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Healthy Zero Energy Buildings (HZEB) Program– Interim Report on Cross-Sectional Study of Contaminant Levels, Source Strengths, and Ventilation Rates in Retail Stores

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1 Introduction

The HZEB research program aims to generate information needed to develop new science-based commercial building ventilation rate (VR) standards that balance the dual objectives of increasing energy efficiency and maintaining acceptable indoor air quality. This interim report describes the preliminary results from one HZEB field study on retail stores. The primary purpose of this study is to estimate the whole-building source strengths of contaminant of concerns (COCs). This information is needed to determine the VRs necessary to maintain indoor concentrations of COCs below applicable health guidelines.

California's building energy efficiency standards Title 24 specifies retail stores to be ventilated at the larger of 7 L/s per person or 1 L/s-m^2, with the per floor area value often used for design purposes. To the best of our knowledge, these minimum ventilation rates (VRs) are based on professional judgment, such as from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2010). It remains a question whether the minimum VRs are sufficient for controlling contaminant levels. Studies have found the types of contaminants and their concentrations to vary considerably among different retail stores (Loh et al. 2006; Eklund et al. 2008; Bennett et al. 2010; Wu et al. 2011). Consequently, the required VRs may also vary by store types. For example, Loh et al. (2006) found that furniture stores tend to have higher formaldehyde concentrations than other retail types. Wu et al. (2011) also found statistically significant differences by building types for formaldehyde and a number of other volatile organic compounds (VOCs), such as ethylbenzene, m/p-xylene, o-xylene, chloroform, PCE, naphthalene, etc.

The goal of this study is to identify contaminants in retail stores that should be controlled via ventilation, and to determine the minimum VRs that would satisfy the occupant health and odor criteria. Twelve stores have been sampled thus far, of which the preliminary results from nine stores are presented in this interim report. Several retail store types are sampled: grocery, furniture/hardware, and apparel, from which we can see if source strengths of contaminants vary among them. The current minimum VR requirement of California Title 24 for all three store types studied are the same, as stated above. Because field sampling and data analysis is on going, revisions to the preliminary results are expected. The nine stores include three grocery stores (G1–G3), three furniture stores (F1–F3), and three apparel stores (A1–A3). The other three stores that were sampled but are not part of this interim report include two hardware stores and one grocery store. Our focus is on VOCs because there are numerous indoor sources, such as from building materials and merchandise. Findings of this work will inform future VR standards in Title 24.

2 Method

Eight of the nine retail stores are recruited from the North Coastal area of California (i.e., Bay Area, including San Francisco, Oakland, San Mateo, etc.). One grocery store is located in the South Coast of California (i.e. Tarzana). Samples were collected for two consecutive days in the first three stores that participated in this study. Remaining stores were sampled for one day only.

Stores were not selected based on building characteristic criteria aside from trade type, so they are a convenience sample.

Besides collecting contaminant samples, we also gathered information about the stores. We counted the number of occupants, including store workers and customers, a few times during the day of sampling. Information about the heating, ventilation, and air conditioning (HVAC) system was noted, such as equipment model, operational mode, air filter rating and conditions, and maintenance schedule. In addition, general information on merchandise types, building materials, store layout, and store activities (e.g., cooking and cleaning) that might be sources of indoor contaminants were also recorded.

The experimental setup in each store is similar. Indoor samples of multiple contaminants were collected from a central location on the sales floor. In larger stores, this is supplemented by two to three additional locations on the sales floor where additional VOC samples were collected. Outdoor samples were collected near the main point of entry of outside air. For the mechanically ventilated stores, the outdoor location was near the rooftop air intake. For stores that are naturally ventilated, outdoor sampling was conducted near the store front door that are typically opened. In addition to the sampling of VOCs, other pollutants and indoor environmental metrics are monitored in real-time, including particulate matter (PM), ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), temperature, and relative humidity.

2.1 Ventilation Rate

Store ventilation rate was measured using a tracer gas decay method. SF_6 was released in the store, or was injected into the air-handlers, in the early afternoon. Up to four Miran SapphIRe® Model 250B infrared gas analyzers were placed at various locations to monitor the tracer concentrations in real time. Different amount of tracer gas was released on the sales floor depending on the store size to achieve an initial concentration of about 1,000 ppm. In the mechanically ventilation stores, contractions typically become well-mixed in about 30 minutes. This is determined by multiple Miran analyzers reading within 10% of one another. In larger stores (floor area ~1,000 m^2 and greater) that are naturally ventilated, a fan was used to help with mixing of the tracer gas. Air-exchange rate was computed from curve fitting to the exponential decay in SF_6 concentrations. Indoor areas other than the sales floor were excluded in our study space, such as offices, employee breakrooms, and warehouse area. Besides the Miran analyzers, grab samples of SF_6 were also collected in polyethylene-lined multi-layer sample bags at a few locations inside the store. About ten samples were collected over one hour to obtain a range of SF_6 concentrations for comparison with the real-time data. Bag samples were analysed by gas chromatograph equipped with an electron capture detector. Concentrations from the bag samples were compared with Miran measurements as a data check. Some bag samples were also collected at locations outside the sales floor to see if there was air exchange between these spaces.

2.2 Volatile Organic Compounds

VOCs were collected using multi-bed Carbopack X® and Carbopack B® sorbent tubes. One-hour samples were collected in the afternoon at one or more indoor locations, and concurrently at one outdoor location. Sample flow of 0.1 Lpm was monitored continuously using a mass flow sensor. The sample flow rates were also verified using a primary air flow calibrator (Gilibrator®) before

sampling. VOCs were qualitatively and quantitatively analyzed by thermal desorption-gas chromatography/mass spectrometry following U.S. EPA Methods TO-1 and TO-17. Multi-point internal standard calibrations were performed using pure compounds and 1-bromo-3-fluorobenzene as the reference compound. A duplicate set of samples was collected for each sample. The VOC concentrations presented here, including formaldehyde and acrolein that were sampled using a different method as described below, are the averaged values from two co-located sample duplicates.

Volatile carbonyl samples were collected using dinitrophenyl hydrazine (DNPH)-coated cartridges (Waters Sep-Pak®). Ambient ozone was removed with potassium iodide scrubbers preceding each DNPH sampler. One-hour samples were collected at the same indoor and outdoor locations at 1 Lpm. DNPH cartridges were extracted with 2-mL aliquots of acetonitrile, and the extracts were analyzed by HPLC with UV detection at λ_{max} = 360 nm (Agilent 1200). A calibration curve for quantification was carried out using authentic standards of the formaldehyde-DNPH hydrazone.

In addition, we collected acrolein samples using pentafluorophenyl hydrazine (PFPH)-coated cartridges that were prepared in our laboratory. This derivatization method is based on Ho and Yu (2004). Silica cartridges were cleaned by passing 2 mL of acetonitrile solution and then air-dried. One mL of 0.125 mg/mL PFPH solution was passed through the cartridge using a syringe, and the excess was removed from the cartridge using a constant stream of helium for five minutes. We are still in the process of refining this recently-developed acrolein method for field sampling, therefore the results presented here are preliminary. We prepared acrolein standards to obtain calibration curves prior to each analysis. The limit of detection was 0.2 ng/m^3 (~0.1 ppt) for one-hour samples. Following the initial two stores (G1 and G2), sampling duration was increased to two hours, so the limit of detection was lowered to approximately 0.05 ppt. Breakthrough was estimated to occur at ~0.02 mg.

2.3 Particulate Matter

Particle counts and mass concentrations were measured at the same central indoor location and also outdoors as the VOC samplers. Real-time particle counts was monitored for six to eight hours using MetOne® Optical Particle Counter Model BT-637 in six channels: >0.3, >0.5, >0.7, >1, >2, and >5 μm. This instrument has a counting efficiency of about 50% for 0.3 μm particles, so particle counts in the first channel are uncertain.

Particle mass was collected onto polytetrafluoroethylene (PTFE) membrane filters, which were measured gravimetrically in a temperature and relative humidity controlled enclosure. PM2.5 and PM10 samples were collected using SKC Personal Environment Monitors at 10 Lpm for approximately 6 hours. Two field blanks were collected on each sampling day. Measurement error is 1 μg, or approximately 0.3 μg/m^3 for a 6-hour sample.

Ultrafine particle (UFP) counts were measured at the central indoor location and also outdoor using a water-based condensation particle counter (TSI® WCPC). The WCPC counts particles >6 nm. The sample inlet has a cyclone with a cut-off diameter of 3 μm. UFP counts were recorded at one-minute time interval.

2.4 Ozone

Concentrations of O_3 were monitored using real-time gas analyzers (2BTech® Model 205) at the central indoor location and also outdoors. The gas analyzers were checked to make sure that the indoor and outdoor units agreed with one another before and after sampling. Zero-offset of the instruments were determined in the laboratory by sampling with an O_3 scrubber attached to the sample inlet. The offset values, which range between 5 to >1 ppb, were subtracted from the field data.

2.5 Carbon Dioxide and Carbon Monoxide

CO_2 and CO were measured at the central indoor location and also outdoor using real-time gas analyzer. The EGM-4 is a high precision CO_2 analyzer used to record concentrations at one-minute time interval. The Langan T15n CO sensor has reporting limit of 0.1 ppm. CO concentrations found in retail stores were often at or below the reporting limit.

2.6 Temperature and Relative Humidity

The indoor air temperature and relative humidity were monitored at multiple locations within the stores using HOBO temperature/relative humidity data logger. The data loggers used also function as storage devices for sample flows and concentration measurements from other instruments. The outdoor air temperature and relative humidity were recorded by a HOBO that is co-located with the suite of outdoor sampling instruments.

3 Results

Nine retail stores located in various California cities were sampled (Table 1). Most of the stores were opened or last renovated within the past 15 years. With the exception of F1 and F2, all the stores had rooftop units to condition the indoor spaces. However, smaller stores, such as F3, A1, and A2, preferred to rely on natural ventilation for most of the year. On the sampling days, these stores operated as usual i.e., the data for stores F1–F3 and A1–A2 were collected when they were naturally ventilated. In store A1, ventilation rates were measured twice, first with the front door opened and HVAC off. During this operate-as-usual period, contaminant concentrations in A1 were measured. Following this, the ventilation rate was measured again with HVAC on and the front door closed. Four of the five stores where it was possible to determine the filter efficiency used MERV 8 rated air filters (Table 1).

Field sampling of the nine stores were conducted in September 2011 through May 2012. Grocery stores tend to be the largest in floor area and also with the most number of occupants. Apparel stores tend to be the smallest, but the least number of occupants were observed in furniture stores. All stores were sampled during weekdays, typically between 10 am and 5 pm.

Table 1 Building characteristics of nine retail stores.

	City	Store Open/Last Major Renovation	Sample Date	Floor Area (m^2)	Ceiling Height (m)	Max # People in Store	Ventilation	Air Filter MERVE Rating
Grocery								
G1	Berkeley	2009	2011/9/27–28	3,270	7.5	260	Mech.	15
G2	Walnut Creek	2001	2011/10/6–7	1,840	6.8	180	Mech.	8
G3	Tarzana	2010	2012/5/14	3,310	10.4	120	Mech.	8
Furniture								
F1	San Francisco	2009	2011/10/24–25	640	4.0	5	Nat.	N/A
F2	Oakland	2004	2011/11/1	1,530	6.0	10	Nat.	N/A
F3	Berkeley	1995	2011/11/2	680	4.0	8	Nat.	N/A
Apparel								
A1	Oakland	1997	2012/2/21	120	3.1	10	Nat./Mech.	8
A2	Oakland	2011	2012/2/22	80	3.4	5	Nat.	N/A
A3	San Mateo	2011	2012/2/28	1,070	9.3	25	Mech.	8

3.1 Ventilation Rate

Figure 1 shows the air-exchange rates of the nine retail stores estimated from the SF_6 decay method. In most cases, results from the different Miran analyzers agreed with one another within about 10%. The estimated air-exchange rates on two days were within 10% for the two mechanically ventilated stores G1 and G2. For store F1, which was naturally ventilated, the difference between the two days was 20%. Overall, naturally ventilated stores had higher air-exchange rates (average from five stores = 2 h^{-1}) than mechanically ventilation stores (average from five stores = 1 h^{-1}). Note that store A1 is counted twice, once as a naturally ventilated store, and also as a mechanical ventilated store with the HVAC on. In store A1, the ventilation rate with HVAC off and front door opened was substantially higher than with HVAC on and front door closed. In this store, employees indicated that they preferred more outside air being moved through the store with the front door opened, so the HVAC is rarely used unless the indoor temperature becomes too uncomfortable.

Substantial spatial and temporal differences in air-exchange rates were observed in some of the naturally ventilated stores. For example, the three Miran analyzers in store F3 agreed initially by using a fan to obtain a uniform SF_6 concentration. But once the fan was turned off, SF_6 concentrations varied in different parts of the store as a result of poor mixing of the indoor air. In store A2, air-exchange rate varied substantially during the day between 1 and 4 h^{-1}. The air-exchange rates shown in Figure 1 are the averages estimated from multiple curve fittings to portions of SF_6 during which the decay rates were roughly linear on log-scale.

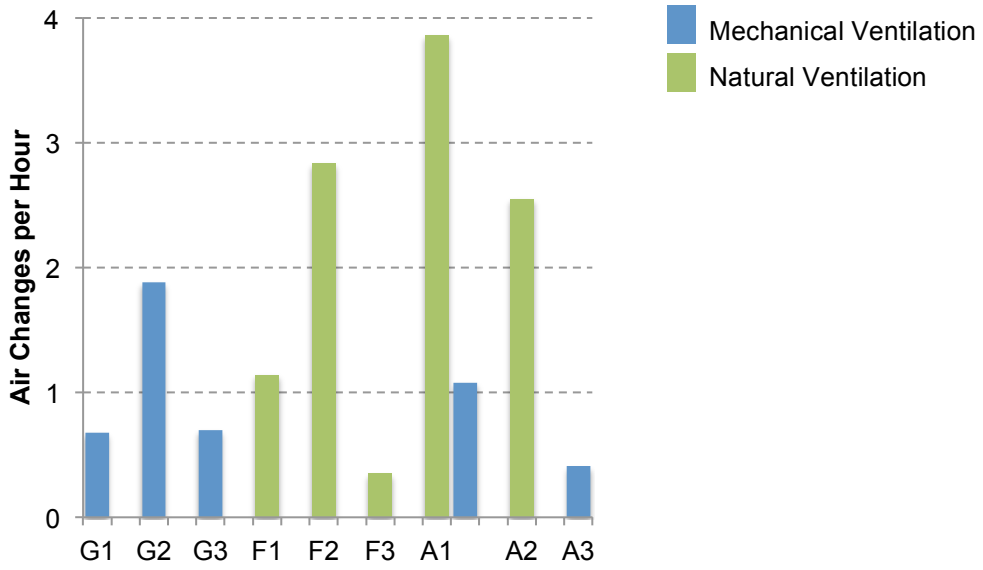

Figure 1 Air-exchange rates estimated from SF_6 decay in nine retail stores.

Relative to California's Title 24 standards, all stores met the minimum ventilation rate on a per person basis (7 L/s-person, see Figure 2a). Furniture stores that generally had fewer occupants had the highest ventilation rate estimates on a per person basis. Estimates for the other two store types appear to have similar ventilation rates on a per person basis (~35 L/s-person). However, store employees indicated that number of customers can increase by five-folds on weekends and holidays in apparel stores. In grocery stores, the number of customers can increase by a factor of two or three in the evenings and on weekends. This would imply a ventilation rate near the minimum requirements during busy hours.

All stores met the per floor area requirement of 1 L/s-m^2 (Figure 2b), with the exception of F3. F3 had low ventilation rate because its front door was closed on the day of sampling, and there was no other openings that would allow outdoor air to enter the store. G2 had the highest VR on a per floor area basis among the mechanically ventilated stores. On the days of sampling at G2, the average outdoor temperature was 13 ^{o}C on day 1 (9–17 ^{o}C), and 16 ^{o}C on day 2 (8–23 ^{o}C). At these temperature ranges, buildings equipped with economizers would bring in outside air at higher rates to cool the store. However, the outside air damper positions at G2 suggest that the store was not operating in economizer mode.

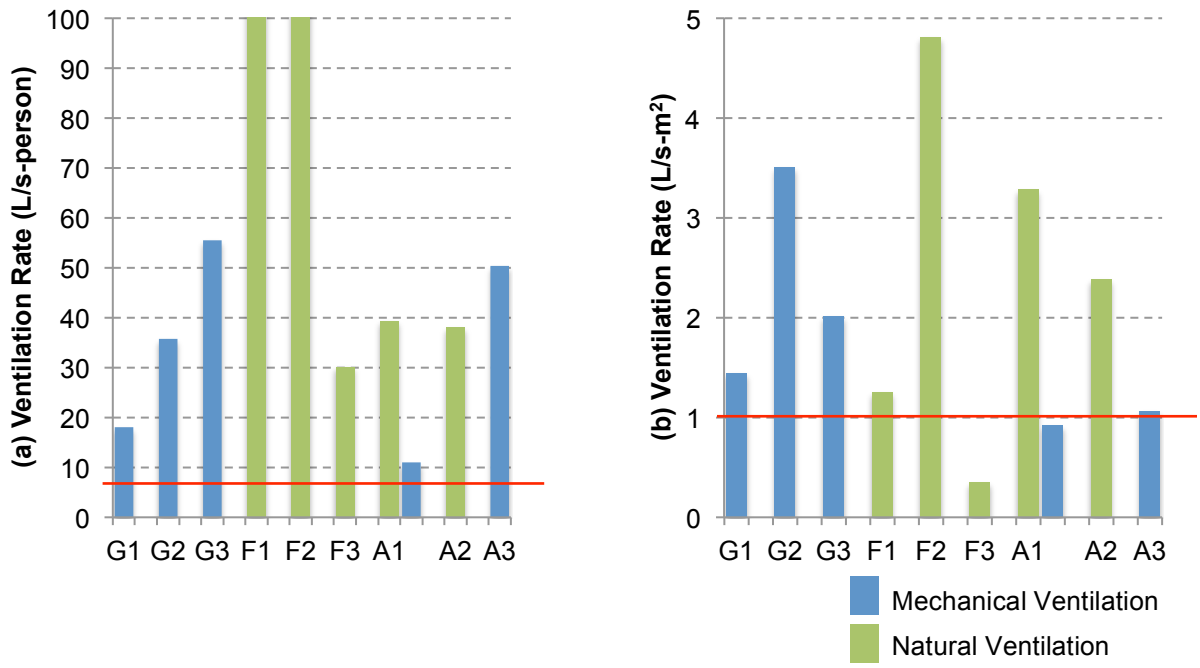

Figure 2 Ventilation rates estimated for nine retail stores on (a) per person and (b) per floor area basis. The red lines indicate California's Title 24 standards. Note: estimates for F1 and F2 >100 L/s-person.

3.2 Volatile Organic Compounds

Indoor concentrations of formaldehyde, acetaldehyde, and acrolein exceeded the most stringent health guideline levels in some of the stores. The chronic health guidelines for these three compounds are 7.3 ppb for formaldehyde[1] (OEHHA risk-based reference exposure levels), 5.0 ppb for acetaldehyde[2] and 0.009 ppb for acrolein[3] (U.S. EPA IRIS reference inhalation concentrations). Figure 3 shows that the highest formaldehyde concentration of ~45 ppb was found in a recently renovated apparel store A2. Store A3 is a larger retail store that was also renovated within the past year. This store belongs to a nationwide chain that considers low emission materials in their choice of interior furnishing and display. As a result, source control is a likely explanation for the low formaldehyde concentration (~7 ppb) found in store A3.

In January 2009, the first formaldehyde emission standards from composite wood products were implemented in California (Phase I, CARB 2012). Since then, the emission standards have been lowered to more stringent levels (Phase II). Phase I and II compliance labels were found on merchandise in the furniture stores that were sampled. Store employees commented that furniture typically stay in the showroom for a few months. Therefore, the relatively low formaldehyde concentrations found in furniture stores (~17 ppb) are evident of the effectiveness of the emission standards.

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[1] Other formaldehyde health guideline levels: NIOSH recommended exposure limit = 16 ppb, WHO guideline for indoor air quality = 100 ppb.
[2] OEHHA chronic reference exposure level for acetaldehyde is 80 ppb.
[3] OEHHA chronic reference exposure level for acrolein is 0.03 ppb.

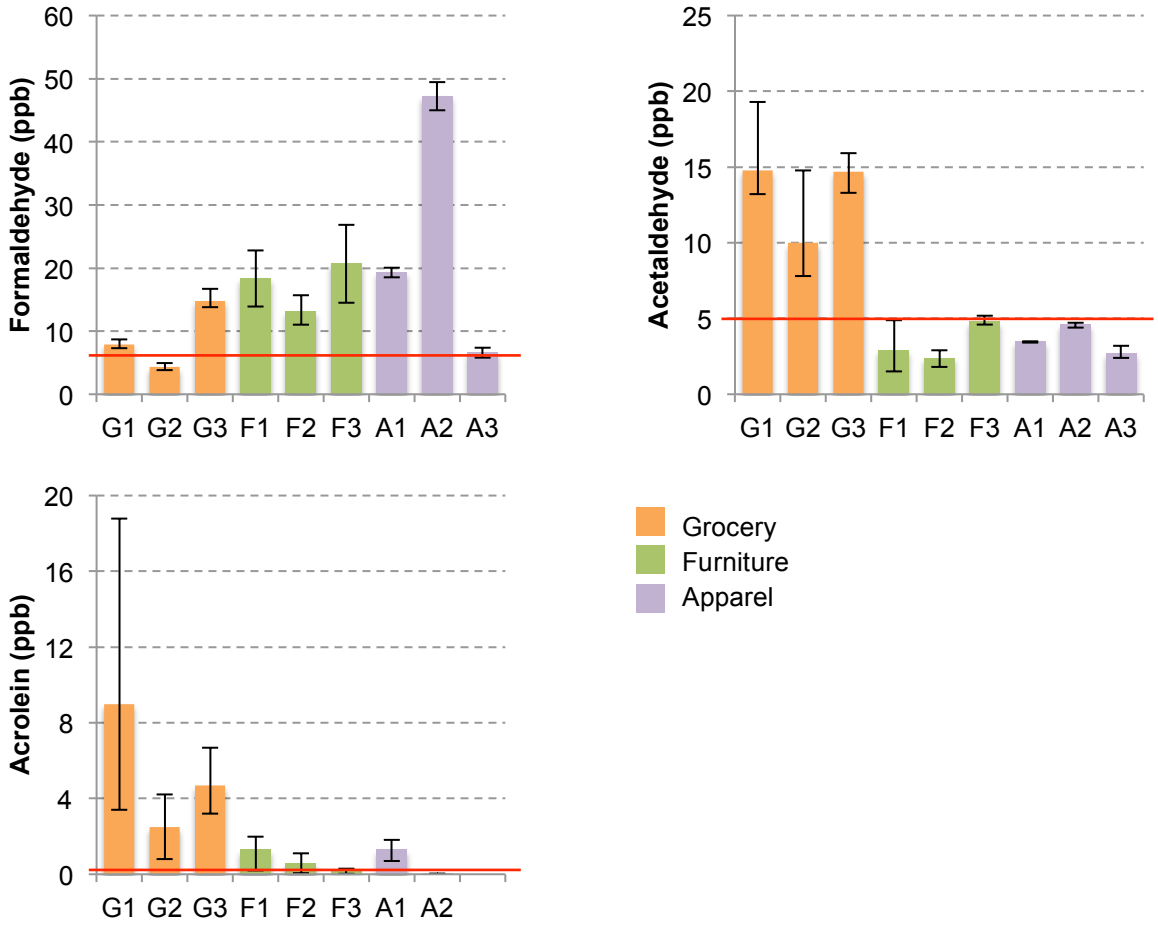

Figure 3 Store average indoor concentrations of formaldehyde, acetaldehyde, and acrolein measured in nine retail buildings. Error bars indicate range of concentrations measured. The red lines indicate the most stringent health guideline levels.

Acetaldehyde concentrations in grocery stores are higher than in other store types likely because of baking (Loh et al. 2006). Acetaldehyde can also be emitted from building materials. However, Figure 3 shows that the acetaldehyde concentrations in furniture and apparel stores are lower in comparison with grocery stores. This suggests that indoor sources associated with grocery stores, such as from baking, likely dominate over sources related to building materials that are more ubiquitous in all buildings.

Acrolein can be of health concerns at very low concentrations. Unfortunately, acrolein is difficult to measure because it is highly reactive. Previous field measurements attempted to measure acrolein concentrations in outdoor and indoor air thus far likely underestimated the concentrations because of losses in the sampling method (Ho and Yu, 2004). To address the need to quantify the concentrations of acrolein in retail stores, we adopted a derivatization method by Ho and Yu (2004) to yield a stable compound that does not decompose after sampling. Figure 3 shows the acrolein concentrations sampled using PFPH cartridges that were prepared in our laboratory. Preliminary results indicate acrolein concentrations on the order of 1 to 10 ppb in grocery stores, and 0.1 to 1 ppb in other stores. Seaman et al. (2007) found 3 ppb of acrolein on average in indoor air of residences using a mist chambers method. The study found that increases

in acrolein concentrations were correlated with air temperature and cooking events. There was also indication of off-gassing and/or secondary formation of acrolein from sampling conducted in newly built, uninhabited homes. In a related study by Seaman et al. (2009), deep-frying resulted in high concentrations of acrolein in the range of 11–28 ppb measured a short distance away (6 m) from the source.

VOCs sampled by sorbent tubes were low (~1 ppb or less). The most commonly measured compounds with indoor concentration >1 ppb are hexanal (concentrations in nine stores range 0.2–5.3 ppb), d-limonene (0.1–5.1 ppb), and toluene (0.4–2.8 ppb). Outdoor concentrations of the first three compounds were low (~0.1 ppb or less), but toluene had indoor concentrations similar the outdoor air (0.1–2.1 ppb), indicating the source of toluene found indoors was likely from outdoor air.

3.3 Particulate Matter

Particle mass concentrations measured gravimetrically are shown in Figure 4. All stores met the 24-hour air quality standards for PM2.5 (U.S. EPA national ambient air quality standard = 35 $\mu g/m^3$) and PM10 (California ambient air quality standard = 50 $\mu g/m^3$). In stores that were either naturally ventilated (F1–F3 and A1–A2), or did not have significant indoor PM source (A3), the indoor-outdoor ratios are nearly one (Table 2). Data presented in Figure 4 suggest the presence of indoor particle sources in grocery stores. G2 and G3 both used MERV 8 air filters. In those two stores, the mass concentrations of PM2.5, and PM10 to a somewhat lesser extent, were higher indoors and outdoors. G1 used air filters that had a much higher efficiency rating (MERV 15) than in G2 and G3. This likely explains why fewer particles were measured indoors than outdoors in G1.

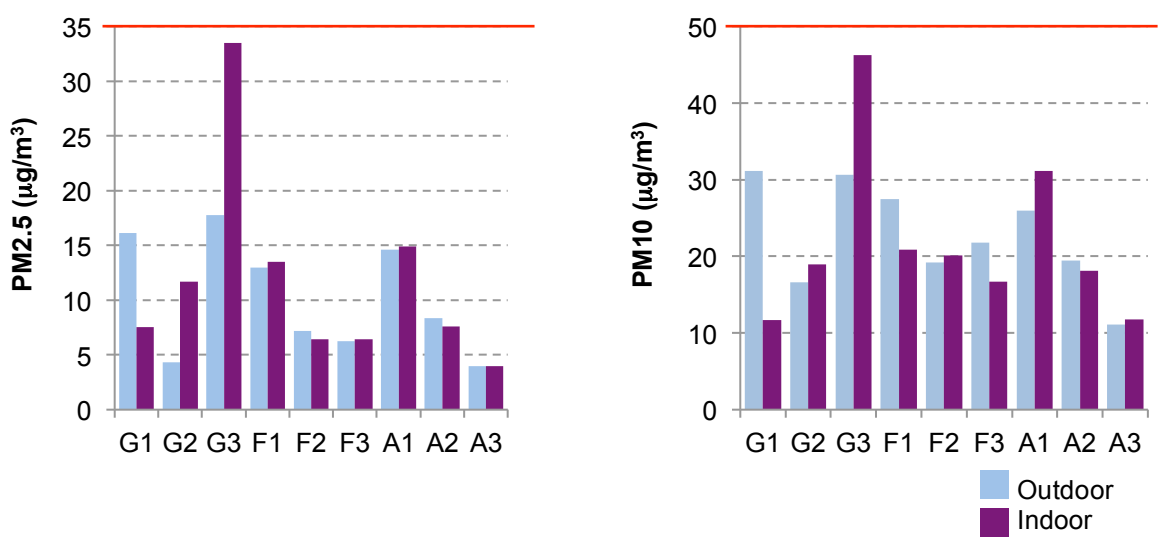

Figure 4 Particle mass concentrations of PM2.5 and PM10 measured outdoors and indoors in nine retail stores. The red lines indicate the 24-hour air quality standards.

Table 2 Indoor-outdoor ratios of the mass concentrations of PM2.5 and PM10.

	PM2.5 Indoor-Outdoor Ratio	PM10 Indoor-Outdoor Ratio
G1 (MERV 15 air filters)	0.5	0.4
G2 (MERV 8)	2.7	1.1
G3 (MERV 8)	1.9	1.5
All Others (F1–A3)	1.0 (0.9–1.0)	1.0 (0.8–1.2)

Differences between G1 and the other two grocery stores (G2 and G3) were also evident from particle count measurements. Figure 5 shows that the indoor-outdoor ratio of ultrafine and fine PM <0.5 μm exceeded 1 in grocery stores G2 and G3, but not in G1. The highest indoor-outdoor ratios were estimated for PM in the 0.3–0.5 μm size range in G2 and G3. This is partly because air filters are less effective at capturing particles that are ~0.3 μm, relative to other particle sizes. Stores that relied on natural ventilation had indoor-outdoor ratio of particle counts ~1 for all particle sizes.

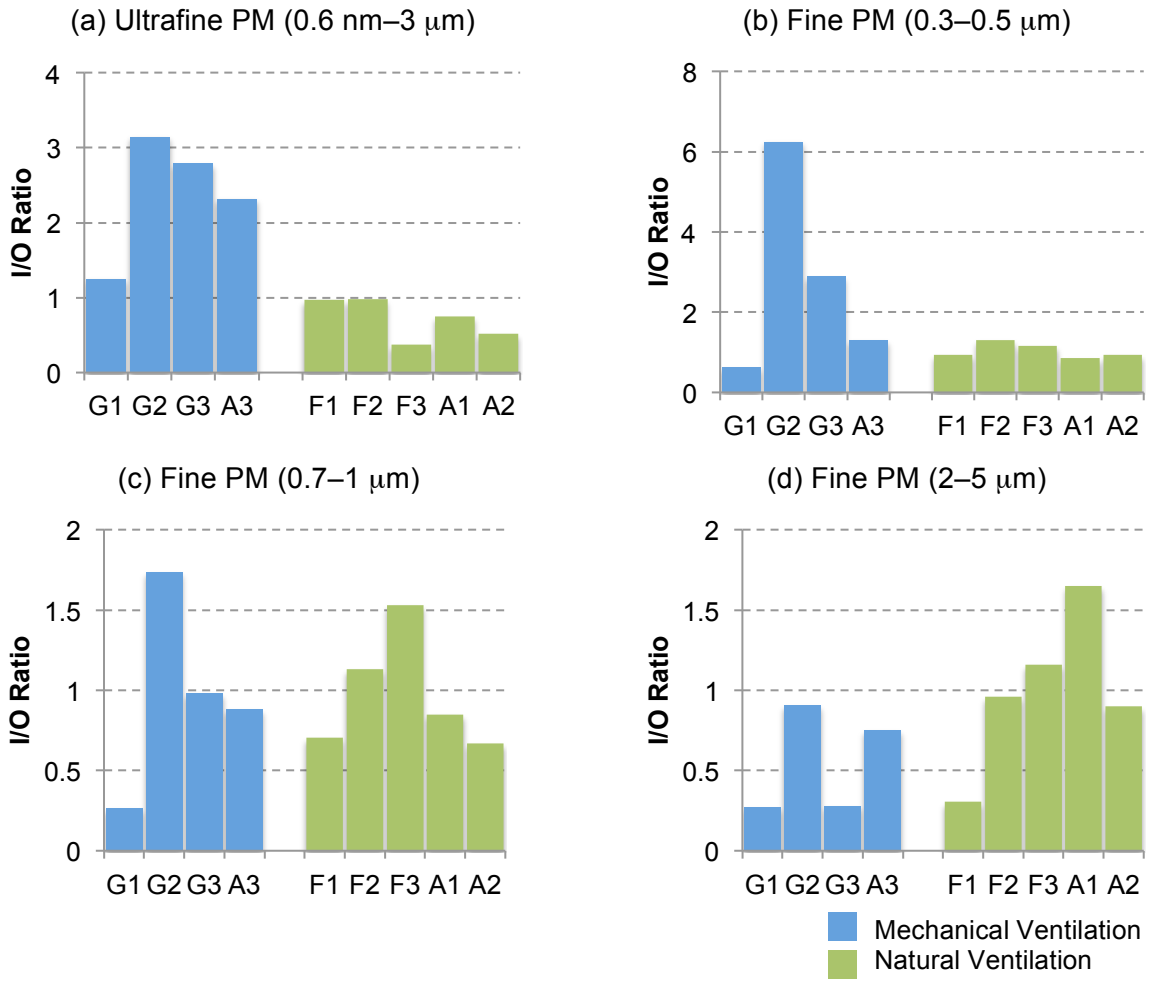

Figure 5 Indoor-outdoor ratio of particle counts measured by two instruments: (a) WCPC and (b–d) six-channel optical counter.

3.4 Ozone

Figure 6 shows the outdoor and indoor O_3 concentrations measured in four stores. The indoor-outdoor ratio was calculated from the one-hour peak concentrations, as indicated in Figure 6. The average O_3 concentrations averaged over the entire sampling period would give roughly the same indoor-outdoor ratios as they are calculated from one-hour peak concentrations. The indoor-outdoor ratio is about 0.4 for both G2 and G3. This is despite the fact that G2 had an air-exchange rate of 1.9 h^{-1}, which is more than twice the rate of 0.7 h^{-1} estimated for G3. An indoor-outdoor ratio that is less than one implies that there are losses of O_3, such as when the outside air passes through air filters and other components of the HVAC (Zhao et al. 2007). In addition, there are other important factors that can influence the ozone concentration indoors (Weschler, 2000), e.g., surface removal rates and reactions between ozone and other chemicals in the air. For the two naturally ventilated stores captured in Figure 6, the indoor-outdoor ratios are 0.3 in F1 and 0.8 in F2. Between these two stores, F2 had an indoor-outdoor ratio closer to one likely because of the higher air-exchange rate of 2.8 h^{-1}, in comparison to the rate of 1.1 h^{-1} in F1.

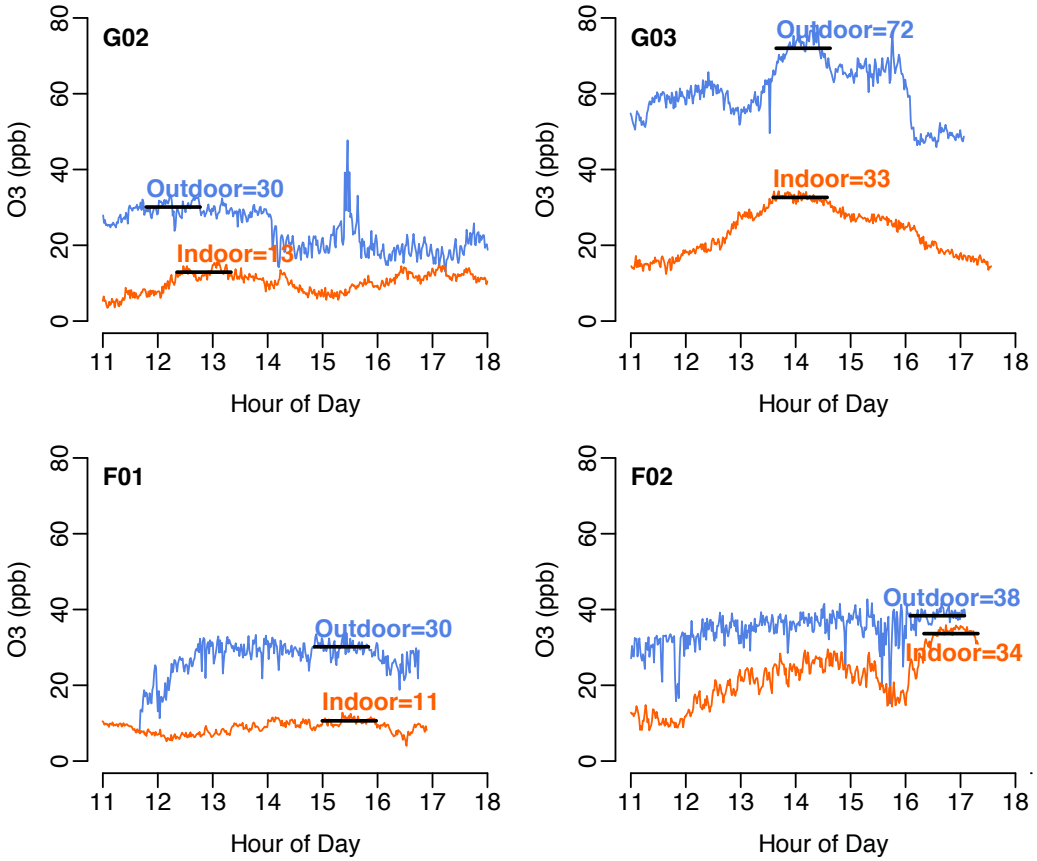

Figure 6 Outdoor and indoor ozone concentrations measured in four retail stores. The 1-hour peak concentrations are indicated.

3.5 Contaminant Source Strength

For setting health-protective ventilation standards, it is necessary to (1) identify contaminants that are of concern and also are appropriate to control using ventilation, (2) characterize the

source strengths of these COCs in different retail trade types, and (3) determine the required VRs that would satisfy both the health and odor criteria for store workers and customers. Whole-building source strengths are calculated as follows:

$$E\left(\frac{\mathrm{g}}{\mathrm{h}\cdot\mathrm{m}^2}\right)=\frac{\left[C_{in}-C_{out}\right]\left(\frac{\mathrm{g}}{\mathrm{m}^3}\right)\times V\left(\frac{\mathrm{m}^3}{\mathrm{h}}\right)}{A\left(\mathrm{m}^2\right)}$$

where E is the emission rate per floor area, C_{in} and C_{out} are the indoor and outdoor concentrations, V is the building volume, and A is the floor area. This equation assumes all parameters are constant, concentrations within the store are well-mixed, and the system has reached steady state. The equation also assumes negligible removal rates of VOCs via other mechanisms, e.g., surface removal, chemical reactions with indoor air pollutants, relative to ventilation. SF_6 decay measurements suggest that the ventilation rates in stores tend to stay the same throughout the day, particular in mechanically ventilated stores. There were some spatial variability in C_{in}, but they appear to be minor. Indoor formaldehyde concentrations, for example, show a coefficient of variance (standard deviation divided by mean) of 0.13 in seven stores where samples were collected from three or more indoor locations. In stores that were sampled on two consecutive days, the day-to-day differences also appear to be minor. For example, the percentage difference between the average formaldehyde concentration measured on the first and second day was 7% in three stores that were sampled for two days. Most stores turned off their ventilation system at least partially during off-hour. It would take several hours, depending on the air-exchange rate, for contaminants to reach a stable level after the store opens. Typically, we collected VOC samples in the afternoon to allow time for this to happen.

Source strength estimates of formaldehyde, acetaldehyde, and acrolein are shown in Figure 7. The highest source strength was estimated from a store that was renovated within the past year. Its estimated emission rate exceeded the maximum value of 0.39 mg/h-m^2 measured in 37 small and medium size commercial buildings in California (Wu et al. 2011). All other stores had source strengths that were substantially lower. For example, A3 was also renovated within the past year, but where low emission materials were reportedly used. The formaldehyde source strength estimated for A3 is 0.024 mg/h-m^2, which roughly equals the geometric mean of formaldehyde emission rates (0.025 mg/h-m^2) measured by Wu et al. (2011).

Grocery stores that were sampled clearly had sources of acetaldehyde and acrolein. The source strengths of these contaminants are many times higher in G1–G3 than in other store types (Figure 7). Wu et al. (2011) found the geometric mean of acetaldehyde emissions to equal 0.014 mg/h-m^2 from the commercial buildings sampled, including two grocery stores, seven retail stores, and other buildings such as offices, restaurants, etc. The geometric mean is roughly the same as that we estimated for the furniture and apparel stores (mean = 0.022 mg/h-m^2). In grocery stores G1–G3, however, acetaldehyde emission rates are much higher (mean = 0.16 mg/h-m^2), likely because of indoor sources, such as emissions from baking. The emission rates estimated for grocery stores approach the maximum emission rate of 0.44 mg/h-m^2 measured by Wu et al. (2011).

Similarly, source strengths of acrolein estimated for grocery stores are many times higher than in other store types (Figure 7). Seaman et al. (2007) estimated average source strength of 0.005 mg/h-m^2 in nine residences based on measurements of acroelin concentrations collected once in the morning and once in the evening. Our estimates for grocery stores are higher by more than an order of magnitude (average = 0.08 mg/h-m^2). In other store types without cooking, the average source strength for acrolein is lower (0.01 mg/h-m^2). These results are consistent with the observations in residences (Seaman et al. 2007), where higher acorlein concentrations were measured in homes with frequent cooking, and in the evenings relative to mornings also because of cooking.

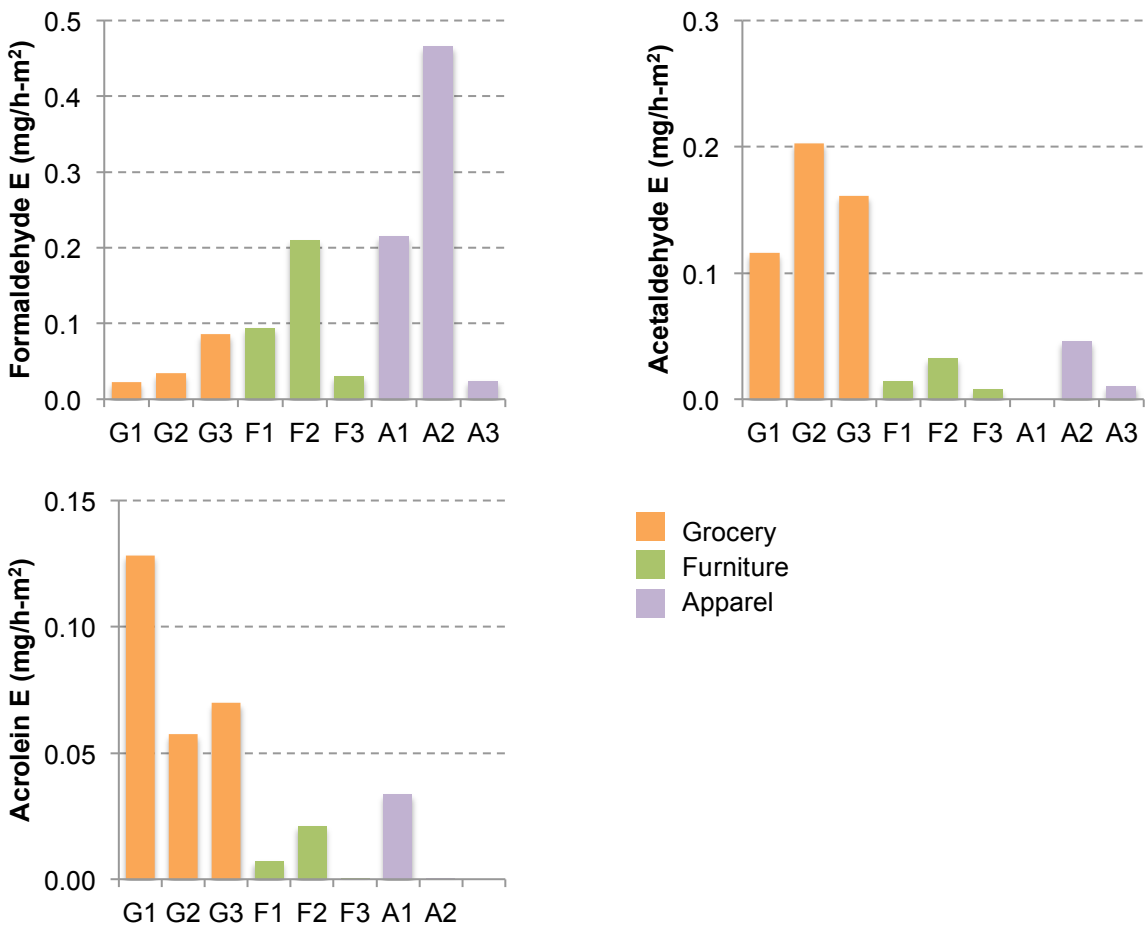

Figure 7 Source strength estimates of formaldehyde, acetaldehyde, and acrolein in nine retail stores.

4 Discussion

Nine retail stores were sampled for ventilation rates and contaminant concentrations. This preliminary analysis focuses on VOCs, and to some extent PM, because indoor sources were present in retail stores. Ventilation rate was measured using SF_6 decay method. Data show that ventilation rates in the nine retail stores that were sampled usually exceed the minimum requirement of Title 24. For stores that choose to rely on natural ventilation, air-exchange rates

tend to be higher than in stores that are mechanically ventilated. Uniform tracer gas concentration was achieved even in larger stores, making this a viable method to measure ventilation rate. However, naturally ventilated buildings had varying air-exchange rates both spatially and temporally. This introduces uncertainty to the ventilation rate estimates. Moving forward, more stores that are mechanically ventilated will be recruited for this study.

Formaldehyde, acetaldehyde, and acrolein concentrations measured in some stores exceeded the most stringent chronic health standards. Concentrations of other VOCs were substantially lower than health guidelines. VOCs with indoor concentrations commonly exceeding 1 ppb are hexanal, d-limonene, and toluene. The sampling methods for measuring VOCs using sorbent tubes and aldehyde cartridges are well established. Acrolein concentrations reported from this study are preliminary results because further method development is needed. One issue remains, for example, is high background noise possibly due to precursor contamination. The VOC concentrations collected from nine stores show within-store variations such that it is necessary to sample from multiple locations in large spaces. Small day-to-day variability was observed, but not significant enough to warrant multi-day sampling in a store. Concentrations measured on one day were reasonably representative of the store, at least in the short-term on the time scale of days.

Stores have varying levels of indoor PM relative to the outdoors. There was a general agreement between particle mass and count instruments. Substantially higher counts of PM <0.5 μm were found in grocery stores, suggesting there were indoor sources, such as from cooking. Stores that used higher efficiency air filters (MERV 15 versus 8) show lower indoor-outdoor ratio of PM both in terms of mass concentrations and counts. In naturally ventilated stores, the estimated indoor-outdoor ratios were approximately 1 for particles of all sizes.

We observed indoor-outdoor ozone ratio of about 0.4 in two mechanically ventilated stores. In two naturally ventilation stores, the indoor-outdoor ratio was also a function of the air-exchange rate: 0.3 and 0.8 in the two stores with lower and higher air-exchange rate, respectively. Both observations mean that bring in more outside air will increase the ozone concentration indoors. The increase may be proportional to the increase in air-exchange rate, but it is possible that the increase will be greater than linear.

Source strengths of formaldehyde, acetaldehyde, and acrolein were computed and normalized to the store floor area. Certain characteristics emerged that differ by store types. For example, the source strengths of acetaldehyde and acrolein in grocery stores are much higher than in furniture and apparel stores. Source strengths of formaldehyde appear to be quite variable from store to store. Future analysis of source strengths may include other VOCs that have significant indoor sources. Such analysis is necessary for setting health-protective VR standards. It will also inform if there is a need for Title 24 standards to consider store types more explicitly in setting VR standards.

The analysis presented in this interim report is not all comprehensive of the data that was collected. The discussion on CO and CO_2 is brief, but their concentrations tend to be low, the later because field sampling was conducted during off-peak hours. Air temperature and relative humidity data will be analyzed and compared with comfort and other relevant guidelines. In

addition, we recognize that only a fraction of the total VOCs mass concentrations in the indoor air are considered in this study. If resources permit, re-analysis of the chromatographs of VOCs samples will be performed. This will allow us to identify 250+ compounds that have indoor concentrations higher than the outdoors. The identification of these little-studied contaminants in the indoor environment can serve as an example of how Title 24 might consider emerging contaminants in future revision of the standard.

5 Ongoing Work

We plan to recruit in total seven to nine stores in each of the three types of retail. Twelve stores had been sampled so far, with the majority of them in the Bay Area, and three in South Coast. The furniture store category has been expanded to also include home improvement/hardware stores. Our future recruitment effort will focus on Central Valley and South Coast, and in larger stores that rely more exclusively on mechanical ventilation system. Our data will include some seasonal variability by conducting field sampling throughout the year. The sampling approach used is well established, so no major change is anticipated. Field sampling is expected to continue through March 2013.

Findings from this study will enable an improved assessment of the minimum ventilation requirements necessary to protect human health in the retail stores. Measurements of VR will be compared with the current minimum rate requirement. This study will generate concentration and source strength data on contaminants commonly found in retail buildings. Data collected will inform if there are contaminants that are common to many retail stores, or if there are significant differences that justify minimum VR requirement that differ by store type. This information is necessary for setting VR requirements for retail stores in California. Moreover, the data collected will be useful for modeling the fate and transport of pollutants in the indoor air. This information will help predict qualitatively the potential effect of changing building VRs on indoor air chemistry and pollutant concentrations in the retail stores.

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