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Pilot Test Results

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Abstract

The Healthy Efficient New Gas Homes (HENGH) is a field study that will collect data on ventilation systems and indoor air quality (IAQ) in new California homes that were built to 2008 Title 24 standards. A pilot test was performed to help inform the most time and cost effective approaches to measuring IAQ in the 100 test homes that will be recruited for this study. Two occupied, single-family detached homes built to 2008 Title 24 participated in the pilot test. One of the test homes uses exhaust-only ventilation provided by a continuous exhaust fan in the laundry room. The other home uses supply air for ventilation. Measurements of IAQ were collected for two weeks. Time-resolved concentrations of particulate matter (PM), nitrogen dioxide (NO_2), carbon dioxide (CO_2), carbon monoxide (CO), and formaldehyde were measured. Measurements of IAQ also included time-integrated concentrations of volatile organic compounds (VOCs), volatile aldehydes, and NO_2. Three perfluorocarbon tracers (PFTs) were used to estimate the dilution rate of an indoor emitted air contaminant in the two pilot test homes. Diagnostic tests were performed to measure envelope air leakage, duct leakage, and airflow of range hood, exhaust fans, and clothes dryer vent when accessible. Occupant activities, such as cooking, use of range hood and exhaust fans, were monitored using various data loggers. This document describes results of the pilot test.

1 Introduction

The Healthy Efficient New Gas Homes (HENGH) field study will collect data on ventilation systems and indoor air quality (IAQ) in new California homes that were built to 2008 Title 24 standards (CEC, 2008). HENGH aims to collect IAQ data in 100 occupied California homes in different locations and seasons. Measurements will include mechanical ventilation system performance, indoor air contaminant concentrations, and other indoor environmental parameters. The collected data will be analyzed to evaluate IAQ in the sampled homes. It will also be used as input data for model simulations to determine how to provide adequate ventilation and acceptable IAQ while reducing air infiltration beyond the 2008 Title 24 standards.

2 Pilot Test Objectives

The main pilot test objective was to determine the most time and cost effective approaches to measuring IAQ in the test homes before testing all 100 homes. The pilot testing was also used to identify potential problems with field measurements. As a result, the field team performed more

intensive air quality sampling and data collection than intended for the full-scale field study so that a subset could be selected that will best achieve the overall project objectives regarding IAQ assessment while being appropriate for a large-scale field study with limited home access.

3 Descriptions of Pilot Test Homes

Two occupied, single-family detached homes built to 2008 Title 24 were recruited. One of the pilot test homes uses exhaust-only ventilation provided by a continuous exhaust fan in the laundry room. The second pilot test home uses supply air for ventilation. Measurements of indoor air quality (IAQ) were collected for two weeks. Different approaches were used to collect data on usage of gas appliances and mechanical ventilation. This document summarizes field data collected from the two pilot test homes. Table 1 describes the basic house characteristics of these two homes. Floor plans are shown in Appendix A. The requirements for participation in the pilot test were that houses must be located in the Bay Area or Sacramento area, built in 2011 or later, have at least three occupants, have mechanical ventilation, and use natural gas for space heating, water heating, and cooking. Smoking must be prohibited. LBNL completed field testing in two homes between July and September 2015.

LBNL Institutional Review Board approved the human subject protocol that was followed in this study. Study participants were paid $560 for their time. Aside from making their homes available for this pilot test, study participants also filled out a daily log to record information about their indoor activities. They gave consent for LBNL to access Title 24 compliance documents from the CHEERS (ConSol Home Energy Efficiency Rating Services) data registry. We found that the compliance documents on file do not contain information on mechanical ventilation. They contain other information (e.g., diagnostic test results, specifications on building components and appliances) that will be helpful for data analysis and interpretation.

Table 1 House characteristics of the two pilot test homes.

	House 1	House 2
Sampling Period: Week 1 Week 2	July 22–29 July 29–August 5	August 19–26 August 26–September 3
Location	Rancho Cordova, CA	Brentwood, CA
Year Built	2015	2013
Floor Area	1777 ft^2	2990 ft^2
Ceiling Height	10 ft	9 ft
Estimated House Volume*	17770 ft^3	26910 ft^3
Number of Stories	1 story	2 story
Number of Bedrooms	3 bedrooms	4 bedrooms
Number of Bathrooms	2 full	3 full
Number of Occupants	3 occupants	5 occupants
Garage	Attached, 3-car	Attached, 2-car

* House volume estimated by multiplying floor area and ceiling height.

4 Building Envelope and Duct Leakage Tests

A team of two researchers from LBNL conducted all sampling and data collection in the Pilot test homes. Building envelope air leakage and duct leakage was measured using the deltaQ test (ASTM, 2013). Table 3 shows the test results. Title 24 compliance documents showed the measured (tested at final, not rough-in) duct leakage at 25 Pa measured using duct pressurization. Note that deltaQ test measured duct leakage at operating conditions, so the results are not directly comparable to results from the duct pressurization test. However, deltaQ results are not very sensitive to the operating pressures of the system, as long as pressure are within a factor of two (Walker et al., 2001). In Table 2, envelope leakage measurements and HVAC airflow was available from the compliance documents for House 2 only.

Table 2 Measured building envelope and duct leakage in two pilot test homes.

		House 1	House 2
Building Envelope Leakage			
	Pressurization leakage	4.5 ACH50	3.2 ACH50
	Depressurization leakage	3.9 ACH50	3.1 ACH50
	Average leakage	4.2 ACH50	3.2 ACH50
	Title 24 Compliance Certificate	--	3.1 ACH50
Duct Leakage*			
	Supply leakage#	35 CFM (2%)	29 CFM (2%)
	Return leakage#	42 CFM (3%)	35 CFM (3%)
	Title 24 Compliance Certificate+	77 CFM (4%)	11 CFM (1%)
HVAC Airflow			
	Rated	1600 CFM	1500 CFM
	Title 24 Compliance Certificate	--	1268 CFM

* % duct leakage calculated using rated airflow for House 1, and measured airflow for House 2.
# Measured using deltaQ test at operating pressures.
+ Measured using duct pressurization test at 25 Pa.

5 Mechanical Ventilation Airflow Measurements

Table 3 shows the mechanical ventilation airflow measurements. Both houses have microwave-combined range hood. Range hood exhaust airflow rates were measured using a custom-made capture box that is fitted under the range hood. A fan and flow meter were connected to the capture box to measure the airflow at three fan speed settings. Airflow of the exhaust fan in bathrooms and laundry room were measured using a powered flow hood. Many of the exhaust fans found in the bathrooms were controlled by a humidistat. Clothes dryer vent airflow was measured only at House 2 at the exterior wall cap using a powered flow hood. The measured airflow was low compared to an expected 100 to 150 CFM for typical clothes dryers (Bendt, 2010). The clothes dryer vent at House 1 was not measured because the exterior vent was located on the roof and inaccessible to the field team.

Table 3 Measured mechanical ventilation airflow rates in two pilot test homes.

	House 1	House 2
Range Hood	158 CFM (High speed) 107 CFM (Mid) 98 CFM (Low)	132 CFM (High speed) 112 CFM (Mid) 104 CFM (Low)
Exhaust Fan – Master Bath	104 CFM (bath, humidistat) 54 CFM (toilet, manual)	98 CFM (bath, humidistat) 56 CFM (toilet, manual)
Full Bath 2	110 CFM	96 CFM (humidistat)
Full Bath 3	--	87 CFM (humidistat)
Laundry Room	86 CFM	86 CFM
Clothes Dryer Vent	Not measured because inaccessible located on roof	45 CFM

The laundry room exhaust fan provided most of the mechanical ventilation in House 1. Anemometer data showed that the fan was operating approximately two-thirds of the time. The required whole-building ventilation per Title 24 is calculated as follows:

$$Q_{cfm} = 0.01\ (A_{floor}) + 7.5\ (N_{br} + 1) = 48\ \text{CFM}$$

where the conditioned floor area (A_{floor}) = 1770 ft^2 and number of bedrooms (N_{br}) = 3. The laundry room exhaust fan would have provided sufficient whole-house ventilation if it were operating continuously. However, the fan was operating intermittently, though not as would be if it were cycled by a timer (see Appendix B). If the ventilation effectiveness of 0.75 were applied as specified in Title 24 for intermittent fans that operate between 60% to 80% of the time, the laundry room exhaust fan must have an airflow of at least 96 CFM to provide sufficient whole-building ventilation.

$$Q_f = 48\ \text{CFM} / (0.67 \times 0.75) = 96\ \text{CFM}.$$

In House 2, mechanical ventilation was provided by an inline fan connected to the return plenum of the air handler. The required whole-house ventilation per Title 24 for House 2 is 68 CFM. The inline fan was observed to be continuously running during field visit. However, its airflow was not measured because it was buried in spray foam and was inaccessible.

In addition, Title 24 required exhaust fans installed to provide local ventilation in kitchen and each bathroom. The requirements for intermittent local ventilation are 100 CFM in kitchen and 50 CFM in bathroom. Both houses met Title 24 in terms of meeting the local ventilation airflow requirement.

6 Activity Monitoring

Table 4 shows the methods used to monitor usage of various appliances, including the cooktop and oven, bathroom exhaust fans, clothes dryer, central forced air system, water heater, and

windows/door opening. Activity data were mostly logged on 1-minute time intervals. Figure 1 through Figure 6 show examples of the locations used for activity monitoring. Table 5 shows the daily average runtime of the devices used to compute the mechanical ventilation rates; see Appendix B for the usage data collected over the two sampling weeks.

Table 4 Methods used to monitor appliance usage at the two pilot test homes.

Usage	House 1	House 2
Cooktop	Wire braid thermocouple	iButton temperature sensor
Oven	Thermocouple probe	Thermocouple probe
Bathroom Exhaust Fan	Motor on/off state logger Digital anemometer	Motor on/off state logger
Range Hood	Digital anemometer	Digital anemometer
Clothes Dryer	Power meter	T/RH at exterior vent
Central forced air system	Power meter T/RH at air register	Digital anemometer T/RH at air register Motor state logger
Water heater	--	Thermocouple probe at draft diverter
Windows/doors	Open/close state logger	Open/close state logger

Table 5 Daily average runtime in two pilot test homes.

	House 1	House 2
Range Hood	11 minutes	17 minutes
Exhaust Fan – Master Bath	24 minutes (bath) 26 minutes (toilet)	74 minutes (bath) 5 minutes (toilet)
Full Bath 2	46 minutes	16 minutes
Full Bath 3	--	44 minutes
Laundry Room	14.9 hours	51 minutes
Clothes Dryer Vent	32 minutes	38 minutes

Figure 1 Wire braid thermocouple (five total: left-front, left-back, right-front, right-back, and center of the burner top) and thermocouple probe used to measure cooktop and oven use in House 1 (top left and right). The red arrow shows where one of the four iButton temperature sensors were placed near the left-front burner top in House 2 (bottom left).

Figure 2 Digital anemometer (upper) and motor state logger (lower) used to monitor bathroom exhaust fan use.

Figure 3 Digital anemometer used to monitor range hood use.

Figure 4 Methods used to monitor central forced air system use: power meter on the air handler (upper left), temperature/relative humidity sensor at the supply grill closest to the air handler (upper right), digital anemometer at the return grill (lower).

Figure 5 Thermocouple probe used to monitor gas water heater usage.

Figure 6 State logger used to monitor opening and closing of windows and doors.

In House 1, four open/close state sensors were used to monitor the following doors: master bedroom door, master bathroom door, sliding door to back patio, and door from garage to house. Windows were not monitored in House 1. More doors and some windows were monitored in House 2, including 11 door sensors (master bedroom and three other bedroom doors, two other bathroom doors, laundry room door, sliding door to back patio, front door, door from garage to house, door from garage to outside) and 7 windows sensors (two master bedroom windows, three playroom windows, living room window, and entry room window).

Figure 7 shows the window use in House 2. Windows in the master bedroom and playroom on the upper floor were left open for 13 hours (master bedroom) and 16 hours (playroom) per day on average. Windows in the living room and entry room on the lower floor were mostly closed. They were opened for 3.8 hours per day on average.

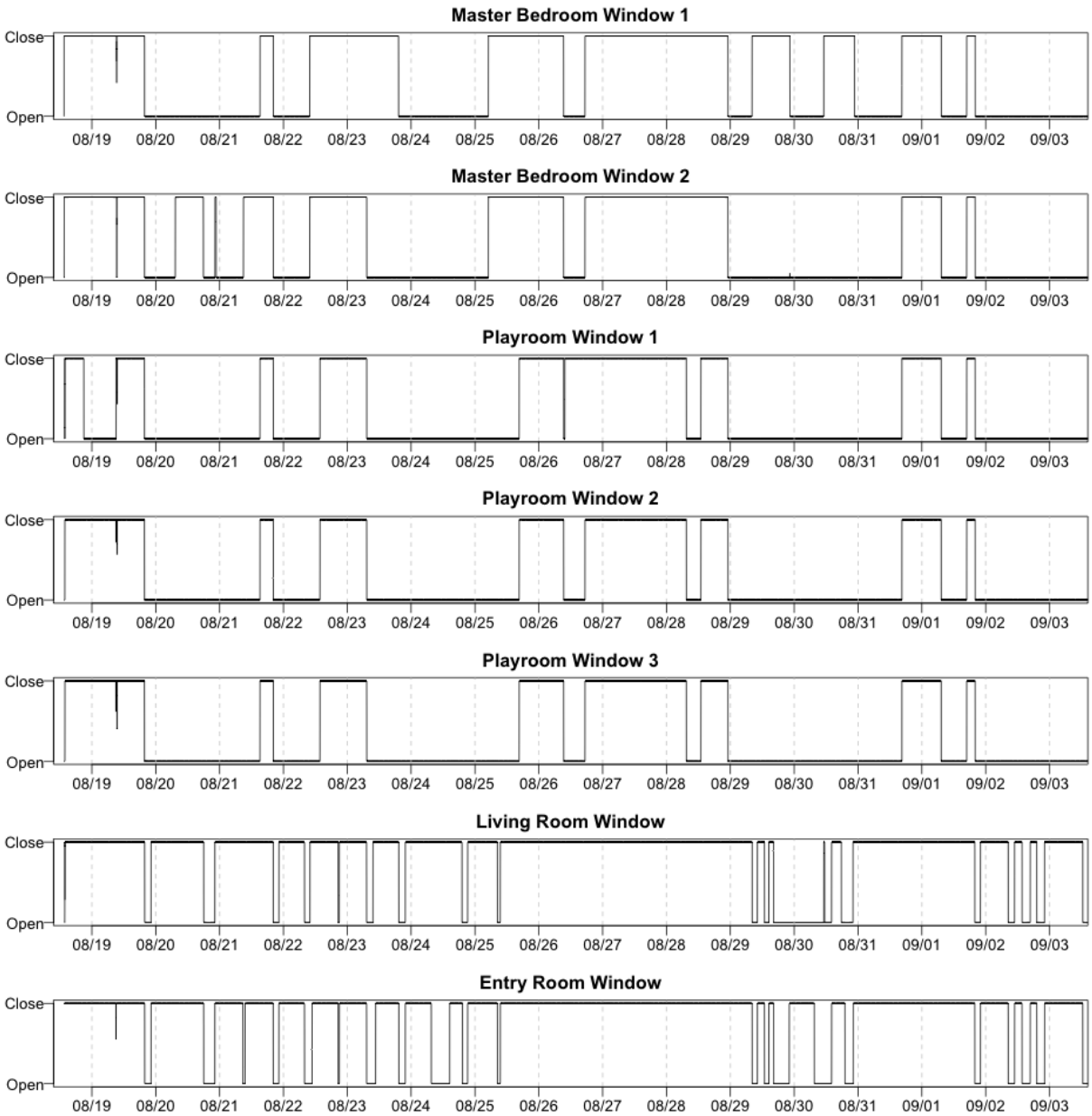

Figure 7 Monitoring data of window use in House 2.

Figure 8 and Figure 9 show the temperature measured at the cooktop and oven in House 1 and House 2, respectively. Cooking events can be identified by a sudden increase in temperature, such as shown in Figure 10 and Figure 11 for example cooking events. The temperature data roughly correspond to the times and durations of cooktop and oven use reported by occupants in their daily activity logs.

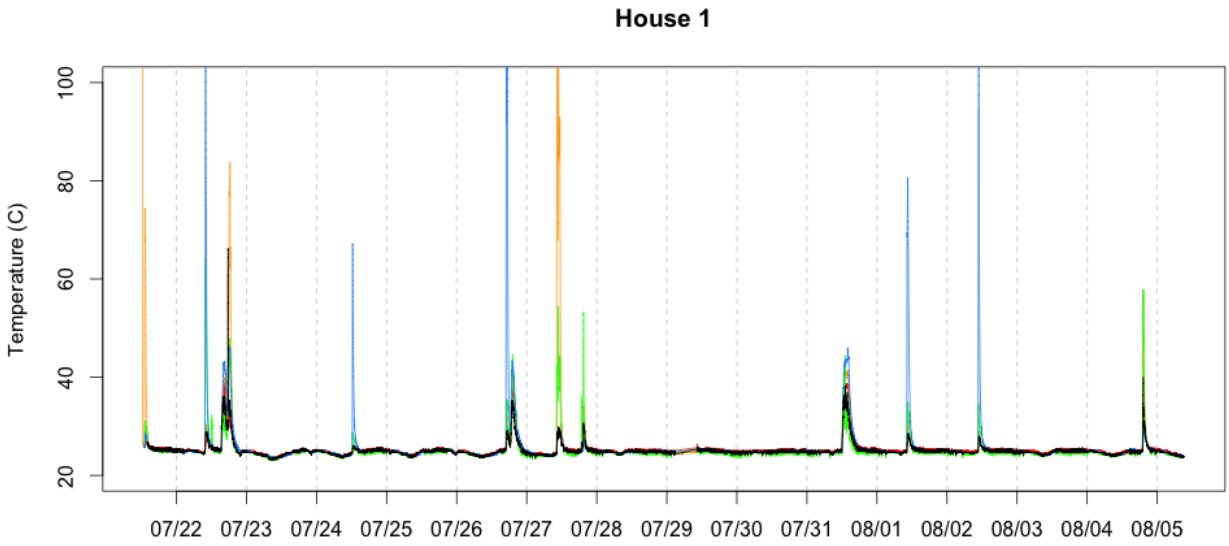

Figure 8 Temperature measured outside of oven (in black) and on cooktop (lines in color indicating temperatures measured near different burners) in House 1.

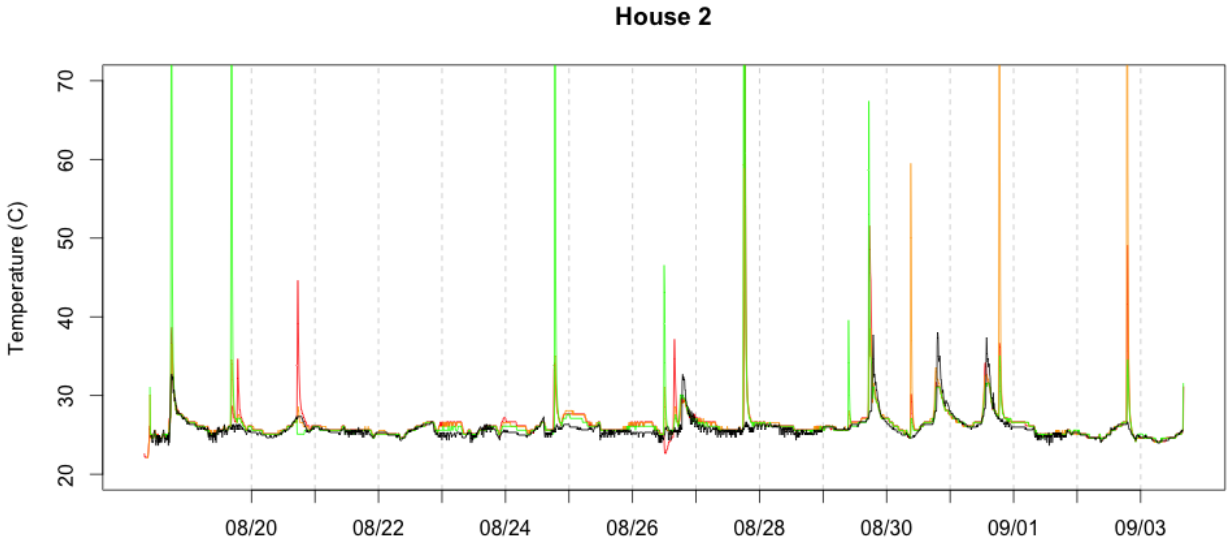

Figure 9 Temperature measured outside of oven (in black) and on cooktop (lines in color indicating temperatures measured near different burners) in House 2.

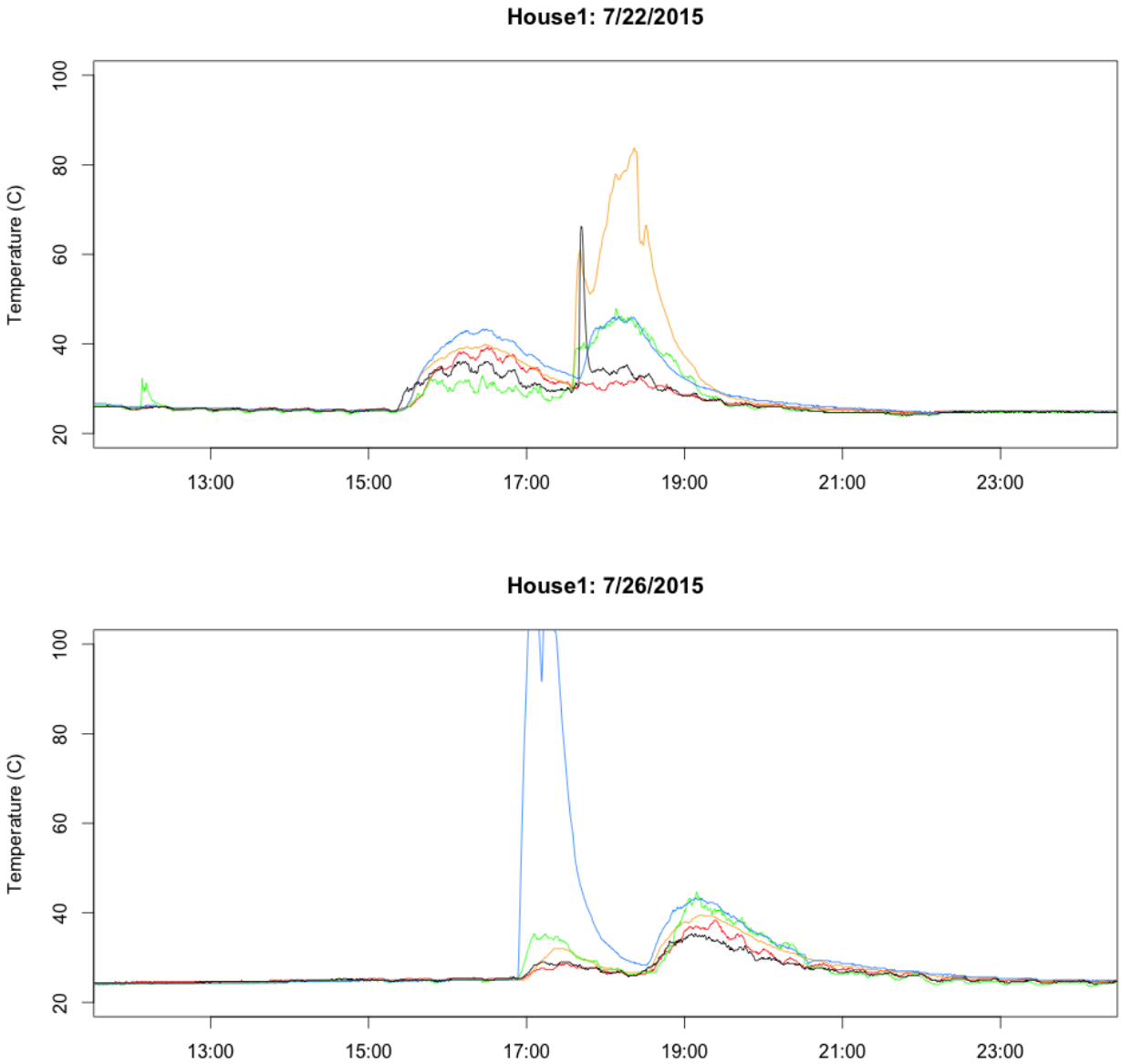

Figure 10 Temperature measured outside of oven (in black) and on cooktop (lines in color). Occupants reported 45 minutes of oven use followed by 1.5 hours of cooktop use on July 22. On July 26, occupants reported 30 minutes of cooktop use followed by 30 minutes of oven use.

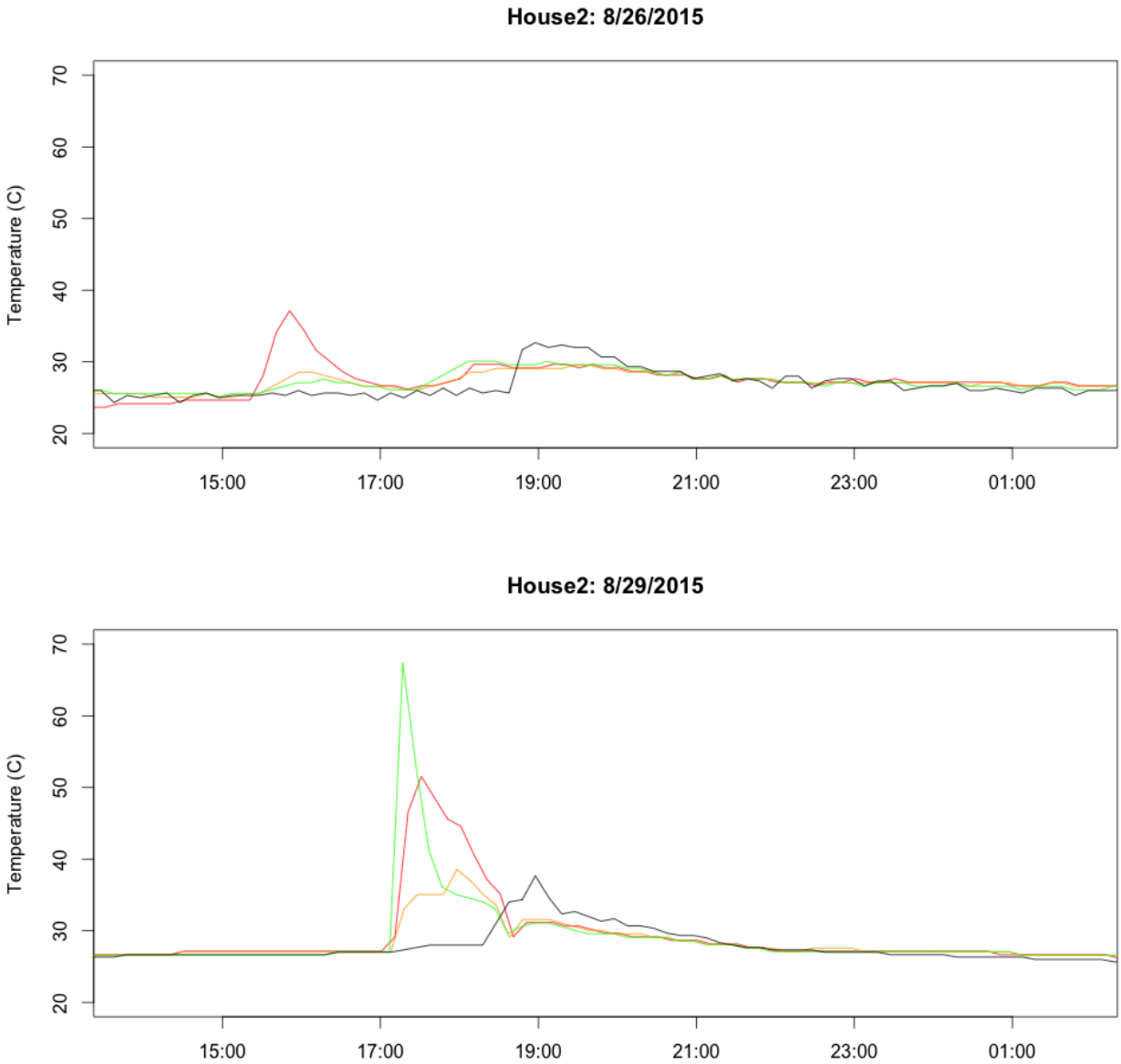

Figure 11 Temperature measured outside of oven (in black) and on cooktop (lines in color). Occupants reported 30 minutes of cooktop use followed by 45 minutes of oven use on August 26. On August 29, occupants reported 40 minutes of cooktop use followed by 30 minutes of oven use.

Figure 12 and Figure 13 show the temperature and relative humidity measured outdoor in House 1 and 2, and also indoor in selected rooms. Indoor temperature and relative humidity were controlled within a fairly narrow range within both homes, despite that outdoor conditions varied greatly during the two weeks of monitoring. Usage of air conditioning could be inferred from rapid changes in temperature and relative humidity measured at a supply air grille of the central forced air system, as shown in Figure 14. From this data, House 1 used air conditioning more

frequently than House 2, which likely explains the more stable indoor temperature in House 1 than in House 2.

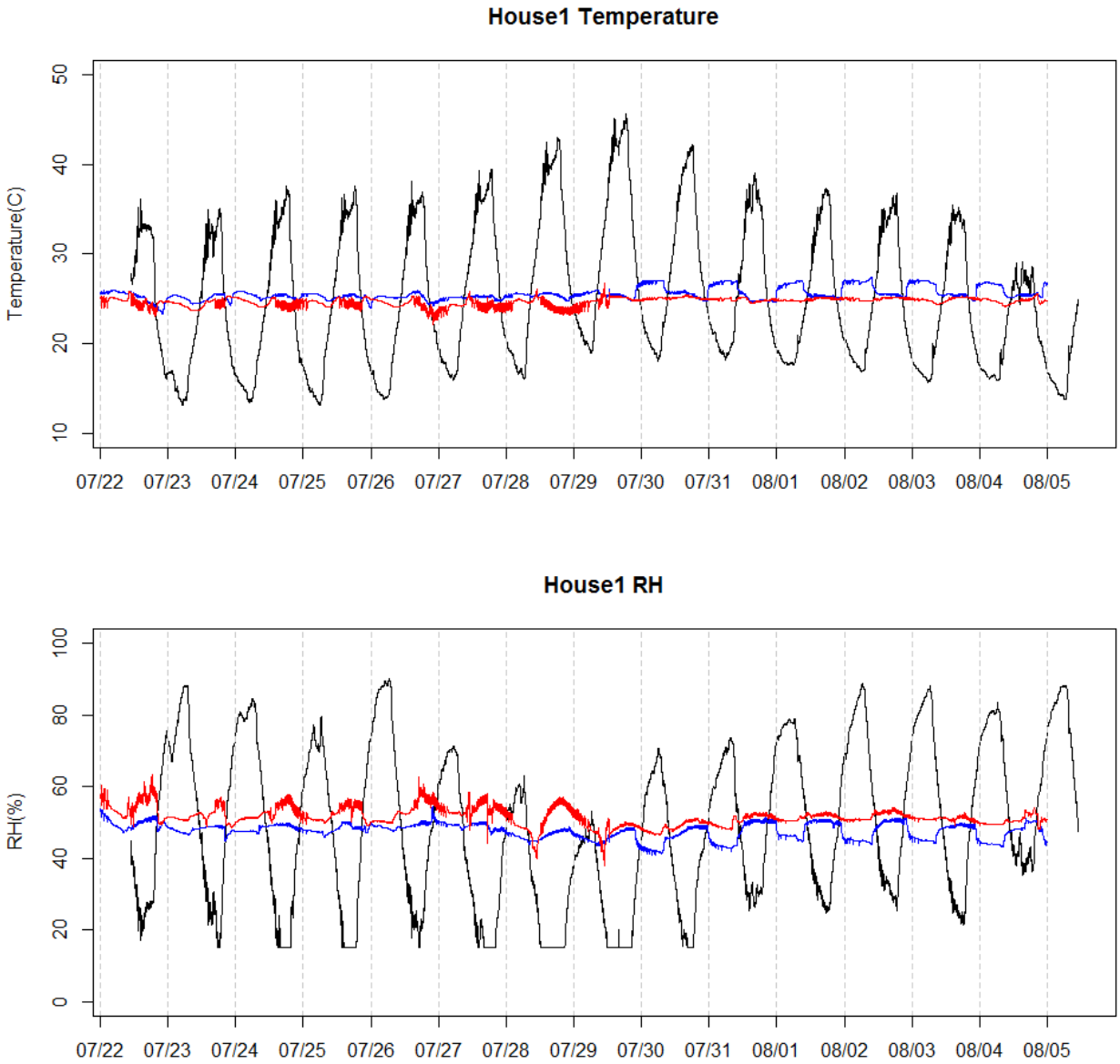

Figure 12 Temperature and relative humidity measured outdoor (in black) and indoor (dinning room in red, master bedroom in blue).

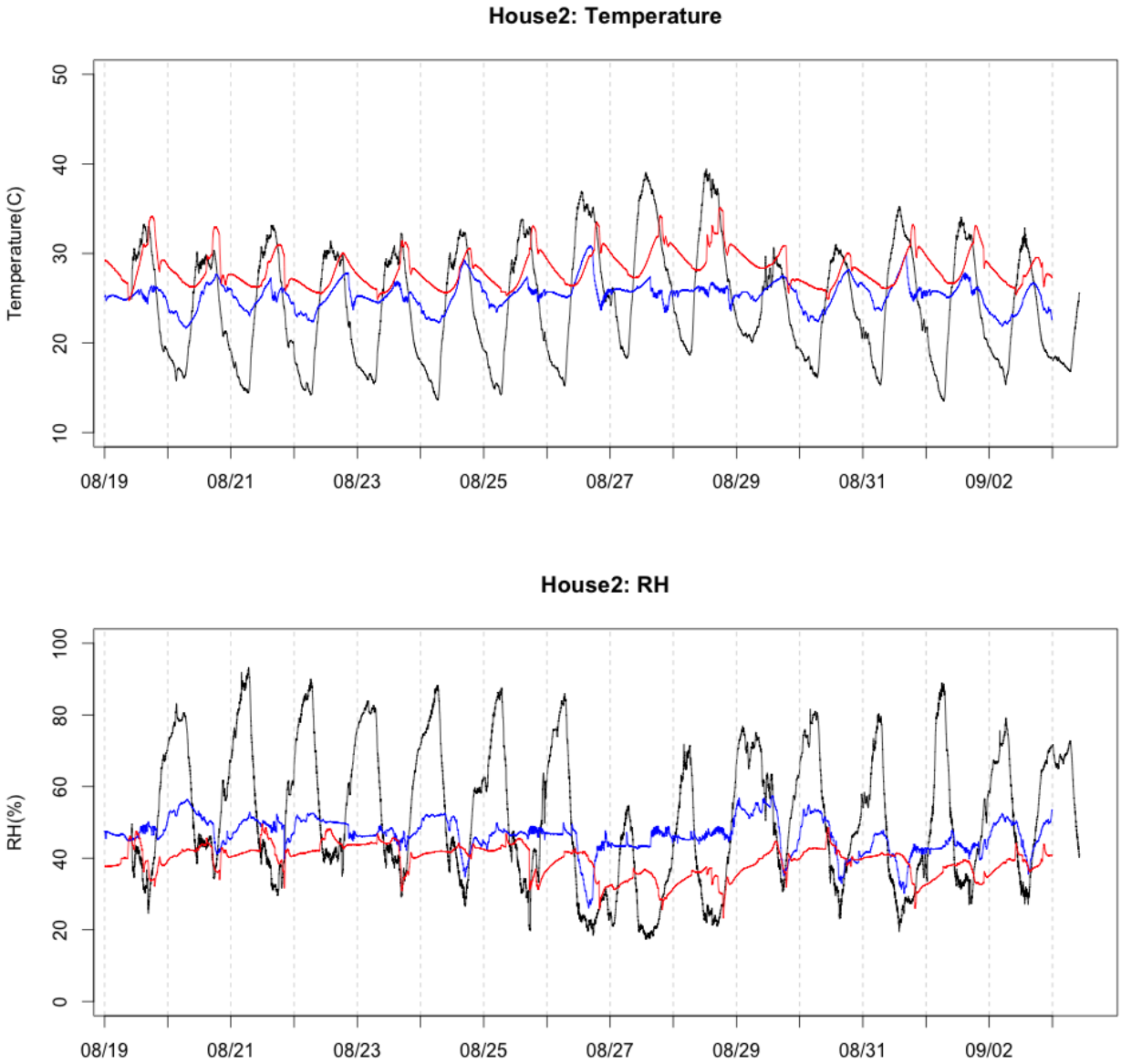

Figure 13 Temperature and relative humidity measured outdoors (black) and indoors (living room in red, master bedroom in blue).

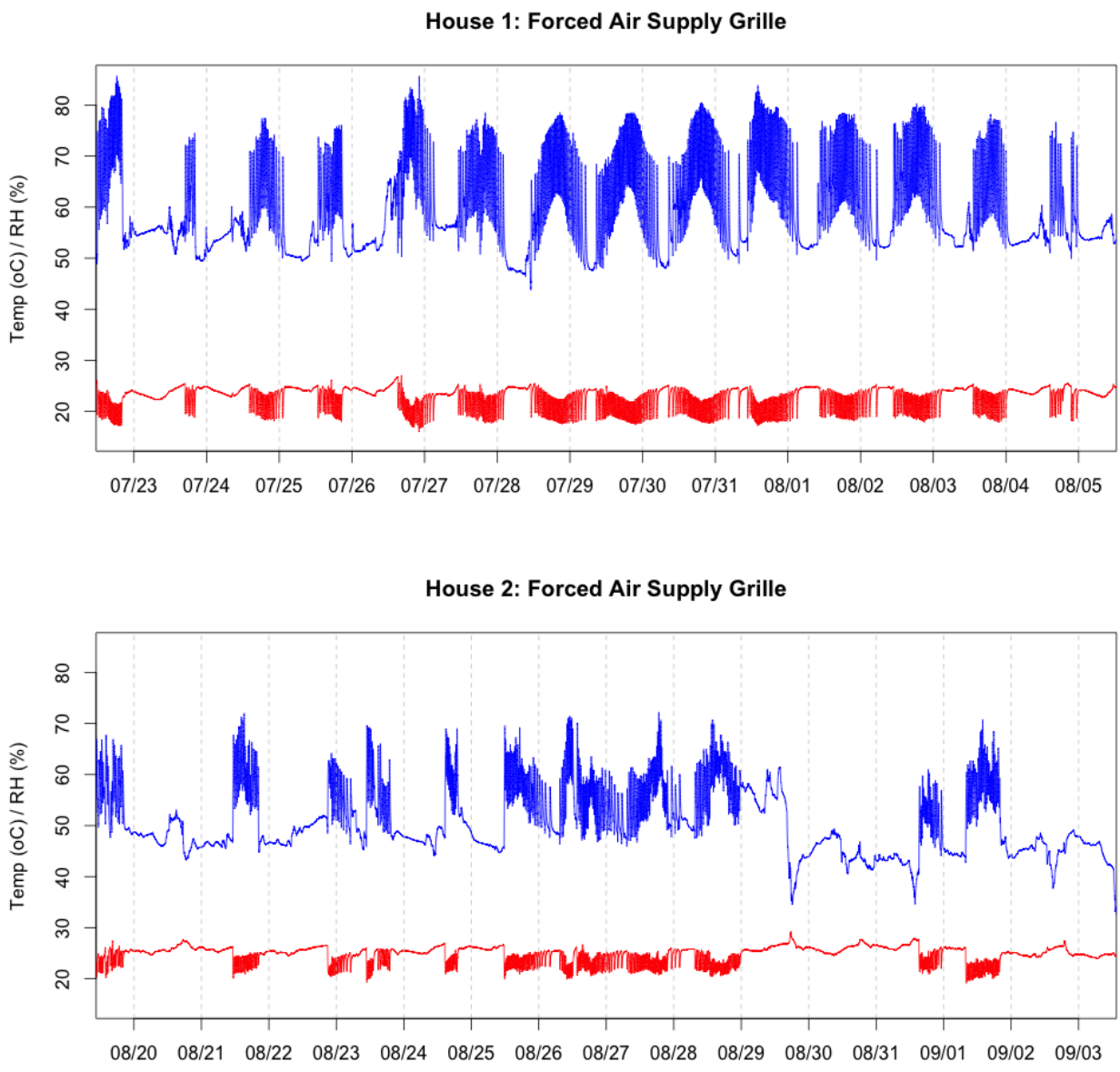

Figure 14 Temperature (in red) and relative humidity (in blue) measured at a supply air grille of the central forced air system in the two pilot homes.

Figure 15 shows the relative humidity measured in the master bathroom, where the exhaust fan was controlled by a humidistat in both homes. It shows that the exhaust fan worked as expected by responding to a sudden increase in relative humidity, likely during showering.

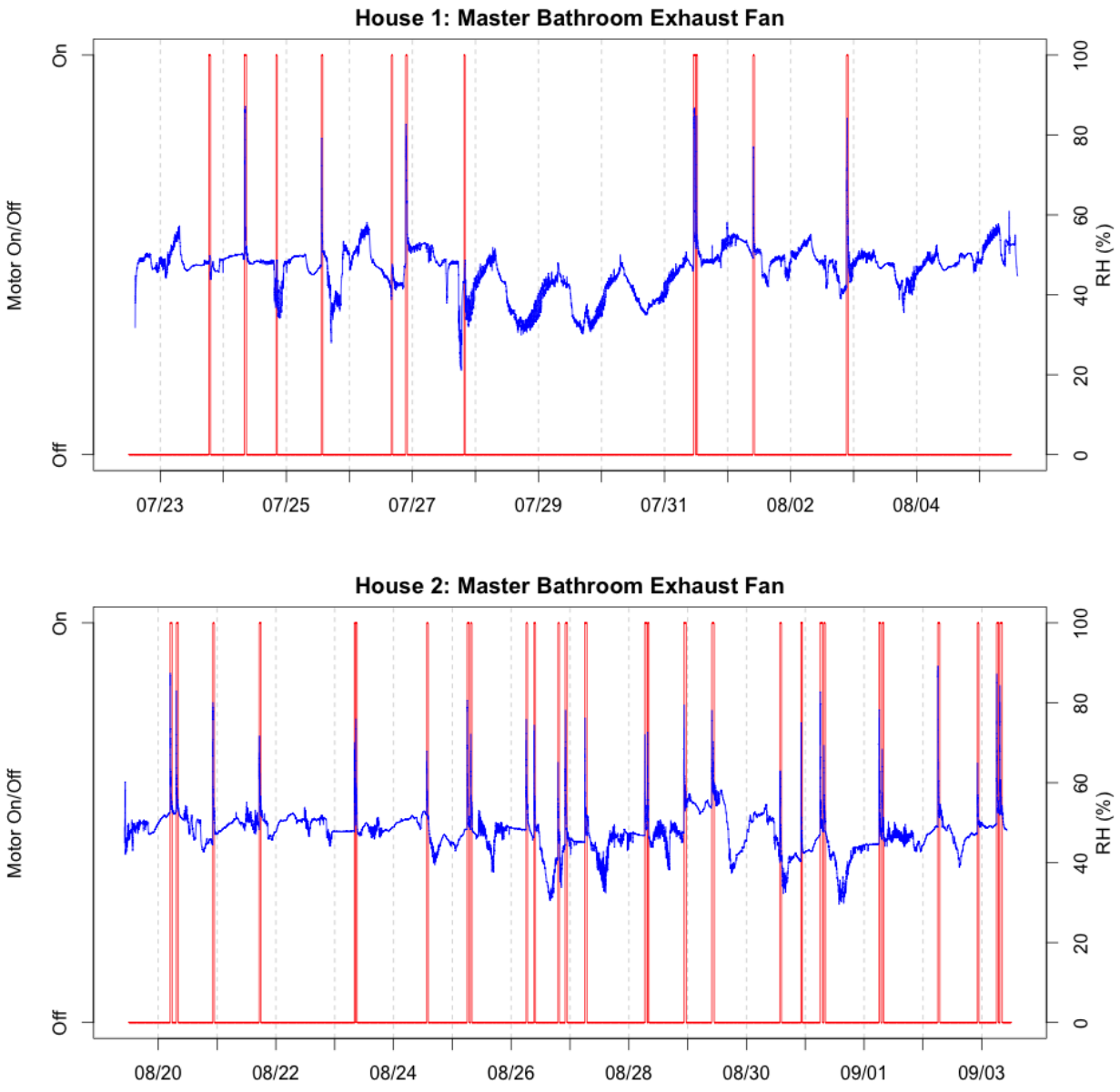

Figure 15 Humidistat-controlled exhaust fans in master bathroom responding to a sudden increase in relative humidity. Relative humidity was measured at the exhaust fan grille, as shown in Figure 16.

Figure 16 Data logger measuring temperature and relative humidity that was attached to a bathroom exhaust fan grille.

7 IAQ Sampling

Several contaminants that are indicators of IAQ and pollutants of a concern for health were measured for two weeks each in the two pilot test homes. Table 6 shows the list of instruments used to measure indoor air contaminant concentrations, the locations where instruments were placed, and the sampling resolution of the contaminant concentrations.

Table 6 Contaminant measurements made in the two pilot test homes.

Contaminant	Instrument	Sampling Locations	Sampling Resolution
PM2.5	MetOne BT-642	Outdoor	1-minute
	MetOne BT-645	Indoor main (dinning or living room)	1-second
	TSI DustTrak II 8530	Indoor main	2-minute
	Thermo pDR-1500	Indoor main	1-second
PM counts	MetOne BT-637	Indoor main	1-minute, 6-channel[1]
	Dylos 700	Indoor main	1-minute, 2-channel >0.5 and >2.5 μm
CO_2	Extech SD-800	Outdoor, indoor main, kitchen, master and other bedrooms	1-minute
CO	Lascar USB-EL-300	Outdoor, Indoor main	1-minute
NO_2	Aeroqual NO_2 monitor	Indoor main, master bedroom	1-minute
	Passive Ogawa samplers	Outdoor, indoor main, master bedroom	1-week
Formaldehyde	Shinyei formaldehyde monitor	Indoor main, master bedroom	30-minute
Volatile	Passive DNPH	Outdoor, indoor main,	1-week

Contaminant	Instrument	Sampling Locations	Sampling Resolution
aldehydes	cartridges	master bedroom	
Speciated VOCs[2]	Passive sorbent tubes	Outdoor, indoor main, master and other bedrooms, laundry room, garage	1-week

[1] The 6-channel size bins were >0.3, >0.5, >0.7, >1.0, >2.5, >10 μm in House 1, and >0.3, >0.4, >0.5, >0.7, >1.0, >2.5 μm in House 2.
[2] Method allows for determination of specific, individual volatile organic compounds. These samples were analyzed for 44 compounds.

7.1 Particulate Matter (PM)

Indoor particulate matter (PM) concentrations were measured using different types of instruments to compare performance. Indoor concentrations tended to be lower than outdoors on average in the two homes. However, both homes had PM2.5 sources that led to PM2.5 concentrations sharply rising to levels that were higher and in some cases much higher than coincident outdoor concentrations for periods of tens of minutes to more than 10 h in one case. High PM2.5 concentrations were measured in House 1 during times when cooking occurred (see Appendix C). In House 2, cooking was a less important source of PM2.5.

Figure 17 shows outdoor PM2.5 concentrations measured using a MetOne BT-642, and the indoor PM2.5 concentrations measured using a BT-645. The BT-642 performs an auto-zero test once every hour (manufacturer default). The BT-645 does not have this function. All PM2.5 instruments were recently calibrated by manufacturers. No adjustment factor was applied to the measured values.

The 24-hour average and daily 1-hour maximum PM2.5 concentrations measured by other instruments indoor are shown in Figure 18 (House 1) and Figure 19 (House 2). PM2.5 mass concentrations were estimated from particle number concentrations or “counts” measured by the Dylos and MetOne BT-637 instruments assuming spherical particles with a density of 1.65 g/cm^3. The Dylos measures number concentration for particles >0.5 and >2.5 um. To estimate PM2.5 mass concentrations from these data, we assumed the particles measured between 0.5 and 2.5 um had a diameter of 1 um. The BT-637 measures number concentrations for particle >0.3, >0.5, >0.7, >1, >2.5, and >10 um in House 1, and >0.3, >0.4, >0.5, >0.7, >1, and >2.5 um in House 2. To estimate PM2.5 mass concentrations in House 1, we used the particle counts measured in the first four bins (0.3-0.5, 0.5-0.7, 0.7-1, and 1-2.5 um) and assumed particle diameters of 0.4, 0.6, 0.85, and 1.75 um, respectively, in those bins. In House 2, we used a similar method, assuming particle diameters of 0.35, 0.45, 0.6, 0.85 and 1.75 um for the first five bins.

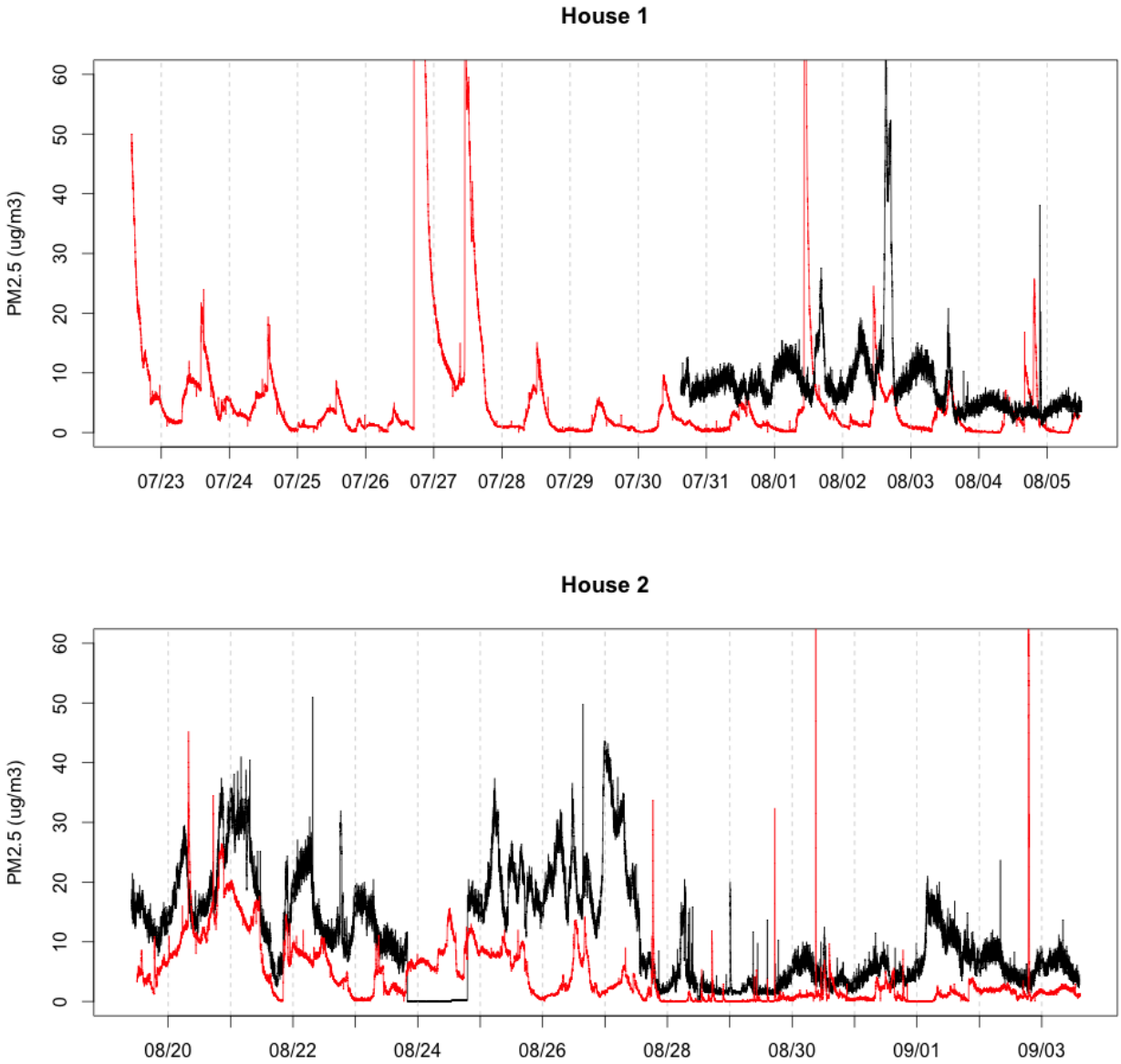

Figure 17 PM2.5 concentrations measured outdoor (black) and in the main living space (red): dining room in House 1, living room in House 2. Operator error led to outdoor PM2.5 only available for week 2 in House 1.

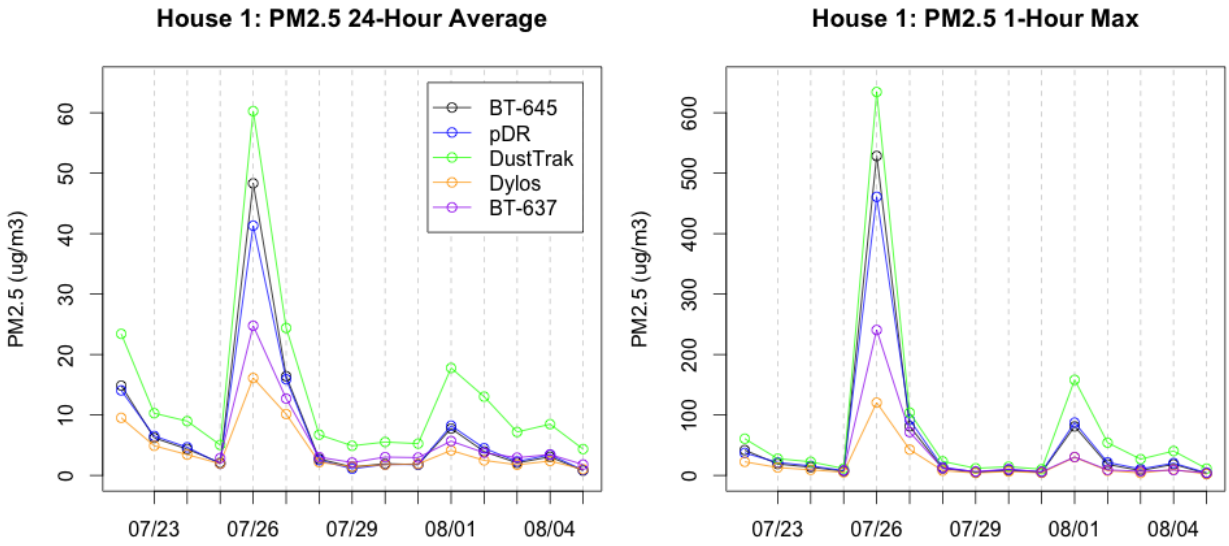

Figure 18 Comparison of PM2.5 mass concentrations measured by different particle instruments in House 1.

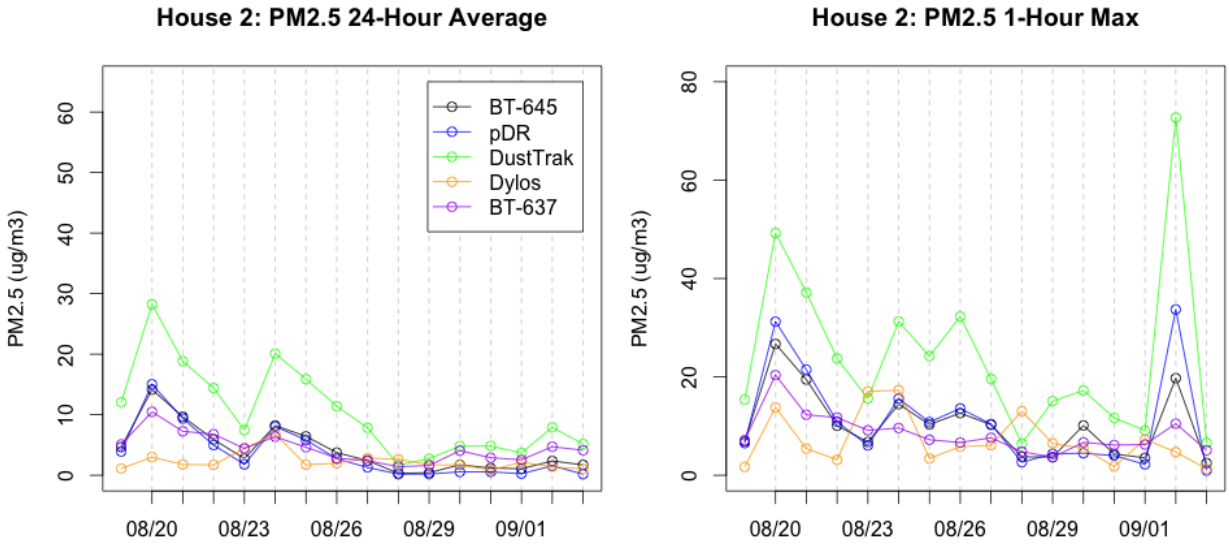

Figure 19 Comparison of PM2.5 mass concentrations measured by different particle instruments in House 2.

Table 7 compares the 24-hour average PM2.5 concentrations measured by the other four instruments in comparison with the MetOne BT-645. The intercept, slope, and correlation coefficient (R^2) were obtained from a linear least-square regression fit of the 24-hour average PM2.5 concentrations as shown in Figure 18 (House 1) and Figure 19 (House 2). Measurements by the pDR and DustTrak, which used similar measurement principle as the BT-645, were highly correlated (R^2 = 0.97 or greater) with the BT-645. Measurements by the Dylos and BT-637,

which measured particle counts instead of PM2.5 mass, agreed less well with the BT-645, especially in House 2. Overall, measurements by the pDR agreed with the BT-645 most closely in magnitude, with slope ~1, and intercept ~0. In comparison, DustTrak measured higher PM2.5 mass than the BT-645, whereas the Dylos and BT-637 gave lower estimates of PM2.5. This may be explained by the difference in wavelength of the laser light source used by the BT-645 (670 nm), pDR (880 nm), and DustTrak (780 nm), leading to different sensitivity to particles in the size range of 0.1 um. The Dylos and BT-637 counts particles >0.5 um and >0.3 um, respectively, so some fractions of the PM2.5 mass made up by particles smaller than the cutoff diameter were not accounted for. Another potential contributing factor is the difference in particle density between indoor particles (assumed 1.65 g/cm^3) and the test dust used by manufacturers (2.6 g/cm^3) to calibrate instruments such as the BT-645, pDR, and DustTrak.

Table 7 Comparison of 24-hour average PM2.5 mass concentrations measured by different particle instruments with respect to MetOne BT-645.

	House 1			House 2		
	Intercept (ug/m^3)	Slope (-)	R^2 (-)	Intercept (ug/m^3)	Slope (-)	R^2 (-)
pDR	-0.75	1.16	1.00	0.98	0.90	0.99
DustTrak	-3.58	0.83	0.98	-1.19	0.51	0.97
Dylos	-3.89	2.70	0.90	2.28	0.82	0.04
BT-637	-3.88	2.01	0.98	-2.57	1.50	0.84

7.2 Carbon Dioxide (CO_2)

CO_2 concentrations were monitored in multiple indoor locations. Data from the pilot test homes (Figure 20) show that indoor CO_2 concentrations can vary substantially from room to room. Sensors used to monitor the open/close state of doors showed that in both houses, the master bedroom doors were closed all the way only for about an hour on average each day. However, doors may have been closed partly, which could still inhibit mixing of air between the master bedroom and the rest of the house. The mixing of air between the master bedroom and the rest of the house may have been affected by the runtime of the air handler system during some nights. In House 1, the air handler ran about 5 hours per day on average. In House 2, the air handler ran about 9 hours per day on average. The longer air handler runtime in House 2 would explain CO_2 concentrations being more uniform spatially than in House 1. Window use overnight would also explain lower CO_2 concentrations in House 2 (Figure 7).

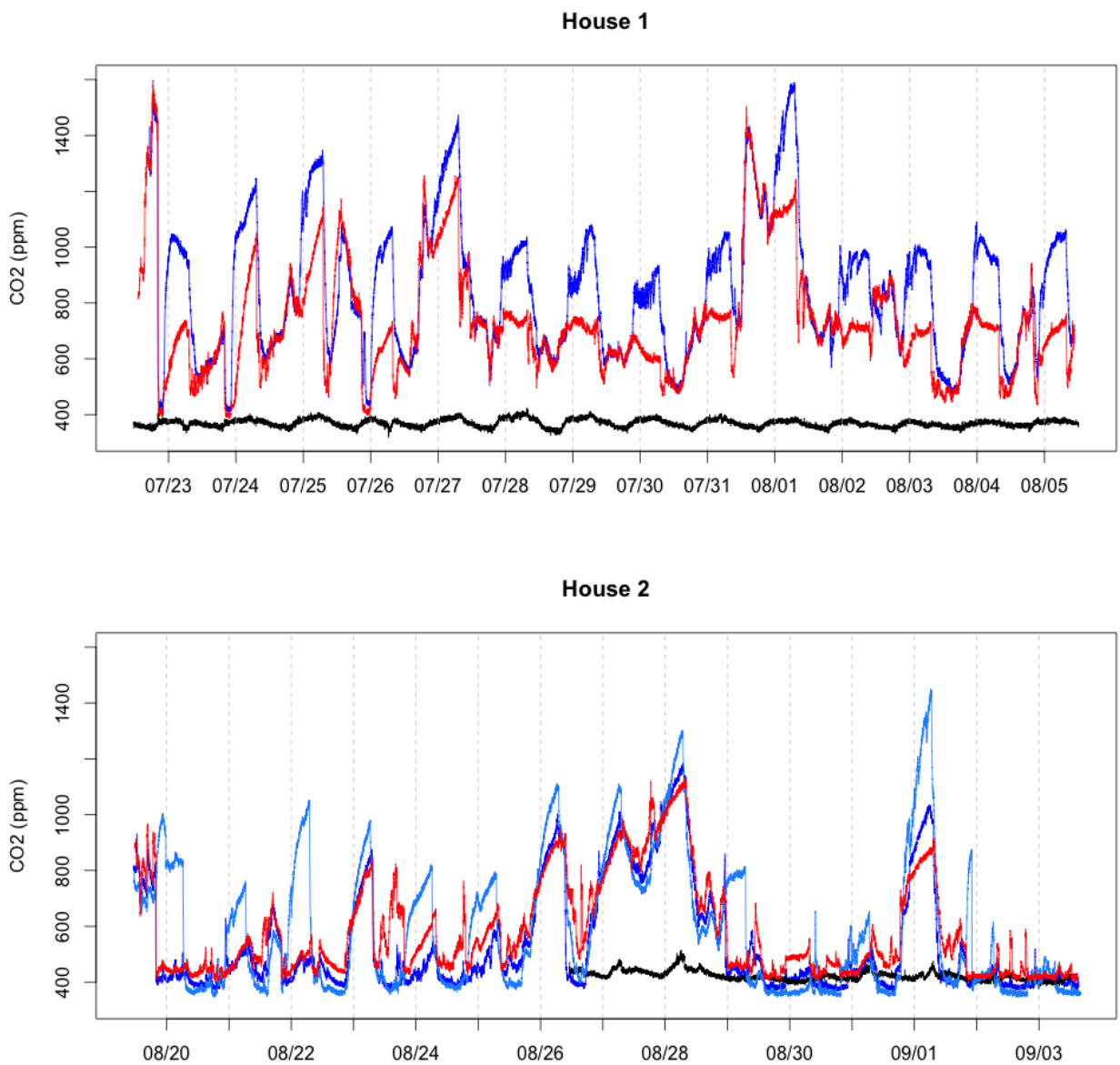

Figure 20 CO_2 concentrations measured outdoor (black), main indoor living space (red), master bedroom (blue), and in another bedroom (light blue, House 2 only). Operator error led to outdoor CO_2 data available only for week 2 in House 2.

7.3 Carbon Monoxide (CO)

Real-time CO concentrations measured in the two pilot test homes were generally below detection limit (<0.5 ppm). Maximum CO concentrations were below 3 ppm.

7.4 Nitrogen Dioxide (NO_2)

Table 8 shows the NO_2 concentrations measured using passive samplers (Mullen et al., 2015). The outdoor concentrations measured agree well with ambient monitoring data. The nearest ambient monitoring site with available hourly NO_2 data is located at downtown Sacramento (T Street) for House 1, and Bethel Island (Contra Costa county) for House 2, where the two-week average concentrations were about 5 ppb and 3 ppb, respective.

Table 8 NO_2 concentrations measured using passive Ogawa samplers.

		NO_2 Concentrations (ppb)	
		House 1	House 2
Outdoor	Week 1	3.4	5.5
	Week 2	2.9	3.8
Indoor Main	Week 1	4.5	4.8
	Week 2	3.6	4.0
Master Bedroom	Week 1	3.6	4.9
	Week 2	2.9	3.4
Garage	Week 2	1.5	--

Figure 21 presents time-resolved NO_2 data measured with the Aeroqual instruments. We observed that the instrument placed in the main living space required a span (slope = 0.65) and offset (-9 ppb) correction. This correction has been applied to the NO_2 concentrations plotted in Figure 21. The time resolved data at different locations in House 2 suggest that the instruments are responding to increases in NO_2 in the home. The increases in NO_2 in the dining / living room when cooking occurred (with gas cooking burners producing NO_2) suggests the instrument has utility at identifying NO_2 emission events. But a comparison to the well-validated time-integrated measurements collected at the same location (Table 8) suggests - as a minimum source of error - that the two Aeroqual measured higher NO_2 concentrations. Thus, this instrument requires a careful calibration check prior to each deployment.

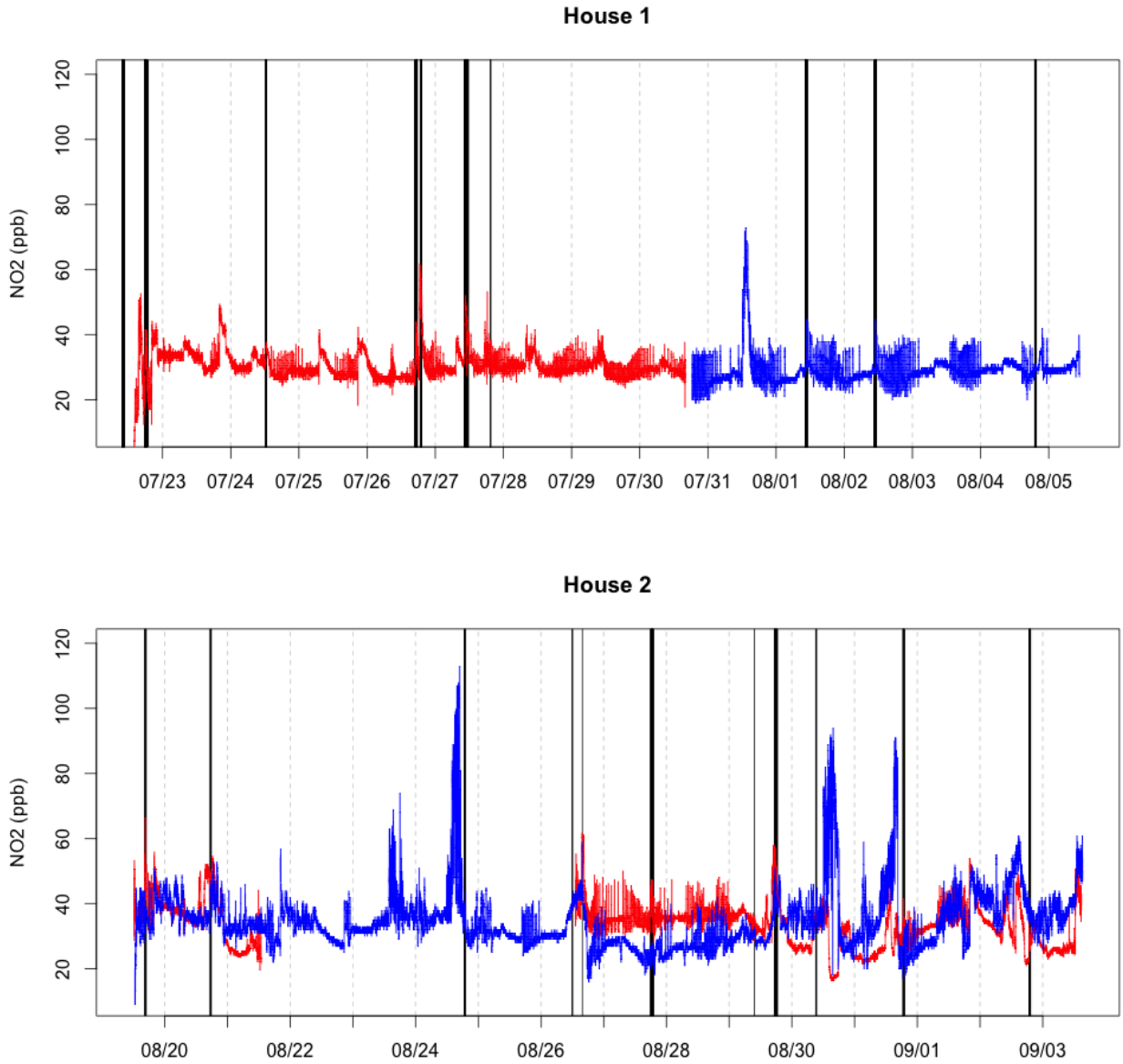

Figure 21 NO_2 concentrations measured by real-time instrument in the main indoor living space (red) and in the master bedroom (blue). Cooking events, as defined by cooktop temperature data, are indicated by black lines. Operator error led to data loss in House 1 such that only 1 week of data was collected at each of two sampling locations. In House 2, instrument in the living space was powered off for several days (reason unknown).

7.5 Formaldehyde

Figure 22 shows the formaldehyde concentrations measured by the real-time instruments in the common area and in the master bedroom of each home. Indoor formaldehyde concentrations measured passively using DNPH cartridges were about 50 ppb in House 1, and about 25 ppb in

House 2 (Table 9). Lacking more suitable data, the passive uptake rates determined by Mullen et al. (2013) for winter conditions were used to calculate these concentrations. Passive measurements were significantly higher than the 25-35 ppb and 15-25 ppb respectively indicated by the real-time measurements. Both the passive and the real-time methods suggested that House 1 had higher formaldehyde concentrations than House 2 (Table 10). However, there are significant differences between the formaldehyde concentrations measured using the two sampling methods. The passive uptake rates determined by Mullen et al. (2013) will need to be checked against the well-established active sampling method using DNPH cartridges for a broader range of outdoor temperatures. Performance of the real-time formaldehyde monitors, which had been tested in laboratory setting (Carter et al., 2014), also requires further comparison with the DNPH method for field applications.

Table 9 Formaldehyde concentrations measured using passive DNPH cartridges.

		Formaldehyde Concentrations (ug/m^3)	
		House 1	House 2
Outdoor	Week 1	12	19
	Week 2	10	15
Indoor Main	Week 1	47	29
	Week 2	48	25
Master Bedroom	Week 1	47	24
	Week 2	56	21

Table 10 Average formaldehyde concentrations measured by the real-time instruments.

		Formaldehyde Concentrations (ug/m^3)			
		House 1		House 2	
		Instrument 1	Instrument 2	Instrument 1	Instrument 2
Indoor Main	Week 1	29	31	21	--
	Week 2	34	34	24	22
Master Bedroom	Week 1	30	25	17	16
	Week 2	32	28	18	16

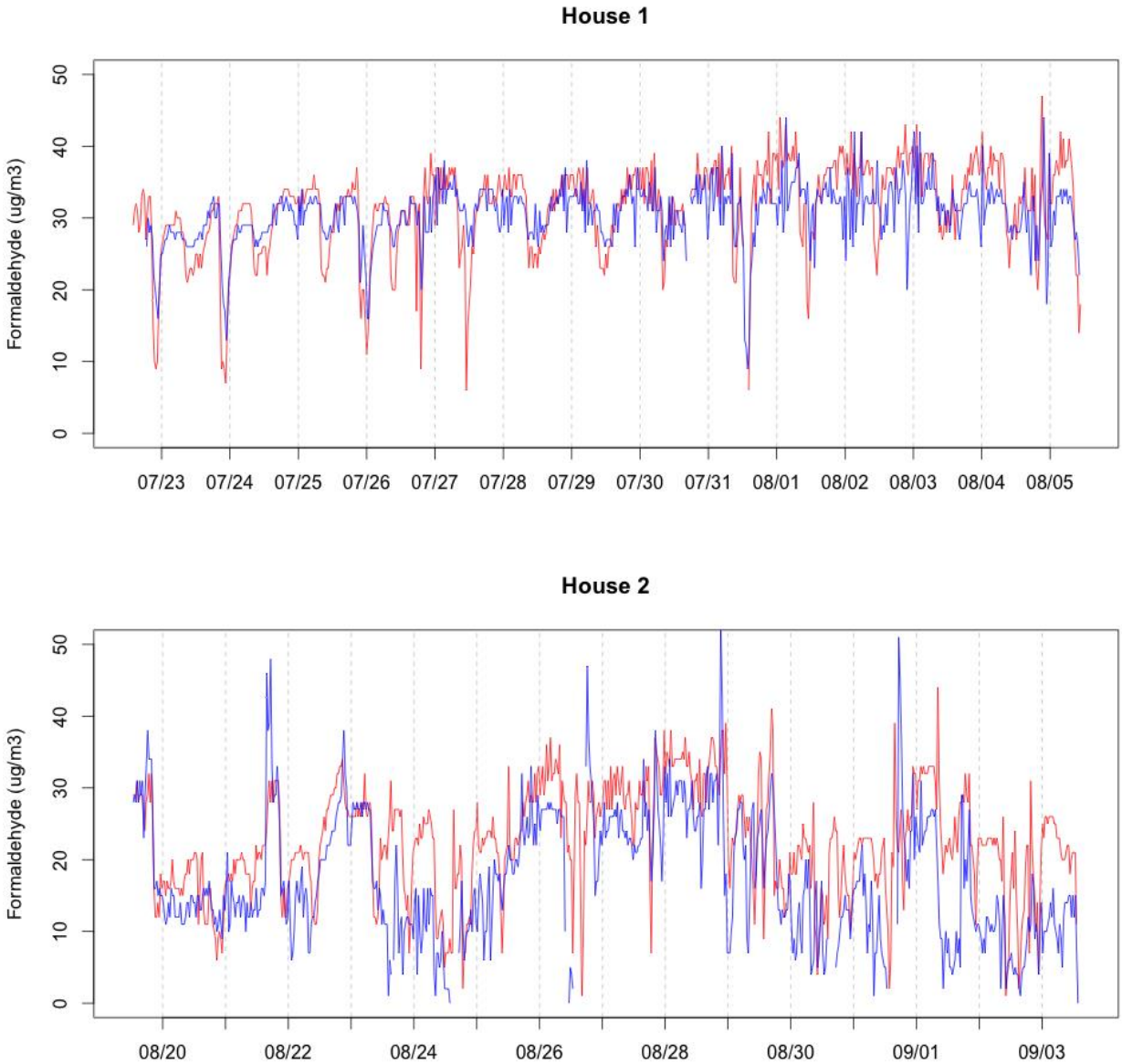

Figure 22 Formaldehyde concentrations measured at 30-minute time integrated intervals in the main indoor living space (red) and in the master bedroom (blue).

7.6 Volatile Organic Compounds (VOCs)

Table 11 shows the maximum 1-week averaged VOCs concentrations measured in the two pilot test homes. Also shown for comparison are the maximum 24-hour averaged VOCs concentrations measured by Offermann (2009) in 108 new California homes, and the health guidelines used in that study as reference. Offermann (2009) measured 20 VOCs that were selected based on California Air Resources Board indoor air guidelines, California Office of Environmental Health Hazard Assessment Chronic exposure levels, and other available health

standards. The study found that none of the maximum indoor concentrations of the 20 VOCs measured in 108 new California homes built between 2002–2004 exceed any of the indoor air contaminant guidelines (Table 11). We also found no VOCs at concentrations above health guidelines.

In addition to the 20 VOCs listed in Table 11, another 24 VOCs were also analyzed. Many of these compounds were below quantitation limits in many of the samples. However, a few VOCs were above odor thresholds, such as from fragrances used in House 1, e.g., hexanal (75 to 110 ug/m^3), a-pinene (280 to 350 ug/m^3), and d-limonene (35 to 45 ug/m^3). House 1 also had relatively high concentrations of D5-siloxanes (100 to 200 ug/m^3), likely emitted from personal care products. Table 12 shows the sum of 44 VOCs measured. In comparison, House 2 had relatively low VOCs concentrations. The concentrations measured in the central location (e.g., great room) generally represent the range of indoor concentrations found indoors.

Table 11 Maximum indoor VOCs concentrations in comparison to health guidelines.

	Ref Health Guideline (ug/m^3)	Maximum Indoor Concentration (ug/m^3)				
		Offermann (2009)	HENGH Pilot Test			
			House 1	Garage	House 2	Garage
Tetrachloroethane	35 [a]	23	0.1	2	0.1	0.1
Naphthalene	9 [a]	5	0.2	0.2	0.2	1.5
Toluene	300 [a]	115	5	9	8	47
Ethylene glycol	400 [a]	120	--	--	--	--
1,4-Dichlorobenzene	800 [a]	219	1.3	1.2	0.04	0.03
Benzene	60 [a]	15	2	0.3	2	11
m,p-Xylene	700 [a]	60	13	8	4	30
Styrene	900 [a]	62	14	19	2	1.2
2-Butoxyethanol	3000 [b]	180	18	7	110	5
Trichloromethane	300 [a]	12	2	0.2	0.4	0.2
Phenol	200 [a]	7	4	7	3	2
o-Xylene	700 [a]	20	7	3	2	10
a-Pinene	2800 [b]	65	352	73	32	12
1,2,4-Trimethylbenzene	3125 [b]	13	0.4	0.5	1.3	11
1-Methyl-2-pyrrolidinone	2000 [b]	8	--	--	--	--
n-Hexane	700 [a]	24	0.8	1.0	2	14
Vinyl acetate	200 [a]	0.3	--	--	--	--
Caprolactam	500 [b]	0.1	--	--	--	--
Hexanal	na	35	110	59	56	17
d-Limonene	na	152	43	9	150	4

[a] OEHHA chronic reference exposure levels.
[b] 1/40th of the 8-hour occupational health guideline in ug/m^3 (e.g., Cal/OSHA permissible exposure limits).

Table 12 Sum of 44 VOCs measured in different locations of the two pilot houses.

House 1	ΣVOCs (ug/m^3)	House 2	ΣVOCs (ug/m^3)
Master Bedroom	846	Master Bedroom#	171
Bedroom 2	752	Bedroom 2#	176
Dinning Room	748 (789)*	Bedroom 3#	145
Great Room	747	Playroom#	132
Kitchen	747	Bedroom 4	227
Laundry Room	765	Great Room	204 (202)*
		Laundry Room	316
Garage	256	Garage	215
Outdoor	15	Outdoor	12 (16)*

* Replicate sample in parenthesis. A duplicate sample was collected at all locations.
# Rooms located on the upper floor.

8 Passive Tracer Gas Measurements

We used three perfluorocarbon tracers (PFTs), PDCB (C_6F_{12}), PMCH (C_7F_{14}), and mPDCH (C_8F_{16}), to estimate the dilution rate of an indoor emitted air contaminant in the two pilot test homes. Five to seven PFT emitters of each compound were distributed in the pilot test homes. One of three PFTs was placed in the garage to estimate the transfer rate of chemicals into the house from the garage. The other two PFTs were distributed in the main living space. PFTs concentrations were measured passively using sorbent tubes. The 1-week average concentrations were typically on the order of 1 ppb.

Measured PFTs concentrations, C (g/m^3), were used to calculate the dilution rate of a constant indoor-generated chemical, k (h^{-1}), as follows:

$$k\ (\mathrm{h}^{-1}) = E\ (\mathrm{g/h}) \,/\, [\ C\ (\mathrm{g/m}^3) \times V\ (\mathrm{m}^3)\ ]$$

where E (g/h) is the emission rate measured by weighing PFT vials before and after at the test house, and V (m^3) is the house volume estimated by floor area times the ceiling height (see Table 1). Placement of PFTs emitters and their emission rates are described in Table 13 (House 1) and Table 14 (House 2). House average dilution rates were computed using average PFTs concentrations measured in

Table 15 and Table 16.

In House 1, the dilution rate of an indoor emitted air contaminant was about 0.2 h^{-1}, calculated based on PMCH that was distributed in the living space (

Table 15). Results suggest that with the exception of Bedroom 2 in week 2, dilution of a distributed source was spatially uniform in House 1. The dilution rate estimated using PDCB that was emitted from the kitchen area only gave similar results.

In House 2, dilution rate was about 0.3 h^{-1} in week 1, and slightly lower at 0.2 h^{-1} in week 2 (Table 16). The dilution rates calculated for the lower floors were very different if mPDCH or if PDCB measurements were used. On the other hand, the dilution rates calculated for the upper floors were more similar. This suggests that the house is not well mixed, especially for chemicals emitted from the upper floors.

Table 13 Placement of PFTs emitters in House 1 and their emission rates determined by weighing of vials.

	Week 1	Week 2
PDCB – 5 emitters distributed in kitchen area (connected to great room)		
E (mg/h) – Per Vial	0.67 (0.64–0.75)	0.60 (0.57– 0.68)
Total	3.33	2.99
PMCH – 5 emitters distributed in throughout the house		
E (mg/h) – Per Vial	0.68 (0.50–1.14)	0.61 (0.45–1.01)
Total	3.42	3.04
mPDCH – 5 emitters distributed in attached garage		
E (mg/h) – Per Vial	0.38 (0.32–0.49)	0.34 (0.30–0.43)
Total	1.88	1.70

Table 14 Placement of PFTs emitters in House 2 and their estimated emission rates.

	Week 1	Week 2
PDCB – 7 emitters distributed in upper floor		
E (mg/h) – Per Vial	0.57 (0.55–0.61)	0.58 (0.55–0.62)
Total	4.02	4.09
PMCH – 6 emitters distributed in the attached garage		
E (mg/h) – Per Vial	0.72 (0.48–1.51)	0.83 (0.50–2.05)
Total	4.33	4.99
mPDCH – 7 emitters distributed in lower floor		
E (mg/h) – Per Vial	0.26 (0.24–0.29)	0.26 (0.25–0.30)
Total	1.81	1.85

Table 15 Estimated dilution rate (h^{-1}) based on PFTs measurements in House 1.

	Week 1		Week 2	
	PMCH (distributed throughout house)	PDCB (emitted from kitchen)	PMCH (distributed throughout house)	PDCB (emitted from kitchen)
Master Bedroom	0.24	0.33	0.22	0.31
Master Bathroom	--	--	0.25	0.32
Bedroom 2	0.24	0.29	0.47	0.56
Dining Room	0.24	0.26	0.22	0.24
Great Room	0.22	0.23	0.20	0.22
Kitchen*	0.22	0.21	0.20	0.17
Laundry Room	0.26	0.28	0.24	0.27
Hallway	--	--	0.22	0.26
Den	--	--	0.23	0.26
House Average	0.24	0.26	0.23	0.26

* Kitchen is connected to the great room.

Table 16 Estimated dilution rate (h^{-1}) based on PFTs measurements in House 2.

	Week 1		Week 2	
	mPDCH (emitted from lower floor)	PDCB (emitted from upper floor)	mPDCH (emitted from lower floor)	PDCB (emitted from upper floor)
Rooms in upper floor				
Master Bedroom	0.48	0.40	0.26	0.29
Bedroom 2	0.55	0.40	0.31	0.31
Bedroom 3	0.52	0.38	0.31	0.30
Playroom	0.46	0.40	0.31	0.30
Rooms in lower floor				
Living Room*	0.26 (0.26)	0.55 (0.56)	0.20 (0.21)	0.36 (0.37)
Laundry Room	0.27	0.64	0.21	0.42
Bedroom 4	0.20	0.42	0.19	0.43
House Average	0.33	0.45	0.24	0.34

* Replicate sample in parenthesis.

The percentage of PFTs entering into the house from the attached garage was calculated using the same method used by Offermann (2009).

$$F\ (\%) = C_h\ (g/m^3) \times k\ (h^{-1}) \times V\ (m^3) / E_g\ (g/h)$$

where E_g (g/m^3) is the emission rate of PFT released in the attached garage, and C_h (g/m^3) is the concentration of that PFT measured inside the house.

The percentage of PFTs entering into House 1 was about 10% for both sampling weeks. In House 2, the estimated percentage was 27% for week 1, and 21% for week 2. These results were calculated using house average dilution rates based on PMCH measurements in House 1, and mPDCH measurements in House 2.

The percentage of air in the house that came from the garage can be calculated by the ratio of C_h/C_g, where C_g (g/m^3) is the concentration of the PFT released in the attached garage. Using PFT concentrations shown in Appendix D, House 1 had 2% of air coming from garage. House 2 had 10% of first floor air, and 5% of second floor air, coming from garage.

These estimates suggested that even though a significant fraction of garage emissions (in this case, 10% to 27%) entered into the house, the airflow from the garage only made up a minor (2% to 10%) of the total air exchange of the house. The result is that the in-house concentrations of contaminants where garage was the likely source (e.g., benzene, toluene, and xylene) were low relative to health guidelines (see Table 11).

9 Calculation of Mechanical Ventilation Rates

Figure 23 shows the mechanical ventilation calculated by summing the airflow from the three bathroom exhaust fans, range hood, and clothes dryer in House 1. The average mechanical ventilation in House 1 was 0.2 Air Changes per Hour (ACH). We did not measure the airflow of the clothes dryer vent, so an assumed value of 100 CFM was used in this calculation. The anemometer data provided some indication of the range hood speed setting that was used. For this calculation, we used the medium setting airflow (107 CFM). Table 5 shows the daily average runtime of the devices considered in this calculation.

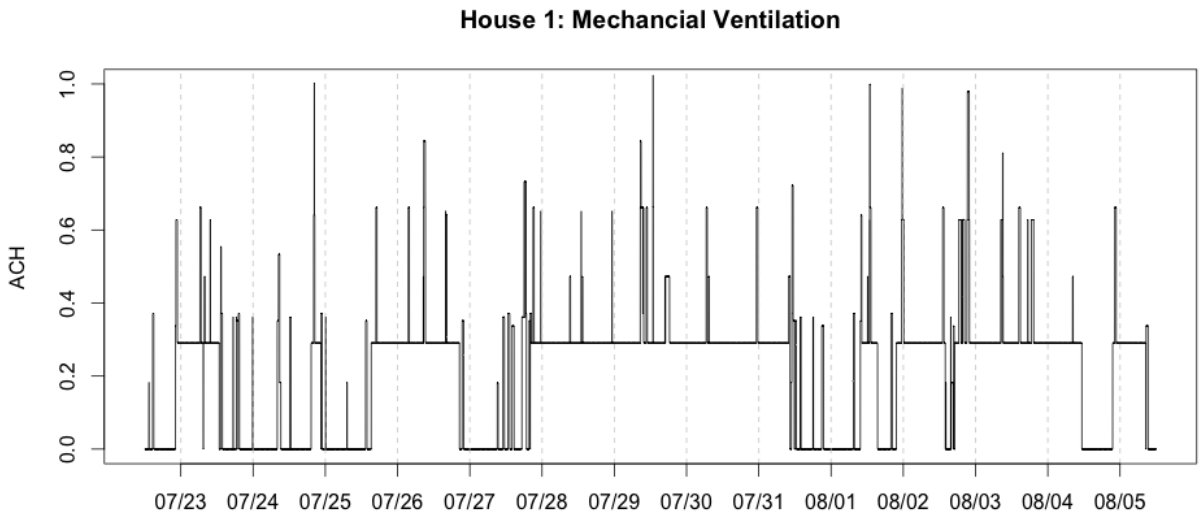

Figure 23 Estimates of mechanical ventilation in House 1 by summing airflows from three bathroom exhaust fans, laundry room exhaust fan, range hood, and clothes dryer.

We assumed the inline fan was designed to provide sufficient ventilation per Title 24.

$$Q_{cfm} = 0.01\ (A_{floor}) + 7.5\ (N_{br} + 1) = 67\ \text{CFM}$$

where the conditioned floor area (A_{floor}) = 2990 ft^2 and number of bedrooms (N_{br}) = 4. Figure 24 shows the estimated air changes per hour provided by mechanical ventilation in House 2. The inline fan alone was estimated to provide 0.15 h^{-1} of ventilation. Mechanical ventilation was calculated by the larger of the supply airflow provided by the inline fan and the sum of exhaust airflow from exhaust fans in bathrooms and laundry room, use of range hood and clothes dryer. This resulted in an estimated average mechanical ventilation of 0.16 h^{-1}.

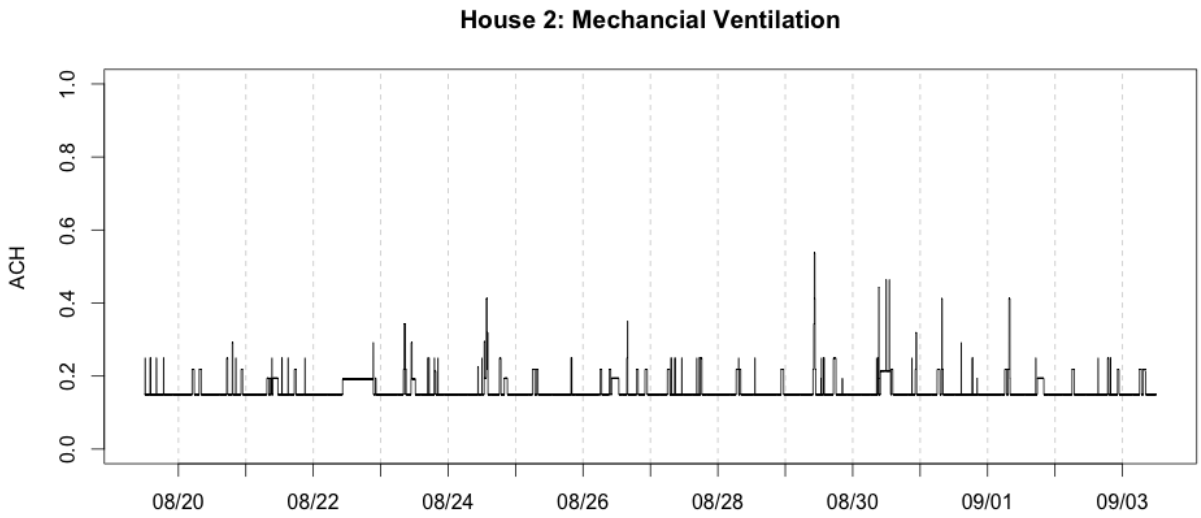

Figure 24 Estimates of mechanical ventilation in House 2 by summing airflows from three bathroom exhaust fans, laundry room exhaust fan, range hood, and clothes dryer.

10 Summary and Next Steps

Learning from the pilot test conducted in two homes will be incorporated to develop the field experimental protocol. For example, steps to identify the whole-house ventilation system need to be described in more details, including instructions of how to measure airflow of an inline supply fan that is buried in insulation. The protocol will include detail procedures to measure building envelope air leakage and duct leakage using blower door and deltaQ test. It will describe various methods for monitoring indoor activities. In cases where more than one method may be used, directions will be given to field team to select an option that is the easiest to implement given field conditions. IAQ sampling of PM2.5, CO_2, CO, NO_2, and formaldehyde will mostly be performed using real-time instruments. Passive samples requiring chemical analysis may only be collected for NO_2 and formaldehyde. In comparison, measurements of VOCs may be a lower priority because indoor concentrations appear to be low relative to health guidelines, as observed by Offermann (2009). Other studies, such as Logue et al. (2012), also concluded similarly, but with formaldehyde and acrolein being the exception where indoor concentrations tend to exceed the health guideline. Assuming that homes relied mostly on mechanical ventilation, then the monitoring of supply and exhaust airflows using activity sensors may provide more detail information than the weekly averages estimated from PFTs measurements. The field experimental protocol will describe operations of IAQ instruments, including calibration and other checks to make sure that the data quality is satisfactory. As discussed, performance of the real-time NO_2 (Aeroqual) and formaldehyde (Shinyei) monitors will be checked against well-established measurement methods prior to the field study. The protocol will specify preferred siting of IAQ instruments indoors and outdoors. LBNL research team will prepare a standard format for field data upload to a central database.

11 Reference

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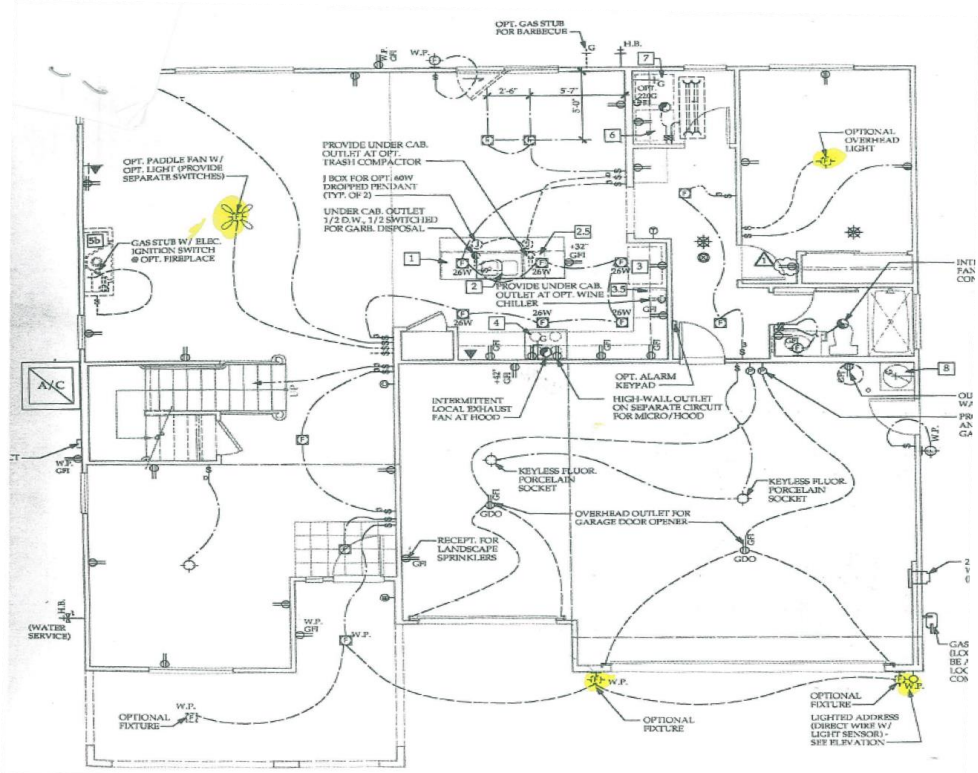
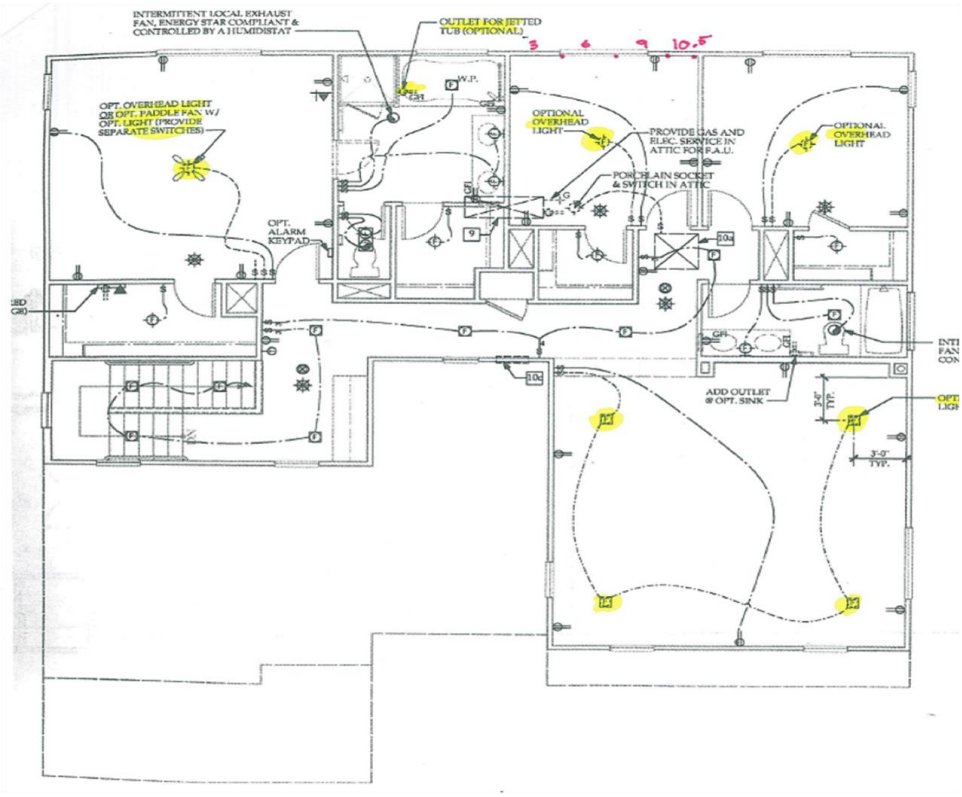
Appendix A

House 1 floor plan.

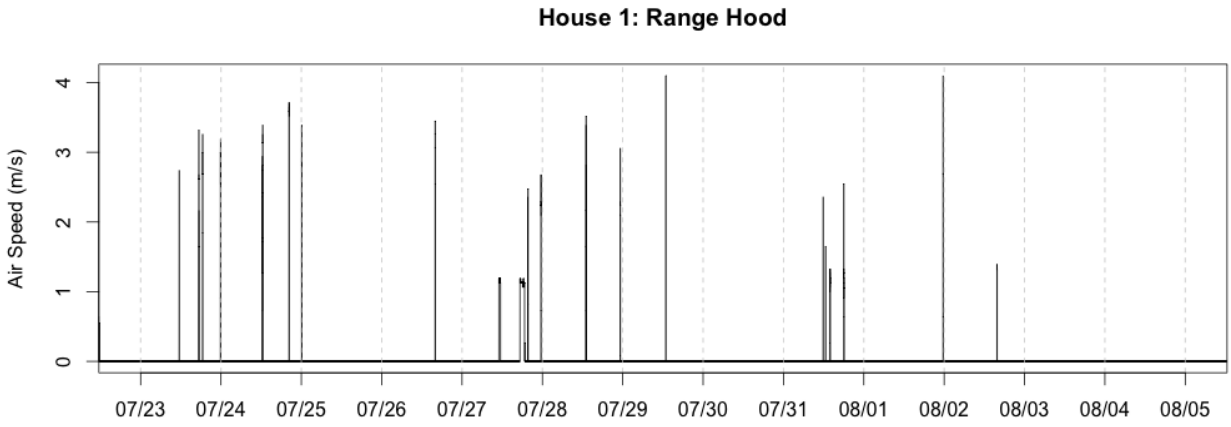
House 2 floor plan: upper floor (top) and lower floor (bottom).

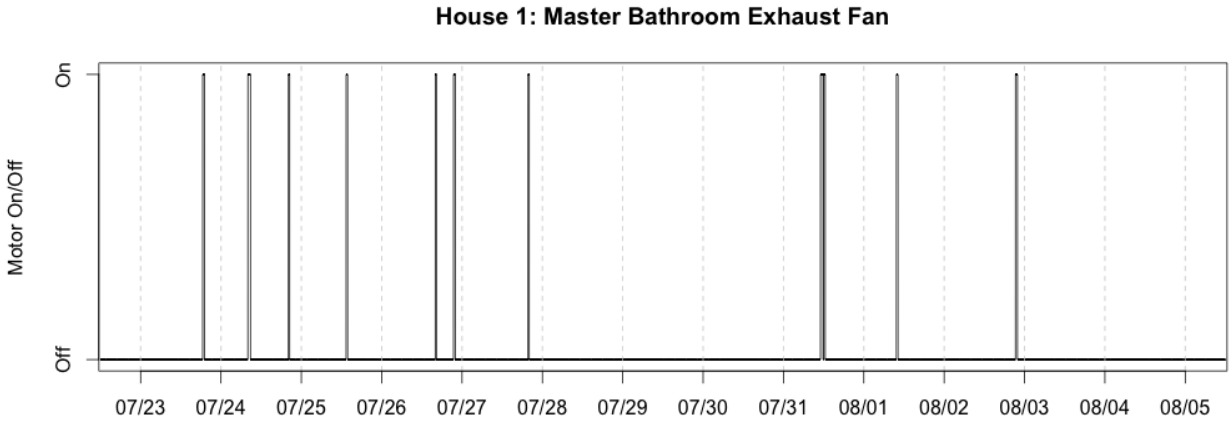


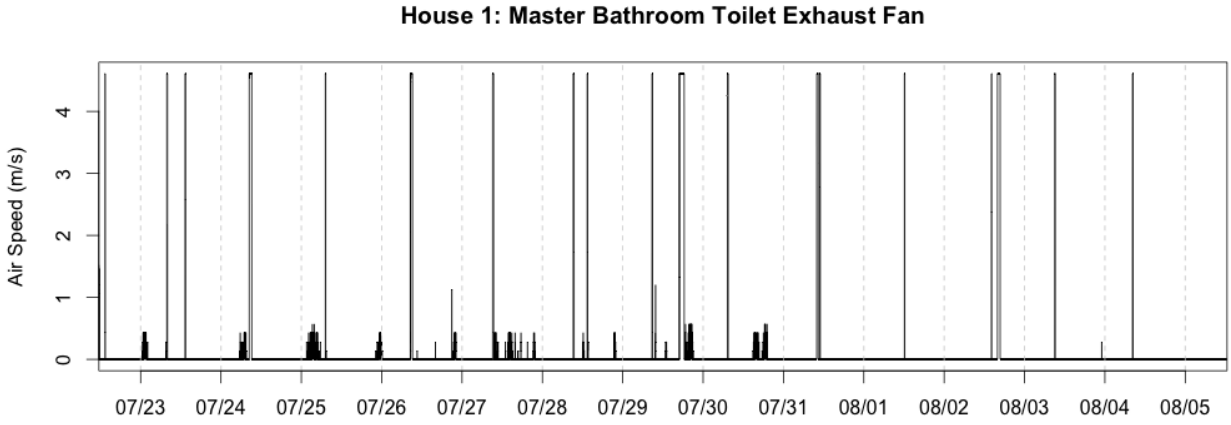


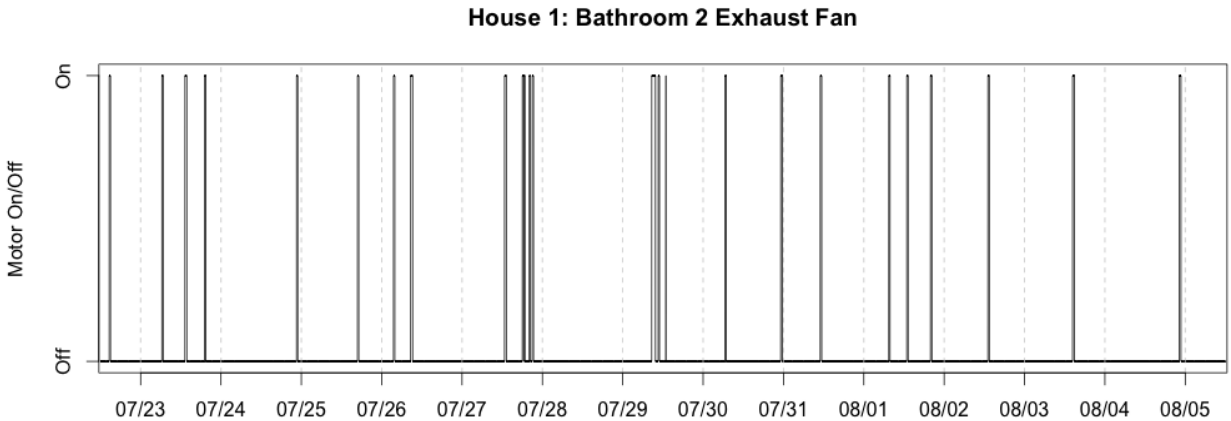
Appendix B

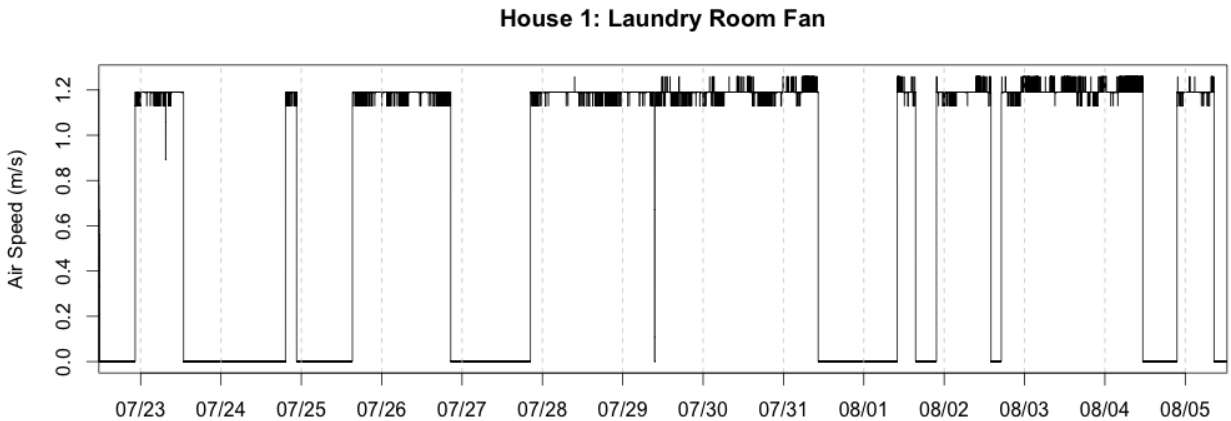
Usage data collected using a number of monitoring devices, including digital anemometers that measured air speeds, on/off state loggers that measured motor operations, power meter readings, and temperature/relative humidity measurements.

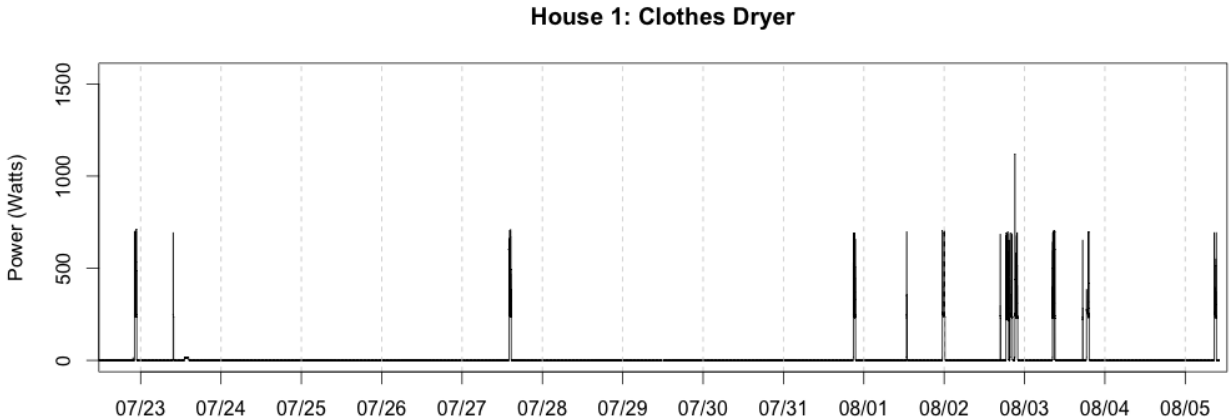


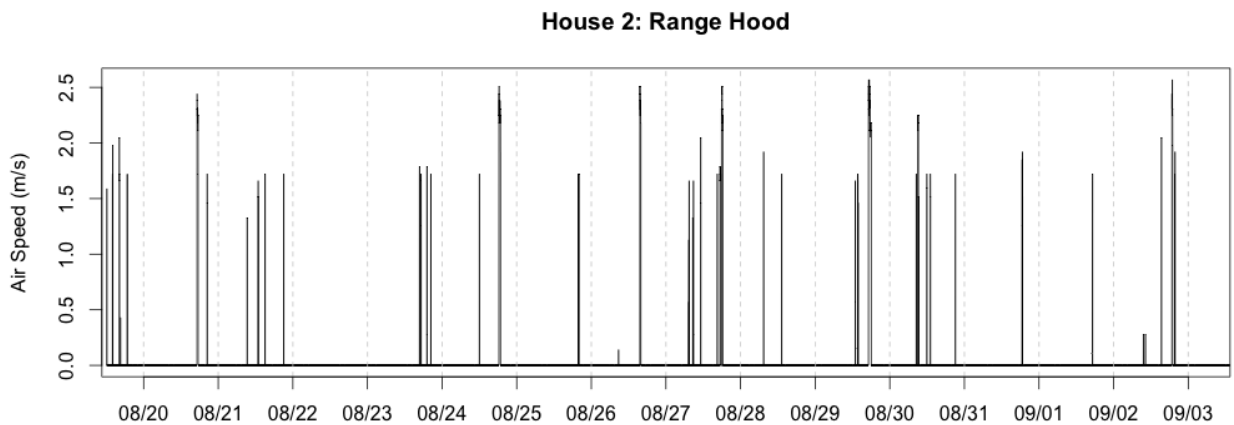


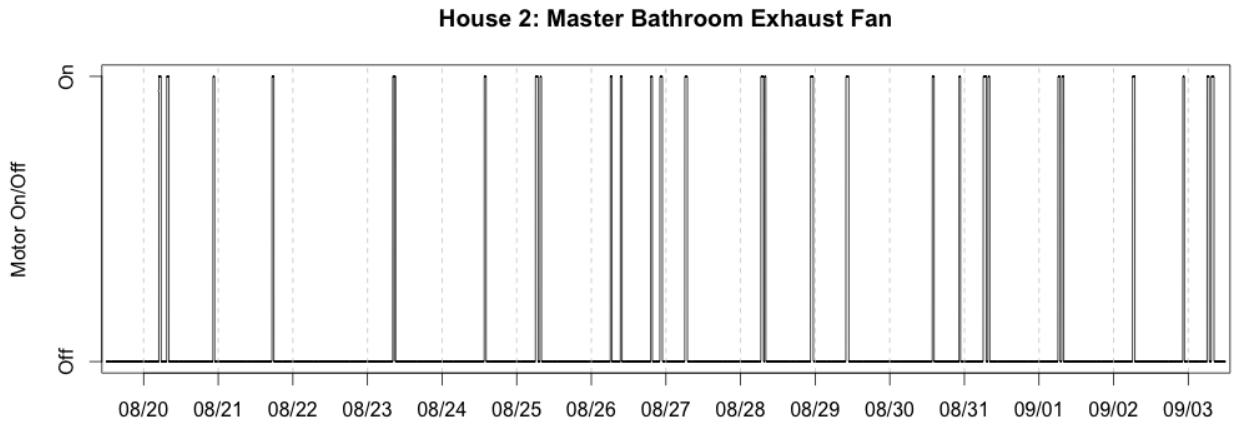


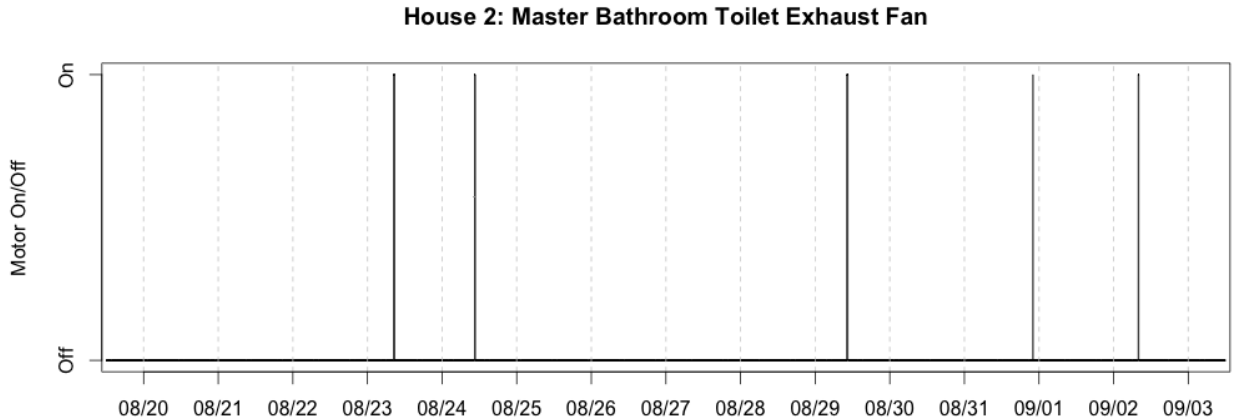

House 1: Bathroom 2 Exhaust Fan
Motor On/Off
On
Off
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

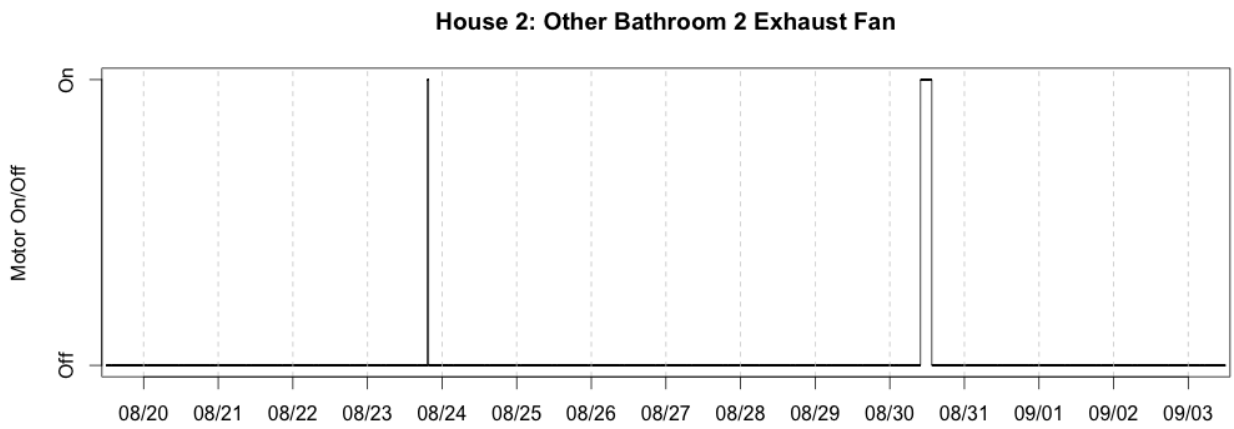

House 1: Laundry Room Fan
Air Speed (m/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

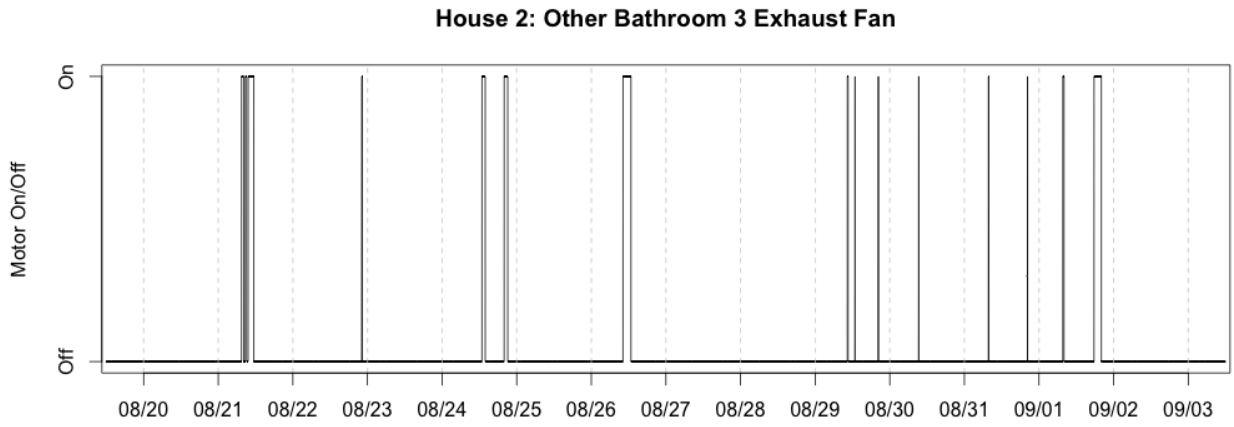

House 1: Clothes Dryer
Power (Watts)
0
500
1000
1500
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

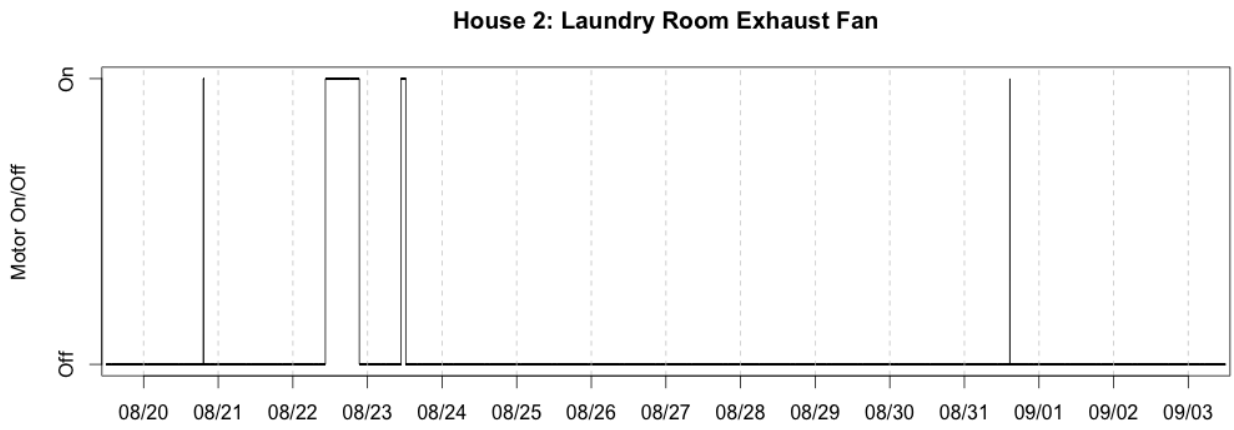

House 2: Range Hood
Air Speed (m/s)
0.0
0.5
1.0
1.5
2.0
2.5
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03

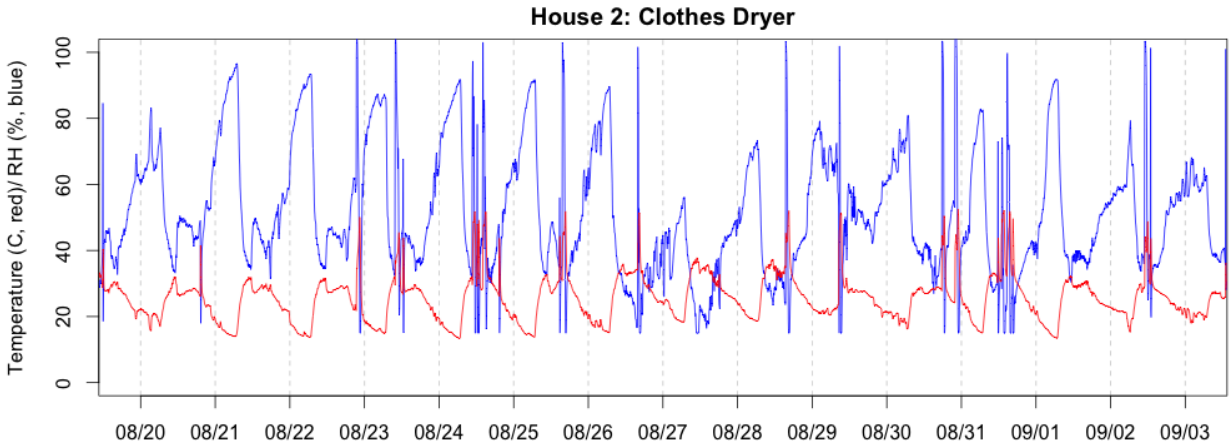

House 2: Master Bathroom Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Master Bathroom Toilet Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Other Bathroom 2 Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Other Bathroom 3 Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Laundry Room Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Clothes Dryer
Temperature (C, red)/ RH (%, blue)
0
20
40
60
80
100
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03

Appendix C

Comparison of PM2.5 mass concentrations measured by five particle instruments: MetOne BT-645, Thermo pDR-1500, TSI DustTrak II 8530. PM2.5 mass concentrations measured by MetOne BT-645, Thermo pDR-1500, and TSI DustTrak are plotted as-measured. Particle counts measured by Dylos and MetOne BT-637 were used to estimate PM2.5 mass concentrations assuming spherical particles having a density of 1.65 g/cm^3, as follows:

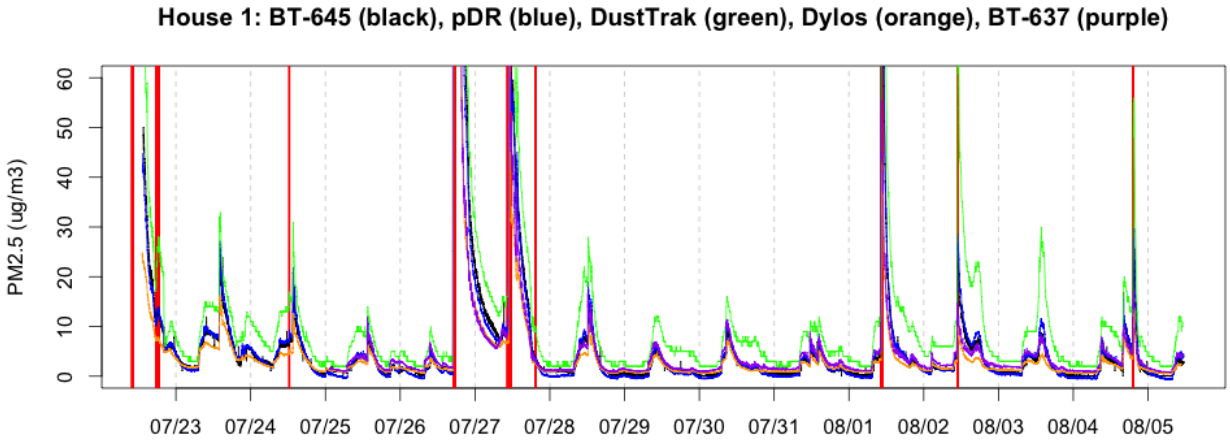
Dylos: PM2.5 (ug/m^3) = N (#/m^3) π/6 (1 um)^3 (1.65 g/cm^3) (10^6 ug/g) (cm^3/10^{12} um^3)
where N is the particle counts measured between the two channels (>0.5 and >2.5 um).

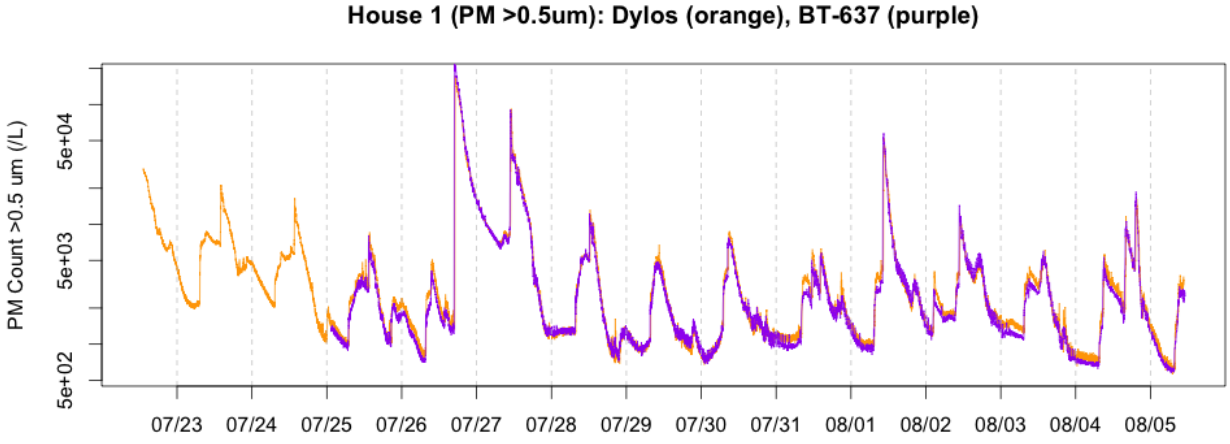
MetOne BT-637:
PM2.5 (ug/m^3) = Σ N_i (#/m^3) π/6 (dp_i)^3 (1.65 g/cm^3) (10^6 ug/g) (cm^3/10^{12} um^3)
where N_i is the particle counts measured within a given size bin, and dp_i is the representative diameter of the particle.

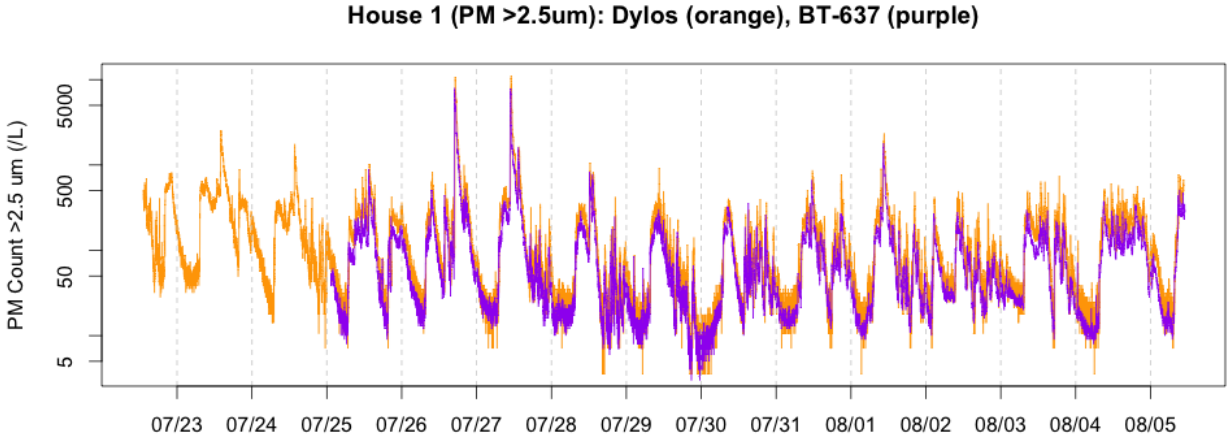
In House 1, N_i were measured at these size bins: 0.3-0.5, 0.5-0.7, 0.7-1, 1-2.5 um, were used to calculate PM2.5 mass concentrations. The assumed dp_i was 0.45, 0.6, 0.85, and 1.75 um, respectively. In House 2, N_i were measured at these size bins: 0.3-0.4, 0.4-0.5, 0.5-0.7, 0.7-1, 1-2.5 um, were used to calculate PM2.5 mass concentrations. The assumed dp_i was 0.35, 0.45, 0.6, 0.85, and 1.75 um, respectively.

Raw particle counts measured by Dylos and MetOne BT-637 were compared in the middle and bottom charts.

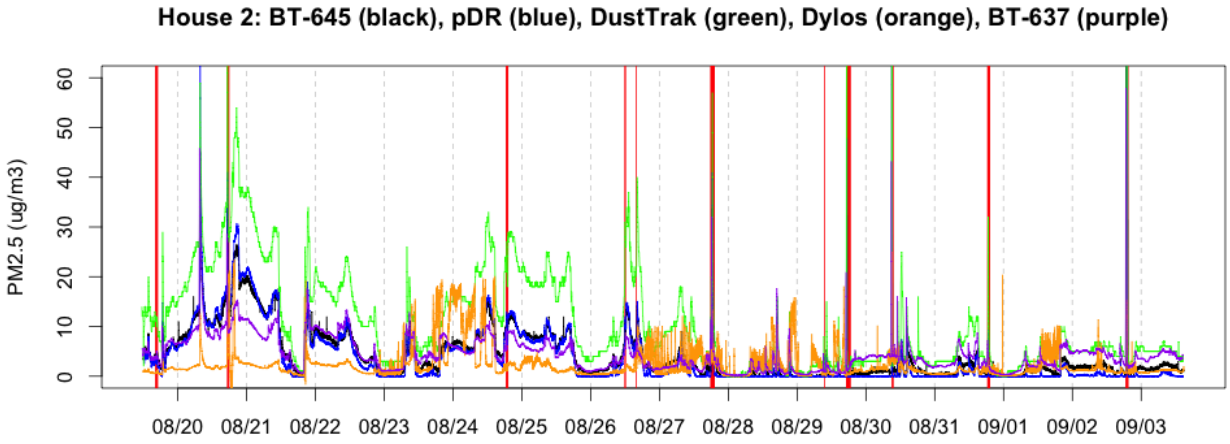
In House 1, cooking events are defined by thermocouple measuring >120 ^{o}F (49 ^{o}C), as indicated by red lines in the top chart.

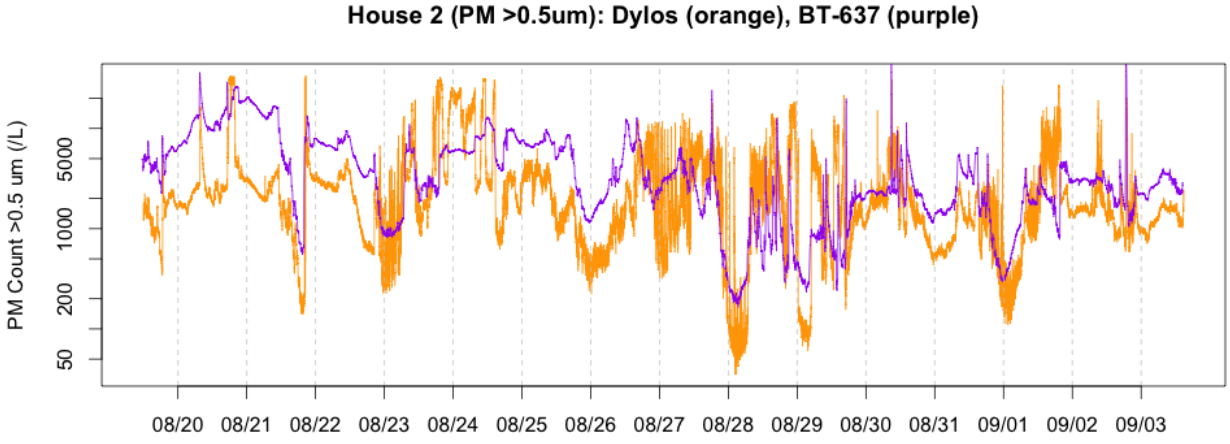


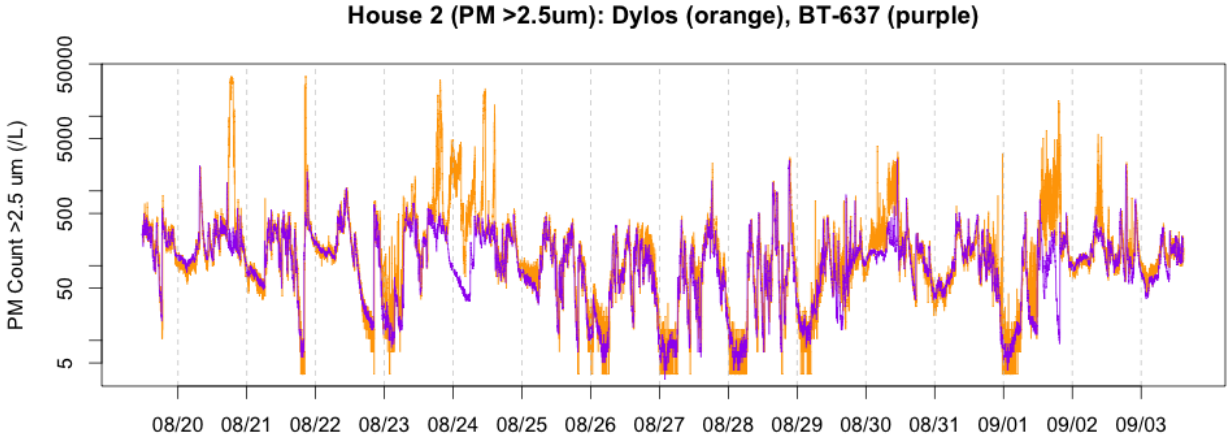




In House 2, cooking events are defined by iButton measuring >35 ^{o}C, as indicated by red lines in the top chart.







Appendix D

PFTs concentrations (ug/m^3) measured in House 1.

	PDCB (emitted from kitchen area)		PMCH (emitted throughout the house)		mPDCH (emitted from attached garage)	
	Week 1	Week 2	Week 1	Week 2	Week 1	Week 2
Master Bedroom	20.1	19.1	27.9	27.1	1.7	1.5
Master Bathroom	--	18.4	--	24.4	--	1.8
Other Bedroom 1	23.0	10.6	28.3	12.9	1.3	0.4
Dining Room	25.5	24.3	28.6	27.2	1.4	1.2
Great Room	28.8	27.4	30.7	29.8	1.3	1.2
Kitchen*	32.2	34.6	30.4	30.9	1.3	1.1
Laundry Room	23.6	22.2	26.4	25.3	2.8	2.3
Hallway	--	22.5	--	27.8	--	1.2
Den	--	23.0	--	26.3	--	1.2
Garage	2.6	2.0	2.3	2.0	64.2	57.8

* Kitchen is connected to the great room.

PFTs concentrations (ug/m^3) measured in House 2.

	PDCB (emitted from upper floor)		PMCH (emitted from attached garage)		mPDCH (emitted from lower floor)	
	Week 1	Week 2	Week 1	Week 2	Week 1	Week 2
Rooms in upper floor						
Master Bedroom	13.1	18.8	2.8	4.3	5.0	9.2
Other Bedroom 1	13.1	17.2	2.9	4.2	4.3	7.9
Other Bedroom 2	13.9	18.1	3.7	4.9	4.6	7.8
Home Office	13.3	17.6	3.1	3.9	5.1	7.9
Rooms in lower floor						
Living Room	9.6	14.9	4.3	5.5	9.1	12.2
(replicate sample)	9.4	14.3	4.6	5.4	9.1	11.6
Laundry Room	8.2	12.9	7.0	9.3	9.0	11.6
Other Bedroom 3	12.6	12.5	8.4	8.0	11.8	12.8
Garage	1.7	2.3	68.0	77.0	0.2	0.7