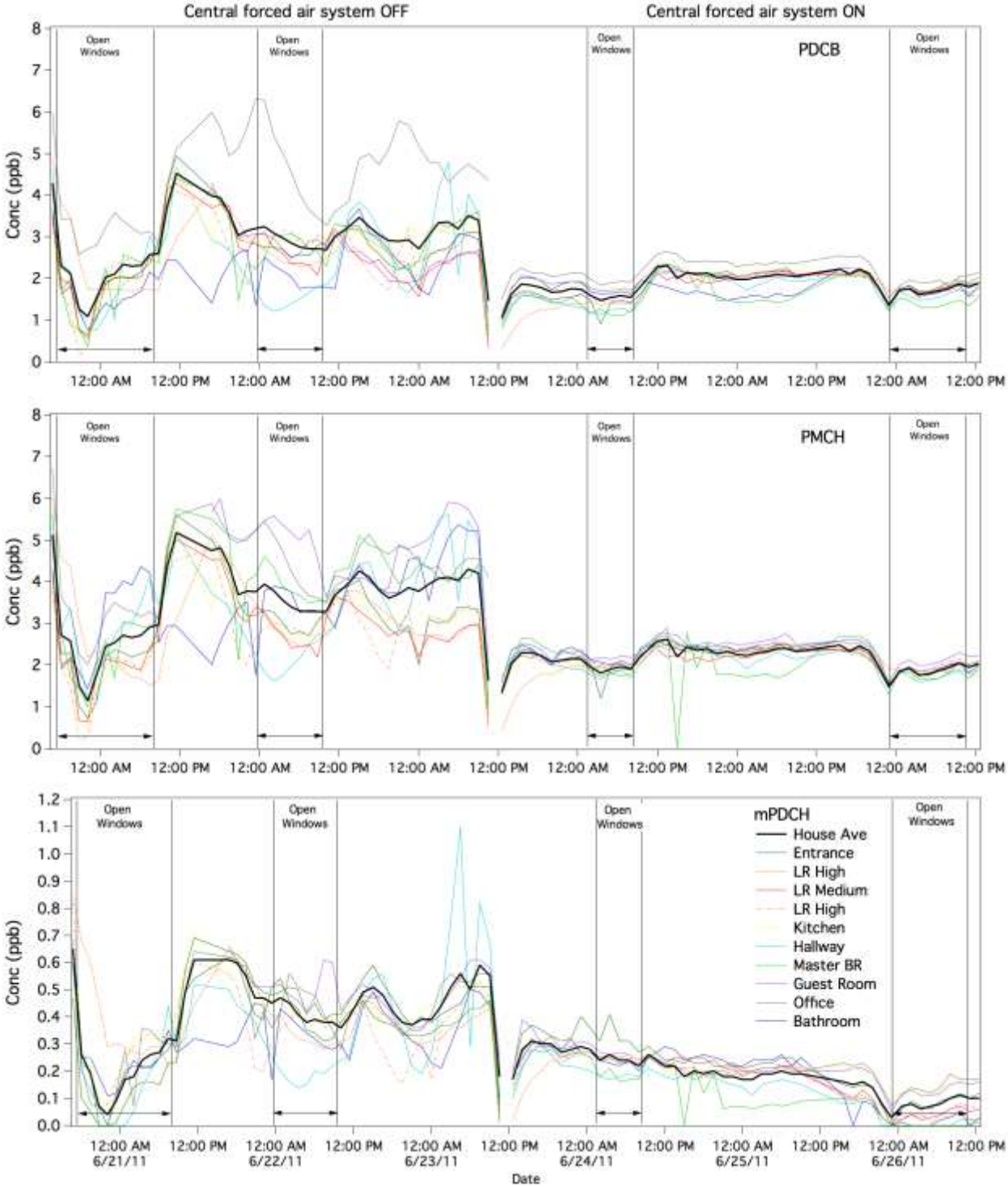

Figure 11: Time resolved concentration in ppb of (a) PDCB, (b) PMCH, and (c) mPDCH measured at House 1 for each active sampling location as well as the volume-weighted house average concentration.

Table 4: The average and standard deviation of the time resolved PFT concentrations in House 1 measured by the active samplers for both experimental conditions. The average and standard deviation of the time resolved volume weighted house average concentration is listed in the first row, followed by the spatial standard deviation calculated using the individual zone averages. All concentrations are in units of ppb.

	PDCB		PMCH		mPDCH	
	No Fan	With Fan	No Fan	With Fan	No Fan	With Fan
House Ave	2.88 ± 0.72	1.85 ± 0.26	3.50 ± 0.90	2.13 ± 0.27	0.39 ± 0.15	0.18 ± 0.07
Spatial St. Dev.	0.76	0.22	0.75	0.10	0.06	0.04
Entrance	2.62 ± 0.86	1.83 ± 0.34	3.01 ± 1.01	2.14 ± 0.31	0.4 ± 0.16	0.22 ± 0.10
LR High	2.65 ± 0.71	1.70 ± 0.42	3.03 ± 0.96	2.05 ± 0.40	0.39 ± 0.13	0.16 ± 0.09
LR Medium	2.43 ± 0.81	1.92 ± 0.81	2.77 ± 0.95	2.11 ± 0.22	0.33 ± 0.16	0.14 ± 0.09
LR Low	2.55 ± 0.88	1.79 ± 0.88	2.68 ± 0.98	2.15 ± 0.25	0.35 ± 0.15	0.17 ± 0.09
Kitchen	2.69 ± 0.82	1.96 ± 0.82	2.88 ± 0.98	2.09 ± 0.30	0.4 ± 0.14	0.21 ± 0.06
Hallway	2.38 ± 1.07	1.68 ± 0.34	3.27 ± 1.21	2.02 ± 0.30	0.32 ± 0.23	0.13 ± 0.08
Master	2.63 ± 0.93	1.50 ± 0.39	3.73 ± 1.20	2.03 ± 0.49	0.39 ± 0.17	0.12 ± 0.09
Guest	2.66 ± 0.59	1.95 ± 0.24	4.85 ± 0.84	2.33 ± 0.28	0.49 ± 0.10	0.21 ± 0.07
Office	4.40 ± 1.04	2.17 ± 0.27	4.25 ± 0.31	2.18 ± 0.31	0.46 ± 0.20	0.21 ± 0.05
Bathroom	2.11 ± 0.79	1.68 ± 0.33	3.47 ± 0.42	2.14 ± 0.42	0.31 ± 0.11	0.18 ± 0.11

Table 5: HB concentrations in House 1 measured using passive samplers as well as the volume weighted house average concentration and standard deviation for both experimental conditions. All concentrations are in units of ppb.

	No Fan	With Fan
House Ave	2.92	2.02
St. Dev.	0.69	0.19
Above Return	2.62	1.90
Bathroom	2.06	1.86
Bedroom – Inner	3.16	1.92
Bedroom – Outer	2.76	1.94
Dining Room	2.32	2.05
Guest	3.07	2.05
Hallway	2.51	1.79
Living Room	2.66	1.93
Office	4.2	2.37
Entrance	2.48	1.9

The weights of the tracer gas emission vials were recorded several times during the experiment. The emission rate was determined by dividing the mass of tracer gas liquid lost by the time elapsed between weighings. The emission rates measured for the four PFT tracers for each of these time periods at each emitter location are located in the appendix. The average emission rates for each PFT are listed in Table 6. At the start of the experiment we noticed that the temperature control of the heating blocks was poor when

the ambient temperatures in the house warmed to a value close to the set point of the heater. As a result, the temperature set point of the heating blocks was increased during the experiment to find a value that would provide stable temperatures. The temperature set points are also listed in Table 6. These adjustments are reflected in the increase of the measured emission rates as the experiment progressed.

Table 6: Emission rates of PMCH, PDCB, mPDCH, and HB in μg/hr for House 1. The dates indicate the time period over which the emission rate was calculated.

	Emission Rate, e_g (μg/hr)					
Tracer Gas	6/17–18	6/18–23	6/23–24	6/24–25	6/25 -26	Exp. Ave
PMCH	575 ± 42	670 ± 54	714 ± 108	658 ± 147	650 ± 149	673
PDCB	836 ± 37	985 ± 26	1086 ± 56	1034 ± 40	1043 ± 42	985/1054*
mPDCH	372 ± 5	427 ± 43	491 ± 17	438 ± 8	448 ± 12	451
HB	430 ± 22	530 ± 54	579 ± 32	567 ± 32	566 ± 36	561
Temp set point (°C)	25	28	30	30	30	

* Two numbers are listed corresponding to the average for the two ventilation conditions.

It is difficult to compare the measured concentrations of different tracer gases both in the same zone and between zones because the amount of gas emitted varies by tracer, as shown in Table 6. To normalize the measured tracer concentration, the mass of tracer measured is divided by the mass of tracer emitted. For the ease of normalization, the emitters are assumed to emit evenly throughout the house. The total mass of tracer emitted per unit time (μg/hr) is

$$M_{e,g} = e_g n_e \qquad 5$$

where e_g is the emission rate of tracer gas g per emitter listed in Table 6 and n_e is the total number of emitters. This emitted mass of tracer translates to the following concentration in the house per unit time

$$C_{e,g} = e_g n_e / \rho_g V \qquad 6$$

where V is the volume of the house and ρ_g is the density of tracer gas g. The normalized concentration, $\widehat{C_g}$, is the measured tracer concentration, $C_{g,z}$, divided by the emitted tracer concentration, $C_{e,g}$

$$\widehat{C_g} = \frac{C_{g,z}}{C_{e,g}} \qquad 7$$

The normalized concentrations allow for comparison of concentrations within each zone for the different PFTs.

Figure 12 shows the average PFT concentrations normalized by the emission rate of that PFT as discussed above for the two ventilation conditions. The average emission rate for the experiment was used, with the exception of PDCB, which had a significantly different emission rate during the two ventilation conditions as shown in Table 6. For PDCB, an average emission rate was calculated separately for the two experimental conditions. Figure 12 also shows the volume-weighted house average concentration normalized in the same manner. The normalized concentrations for the passively sampled PFT, HB, are shown in Figure 13 for both experimental ventilation conditions. Table 7 lists the

normalized value of the volume-weighted house average concentration as well as the relative standard deviation of the individual measurements.

The normalized house averaged concentration of PDCB and PMCH are similar whereas that of HB is slightly higher. The average normalized concentration of mPDCH is significantly lower than the other three PFTs when the system fan is running. These lower concentrations may be due to the fact that one of the two emitters for mPDCH is located next to the system return, and thus losses in the ducting have a larger impact on the concentrations in the house for this PFT. The normalized concentrations of all PFTs are lower when the system fan is operating, indicating a higher air exchange rate in the home during fan operation.

The individual values of the normalized concentrations shown in Figure 12 and Figure 13 show more spatially variability when the heating system fan is not running then when it is. This difference in the spatial variability is reflected by the fact that the average relative deviation for the no fan ventilation condition is 0.20 while it 0.12 when the forced air system fan is operating and indicates improved mixing of the tracers in the home. The relative standard deviation of PMCH and HB is significantly lower when the central forced air fan was operating. Both of these PFTs were emitted in all eight locations in the home. The relative standard deviation of PDCB (4 emitter locations) did not decrease by as much, and it increased for mPDCH (2 emitter locations) when the fan was operating. This result indicates that the decrease in spatial variability due to the improved mixing of the tracers was more effective on the PFTs that had more sources throughout the home. It may be that even with improved mixing, the emission of PDCB in a subset of the zones in the home contributes to spatial variability in its concentration.

While the variability of the individual concentrations is greater when the forced air fan was not operating, the normalized concentrations of PDCB, PMCH, and HB of the interconnected zones of the house shown in Figure 12, the living room, dining room, and kitchen, have similar values for the case where the heating system fan is not operating indicating that this large open space is relatively well mixed. By contrast, the normalized concentration of PMCH is greater than PDCB in the master bedroom, guest room, and bathroom, which are rooms where the only PMCH was emitted. The variability of the PFT concentrations is also larger in these individual rooms, which do not mix as readily with the rest of the house when the system fan is not operating.

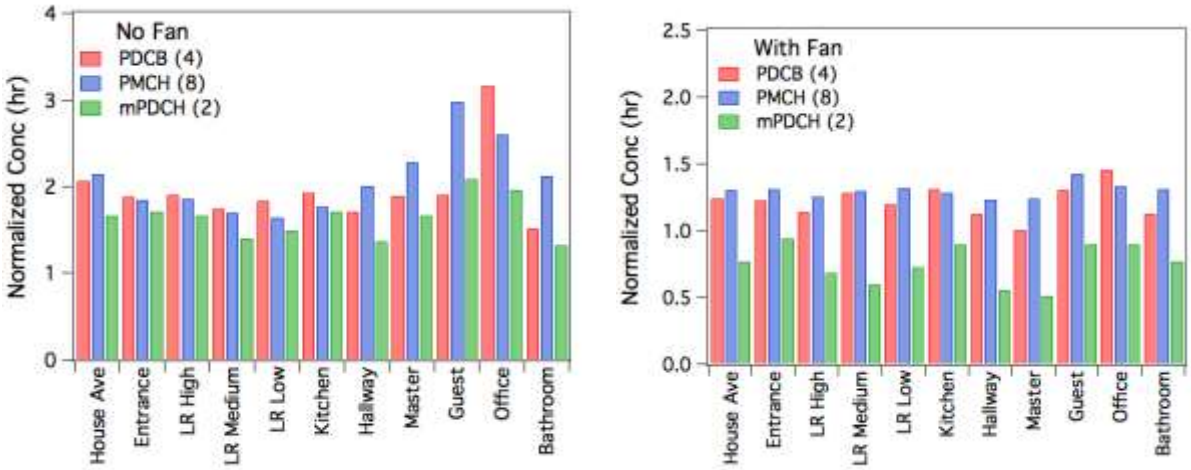

Figure 12: Normalized average concentration of PDCB, PMCH, and mPDCH measured at each active measurement location in House 1. The numbers after each PFT show the number of emitters used in the house. The two graphs show results for the experiments conducted with no heating system operation and with continuous system fan operation.

Two sets of passive samplers were placed in the same zone but in different locations. The first is the pair labeled 'hallway' and 'hall above return' in Figure 13. The hallway location was co-located with the inlet to the active sampler place there, while the hallway above return was attached to a ceiling fixture. The sampler attached to the ceiling was approximately 1.5 meters higher than the lower sampler and approximately 1 meter away horizontally. There was no significant difference between the normalized concentrations measured at these locations for either ventilation condition. The second sample pair was located in the master bedroom. The one labeled 'master inner' was on a shelf on the inside wall of the room, while the one labeled 'master outer' was on the outer wall next to the windows. The concentration at the inner location was higher than the outer location when the heating system fan was not running. The open window may contribute to the lower concentration for the outer measurement for the first ventilation condition as the sampler was close to the window. In contrast, the two concentrations were essential equal when the fan was operating, despite the occasional times when the bedroom window was open. This result indicates improved mixing of tracer gas in the zone from the operation of the heating system fan.

Table 7: Normalized value of the volume-weighted house average concentration of all PFTs and the relative standard deviation for both experimental conditions for House 1. The units of the normalized concentration are hr.

	Normalized Concentration (hr)	
Tracer	No Fan	Const Fan
PDCB	2.07 ± 20%	1.24 ± 12%
PMCH	2.14 ± 21%	1.31 ± 5%
mPDCH	1.67 ± 16%	0.77 ± 22%
HB	2.33 ± 22%	1.61 ± 9%

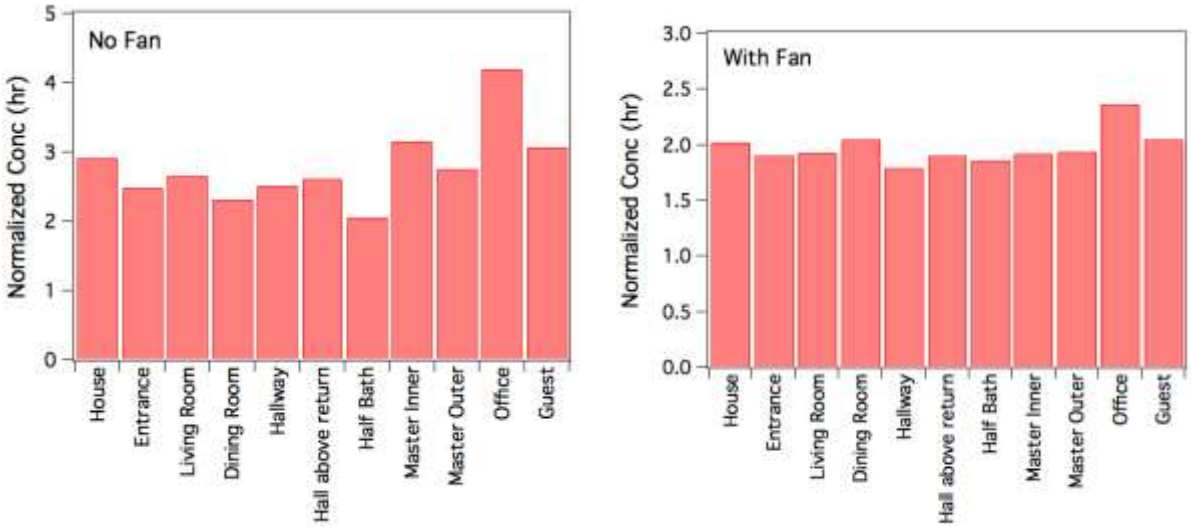

Figure 13: Normalized average concentration of HB measured at each passive measurement location as well as the volume-weighted house average concentration collected in House 1. The two graphs show results for the experiments conducted with no heating system operation and with continuous system fan operation.

The passive sample located in the half bath was particularly interesting. The half bath was isolated from the rest of the house by a door that was always closed. The half bath does, however, have a supply for the heating system located in the room. The normalized concentration measured during the experiment with no heating system fan operating resulted in a lower concentration of the tracer gas relative to other zones, as expected. This lower concentration was still only 29 percent below the house average concentration. When the fan was running, the concentration in the half bath was similar to all other measurement locations.

Figure 14 shows normalized concentrations measured by the passive technique paired with the closest active measurement location. Cases denoted by an asterisk show the co-located active and passive measurement locations. The normalized concentrations of HB, PMCH, and PDCB for most locations are similar, reflected by the fact that the average normalized concentration of the three PFTs are within 10 percent of each other and the standard deviations of the measurements are almost equivalent. This result indicates that both the active and passive sampling techniques measure equivalent PFT concentrations, at least for this house. The passive sampler in the guest room was placed in a location that was considered less than optimal – against a lateral support of a low table that had a modest level of airflow obstruction. When the heating system fan was not running, the normalized concentration of HB was considerably lower than PMCH even though they were both emitted in the room. When the system fan was running, the normalized concentrations were essentially equal, indicating that improved tracer gas mixing resulting from a central ventilation system provides more latitude in locating samplers.

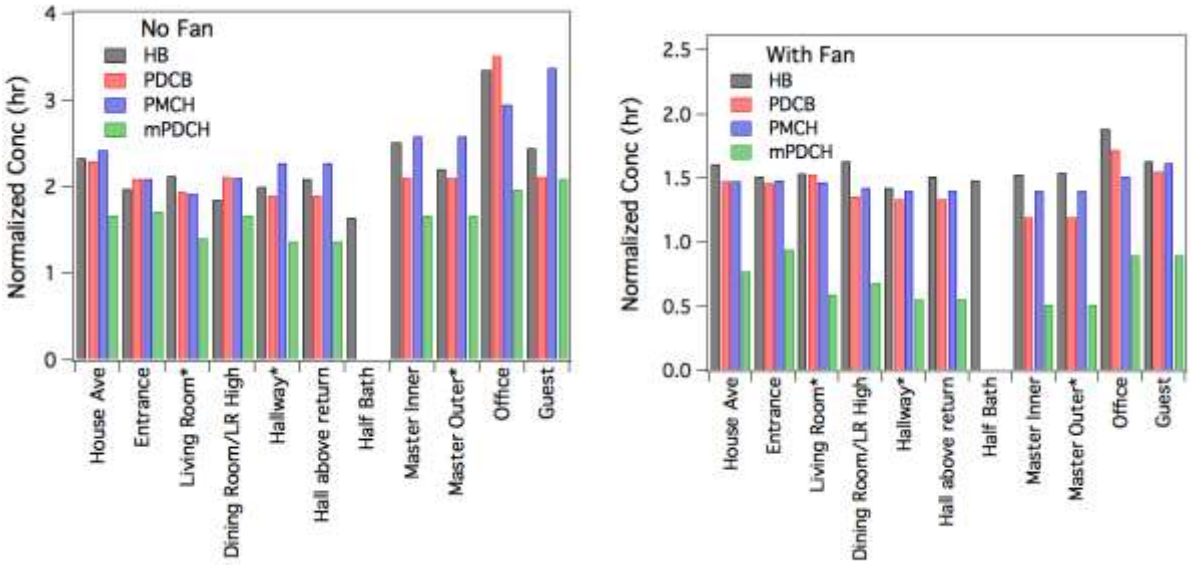

Figure 14: Normalized HB concentrations measured at each passive measurement location compared to the normalized concentration of the active PFT located closest to the passive location. Co-located measurements are indicated with asterisks. The two graphs show results for the experiments conducted with no heating system operation and with continuous system fan operation.

The percent difference between the concentrations measured at the individual active measurement locations and the volume-weighted house average concentration is shown in Figure 15. The figure shows that when the heating system fan was not in use, the concentrations in the connected common area of living room, dining room, and kitchen were below the house average while the office and guest room were greater than this average value. The difference between the measured concentrations and the house average were greatly reduced when the system fan was running, for all the tracers but mPDCH. The largest variations from the house average when the system fan was running continue to occur in the individual rooms of the home.

House 2

The time resolved concentration of the PFTs measured by the active gas samplers are shown in Figure 16 for all three ventilation conditions. The figure shows concentrations measured for each of the 12 locations as well as the volume-weighted house average concentration. The vertical lines indicate time periods when any windows were opened in some part of the house. The only window that was opened during the experiment was located in Bedroom 2. The doors to bedroom 1, bedroom 2, and the master bedroom were closed at night. While the experiments in house 2 did not include a ventilation condition with no HVAC operation, the measured tracer concentrations still show significantly lower spatial and temporal variability when the HVAC system fan was operating continuously than when the system was operating automatically. Similar to House 1, the time resolved behavior of the concentrations of all three tracer gases is similar, even for mPDCH which was emitted at only one location in the house. The concentrations of these actively sampled PFTs averaged over each three-day experimental ventilation condition are listed

in Table 8. The concentrations of HB measured by the passive technique are listed in Table 9.

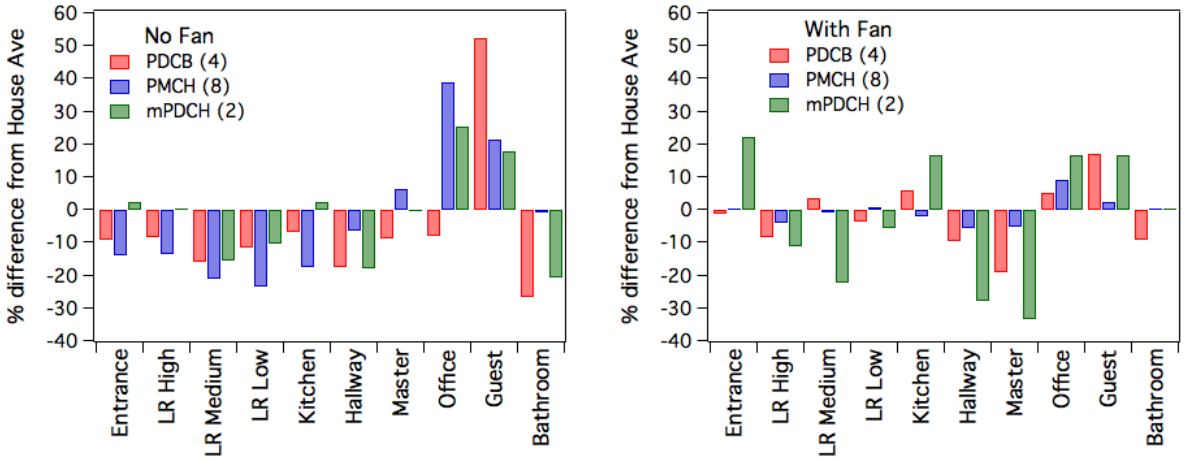

Figure 15: The percent difference of the concentrations of PDCB, PMCH, and mPDCH measured at each active measurement location and the volume weighted house averaged concentration. The two graphs show results for the experiments conducted with no HVAC operation and with constant HVAC fan operation.

The time-resolved concentration data shown in Figure 16 shows an example of how door operation influences the distribution of the tracer gas throughout a home. The concentrations of PDCB measured in the master bedroom increased in the evenings when the door to the room is closed, while the concentration of PMCH decreased. The master bedroom contained emitters for PDCB but not PMCH. When the door to the room is closed, the measured concentrations for these two tracers reflect the decrease of airflow into and out of the room. The variability in PFT concentrations due to closed doors are largely eliminated when the HVAC system fan is operating.

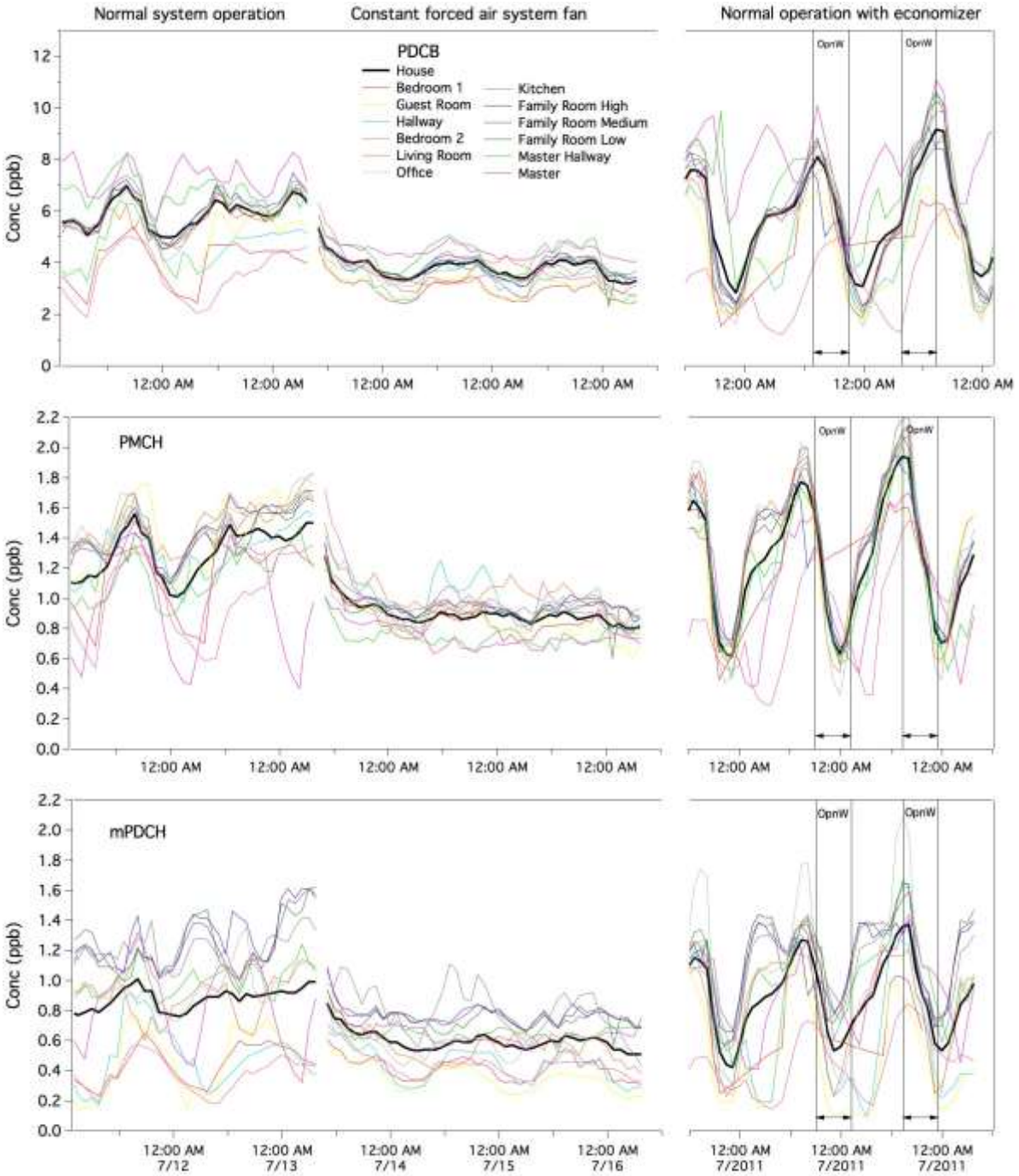

Figure 16: Time resolved concentration of (a) PDCB, (b) PMCH, and (c) mPDCH measured at House 2 for each active sampling location as well as the house average concentration. The data between noon of July 11th to July 13rd were collected with routine HVAC operation, the data between noon of July 13rd to June 16th were collected with constant HVAC fan operation, and the data between noon of July 18th to June 21th were collected with normal HVAC operation but with an economizer turned on. The vertical lines indicate times when windows in Bedroom 2 room were open.

Table 8: The average and standard deviation of the time resolved PFT concentrations in House 2 measured by the active samplers for both experimental conditions. The average and standard deviation of the time resolved volume-weighted house average concentration is listed in the first row, followed by the spatial standard deviation calculated using the individual zone averages. All concentrations are in units of ppb.

	PDCB			PMCH			mPDCH		
	Norm Op	Const Fan	With Econ	Norm Op	Const Fan	With Econ	Norm Op	Const Fan	With Econ
House	5.93 ± 0.52	3.81 ± 0.41	5.75 ± 1.68	1.31 ± 0.15	0.9 ± 0.08	1.24 ± 0.39	0.88 ± 0.07	0.6 ± 0.07	0.89 ± 0.26
St. Dev.	0.88	0.45	1.23	0.20	0.11	0.13	0.25	0.13	0.21
Bedroom 1	4.21 ± 0.84	2.98 ± 0.43	5.04 ± 1.74	1.17 ± 0.22	0.84 ± 0.11	1.33 ± 0.39	0.49 ± 0.15	0.42 ± 0.08	0.73 ± 0.33
Guest	5.11 ± 1.03	3.08 ± 0.43	4.32 ± 1.64	1.44 ± 0.25	0.86 ± 0.13	1.22 ± 0.38	0.5 ± 0.20	0.35 ± 0.09	0.48 ± 0.34
Hallway	4.96 ± 0.94	3.42 ± 0.63	4.79 ± 2.02	1.34 ± 0.18	1.0 ± 0.15	1.3 ± 0.44	0.57 ± 0.23	0.44 ± 0.11	0.64 ± 0.40
Bedroom 2	3.86 ± 1.01	3.46 ± 0.72	3.45 ± 1.33	1.08 ± 0.27	0.96 ± 0.19	0.89 ± 0.35	0.43 ± 0.15	0.44 ± 0.09	0.45 ± 0.19
Living Room	5.77 ± 0.63	3.67 ± 0.50	5.16 ± 2.04	1.5 ± 0.16	1.02 ± 0.12	1.34 ± 0.47	0.87 ± 0.13	0.57 ± 0.11	0.83 ± 0.32
Office	5.92 ± 0.78	3.61 ± 0.45	5.38 ± 2.37	1.46 ± 0.20	0.93 ± 0.10	1.32 ± 0.53	0.96 ± 0.13	0.58 ± 0.09	1.01 ± 0.50
Kitchen	6.11 ± 0.74	3.86 ± 0.42	5.67 ± 2.14	1.45 ± 0.17	0.95 ± 0.09	1.37 ± 0.45	1.18 ± 0.11	0.8 ± 0.17	1.1 ± 0.28
Family Low	5.94 ± 0.65	3.75 ± 0.44	5.79 ± 2.36	1.38 ± 0.13	0.92 ± 0.08	1.31 ± 0.42	1.2 ± 0.18	0.74 ± 0.06	1.14 ± 0.29
Family Medium	5.87 ± 0.70	3.93 ± 0.42	5.68 ± 2.20	1.39 ± 0.14	0.96 ± 0.08	1.31 ± 0.41	1.19 ± 0.17	0.77 ± 0.07	1.13 ± 0.27
Family High	6.09 ± 0.68	3.81 ± 0.42	5.48 ± 1.92	1.43 ± 0.16	0.96 ± 0.08	1.13 ± 0.37	1.24 ± 0.20	0.77 ± 0.07	1.12 ± 0.24
Master Hallway	6.62 ± 0.60	4.29 ± 0.59	6.72 ± 1.79	1.14 ± 0.15	0.75 ± 0.06	1.16 ± 0.41	1.0 ± 0.10	0.65 ± 0.05	1.04 ± 0.27
Master	7.22 ± 0.68	4.48 ± 0.32	7.97 ± 1.36	0.99 ± 0.32	0.75 ± 0.08	1.07 ± 0.40	0.85 ± 0.25	0.64 ± 0.06	0.94 ± 0.26

Table 9: HB concentrations in House 2 measured by passive samplers and the volume weighted house average concentration for both experimental conditions. All concentrations are in units of ppb.

	Normal Op	With Fan	With Econ
House	7.07	4.46	6.57
St. Dev.	1.06	0.66	1.61
Bedroom 1	5.38	3.41	3.48
Guest	7.49	4.81	6.28
Hallway	8.37	4.84	7.31
Bedroom 2	7.13	4.15	6.27
Living Room	7.08	4.43	6.54
Office	5.84	3.25	5.36
Kitchen	7.11	5.01	7.00
Family Low	7.06	4.28	6.31
Family Medium	8.23	5.22	9.31
Family High	4.98	3.74	4.39
Master Hallway	7.07	4.46	6.57
Master	5.38	3.41	3.48

The emission rates of the tracer gases in House 2 were measured only once, with the weight of each vial measured when placed in the home and at the end of the experiment. These emission rates for the experiment are shown in Table 10.

Table 10: Emission rates of PMCH, PDCB, mPDCH, and HB in μg/hr measured in House 2.

Tracer Gas	Emission Rate (μg/hr)
PDCB	1229 ± 44
PMCH	871 ± 35
mPDCH	644
HB	730 ± 96

Figure 17 shows the average PFT concentrations measured at each active sampling location normalized by the emission rate of that PFT for the experiment, listed in Table 10. This figure also shows the volume-weighted house average concentration normalized in the same manner for the house. The concentrations of HB measured by the passive samplers normalized by the HB emission rate are shown in Figure 18 for all three experimental ventilation conditions. **Error! Reference source not found.** lists the normalized values of the volume-weighted house average concentration as well as the relative standard deviation of the individual measurements for all of the tracer gases.

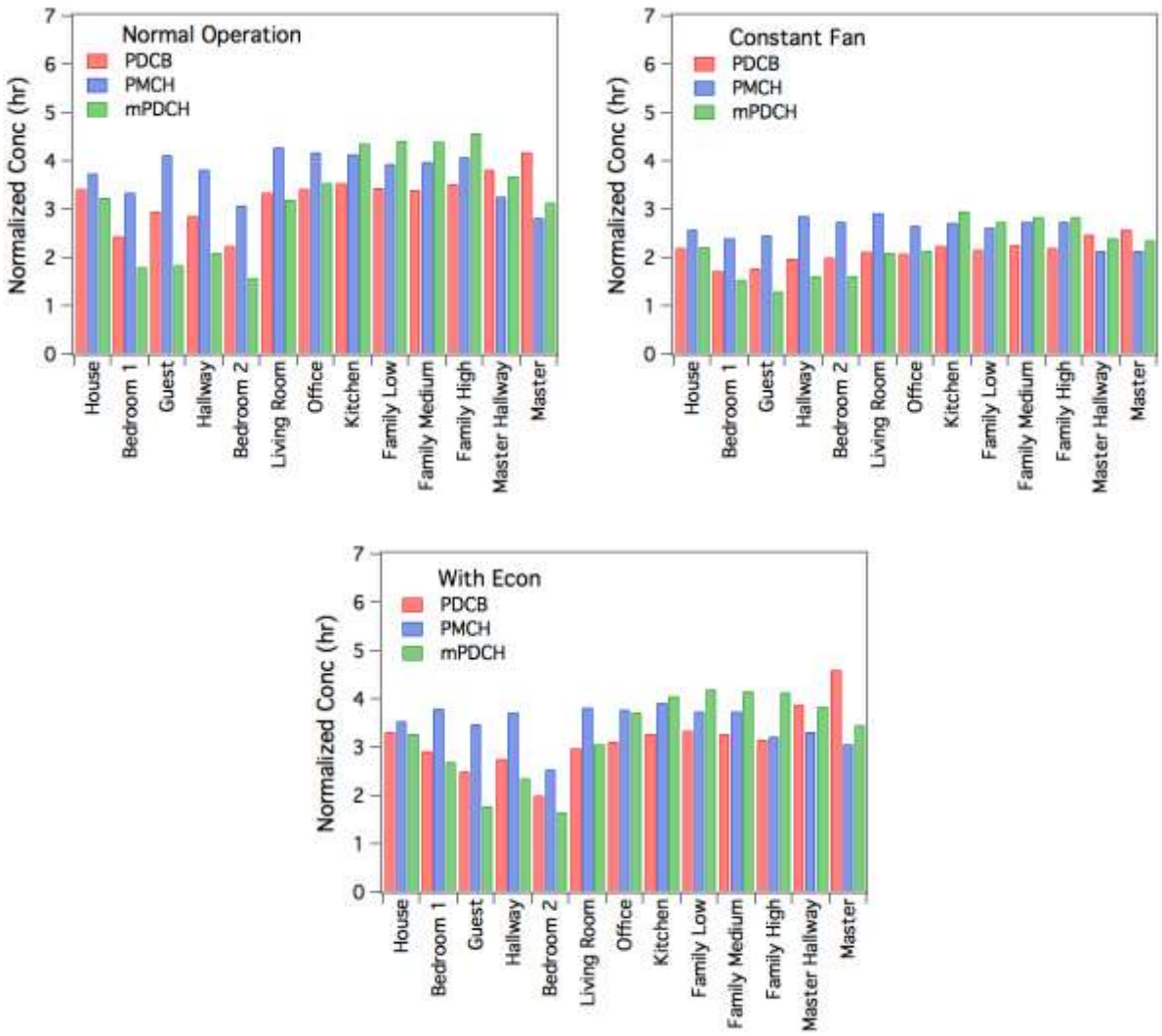

Figure 17: Average normalized concentration of PDCB, PMCH, and mPDCH measured at each active measurement location in House 2. The three graphs show results for the experiments conducted with routine HVAC operation, constant HVAC fan operation, normal HVAC operation but with an economizer turned on.

Table 11: Normalized value of the volume-weighted house average concentration and relative standard deviation for all three experimental conditions for House 2. The units of the normalized concentration are hr.

	Normalized Concentration (hr)		
Tracer	Normal Op	Const Fan	With Econ
PDCB	3.43 ± 15%	2.20 ± 12%	3.32 ± 21%
PMCH	3.74 ± 15%	2.57 ± 12%	3.54 ± 10%
mPDCH	3.25 ± 28%	2.21 ± 22%	3.28 ± 24%
HB	4.26 ± 15%	2.69 ± 15%	3.96 ± 25%

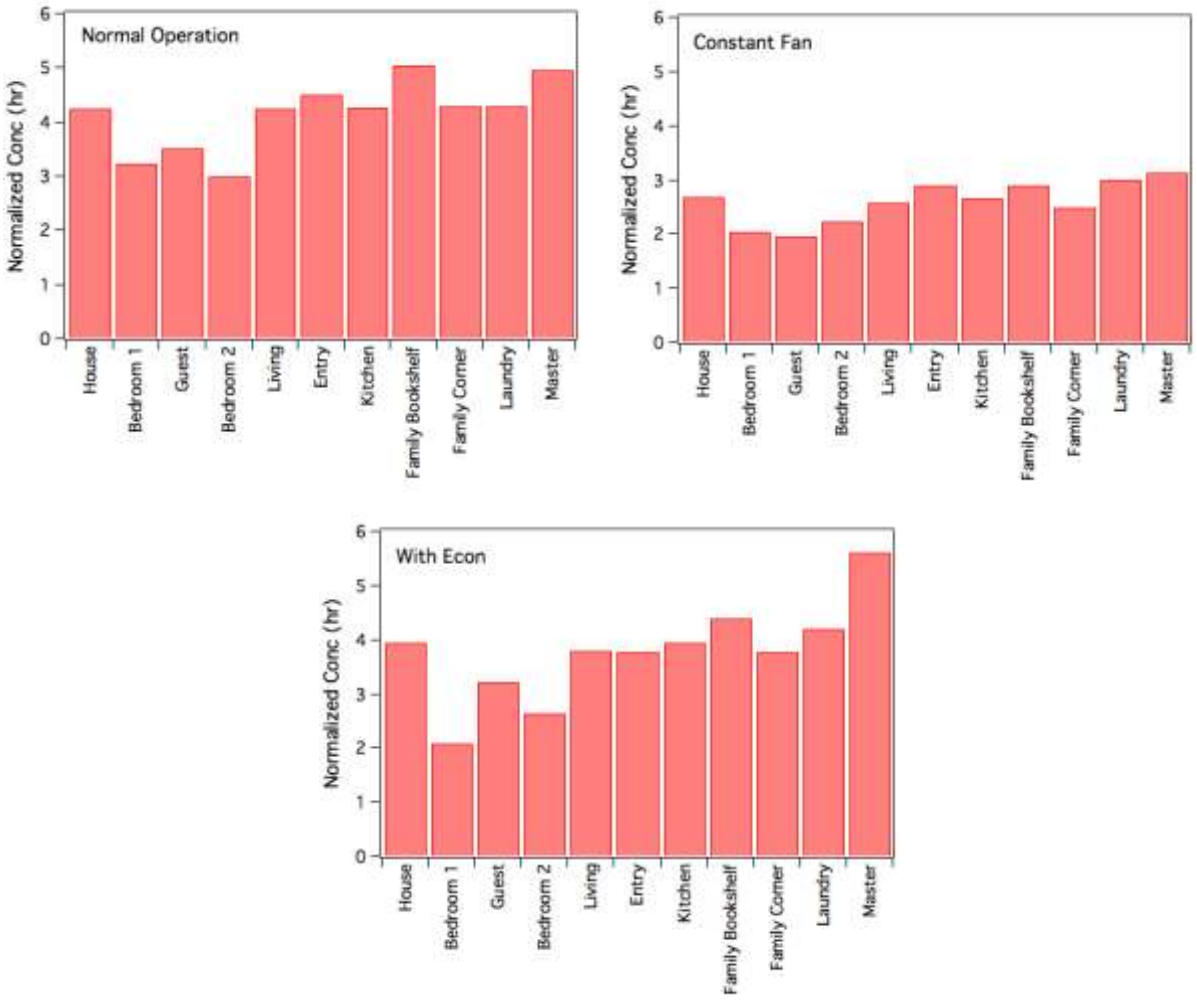

Figure 18: Average normalized concentration of HB measured at each passive measurement location as well as the volume-weighted house average concentration collected in House 2. The three graphs show results for the experiments conducted with routine HVAC operation, constant HVAC fan operation, and normal HVAC operation but with an economizer turned on.

The data in Table 11 show that the house average normalized concentrations of PDCH and mPDCH were similar for all three ventilation conditions, with a maximum difference of 5 percent measured during the experimental with the HVAC system operating normally. The average normalized concentration of PMCH was higher than both PDCB and mPDCH, ranging from approximately 15 percent when the system fan was operating continuously to 8 percent when the economizer was running. PMCH was only emitted in the part of the house with the bedrooms and living spaces. The house average normalized concentration of HB was greater than the actively sampled PFTs, particularly when the HVAC system was operating normally and when the economizer was running. The relative standard deviation, representing the spatial variability of the concentrations, was lowest when the central forced air system fan was operating continuously, and was greatest when the economizer was running. The spatial variability of PDCB, PMCH, and HB were similar during normalized system operation and continuous fan operation, with average values of 15 and 13 percent, respectively. The relative standard deviation of 10 percent for PMCH

was much lower than the average value of 23 percent for PMCH and mPDCH when the economizer was running. PMCH was only emitted in the bedroom side of the house, which is the side of the house served by the primary HVAC system that used the economizer. It appears the economizer, which used outdoor air to ventilate the home when outdoor temperatures are low enough, assists in the mixing of the PMCH emitted in that half of the house while increasing the spatial variability of PDCB and HB emitted throughout the house. The spatial variability of mPDCH was significantly higher than the other three PFTs. The higher variability reflects the fact that it was only emitted in one location in the house and did thus not mix as effectively throughout the home.

The normalized concentrations of all four tracer gases tended to be lower in the bedroom half of the house (the opposite end from the master bedroom) with PMCH showing the least effect. PDCB concentrations were highest in the master bedroom wing of the house. Concentrations of mPDCH were higher than the other tracer gases in the open kitchen and family room area, which was the only location where that tracer was emitted. The concentrations of HB and PDCB measured in the master bedroom when the economizer was running were noticeably larger than the concentrations in the rest of the house. Both of these tracers were emitted throughout the house. When the economizer is operating, outdoor air is used to ventilate the majority of the house that is served by the primary HVAC system. Higher HB and PDCB concentrations in the master bedroom area of the house suggest that the he economizer does not influence the tracer concentration in these areas.

Figure 19 shows the normalized passive concentrations paired with the normalized average concentration of the actively sampler located close to each passive sampler. The figure shows that the normalized concentration of HB and PMCH are generally higher than PDCB even though both HB and PDCB are emitted throughout the entire home. The concentrations of mPDCH are lower than the other PFTs with the exception of the kitchen and family room areas, which is the only area where that PFT was emitted.

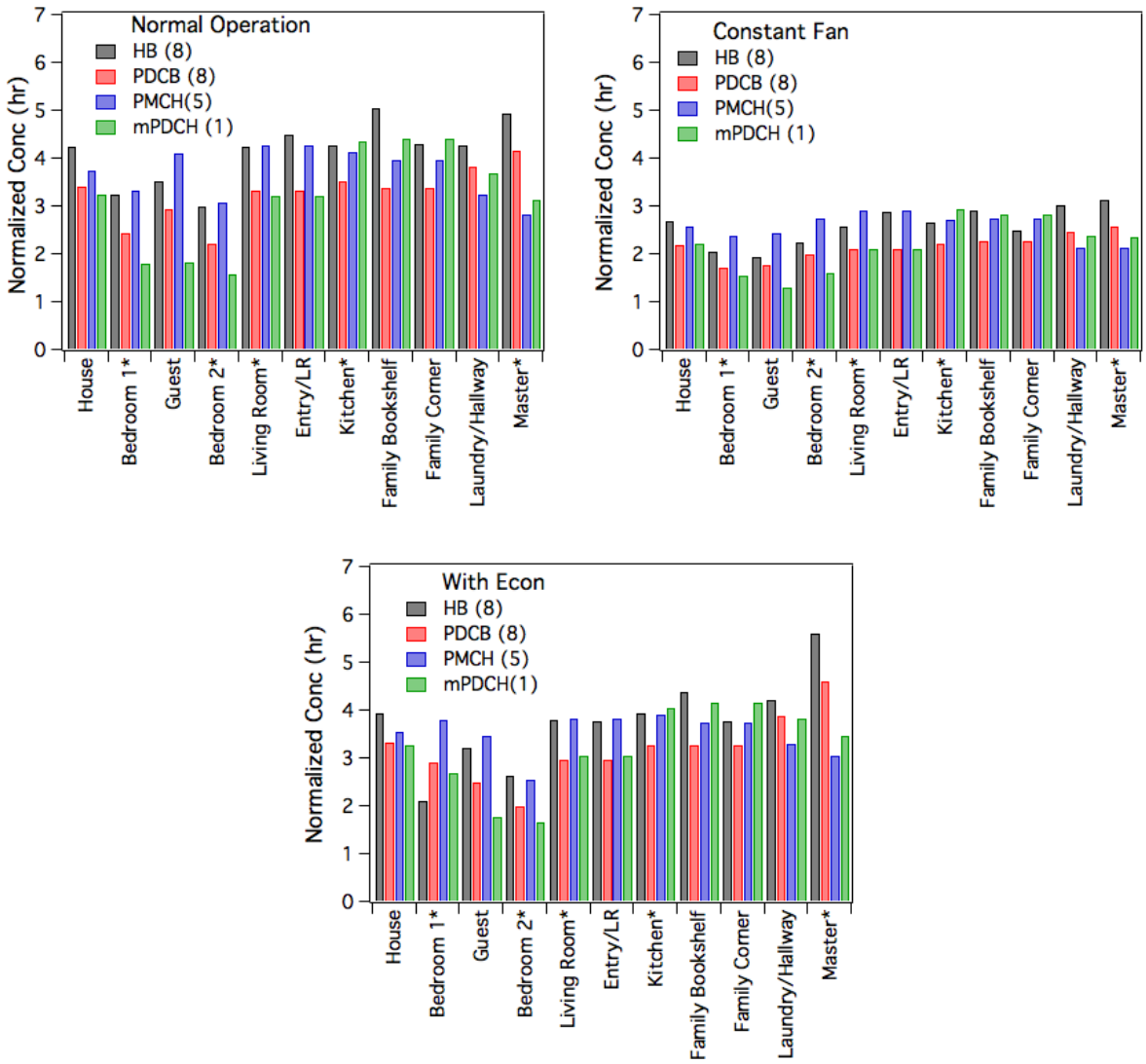

Figure 19: Normalized HB concentrations measured at each passive measurement location plotted with the normalized concentrations of the active PFT located closest to the passive location in House 2. Co-located measurements are indicated with asterisks. The three graphs show results for the experiments conducted with routine HVAC operation, constant HVAC fan operation, and HVAC operation using an economizer.

Figure 20 shows the percent difference between the concentrations measured at the individual active measurement locations and the volume-weighted house average concentration. The results show a spatial directionality to the amount that the tracer gas concentrations from the house average. PDCB is lower than the house average in the bedroom/guest room side of the house and higher than average on the master bedroom side of the house. This pattern is the same for all three ventilation conditions, and indicates a net airflow in the home from bedroom 1 to the master bedroom. mPDCH shows the same pattern but the magnitude of the variations are larger than for PDCB. The variation of PMCH concentrations from the house average does not show as pronounced a directionality as the other tracer gases, and is lower than the house average concentration in the master bedroom and hallway. PMCH was emitted only in the bedroom/living room

side of the house, and thus will not have as high concentrations in the master bedroom side. PMCH does mix into the living and family room area, however, fairly readily.

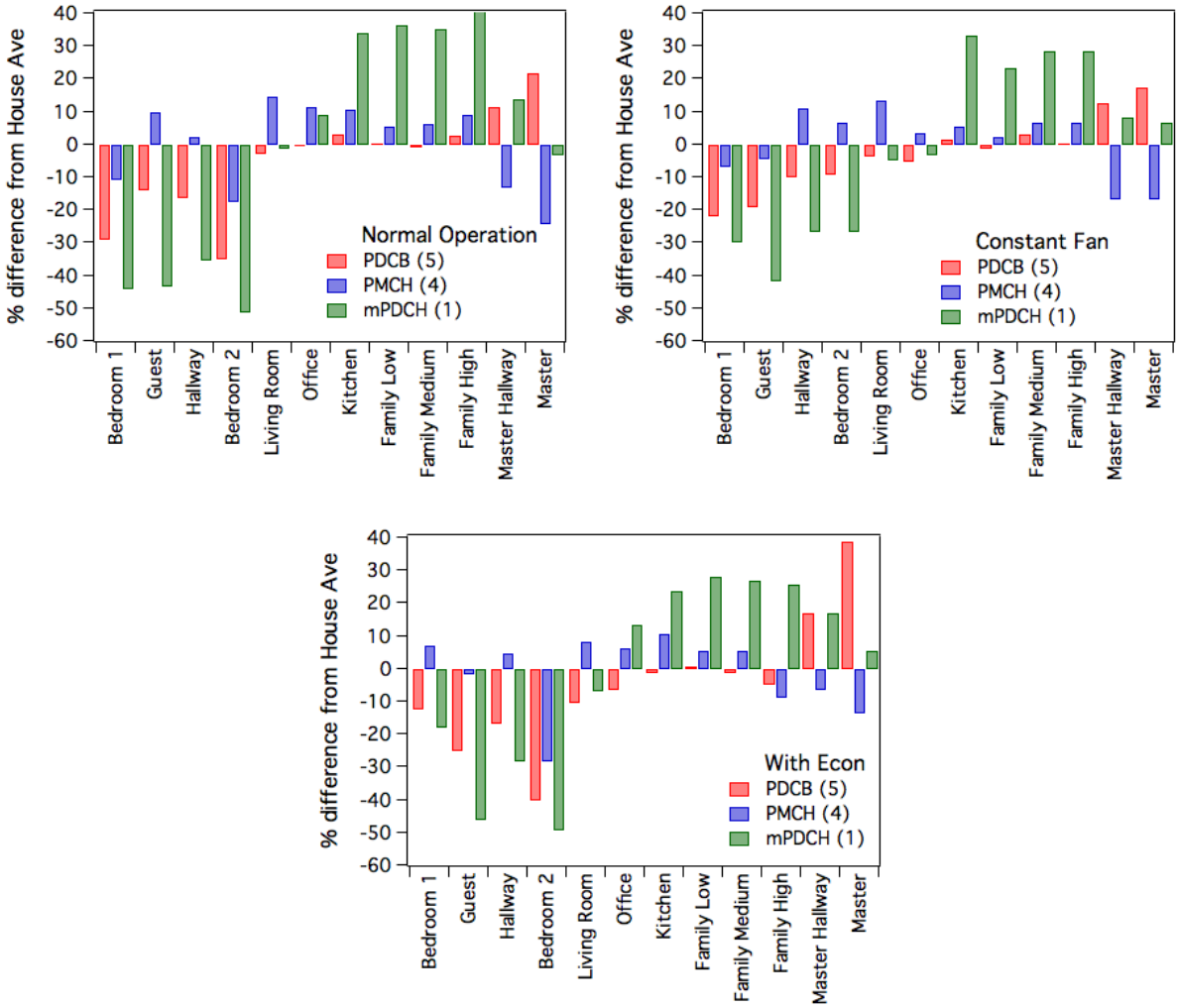

Figure 20: The percent difference of the concentrations of PDCB, PMCH, and mPDCH measured at each active measurement location and the volume weighted house averaged concentration for House 2. The three graphs show results for the experiments conducted with routine HVAC operation, constant HVAC fan operation, and HVAC operation using an economizer.

House 3

The time resolved concentration of the PFTs measured by the active gas samplers are shown in Figure 21 for the two ventilation conditions where the heating system fan was not operating and Figure 22 for the two ventilation conditions where the heating system fan was operating continuously. The figures shows both the concentrations measured for each of the 12 locations and the volume-weighted house average concentration. This house was largely unoccupied during the experiment and there were no time periods when the windows were opened. The interior doors were kept closed during the second and third ventilation conditions when the kitchen exhaust fan was operating. Unlike the other two experimental homes, the tracer gases measured using the active samplers were segregated by floor, with PMCH on the first, PDCB on the second, mPDCH on the third, and HB on all floors. The effect of this segregation of the PFTs is generally reflected in Figure 21 and Figure 22; the maximum concentration on each floor is usually from the tracer gas emitted on that floor.

The concentrations of PDCB and PMCH averaged over each three-day experimental ventilation condition are listed in Table 12. The concentrations of mPDCH averaged over each three-day ventilation condition are listed in Table 13 along with the concentrations of HB measured by the passive technique. The data show that the temporal variability in the individual tracer measurements is greatest when the kitchen fan was operating but the heating system fan was not, but the magnitude of this variability was strongly dependent on the tracer gas. During this ventilation condition, the relative standard deviation in the time resolved measurements ranged from 8 to 190 percent for PDCB, 7 to 77 percent for PMCH, and 20 to 660 percent for mPDCH. The spatial variability in tracer gas concentration was also largest for this ventilation condition, with relative standard deviations of 81, 111, 196, and 68 percent for PDCB, PMCH, mPDCH, and HB respectively. When the heating system fan was running but the kitchen fan was not, the relative standard deviations of the spatial tracer gas concentrations had values of 10, 5.3, 72, and 17 percent for PDCB, PMCH, mPDCH, and HB respectively. With the exception of mPDCH, these values are similar in magnitude to Houses 1 and 2 for constant central system fan operation.

The emission rates of the tracer gases for this experiment were measured each day of the experiment, and are shown in Table 14. These daily measurements allowed the spatial and temporal variability of the emission rates to be characterized. The results show that the standard deviation of the emission rates varied spatially from 2 to 11 percent. The standard deviation of the day-to-day variability in emission rates varied from 1.6 to 4.5 percent. The size of these variations compares with the uncertainty in the emission rate of the ~8 percent due to the precision of the temperature control on the dry block heaters discussed previously.

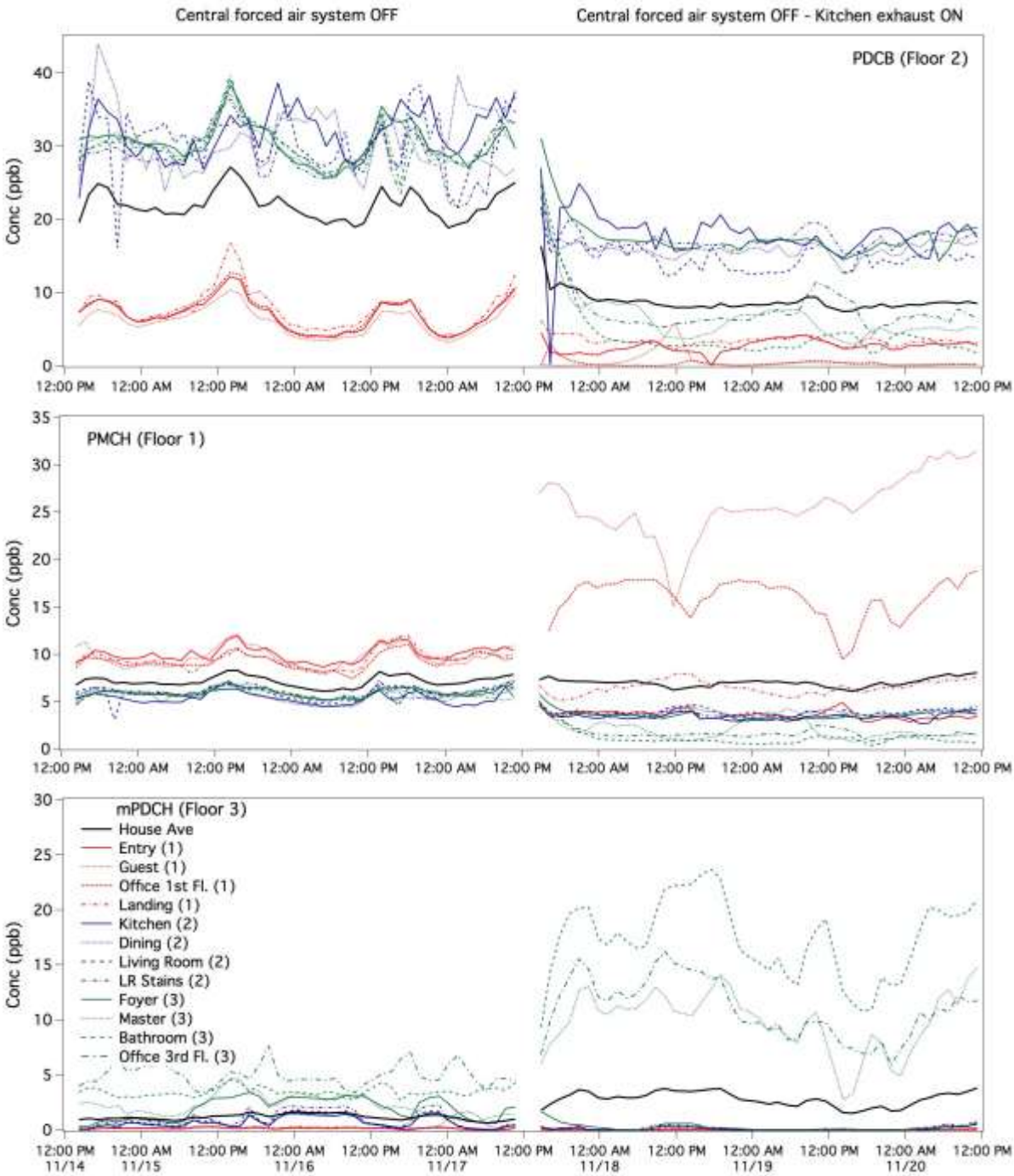

Figure 21: Time resolved concentration of (a) PDCB, (b) PMCH, and (c) mPDCH measured at House 3 for each active sampling location as well as the house average concentration for the first two experimental ventilation conditions. The data between noon of Nov 14th to Nov 17th were collected with no heating system operation, the data between noon of Nov 17th to Nov 20th were collected with no heating system operating but with the kitchen exhaust fan running continuously. The floor location of each room is noted in the graph annotation. Note that when the kitchen exhaust fan was running, all internal doors were kept closed.

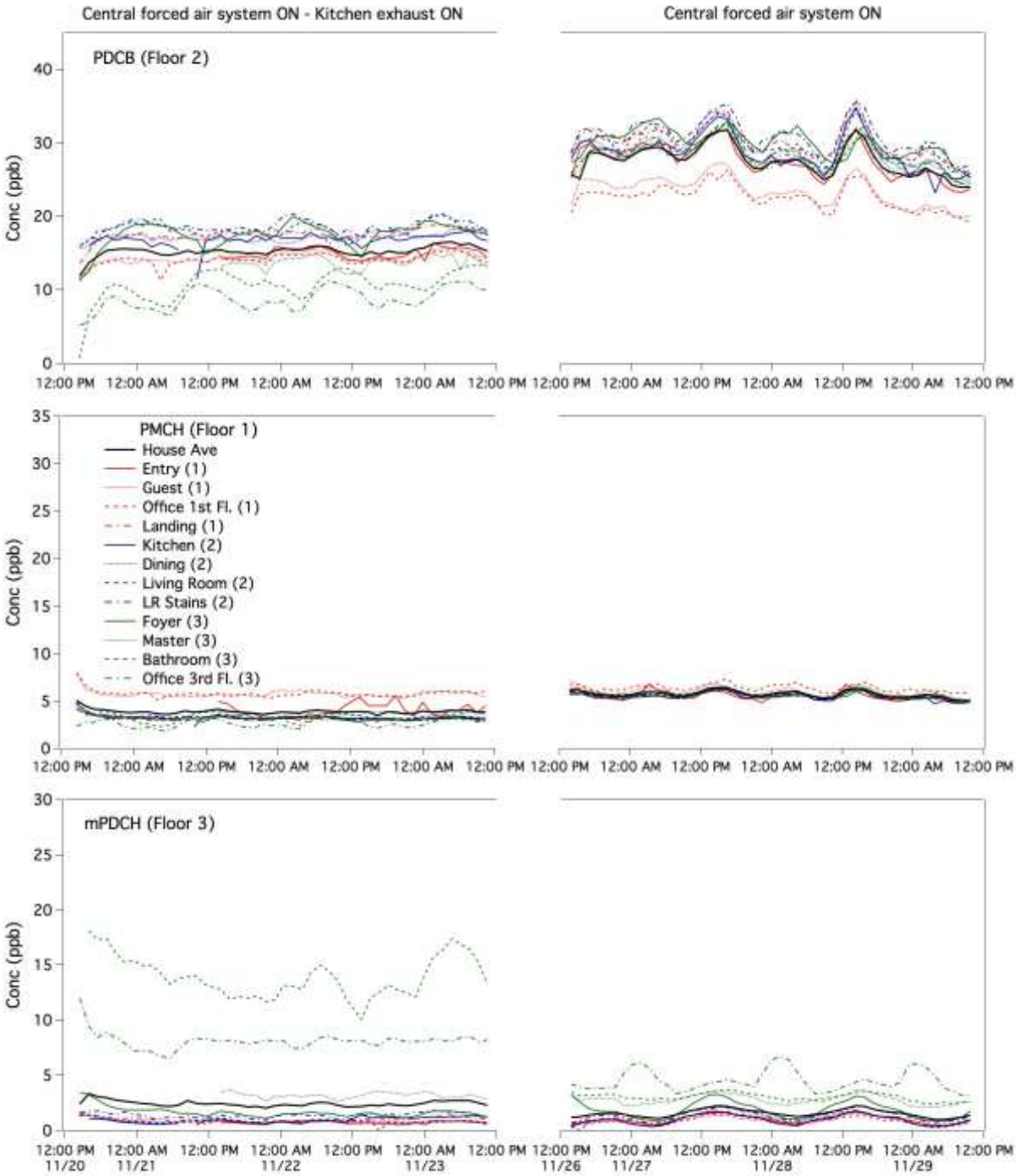

Figure 22: Time resolved concentration of (a) PDCB, (b) PMCH, and (c) mPDCH measured at House 3 for each active sampling location as well as the house average concentration for the second two ventilation conditions. The data between noon of Nov 20th to Nov 23rd were collected with continuous heating system and kitchen exhaust fan operation, and the data between noon of Nov 26th to Nov 29th were collected only with continuous heating system fan operation. The floor location of each room is noted in the graph annotation. Note that when the kitchen exhaust fan was running, all internal doors were kept closed.

Table 12: The average and standard deviation of the time resolved PFT concentrations in House 3 measured by the active samplers for both experimental conditions. The average and standard deviation of the time resolved volume weighted house average concentration is listed in the first row, followed by the spatial standard deviation calculated using the individual zone averages. All concentrations are in units of ppb.

	PDCB				PMCH			
	No Fan	No Fan w Exhaust	With Fan w Exhaust	With Fan	No Fan	No Fan w Exhaust	With Fan w Exhaust	With Fan
House	21.94 ± 2.13	8.83 ± 0.85	15.26 ± 0.72	27.54 ± 2.27	7.13 ± 0.81	7.02 ± 0.66	3.89 ± 0.68	5.73 ± 0.48
St. Dev.	11.82	7.19	2.89	2.75	1.93	7.80	1.11	0.30
Entry	6.90 ± 1.84	2.66 ± 1.06	14.97 ± 0.74	27.50 ± 1.96	10.01 ± 1.08	3.53 ± 3.17	4.03 ± 0.40	5.54 ± 0.47
Guest	6.03 ± 2.23	0.54 ± 0.47	14.33 ± 0.84	23.37 ± 1.74	9.70 ± 0.79	25.80 ± 2.07	5.76 ± 0.42	5.97 ± 0.38
Office Fl. 1	7.10 ± 2.64	0.32 ± 0.64	14.09 ± 0.87	22.55 ± 2.26	9.25 ± 0.96	16.05 ± 0.70	5.80 ± 0.25	6.37 ± 0.37
Landing	7.70 ± 3.36	3.47 ± 3.65	17.44 ± 0.99	30.00 ± 2.40	9.50 ± 0.59	6.47 ± 0.34	3.12 ± 0.22	5.49 ± 0.36
Kitchen	32.00 ± 4.34	18.04 ± 1.23	16.77 ± 0.60	28.53 ± 2.36	5.32 ± 0.67	3.36 ± 0.28	3.20 ± 0.26	5.47 ± 0.35
Dining	31.39 ± 4.33	15.92 ± 2.04	17.13 ± 0.92	28.82 ± 4.89	5.58 ± 0.74	3.79 ± 0.68	3.34 ± 0.55	5.51 ± 0.36
Living Room	30.59 ± 3.54	14.97 ± 1.55	18.24 ± 0.92	29.02 ± 2.22	5.87 ± 0.51	3.83 ± 0.30	3.25 ± 0.28	5.52 ± 0.36
LR Stairs	28.69 ± 2.65	17.17 ± 3.85	18.61 ± 1.70	30.89 ± 1.91	6.08 ± 0.45	3.64 ± 0.71	3.27 ± 0.23	5.59 ± 0.32
Landing Fl. 3	30.36 ± 2.53	17.27 ± 3.97	17.52 ± 0.79	29.91 ± 1.87	5.90 ± 0.43	3.50 ± 1.02	3.19 ± 0.17	5.53 ± 0.33
Master	29.68 ± 2.65	6.83 ± 4.63	13.77 ± 2.20	27.99 ± 1.99	5.73 ± 0.50	2.10 ± 0.88	3.78 ± 0.64	5.80 ± 0.34
Bathroom	30.03 ± 2.78	4.52 ± 3.40	10.53 ± 1.54	28.13 ± 1.95	5.86 ± 0.50	1.15 ± 0.66	3.20 ± 0.41	5.76 ± 0.33
Office Fl. 3	30.05 ± 1.96	7.79 ± 1.38	8.70 ± 0.74	28.42 ± 2.04	5.87 ± 0.56	1.69 ± 0.43	2.63 ± 0.24	5.72 ± 0.35

Table 13: The average and standard deviation of mPDCH and HB concentrations in House 3 measured by the active samplers, the volume weighted house average concentration, and the standard deviation of the average of the active samplers, for all experimental conditions. All concentrations are in units of ppb.

	mPDCH				HB			
	No Fan	No Fan w Exhaust	With Fan w Exhaust	With Fan	No Fan	No Fan w Exhaust	With Fan w Exhaust	With Fan
House	1.17 ± 0.06	2.81 ± 0.04	2.45 ± 0.11	1.55 ± 0.36	12.31	12.65	9.40	10.95
St. Dev.	1.42	5.52	3.57	1.11	2.87	8.65	5.80	1.81
Entry	0.15 ± 0.07	0.02 ± 0.03	0.72 ± 0.20	0.99 ± 0.32	10.45	3.77	7.00	10.60
Guest	0.13 ± 0.08	0.01 ± 0.01	0.79 ± 0.19	0.86 ± 0.34	9.85	22.63	7.53	9.44
Office Fl. 1	0.14 ± 0.08	0.00 ± 0.04	0.80 ± 0.18	0.82 ± 0.38	9.67	14.58	7.79	9.61
Landing	0.17 ± 0.49	0.02 ± 0.15	1.02 ± 0.26	1.07 ± 0.42	10.93	6.84	6.75	10.69
Kitchen	0.68 ± 0.48	0.10 ± 0.15	0.93 ± 0.16	0.95 ± 0.49	12.01	6.46	6.47	9.66
Dining	0.70 ± 0.58	0.11 ± 0.13	0.85 ± 0.21	1.07 ± 0.44	11.69	5.76	6.66	9.35
Living Room	0.76 ± 0.75	0.10 ± 0.21	0.85 ± 0.23	0.93 ± 0.45	11.37	6.19	6.69	10.43
LR Stairs	1.01 ± 0.99	0.15 ± 0.33	1.39 ± 0.48	1.35 ± 0.74	11.48	6.15	7.45	11.31
Landing Fl. 3	1.91 ± 0.94	0.22 ± 2.74	1.67 ± 0.25	1.83 ± 0.44	12.64	6.34	7.74	10.97
Master	2.20 ± 0.43	9.93 ± 3.55	3.19 ± 2.76	2.80 ± 0.35	15.70	20.49	10.02	13.18
Bathroom	3.45 ± 0.95	17.26 ± 2.68	13.67 ± 0.78	3.04 ± 0.95	16.45	30.87	28.46	13.57
Office Fl. 3	4.97 ± 0.26	10.94 ± 0.65	8.12 ± 0.26	4.50 ± 0.35	19.30	22.65	17.59	15.13

Table 14: Emission rates of PMCH, PDCB, mPDCH, and HB in μg/hr measured in House 3. The dates indicate the time period over which the emission rate was calculated. The average emission rate is calculated for all vial locations, and the standard deviation is calculated across vials.

Tracer Gas		Emission Rate													
		11/14	11/15	11/16	11/17	11/18	11/19	11/20	11/21	11/22	11/23	11/2	11/28	11/29	Exp Ave
PMCH	Ave	5.48	5.64	5.66	5.81	5.40	5.57	5.48	5.44	5.48	5.46	5.50	5.53	5.47	5.54
	St. Dev	0.54	0.58	0.56	0.60	0.23	0.18	0.24	0.25	0.22	0.17	0.27	0.20	0.23	0.11
PDCB	Ave	26.87	27.20	27.32	27.32	27.07	26.99	26.98	26.24	27.01	26.98	27.17	25.84	26.19	26.86
	St. Dev	0.60	0.69	1.01	0.74	0.71	0.90	0.89	1.12	0.63	0.70	0.75	0.75	1.04	0.45
mPDCH	Ave	5.06	4.87	4.79	4.75	4.66	4.66	4.37	4.52	4.35	4.40	4.52	4.55	4.42	4.57
	St. Dev	0.33	0.26	0.22	0.25	0.20	0.32	0.23	0.33	0.17	0.23	0.23	0.30	0.27	0.21
HB	Ave	3.23	3.35	3.34	3.36	3.26	3.29	3.15	3.22	3.23	3.23	3.25	3.15	3.07	3.24
	St. Dev	0.36	0.36	0.35	0.38	0.22	0.19	0.19	0.25	0.19	0.19	0.20	0.19	0.33	0.08

Figure 23 shows the PFT concentrations measured at each active sampling location averaged over each of the four ventilation conditions normalized by the emission rate of that PFT. This figure also shows the volume-weighted house average concentration normalized in the same manner. The figure also shows the normalized concentrations of HB by the passive samplers as all of the samplers were co-located. Table 15 lists the normalized values of the volume-weighted house average concentration as well as the relative standard deviation of the individual measurements for all of the tracer gases. The results listed in Table 15 show that magnitude of the spatial variability is a strong function of both the tracer gas and the ventilation condition. In general, the spatial variability of tracer gas concentrations was greatest when the kitchen fan was running and interior doors closed but the heating system fan not operating and was lowest when only the central heating system fan was running. mPDCH showed the largest degree of spatial variability. As stated above, the relative standard deviation of the tracer gas concentrations measured with the fan running (with the exception of mPDCH) are similar to those measured in Houses 1 and 2 for the same ventilation condition.

Table 15: Normalized value of the volume-weighted house average concentration and relative standard deviation for all four experimental conditions for House 3. The units of the normalized concentration are hr.

	Normalized Concentration (hr)			
	No Fan	No fan w Exhaust	With Fan w Exhaust	With Fan
PDCB	2.45 ± 54%	0.99 ± 81%	1.71 ± 19%	3.10 ± 10%
PMCH	3.86 ± 27%	3.80 ± 111%	2.11 ± 29%	3.10 ± 5%
mPDCH	0.77 ± 122%	1.84 ± 196%	1.61 ± 146%	1.02 ± 72%
HB	3.80 ± 23%	3.90 ± 68%	2.90 ± 62%	3.38 ± 17%

The results in Figure 23 show that when the heating system fan is not running, the normalized concentrations of the actively sampled PFTs tend to be greatest on the floor on which they were emitted whether or not the kitchen exhaust fan was running. When the kitchen exhaust fan was not on, the PFTs emitted on the first and second floors, PMCH and PDCB respectively, had significant concentrations on the floors above where they were emitted. This indicates a stack flow in the house from the lower to the upper floor. This indication of stack flow is also reflected in the HB concentration data. While the HB tracer gas was emitted on all floors, the concentration increases on the upper floors of the home. When the kitchen exhaust fan is turned on, the stack effect concentration pattern is modified slightly. The kitchen is located on the second floor, thus this location of the fan does result in a strong flow towards that floor. The concentration of PMCH, emitted on the first floor, still shows significant concentrations on the second floor but the concentrations on the third floor are reduced. Similarly, the concentration of PDCB, emitted on the second floor, is reduced on the third floor. However, when the kitchen fan was on, the interior doors in the home were closed. The effect of these closed doors is reflected in the elevated concentrations in the rooms that had doors, namely the Office on the 1st floor, the guest bedroom, and the master bedroom, bathroom, and office on the 3rd floor.

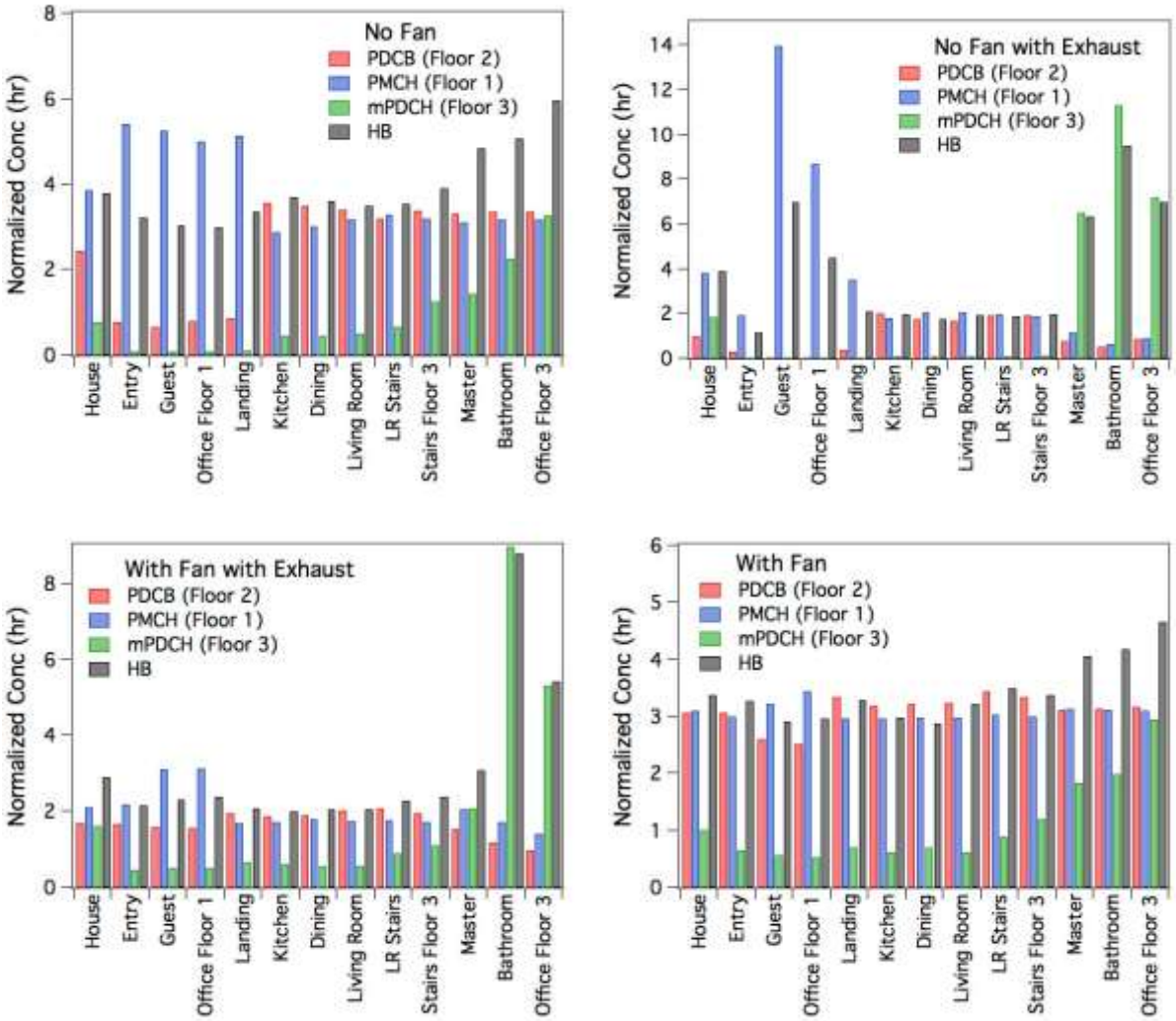

Figure 23: Average normalized concentration of PDCB, PMCH, mPDCH, and HB measured at each measurement location in House 3. The four graphs show results for the experiments conducted with no heating system operation, no heating system operation but with the kitchen exhaust running continuously, continuous heating system and kitchen exhaust fan operation. and continuous heating system fan operation.

The concentrations of all tracer gases were much more uniform across the different floors for the two experiments where the heating system fan was operating. When the system fan was on, the kitchen exhaust fan did not have as great effect on the distribution of PFT concentrations in the house as when the system fan was not on. When both the heating system and kitchen exhaust fan were running, there are elevated concentrations of PMCH (emitted on the 1st floor) in the two rooms on the first floor with doors, the office and guest bedroom, as well as elevated concentrations of mPDCH (emitted on the 3rd floor) in the third floor rooms with doors, the master bedroom, bathroom, and office when compared to results when kitchen fan was not running. While there are two changes between the two experimental conditions where the heating system fan is running, kitchen fan use and

closed doors, the closed doors do result in decreased mixing between those rooms and the rest of the house.

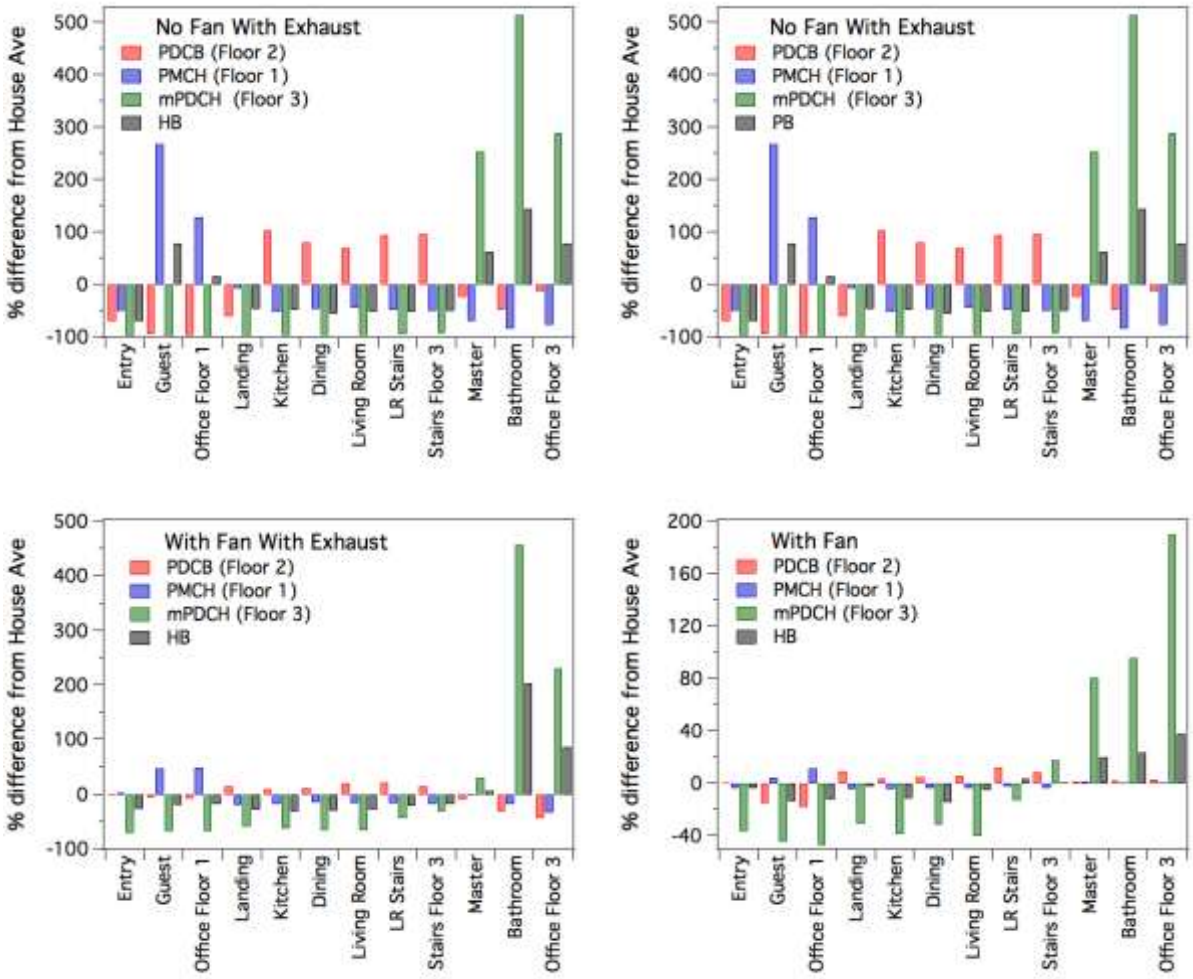

Figure 24: The percent difference between the concentrations of PDCB, PMCH, mPDCH, and HB measured at each measurement location and the volume-weighted house averaged concentration for House 3. The four graphs show results for the experiments conducted with no HVAC operation, no HVAC operation but with the kitchen exhaust running, constant HVAC fan operation with the kitchen exhaust running, and constant HVAC fan operation.

Figure 24 shows the percent difference between the concentrations measured each measurement location and the volume weighted house average concentration. The results show the same patterns observed in normalized concentration data presented in Figure 23 and Table 15. The measurements at individual locations varied more from the house average when the forced air fan was not running. The concentrations on the third floor tend to be higher than the house average, especially in the bathroom and office. Note that the third floor office and bathroom are not connected to the central system and thus have no supply ducts.

Summary

Experiments were carried out in three homes to assess the methodology used to determine air exchange rates using the passive tracer techniques. The results characterize the factors of the execution and analysis of the passive tracer technique that affect the uncertainty in the calculated air exchange rates. These factors include uncertainties in tracer gas emission rates, differences in measured concentrations for different tracer gases, temporal and spatial variability of the concentrations, the comparison between different gas sampling methods, and the effect of different ventilation conditions.

Laboratory measurements of the emission rate of a number of PFTs showed that emission rates change by approximately 4 percent for every 1°C change in temperature. The dry block heaters used to control the temperature of the tracer gas emitters in these experiments allowed for a precision of +/- 1°C, resulting in an uncertainty of approximately 8 percent in the emission rate of the PFT tracers. The daily tracer emission rates in House 3 showed spatial variations that ranged from 2 to 11 percent for different PFTs, and day-to-day variability of 1.6 to 4.5 percent. These values are comparable to the value that would be predicted based on uncertainty of the temperature of the emitters.

The results from the three experiments include detailed measurements of the spatial variability of the concentration of tracers in the house. These results are summarized in Table 16. These results show variability due to differences in number and placement of emitters, as well as the ventilation condition in the home. It is difficult to draw broad conclusions from the data presented in Table 16 due to these experimental differences. The data show that this spatial variability ranged from a relative standard deviation of 5 percent to values over 100 percent.

On average, the spatial variability of the tracer concentrations decreased with use of a central ventilation system fan, reflecting more effective mixing within the house. The average relative standard deviation for House 1 was 22 percent when the system fan was off versus 12 percent when the fan was in use. House 2 did not have a ventilation condition where the fan was completely off. However, the average relative standard deviation when the fan was running continuously was 15 percent, versus values of 18 and 20 percent when the system was operating normally (i.e. intermittent fan operation) with and without the economizer, respectively. The average relative standard deviation of tracer concentrations in House 3 was 26 percent for continuous system fan operation, compared to a value of 56 percent when it was not running.

The spatial variabilities of tracer concentrations were similar for Houses 1 and 2. Both of these homes were single story. The average relative standard deviations of all tracers measured with continuous central ventilation system fan operation were 12 and 15 percent for Houses 1 and 2, respectively. The ranges of the relative standard deviations were as similar for both homes, with values ranging from 5 to 26 percent; however, House 2 had over three times more floor area than House 1. Both homes had the same physical number of tracer emitters, suggesting that the floor area per emitter was not as crucial to achieve good tracer distribution in the home when compared to the effect of operating a central ventilation fan.

The spatial variabilities of the tracer gases measured in House 3 were quite a bit larger than those measured in Houses 1 and 2. An important factor contributing to these large variabilities is the fact that the emitters for three of the four PFTs were isolated on individual floors – the PFTs were not emitted uniformly throughout the house. The tracer that was emitted uniformly throughout the house, HB, had values of the relative standard deviation of 23 and 17 percent for the ventilation conditions with and without central system fan operation and with the kitchen fan off, respectively. These values are similar to those measured in Houses 1 and 2, indicating that uniform placement of tracers in a multistory home provide a spatial concentration distribution that is comparable to that observed in single story homes.

The data in this report provide measurements of the magnitude of the variability in parameters that will affect the uncertainty in the calculated ventilation rate. The experiments resulted in a rich data, whose further analysis will provide information on the relationship between the experimental methods and the resulting air exchange rate. The results of these upcoming analyses will be used to recommend best practices for measurements of air exchange rate using the constant injection method as well as to assess the overall capability of passive tracer gas techniques to determine air change rates.

Table 16: Volume-weighted house average concentration of PDCB, PMCH, mPDCH, and HB for each house and ventilation condition as well as the standard deviation and coefficient of variation individual measurement locations. All concentrations are in units of ppb.

		House 1		House 2			House 3			
		No Fan	Const Fan	Norm Op	Const Fan	With Econ	No Fan	No Fan w Exhaust	With Fan w Exh.	With Fan
PDCB	Ave	2.88	1.85	7.70	4.95	7.47	21.94	8.83	15.26	27.54
	St Dev	0.76	0.22	0.88	0.45	1.23	11.82	7.19	2.89	2.75
	Coef Var	0.26	0.12	0.15	0.12	0.21	0.54	0.81	0.19	0.10
PMCH	Ave	3.50	2.13	1.31	0.90	1.24	7.13	7.02	3.89	5.73
	St Dev	0.75	0.1	0.2	0.11	0.13	1.93	7.8	1.11	0.3
	Coef Var	0.21	0.05	0.15	0.12	0.10	0.27	1.11	0.29	0.05
mPDCH	Ave	0.39	0.18	0.88	0.60	0.89	1.17	2.81	2.45	1.55
	St Dev	0.06	0.04	0.25	0.13	0.21	1.42	5.52	3.57	1.11
	Coef Var	0.15	0.22	0.28	0.22	0.24	1.21	1.96	1.46	0.72
HB	Ave	2.92	2.02	7.07	4.46	6.57	12.31	12.65	9.40	10.95
	St Dev	0.69	0.19	1.06	0.66	1.61	2.87	8.65	5.8	1.81
	Coef Var	0.24	0.09	0.15	0.15	0.25	0.23	0.68	0.62	0.17

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Appendix:

Table A1a: Emission rates of PMCH for each emitter location in House 1 in μg/hr. The dates indicate the time period over which the emission rate was calculated.

	6/17-6/18	6/18 – 6/23	6/23 – 6/24	6/24 – 6/25	6/25 – 6/28
Entrance	604	720	780	724	723
Living Room	577	729	717	683	680
Dining Room	572	658	772	736	715
Hallway	511	564	648	602	612
Master	661	679	867	825	807
Office	546	679	476	301	282
Guest Room	550	721	701	669	656
Bathroom	575	613	753	723	723
Average	575	670	714	658	650
St. Dev.	42	54	108	147	149

Table A1b: Emission rates of PDCB for each emitter location in House 1 in μg/hr. The dates indicate the time period over which the emission rate was calculated.

	6/17-6/18	6/18 – 6/23	6/23 – 6/24	6/24 – 6/25	6/25 – 6/28
Living Room	845	1009	995	969	975
Dining Room	810	988	1135	1078	1080
Hallway	893	943	1128	1041	1075
Office	796	1003	1088	1048	1044
Average	836	985	1086	1034	1043
St. Dev.	37	26	56	40	42

Table A1c: Emission rates of mPDCB for each emitter location in House 1 in μg/hr. The dates indicate the time period over which the emission rate was calculated.

	6/17-6/18	6/18 – 6/23	6/23 – 6/24	6/24 – 6/25	6/25 – 6/28
Living Room	367	469	474	431	436
Hallway	377	384	508	446	459
Average	372	427	491	438	448
St. Dev.	5	43	17	8	12

Table A1d: Emission rates of HB for each emitter location in House 1 in μg/hr. The dates indicate the time period over which the emission rate was calculated.

	6/17-6/18	6/18 – 6/23	6/23 – 6/24	6/24 – 6/25	6/25 – 6/28
Living Room	430	578	551	546	544
Dining Room	427	508	577	576	573
Hallway	409	464	562	540	538
Office	453	573	626	604	609
Average	430	530	579	567	566
St. Dev.	22	54	32	32	36

Table A2: Emission rates of PMCH, PDCB, mPDCH, and HB in μg/hr for each emitter location in House 2.

	PDCB	PMCH	mPDCH	HB
Guest Room	1250.8	823.3		710.5
Hallway	1210.2	906.5		883.9
Living Room	1244.9	906.7		764.1
Dining Room	1184.4	838.1		623.9
Kitchen	1211.8	878.4	643.7	718.2
Family Room	1167.1			694.4
Master Hallway	1249.2			717.4
Master Bedroom	1316.9			724.1
Average	1229.4	870.6		729.6
St. Dev.	43.8	34.5		69.0

Table A3a: Emission rates of PMCH for each emitter location in House 3 in units of μg/hr. The dates indicate the time period over which the emission rate was calculated.

	11/14	11/15	11/16	11/17	11/18	11/19	11/20	11/21	11/22	11/23	11/27	11/28	11/29
Entry	6894.9	7133.3	7127.4	7357.2	6322.6	6441.7	6397.2	6376.6	6347.8	6270.6	6460.4	6417.9	6398.0
Guest Room	5632.0	5816.6	5896.1	5933.7	5763.8	6004.7	5760.7	5954.2	6050.0	5988.9	6024.3	5960.4	5929.7
Office	5621.2	5752.4	5731.5	5954.0	5821.3	6027.8	6015.4	5705.7	5754.9	5827.9	5746.6	5938.5	5801.9
Average	6049.4	6234.1	6251.7	6415.0	5969.3	6158.1	6057.8	6012.2	6050.9	6029.1	6077.1	6105.6	6043.2
St. Dev.	597.9	636.4	622.9	666.3	251.0	200.8	261.6	276.9	242.0	182.9	293.8	221.0	256.2

Table A3b: Emission rates of PDCB for each emitter location in House 3 in units of μg/hr. The dates indicate the time period over which the emission rate was calculated

	11/14	11/15	11/16	11/17	11/18	11/19	11/20	11/21	11/22	11/23	11/27	11/28	11/29
Kitchen	28089.4	28433.1	28350.7	28268.8	27990.5	27679.8	27940.4	27376.2	27521.2	28079.2	28059.3	27655.8	28065.7
LR Central	28024.4	28489.1	29194.2	28915.9	28636.0	28916.9	28742.3	28130.9	28641.4	28397.5	28802.1	26001.2	25489.2
LR near stairs	26746.2	26955.9	26697.3	27078.8	26865.6	26641.8	26523.7	25401.7	27121.2	26727.8	26927.1	26035.1	27205.5
Average	27620.0	27959.4	28080.7	28087.9	27830.7	27746.1	27735.5	26969.6	27761.3	27734.9	27929.5	26564.0	26920.1
St. Dev.	618.5	709.9	1037.1	760.8	731.5	930.0	917.2	1150.7	643.4	723.8	771.0	772.1	1071.0

Table A3c: Emission rates of mPDCH for each emitter location in House 3 in units of μg/hr. The dates indicate the time period over which the emission rate was calculated

	11/14	11/15	11/16	11/17	11/18	11/19	11/20	11/21	11/22	11/23	11/27	11/28	11/29
Bedroom	4261.8	4178.9	4061.6	4076.8	3926.9	3980.8	3767.1	3898.1	3688.8	3757.4	3801.1	3952.7	3826.7
Bathroom	4620.8	4346.5	4263.6	4242.7	4148.1	4250.0	3875.1	4117.6	3836.2	3926.1	4056.8	4098.5	3966.0
Laundry	3943.5	3827.0	3816.9	3728.0	3727.3	3593.2	3426.0	3453.3	3490.9	3463.6	3588.9	3493.7	3418.6
Average	4275.4	4117.4	4047.4	4015.9	3934.1	3941.3	3689.4	3823.0	3672.0	3715.7	3815.6	3848.3	3737.1
St. Dev.	276.6	216.5	182.6	214.5	171.9	269.6	191.4	276.4	141.5	191.1	191.3	257.7	232.3

Table A3d:Emission rates of HB for each emitter location in House 3 in units of μg/hr. The dates indicate the time period over which the emission rate was calculated

	11/14	11/15	11/16	11/17	11/18	11/19	11/20	11/21	11/22	11/23	11/27	11/28	11/29
Entry	2204.1	2285.1	2251.0	2296.0	1926.7	1961.0	1837.7	1926.5	1916.0	1888.5	1856.4	1691.8	1225.0
Guest Room	1539.8	1617.8	1596.5	1625.4	1582.1	1651.2	1559.6	1603.7	1654.3	1643.8	1616.0	1603.3	1572.3
Office	1603.7	1690.4	1671.6	1668.6	1644.4	1745.2	1613.3	1634.7	1613.0	1622.6	1636.1	1613.6	1644.2
Kitchen	1795.7	1811.1	1888.1	1875.8	1848.0	1809.3	1742.8	1895.4	1890.1	1892.1	1904.3	1631.1	1687.7
LR Central	1814.1	1861.0	1816.3	1897.6	1859.7	1860.3	1856.7	1871.2	1772.8	1761.7	1812.5	1879.7	1862.3
LR near stairs	1527.9	1586.8	1577.6	1569.2	1601.6	1651.0	1582.6	1537.2	1617.0	1622.5	1603.8	1555.0	1606.7
Bedroom	1724.2	1770.6	1770.9	1766.2	1751.4	1735.1	1704.5	1677.9	1735.2	1746.3	1750.7	1740.3	1733.2
Bathroom	1800.1	1850.6	1852.6	1860.4	1850.0	1855.7	1757.7	1809.3	1778.9	1812.6	1846.8	1839.1	1865.5
Laundry	1672.1	1743.2	1761.7	1743.6	1748.8	1674.1	1624.8	1658.9	1676.8	1687.0	1734.5	1693.8	1670.7
Average	1742.4	1801.8	1798.5	1811.4	1757.0	1771.4	1697.8	1735.0	1739.4	1741.9	1751.2	1694.2	1652.0
St. Dev.	193.2	193.4	189.7	202.5	117.3	101.6	102.9	134.1	104.7	100.3	105.9	103.1	179.1