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Efforts to improve energy efficiency in homes and buildings have led to tighter structures. However, these changes can also produce negative consequences for indoor air quality and human health. One of the dramatic effects of climate change and weather is the increase in destructive wildfires, such as those experienced in the Pacific Northwest during the summer of 2015. The current article presents data for measurements at two houses during periods with and without high levels of wildfire smoke outdoors. For each house, indoor and outdoor pollutant measurements were obtained for ozone (O_3), fine particulate matter ($PM_{2.5}$), and volatile organic compounds along with outdoor weather conditions and occupant activities including the use of windows and doors. The volatile organic compound measurements were obtained using a Proton Transfer Reaction Mass Spectrometer. Compounds monitored included acetonitrile (a biomass burning tracer), formaldehyde, acetaldehyde, methanol, acetone, benzene, toluene, and C2-alkylbenzenes (i.e., sum of xylenes and ethylbenzene), C3-alkylbenzenes (i.e., sum of trimethylbenzene, ethyltoluene, and propylbenzene isomers), and C4-alkylbenzenes (i.e., sum of tetramethylbenzene and its isomers). A carbon dioxide tracer method was used to measure *in situ* ventilation rates, and blower door tests were also completed to determine standard ventilation rates. For smoky periods with elevated outdoor pollutant levels, penetration factors, defined as the ratio of indoor/outdoor concentrations were quite low. Penetration factors for $PM_{2.5}$ were 11% for H2 and 15% for H3, except when windows or doors were open. The penetration factors for O_3 were also low at 24% for H2 and 5% for H3. Elevated indoor volatile organic compound levels were not typically associated with outdoor levels, but reflected significant indoor sources. During smoke events, acetonitrile, a biomass burning tracer compound, was elevated outdoors and indoors in both houses, and benzene was elevated outdoors and indoors in H3.

Introduction

The American Heart Association has characterized fine particulate matter ($PM_{2.5}$) exposure as a modifiable factor that contributes to cardiovascular disease (CVD), mortality, and morbidity, and found that fine particulate matter (PM) is a risk factor for acute cardiac events (Haikerwal et al. 2015). Exposure to $PM_{2.5}$ has been associated with increased risk of out-of-hospital cardiac arrests and ischemic heart disease (IHD) during the 2006–2007 wildfires in Victoria, Australia. In the Northwestern United States and Canada, Benmarhnia et al. (2014) have reported that smoke from distant wildfires impacts the Northwest, particularly in relation to particles and particle size that can occur even at extended distances from fire sites (Benmarhnia et al. 2014). This evidence suggests that $PM_{2.5}$ may act as a triggering factor for acute coronary events during wildfire episodes.

The objective in the current article is to assess the impact on indoor air quality (IAQ) due to heavy smoke events from wildfires and to investigate the relative importance of outdoor smoke versus indoor sources of pollutants. IAQ data were collected from two occupied houses located in Pullman, Washington during July through August of 2015 which coincided with periods of extensive wildfires in the region that produced very high levels of $PM_{2.5}$ and other pollutants in the Pullman area. These measurements are part

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Table 1. Description of houses H2 and H3.

House	Year built	Square footage	Volume conditioned: Unconditioned	Attached garage	Stories	Number of occupants: Pets	Blower door results (ACH_{50})*
H2**	1963	1765	13,614: 4,308 cu ft	Yes	2	2: 2	13.60 hr^{-1}
H3***	2011	3440	33,598: 3,663 cu ft	Yes	2	4: 2	11.45 hr^{-1}

*Exchange rate at 50 Pascals.
**H2 is a split level (three levels) wood frame home.
***H3 is a structural insulated panel (SIP) home with a crawl space.

of an ongoing IAQ and climate change project involving automated ventilation rate and IAQ measurements, including the use of occupant activity sensors, to yield a comprehensive database for assessing the effects of climate variability, including extreme weather events such as wildfires, on occupant behavior, energy consumption, and corresponding IAQ.

IAQ measurements

The summer of 2015 had several extreme wildfire events throughout the Inland Northwest, including at least 46 fires in Washington, Oregon, and Idaho between March 31 and October 31 (GlobalIncidentMap.com, Copyright 2006–2012). The 2015 Northwest Annual Fire Report from the Northwest Interagency Coordination Center (2016) out of Portland, Oregon reported that 1,005,423 acres burned in Washington, the largest being the North Star fire covering 218,138 acres. Smoke plumes from several of these fires were transported over Pullman, Washington, causing PM levels that created a hazardous air quality index for $PM_{2.5}$ on several days (EPA AirNow 2016). Results for two houses tested in summer, 2015, referred to as H2 and H3, are reported here as these houses were directly affected by wildfire smoke which occurred during the testing period. These two homes were unexpectedly caught during a wildfire episode while performing an ongoing Environmental Protection Agency (EPA)-funded research study on IAQ of occupied homes in Eastern Washington. The total number of homes being studied is 12. Descriptions of the houses H2 and H3 are shown in Table 1. In H2, measurements were conducted covering 28 days, which included periods with and without intensive wildfire smoke in the area and which included extended times with the homeowners present or absent. In H3, measurements were conducted covering 13 days, including days with and without heavy outdoor smoke.

Prior to these measurements, H2 and H3 were equipped with occupancy sensors on the exterior doors and windows to indicate when each was opened or closed, as well as indoor motion and temperature sensors for assessing occupant activities. Blower door tests at 5–50 Pa were performed on H2 and H3 to determine air exchange per hour (ACH_{50}) using standard industry practices. The so-called air exchange per hour natural ($ACH_{50,\,natural}$), estimated via logarithmic extrapolation at 0 Pa pressure difference, can be used to characterize house tightness (see Table 1). Both outdoor and indoor trace gases and PM were monitored at each site, along with outdoor meteorological conditions. Additionally, carbon dioxide (CO_2) tracer tests were conducted throughout each measurement period to determine air exchange rates. Table 2

Table 2. Measurement periods, variables, and instrumentation for houses H2 and H3.

Outdoor air	Indoor air	Ventilation	Weather (Airmar, Inc.)
H2: July 23–Aug 20	H2: July 23–Aug 18	H2: July 23–Aug 20	H2: July 23–Aug 20
H3: Aug 25–Sep 2	H3: Aug 20–Sep 2	H3: Aug 20–Sep 2	H3: Aug 25–Sep 2
VOCs (PTR-MS)	VOCs (PTR-MS)	Blower door test	Air temperature
CO_2/H_2O (LiCOR 840A)	$CO_2/H_2O/CH_4$ (Los Gatos UGGA)	CO_2 injection-decay (LiCOR 840A)	Dewpoint
O_3 (TECO 48)	O_3 (2B Tech. 205)	Window/door position (smart home sensors)	Relative humidity
$NO/NO_2/NO_x$ (TECO 42C)*	$NO/NO_2/NO_x$ (2B Tech. 405)*		Barometric pressure
$PM_{2.5}$ (DustTrak)	$PM_{2.5}$ (DustTrak)		Wind direction,
CO (Monitor Labs)*	$CO/O_3/NO$** (Alphasense B4 series)		Wind direction, mag.
	Particle counts (Dylos)		Wind speed
	Air Temperature (thermocouple)		

*$NO/NO_2/NO_x$ and CO data were not included in the current article.
**Alphasensors were deployed in H2 only.

summarizes the variables monitored and the instrumentation used for each house. Volatile organic compounds (VOCs) were measured with a Proton Transfer Reaction Mass Spectrometer (PTR-MS, Ionicon Analytik GmbH) that allows for high time resolution monitoring (~1 min) of a range of compounds including known air toxics (Jobson and McCoskey 2010). Compounds monitored included acetonitrile (a wood smoke tracer), formaldehyde, acetaldehyde, methanol, acetone, benzene, toluene, and C2-alkylbenzenes (i.e., sum of xylenes and ethylbenzene), C3-alkylbenzenes (i.e., sum of trimethylbenzene, ethyltoluene, and propylbenzene isomers), and C4-alkylbenzenes (i.e., sum of tetramethylbenzene and its isomers).

Description of H2 and H3 homes and ventilation systems

Home H2, built in 1963, is a multi-level stick frame home with a double car garage beneath the upper level. Multi-level or "split-level" homes were very popular in the 1960s. These homes were designed and built with the construction philosophy of allowing it to breathe. However, many of these multi-level homes with garages beneath have infiltration leakage problems due to the multi-level construction and stacking of lumber connections. Leaks between the plates and corner and cripple studs are common. In addition, the sheathing used in many of these homes built in the 1960s consisted of 0.5′ fiber board with open seams. Because the fiber board was impregnated with tar, a house wrap of 30 lb tar paper was not used. Builders of these 1960s homes, especially in the Northwest where the power needs were met with plentiful inexpensive electricity from hydropower, were not concerned about infiltration rates or duct leakage, and at the time had little knowledge of IAQ or the reasons for tightening up a home against infiltration. Rather, the common belief at the time was to reduce energy using minimum thermal packages R-11 in walls and R-19 in the roof assemblies. However, their design limited the amount of thermal insulation, especially at the attic and between roof joists, due to flatter roof pitches, cathedral ceilings, and smaller roof joists. As electricity prices rose in the Northwest and natural gas became cheaper, many of these homes were converted to natural gas to reduce the cost of energy. However, the original duct systems were kept in place by using cavities between floor joists or between wall studs for some supply and return air, which was common practice prior to modern codes requiring enclosed ducts.

During the blower door and duct testing of home H2, duct leakage was readily apparent. Typically, these multi-level homes will lose air through wall and floor cavities when the ducts are pressurized becuase the air returns use the wall and floor cavities as unsealed ducts. The most common locations where air will leak is through holes drilled for wires and plumbing between wall studs and floor joists, as well between floor and wall plates into unconditioned and conditioned spaces. H2 was built with a forced air ventilation system, and does not have a fresh air intake according to the code at the time. A fresh air intake was never added after subsequent upgrades to the heating system. The estimated duct leakage as a percentage of the air handler flow in H2 was measured at 50.4% based on using a duct leakage tester and blower door at 25 Pa and 120 cfm.

Home H3, built in 2011, is a structural insulated panel (SIP) home with a crawlspace. The roof has a typical truss built system and was not constructed using SIP roof panels. The home has a forced air ventilation system, and per Washington State Energy code (WSEC), has a heat recovery ventilator (HRV) unit. All ducts are metal and assumed to be adequately sealed by code. Homes with SIPs are designed and built with the focus of reducing infiltration rates by eliminating floor plates and openings in the thermal envelope. The H3 SIPs are made of oriented strand board (OSB) and a molded expanded polystyrene (EPS) core. The home also has a code approved building wrap.

Although H3 was designed to save energy by using SIPs to increase its insulating capability, to eliminate conductivity through the structural building components (wall studs and plates), and to reduce leaks at bottom and top plates, the testing indicated that the home had an unusually high infiltration rate for this type of construction. During the blower door and duct test, the home was examined using a thermal imaging camera and found numerous leaks where the panels meet the foundation. Further examination by inspection of the crawlspace confirmed the leakage. In addition, the home has numerous recessed can lights which can be problematic for infiltration and exfiltration. This leakage was confirmed through thermal imaging.

During the duct testing, a stable pressure was unable to be attained in order to reach a reliable measurement. Upon further inspection, the ductwork appears not to be to code and the HRV appears to be installed backwards. The state of Washington did not require duct testing in 2011; however, since 2015, WSEC section R402.4.1.2 requires air leakage testing for all new houses and additions. Energy codes are enacted to reduce energy usage, improve (IAQ), and increase comfort level. However, one key element that codes do not address is improper construction due to a builder's lack of construction knowledge and poor quality of workmanship. Even though H3 is located on acreage in a newer, high-end development, the leakage found during the present testing would indicate that this particular home was not constructed properly to achieve energy efficiency.

Even though both homes have rather high infiltration rates, and have forced air ventilation systems that either met the code or not at the time they were built, they both exhibited the ability to self-filter during the testing. When reviewing the preceding figures and data, the wildfire smoke events producing elevated levels of $PM_{2.5}$, O_3, toluene, a-pinene, acetonitrile, etc., the levels were noted to be considerably less indoors than in the outdoor measurements. This would support the early work by Hines in his 1982 book, Aerosol Technology, as cited by Thornburg et al. (2001), Lamb et al. (1985), and Thatcher and Layton (1995) that homes and buildings perform self-filtration. This phenomenon has been evident to builders for years, who have often noted significant amounts of very fine particles that have accumulated over time in wall and floor cavities of homes and buildings being remodeled.

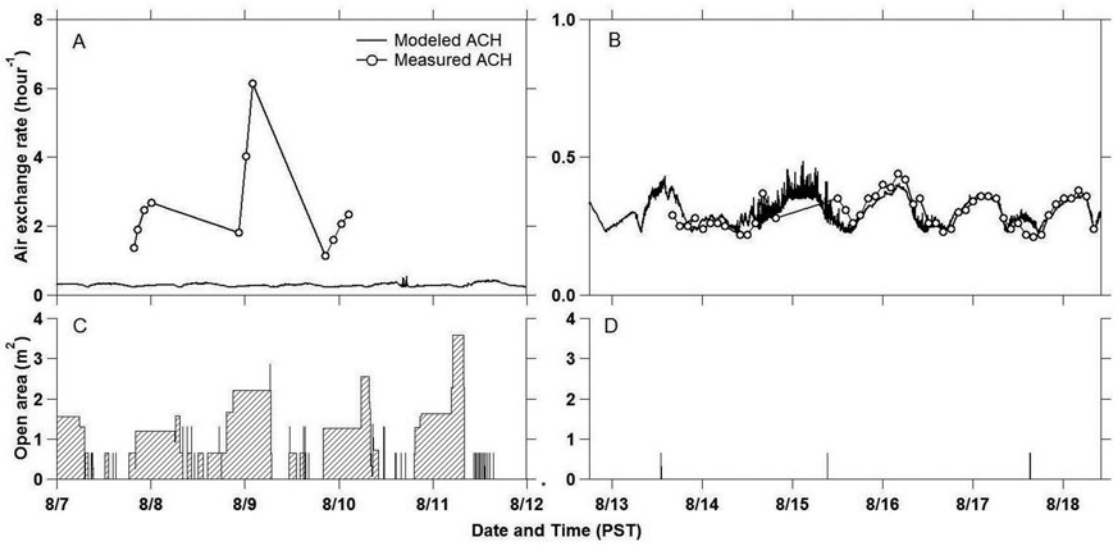

Fig. 1. Measured air exchange rates (ACH, open symbols) from H2 using the CO_2 tracer method for occupied (A) and unoccupied (B). Line shows calculated ACH from delta-temperature (ΔT) and wind speed (WS). Bottom panels (C, occupied; D, unoccupied) show estimated open area of windows and doors based on sensor data.

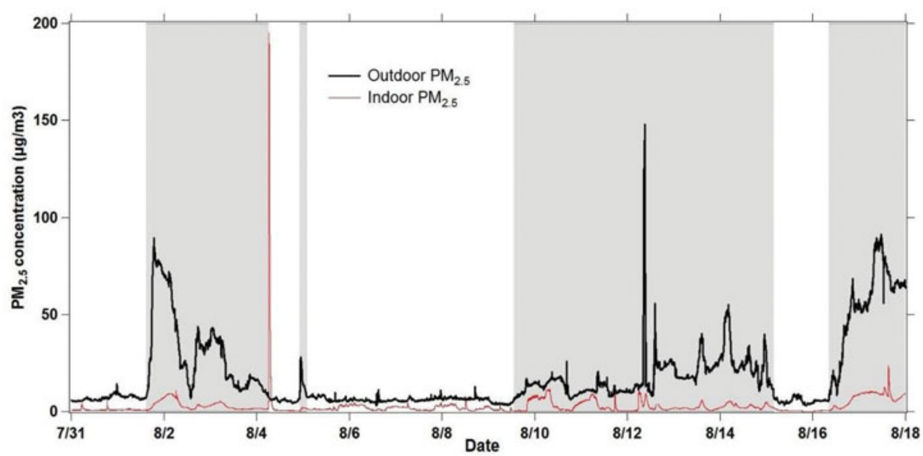

Fig. 2. Indoor and outdoor $PM_{2.5}$ during sampling period at H2 (shaded areas indicate wildfire smoke events).

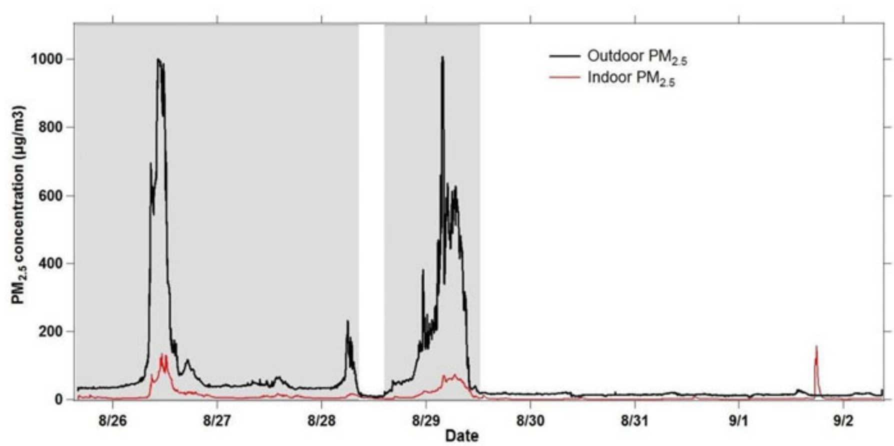

Fig. 3. Indoor and outdoor $PM_{2.5}$ during sampling period at H3 (shaded areas indicate wildfire smoke events).

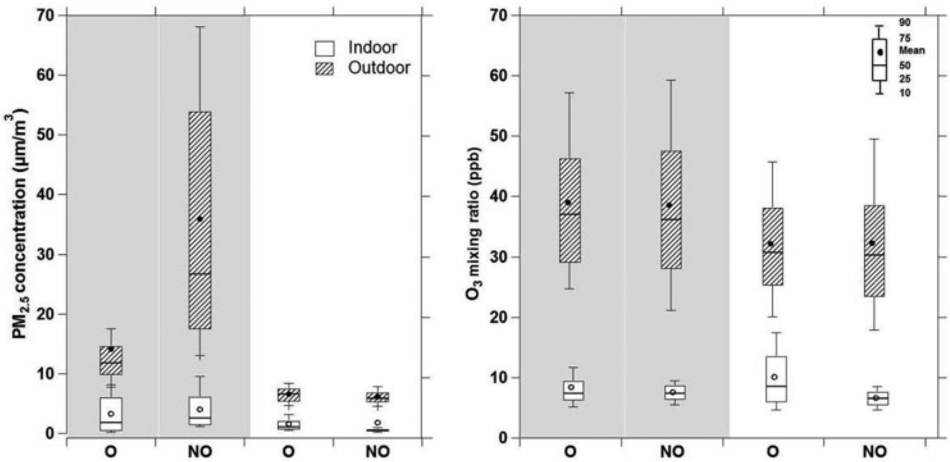

Fig. 4. Indoor and outdoor $PM_{2.5}$ and O_3 for H2 for wildfire periods (shaded area) and nonwildfire periods with the home occupied (O) and not occupied (NO).

Results and discussion

Air exchange rates and occupant activity

H2 is nestled up against a hillside and is protected by large trees from the prevailing westerly winds. H3 is located on top of an exposed hill with no trees or adjoining structure to protect it. Wind conditions, shielding, occupant behavior, age of home, type of construction, and size of a home, as well as other conditions all affect and play vital roles in estimating a home's indoor natural air exchange rates.

Air exchange rates per hour (ACH_{CO2}) were determined using a CO_2-tracer test during which a large volume (~20 L) of 100% CO_2 was injected periodically into the house circulation system, and the rate of decay of the resulting CO_2 concentration peaks was monitored. These data were combined with the measured outdoor CO_2 concentration and estimates of human respired CO_2 to model the true air exchange rate according to Equation 1.

$$C(t) = \left[\frac{S/V + C_o n}{n+k}\right]\left[1 - e^{-(n+k)t}\right] + C(0)\,e^{-(n+k)t}, \qquad (1)$$

where $C(t) = CO_2$ indoor mixing ratio observed at time t; $C_o = CO_2$ outdoor mixing ratio; $C(0) = CO_2$ indoor mixing ratio at $t = 0$; $S = CO_2$ source emission rate; V = volume of the house; n = air exchange rate; $k = CO_2$ reaction rate; t = elapsed time.

In terms of the CO_2 source, human respired CO_2 rates were used: 0.20 L/min for average sized adult sleeping and 0.30 L/min for average size adult engaged in office work (ASHRAE 2013). No CO_2 reaction or deposition was assumed in the house so that $k = 0$. The house volume (V) was calculated from interior measurements. For each injection period, the air exchange rate (n) was determined from the best fit of Equation 1 to the measured indoor CO_2 concentrations.

At H2 there were opportunities to monitor air exchange rates during periods of time when there was no activity in the home (representing a CO_2 source term of $S = 0$), and when there was a lot of activity in the home—therefore, delineating the effects of human presence on air exchange rates for that home. The air exchange rate using (ACH_{CO2}) with the homeowners absent and all doors and windows closed was estimated as $0.30 \pm 0.06\ hr^{-1}$ based on the CO_2-tracer injections.

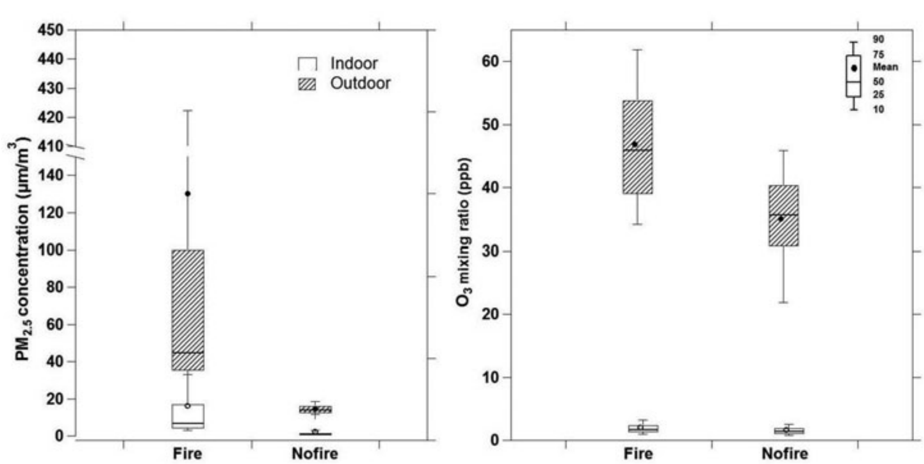

Fig. 5. Indoor and outdoor $PM_{2.5}$ and O_3 for H3 during wildfire and nonwildfire periods. Note: $PM_{2.5}$ axis has a split scale.

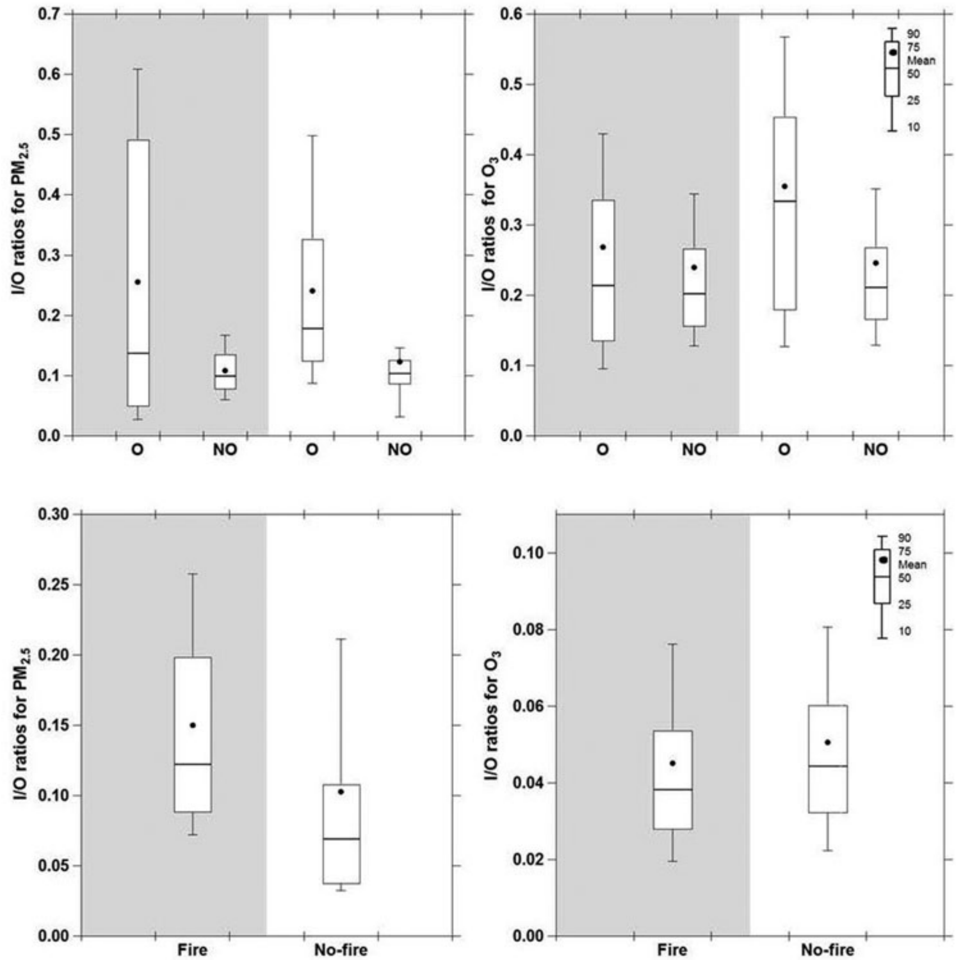

Fig. 6. I/O ratios for $PM_{2.5}$ and O_3 for H2 (top) and H3 (bottom). I/O ratios are calculated as the ratio of indoor/outdoor concentrations and do not account for deposition or filtration losses indoors. Shaded area indicate data measured in wildfire. For H2, occupied (O) and not occupied (NO) data were showed separately.

This value is 53% lower than the natural $ACH_{50,\,natural}$ from the multi-point blower door test results, which was 0.64 hr^{-1}.

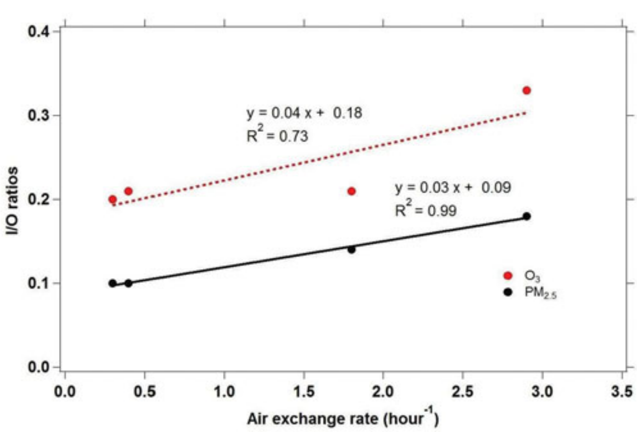

Fig. 7. Median $PM_{2.5}$ and O_3 I/O rates as a function of measured air exchange rates for H2 including occupied and unoccupied periods and with and without wildfire smoke.

The average ACH_{CO2} when the homeowners were present was 2.5 ± 1.4 hr^{-1}; during these times, the house was completely opened for cooling through the night, while during the day the home was kept closed to avoid the summer heat. With greater window and door activity, the average ACH_{CO2} when the homeowners were present was four times as much as the natural $ACH_{50,\,natural}$, estimated from the blower door test.

For H2, the homeowner-absent air exchange rates over time were well-predicted using the best-fit relationship between air exchange rate (ACH_{CO2}), the outdoor wind speed (WS), and outdoor and indoor temperature difference (ΔT) as described by Lamb et al. (1985) and given in Equation 2.

$$ACH = a + b WS^2 + c\,|\Delta T|\,. \tag{2}$$

The ACH_{CO2} values calculated from this relationship are shown with measured ACH_{CO2} data in Figure 1a and 1b The measured air exchange rate in H2 when the homeowners were present was significantly higher at 1.8 ± 0.5 hr^{-1} during fire periods, and 2.9 ± 1.5 hr^{-1} during smoke free periods.

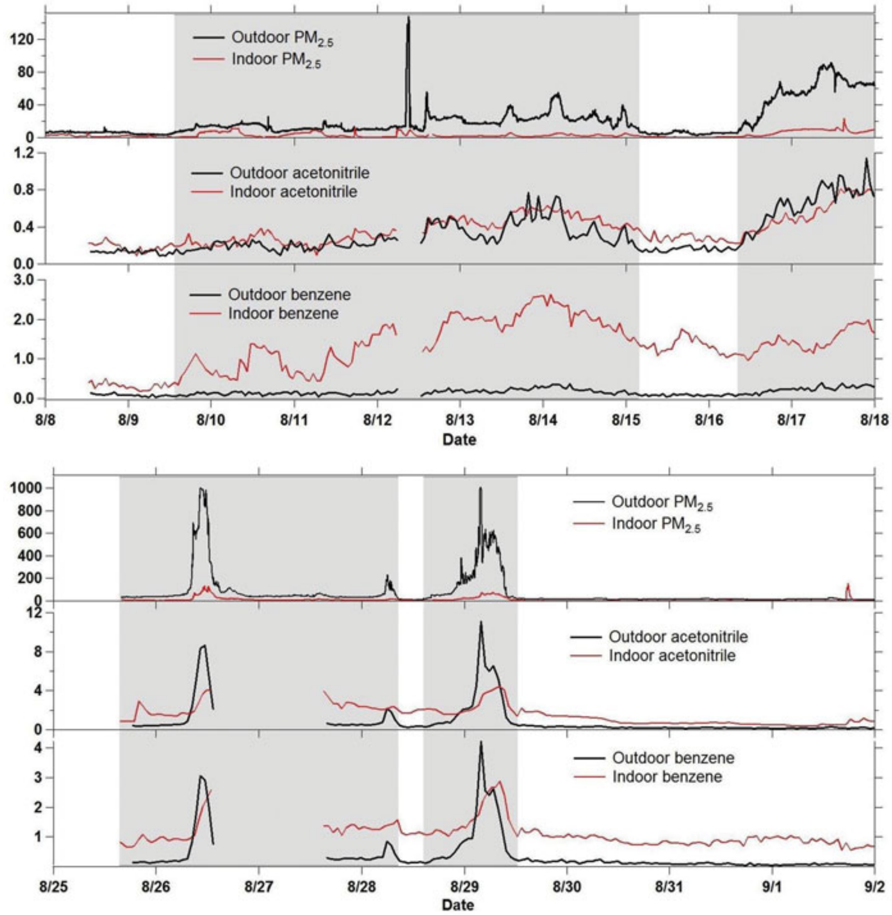

Fig. 8. Indoor and outdoor concentrations of $PM_{2.5}$ (unit: µg m^{-3}), acetonitrile (unit: ppbv), and benzene (unit: ppbv) for H2 (top) and H3 (bottom). Shaded areas indicate wildfire period.

When the homeowners were present, the window and door activity routine is clearly indicated by the window sensor data in Figure 1c, opened during the night and closed during the day. The window sensor data was used to estimate a total open area of the building envelope; this ranged from zero during the day when all windows and doors were closed to values between 2 to 3 m^2 at night due to open windows. During the unoccupied period, there were only 3 occasions when instrument operators entered the house to check on equipment; this is indicated in Figure 1d as three "spikes" at 0.5 m^2 due to door openings around noon on August 13, 15, and 17. On August 4, the opening of the door resulted in a sharp spike in indoor $PM_{2.5}$ concentrations due to wildfire smoke in the area, as can be seen in Figure 2.

H3 is a relative new house built using SIPs and it was chosen as a study site in part because it was hypothesized that it was more tightly constructed house. Based on the H3 blower door test, the natural $ACH_{50,\,natural}$ was 0.45 hr^{-1} which is about 30% lower than the 0.64 hr^{-1} H2 natural $ACH_{50,\,natural}$, indicating tighter construction. CO_2-tracer tests were completed on H3 and gave an average ACH_{CO2} of 0.41 ± 0.29 hr^{-1} which included periods with the occupants at home and periods with the occupants absent. During the wild fire smoke periods the measured ACH_{CO2} was 1.4 ± 1.5 hr^{-1}, suggesting windows were sometimes open during this period to cool the house at night. In this case, only measurements in the living room were available for ventilation rate calculations. Both the blower door test results and the ACH_{CO2} estimated from CO_2 injections indicate that H3 is more tightly constructed than H2, as was expected (see Description of H2 and H3 homes and ventilation).

Outdoor pollutant concentration and indoor penetration patterns

Wildfire smoke events produced elevated levels of $PM_{2.5}$, ozone (O_3), and several VOCs notably formaldehyde, benzene, and acetonitrile; the latter VOC is an established tracer for biomass burning. The outdoor $PM_{2.5}$ levels exhibited a large range with maximum concentrations reaching 1000 µg m^{-3} during smoke events (H3) and the indoor $PM_{2.5}$ levels were also elevated during the wildfire events to about 10 µg m^{-3} and 120 µg m^{-3} for H2 and H3, respectively, as shown in Figures 2 and 3 for H2 and H3, respectively. These events persisted for extended periods from less than a day to as long as 5 days. With smoke absent, the outdoor $PM_{2.5}$

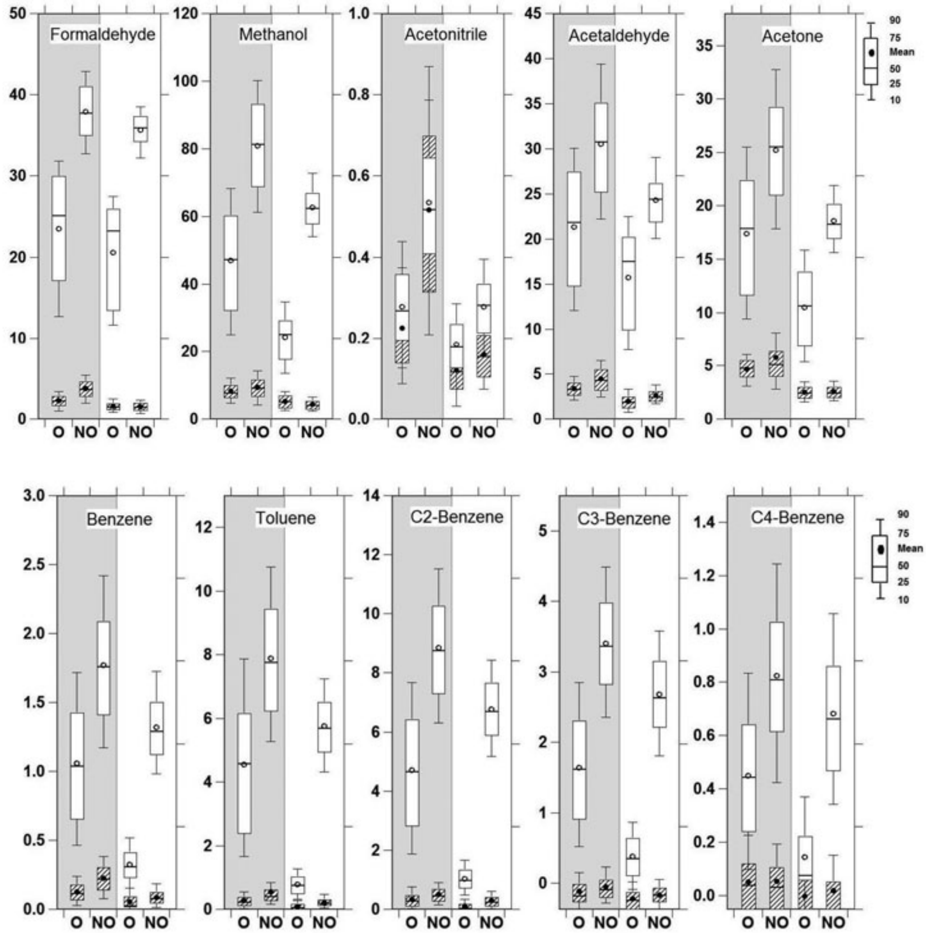

Fig. 9. Wildfire effects on VOCs (unit: ppbv) in H2; home occupied (O) or not occupied (NO). Patterned boxes indicate outdoor measurements and blank boxes show indoor measurements.

concentrations were less than 5 μg m^{-3}. Outdoor O_3 levels were moderate in the range from 20 to 60 ppb and there was approximately 10 to 20 ppb more ozone during the smoke events. A comparison between indoor and outdoor levels of $PM_{2.5}$ and O_3 measured in H2 and H3 is shown in Figures 4 and 5.

The indoor/outdoor (I/O) ratios for $PM_{2.5}$ and O_3 for H2 and H3 are summarized in Figure 6 and Table 3. I/O ratios were calculated as the ratio of indoor to outdoor concentrations. Note that these ratios do not differentiate between losses due to penetration and any deposition, filtration, or chemistry losses within the home. Depositional loss of $PM_{2.5}$ and O_3 is expected as outdoor air penetrates the closed building envelope through cracks around doors, windows, and structural components. Generally, Hinds postulates (as cited in Thornburg [2001]), that low I/O ratios for PM are not unexpected due to the removal of larger particles via impaction or for small particles via diffusion as particles traverse cracks around windows, doors, and structural components. In addition, some particles may have also been removed by the homes' furnace filters since the fans were operating continuously during the study periods. The fan filter in H3 was observed to be a flat, minimal filtration, disposable fiberglass panel filter with an approximate minimum efficiency reporting value (MERV) rating of 4, purchased from a local hardware store. The filter was also observed to be past its replacement period, being clogged and dirty. The purchase of the filter was confirmed by the homeowner.

In H2, with the homeowners present and with doors and windows frequently open at night, the mean PM2.5 I/O ratios were approximately 25% during both smoky and clear air periods. With the homeowners absent and the house completely closed, I/O ratios were approximately 12% during both clear and smoky periods. In both cases, the ACH $_{CO2}$ value was similar, 0.3 to 0.4 hr^{-1}. For H3 during the wildfire smoke period, the PM2.5 I/O ratios were slightly higher at 15% and the ACH_{CO2} was similar to H2, but more variable (0.4 ± 0.5 hr^{-1}). Please note that H3 was occupied during the full testing period while H2 was not. The higher I/O ratios with a similar ACH_{CO2} could be due to normal building operation (Stephens et al. 2012). Cited within the same article was research by Avol et al. (1998) and Lee et al. (2002) in which they discovered ozone concentration ratios of 0.37 ± 0.25 in

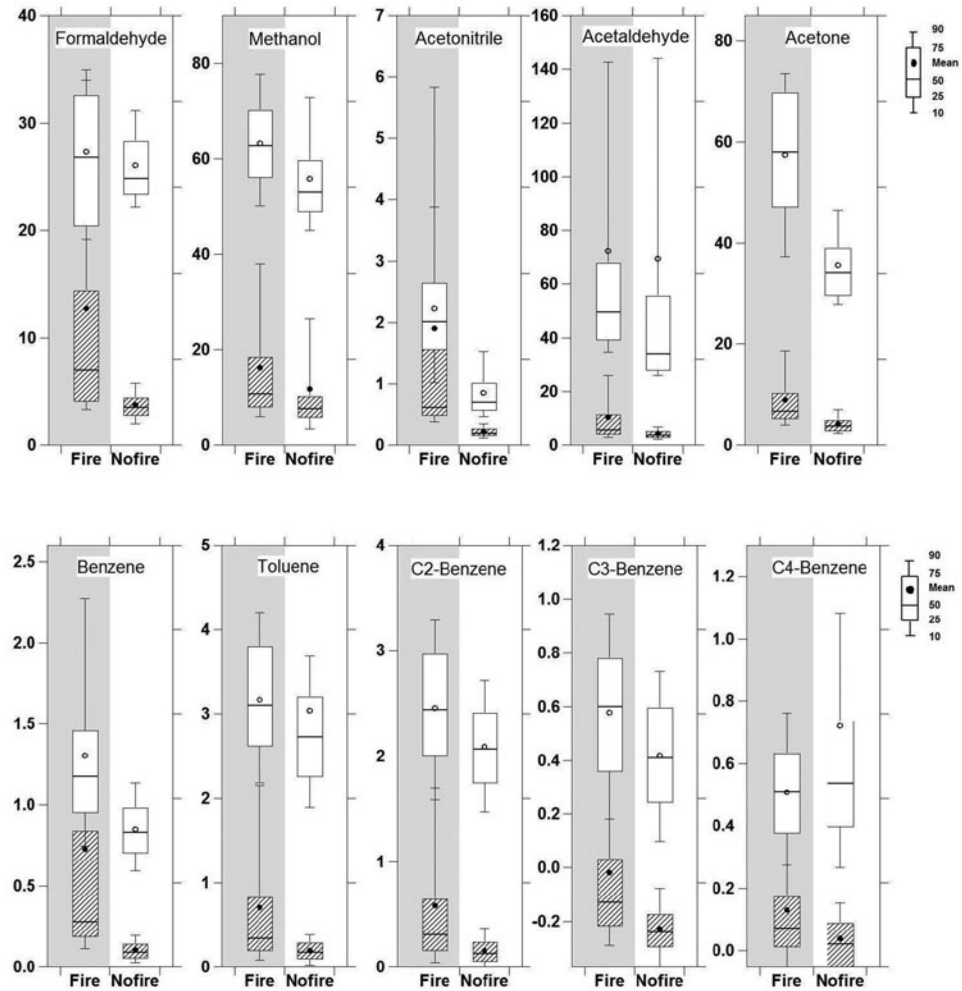

Fig. 10. H3 VOCs (unit: ppbv) whisker plots for indoor and outdoor air during wildfire and nonwildfire periods. Patterned boxes indicate outdoor measurements and blank boxes show indoor measurements.

Table 3. Penetration factors and air exchange rates for H2 and H3 under varying conditions.

House	Pollutant	Status	Mean I/O ratios	Stdev I/O ratios	Median I/O ratios	Mean ACH_{CO2} hr^{-1}	Stdev ACH_{CO2} hr^{-1}
H2	$PM_{2.5}$	fire_occupied	26%	24%	14%	1.8	0.5
H2	$PM_{2.5}$	fire_not occupied	11%	4%	10%	0.3	0.1
H2	$PM_{2.5}$	no fire_occupied	24%	17%	18%	2.9	1.5
H2	$PM_{2.5}$	no fire_not occupied	12%	20%	10%	0.4	0.1
H3	$PM_{2.5}$	fire	15%	9%	12%	0.4	0.5
H3	$PM_{2.5}$	no fire	10%	11%	7%	1.4	1.6
H2	O3	fire_occupied	27%	63%	21%	1.8	0.5
H2	O3	fire_not occupied	24%	37%	20%	0.3	0.1
H2	O3	no fire_occupied	36%	74%	33%	2.9	1.5
H2	O3	no fire_not occupied	25%	34%	21%	0.4	0.1
H3	O3	fire	5%	3%	4%	0.4	0.5
H3	O3	no fire	5%	4%	4%	1.4	1.6

126 homes and 0.24 ± 0.18 in 119 homes, and found significant differences in I/O ratios due to window opening behavior and the operation of air-conditioning systems. The I/O ratios being slightly higher at 15% for H3 with a similar ACH_{CO2} found in H2 could be due to the geometry, surface material and pressure drop along the leakage paths as cited by Liu and Nazaroff (2001). Even with these low I/O ratios, intense smoke plumes impacting H3 resulted in indoor PM2.5 concentrations exceeding 50 µg m-3 for most of the day. For H2, indoor O_3 levels exhibited a muted diurnal fluctuation during homeowner absent periods, indicating that as O_3 penetrates the home, it is removed from the air via reaction or deposition on surfaces. When homeowners were present, the doors and windows provided more direct air exchange and the daytime increase in indoor O_3 was larger. Ultimately, however, indoor O_3 levels never reached the outdoor levels. Mean I/O ratios for O_3 were approximately 25% for periods with the homeowners absent with or without fire, and increased to 27% for fire periods and 36% for nonfire periods with the homeowners present, reflecting the greater opening of windows and doors in the evening. For H2, the relationship between I/O ratios for both $PM_{2.5}$ and O_3 and air exchange rates are linear as shown in Figure 7 independent of the fire versus no-fire periods, and the I/O ratios for O_3 were generally higher than for $PM_{2.5}$. For H3, the O_3 I/O ratios were much less at 5% and there was no difference in penetration rates for O_3 during fire and no-fire periods.

Among the monitored VOCs in H2, only acetonitrile exhibited penetration from outdoors to indoors (see Figure 8 top). This compound is a well-known tracer for biomass burning and outdoor levels were significantly elevated during the smokey periods. For all the other VOCs, indoor levels were higher than outdoors and were not affected by outdoor levels, which indicates the presence of indoor sources. For formaldehyde, the indoor concentration ranges were from 8 to 48 ppbv in H2 and from 16 to 65 ppbv in H3 (Figure 8). In H2, the carpet was only 3-years-old and a simple flux chamber experiment was performed to derive an estimated formaldehyde flux of 22 µg m^{-2} hr^{-1} (carpet emission rate of 1.8 mg hr^{-1} for the whole house). Because this research is examining homes under normal *in situ* conditions, finding the actual carpet or pad samples and/or any fixture or product, then deriving their manufacture and make-up is difficult at best. Although in this case, the authors did acquire a cut-pile carpet sample; however, the actual weight of the carpet, glue used in manufacturing, or the pad type is not known. Whisker plots of VOC levels indoors and outdoors for H2 are shown in Figure 9.

For H3, from the timeseries plot (Figure 8 bottom), both acetonitrile and benzene indoor levels were elevated during the wildfire period due to the introduction from outdoor pollutants, which can be explained by the higher ACH_{CO2} in the previous discussion. Similarly, most VOCs in H3 were found to be much higher indoors than outdoors as shown in Figure 10. Some indoor VOC levels were found to be different in the two homes. H2 had higher levels of C2- and C3-alkylbenzenes, while H3 had significantly higher levels of acetone. Other VOCs appeared to have similar concentrations in both homes. The difference in concentration of certain VOCs in the homes indicates that the homes have different sources—either built into the home or brought into the home by the homeowners.

Conclusion

House air exchange rates can be reliably modeled if the relationship between air exchange rate, wind speed, and indoor and outdoor temperature can be established during a period of time when the homeowners are absent. Blower door test results used to estimate natural exchange rates seem to overestimate the actual air exchange rate of the home, but if the HVAC system provides for whole house circulation and mixing, the air exchange rate can be determined using a CO_2-release tracer test. Human activity (opening and closing of doors and windows) can significantly increase the average air exchange rate of the home.

Indoor $PM_{2.5}$ levels are significantly lower than outdoor levels. However, wildfire events can significantly increase indoor $PM_{2.5}$ concentrations, even in a fully closed home. While being indoors provides a safer breathing environment during these events, IAQ could still be a concern for certain people with asthma or other health problems. Penetration rates for O_3 were much higher than for $PM_{2.5}$ in H2, but were less than for $PM_{2.5}$, and very low in H3.

For H2, nearly all VOCs monitored were shown to have higher concentrations indoors than outdoors, indicating the presence of indoor sources. Acetonitrile was the only VOC shown in both houses to have a primarily outdoor source; however, all outdoor VOC trends aligned well with outdoor $PM_{2.5}$ trends during wildfire events. For H3, elevated indoor levels of benzene were associated with much higher outdoor levels. Many VOCs, such as formaldehyde, may have multiple indoor and outdoor sources, but flux chamber measurements in H2 suggest that carpet is the primary source of formaldehyde in H2.

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