

Effect of outside air ventilation rate on volatile organic compound concentrations in a call center

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Abstract

A study of the relationship between outside air ventilation rate and concentrations of volatile organic compounds (VOCs) generated indoors was conducted in a call center office building.

The building, with two floors and a floor area of 4,600 m², was located in the San Francisco Bay

Area, CA. Ventilation rates were manipulated with the building's four air handling units

(AHUs). VOC concentrations in the AHU returns were measured on seven days during a 13-

week period. VOC emission factors were determined for individual zones on days when they

were operating at near steady-state conditions. The emission factor data were subjected to

principal component (PC) analysis to identify groups of co-varying compounds. Potential

sources of the PC vectors were ascribed based on information from the literature supporting the

associations. Two vectors with high loadings of compounds including formaldehyde, 2,2,4-

trimethyl-1,3-pentanediol monoisobutyrate, decamethylcyclopentasiloxane (d5 siloxane), and

isoprene likely identified occupant-related sources. One vector likely represented emissions

from building materials. Another vector represented emissions of solvents from cleaning

products. The relationships between indoor minus outdoor VOC concentrations and ventilation

rate were qualitatively examined for eight VOCs. Of these, acetaldehyde and hexanal, which

were likely associated with material sources, and d5 siloxane exhibited general trends of higher

concentrations at lower ventilation rates. For other compounds, the operation of the building and variations in pollutant generation and removal rates apparently combined to obscure the inverse relationship between VOC concentrations and ventilation. This result emphasizes the importance of utilizing source control measures, in addition to adequate ventilation, to limit concentrations of VOCs of concern in office buildings.

Key word index: Indoor air quality, Office building, VOC emission rates, Formaldehyde,
Principal component analysis

Introduction

Ventilation defined as the delivery of outdoor air (OA) to occupied spaces occurs in most large commercial buildings through integrated mechanical systems, also providing heating and cooling. Contributions of infiltration of OA through the building envelope are relatively small. In office buildings, mechanical systems are designed to provide a specific flow rate of OA per occupant. The importance of providing adequate ventilation in office buildings is supported by studies that have investigated the association of ventilation rates or carbon dioxide concentrations with occupant responses as reviewed and assessed by Seppänen *et al.* (1999). The human outcomes typically were the prevalence of sick building syndrome symptoms or perceived air quality problems ascertained by self-administered questionnaires. Many of the studies found that ventilation rates below 10 L s^{-1} per person were associated with one or more adverse outcomes. Ventilation rate increases above this rate were found in some studies to decrease symptom prevalence or improve perceptions. Since ventilation does not directly affect occupant health or perception, the associations were presumably due to improvements in environmental conditions such as reductions in the concentrations of airborne gas- and particle-

phase contaminants (*ibid.*). Among these, considerable attention has been directed toward volatile organic compounds (VOCs), which have numerous indoor sources and the potential to affect health and comfort. This important contaminant class is the focus of this paper.

Despite a general association of occupant health and satisfaction with increased ventilation, the effectiveness of ventilation for controlling concentrations of gas-phase pollutants in office buildings remains an open question. In well-mixed spaces operating at constant conditions with respect to ventilation and pollutant parameters, the concentrations of gas-phase pollutants from indoor sources are inversely related to ventilation by steady-state mass-balance considerations. However, ideal steady-state conditions rarely may prevail in real occupied buildings. In addition, the relationship between ventilation and gas-phase concentrations likely is complicated by other building- and pollutant-related factors. The importance of such factors was addressed by the study reported on here, which investigated how the concentrations of VOCs generated indoors in a single office building were affected by manipulated changes in ventilation rate. This study was conducted in conjunction with an investigation of the effects of ventilation rate on the productivity of call center workers (Fisk *et al.*, 2002).

Methods

The study was conducted in a health maintenance organization call center located in the San Francisco Bay Area, CA. The building, constructed in 1998, had two floors and a total floor area of 4,600 m². It had sealed windows and a mechanical ventilation system with air conditioning. Floors were carpeted, ceilings were open, and smoking was not allowed. The building was divided into four interior zones ranging in size from 840 to 1,460 m². Each zone was served by a roof-mounted, variable air volume, air handling unit (AHU) that modulated the supply rates of

cool or warm air to maintain indoor temperatures in the desired range (Table 1). Corridors and doorways separated the interior zones although there likely was considerable air mixing among zones. One AHU (2-2) served the entryway, staff lounge, and offices for management staff and meetings. The other AHUs served the three zones occupied by advice registered nurses (RNs) and telecommunications service representatives (TSRs). The numbers of RNs and TSRs logged into work was determined in half-hour increments. There were ~40 administrators and support staff. The workforce was predominantly female. The total occupant density during the study was approximately five persons per 100 m², although the building was designed for higher occupancy.

Each AHU had an economizer control system. Equipment was added to enable automatic manipulation and measurement of OA ventilation rates (Fisk *et al.* 2002). AHU supply flow rates were measured using arrays of pitot tubes in supply ducts, with pressure differences logged. The OA flow rate in each AHU was computed as the product of the supply air flow rate and the fraction of outside air (FOA) in this air stream. A single CO₂ monitor, calibrated weekly with multi-level gas standards, measured concentrations of CO₂ on a 7.2 minute cycle in OA, the return air streams, and the supply air streams. The FOA was calculated by simple mass balance.

The dampers in AHU 2-2 were fixed in one position. For the three AHUs serving zones occupied by RNs and TSRs (1-1, 2-1 and 2-3), three fixed damper positions were selected to provide periods of low, medium, and high ventilation rates. The damper positions for the low period were set at positions intended to provide near the code-minimum OA supply rate of 76 L s⁻¹/100 m². The damper positions for medium and high periods were set to provide approximately 2- and 4-times the code minimum. In a fourth ventilation setting, the normal control systems for the OA supplies, including the outside air economizers, were activated.

Using these methods, periods of ventilation were scheduled over 13 weeks (July 28 through October 24, 2000) in one of four modes: low, medium, high, and economizer mode. In weeks 3-6, 9 and 10, the rates were randomized and changed daily. The rates were generally fixed at one setting throughout each of the other weeks.

Sampling for VOCs and aldehydes was conducted on weeks 2, 3, 6-8, 11 and 13. Air samples were collected simultaneously from the return air ducts of the four AHUs and OA on Tuesdays. Sampling began at 10:00 and ended at 15:00 to encompass the period of maximum occupancy.

Air samples for VOCs were collected on Tenax-TA™ sorbent tubes (P/N CP-16251; Varian, Inc.) modified by substituting a 15-mm section of Carbosieve S-III 60/80 mesh (P/N 10184, Supelco Inc) at the outlet end. Air was pulled through the sorbent tubes using peristaltic pumps actuated by timers. Pump flow rates, measured near the beginning and end of each sampling period, were $\sim 5 \text{ mL min}^{-1}$ yielding sample volumes of $\sim 1.5 \text{ L}$. Each sample was collected in duplicate. Field blanks were obtained weekly. These samples were quantitatively analyzed for individual VOCs by thermal desorption-gas chromatography/mass spectrometry (U.S. EPA, 1984). Samples were thermally desorbed and concentrated on a cryogenic inletting system (Model CP-4020 TCT; Varian, Inc.). Desorption temperature was set to $235 \text{ }^\circ\text{C}$ for 6.5 min. The cryogenic trap was held at $-100 \text{ }^\circ\text{C}$ and then heated to $235 \text{ }^\circ\text{C}$ for injection. Multi-point calibrations were referenced to 1-bromo-4-fluorobenzene as an internal standard. There were 62 target compounds spanning broad ranges of volatility and chemical functionality.

Air samples for formaldehyde and acetaldehyde were collected onto treated silica-gel cartridges (P/N WAT047205, Waters Corp.) using separate peristaltic pumps. Sampling flow rates were $\sim 150 \text{ mL min}^{-1}$ yielding sample volumes of $\sim 45 \text{ L}$. Each cartridge was extracted with

2 mL of acetonitrile. Extracts were analyzed by high-performance liquid chromatography with a diode array detector at a wavelength of 365 nm (ASTM, 1997a). Extract concentrations were determined from multi-point calibrations of external standard mixtures.

Concentrations of individual VOCs and aldehydes (ppb; 298° K, 101 kPa) and CO₂ (ppm), averaged over the 5-h sampling interval, were determined for OA and the return air of the four AHUs on each day of sampling. Emission rates (mg h⁻¹) were derived by the steady-state form of the mass-balance model for continuously stirred tank reactors using the indoor minus outdoor (In-Out) concentrations and the OA flow rates in each AHU (ASTM, 1997b). Losses of compounds due to factors other than ventilation (*e.g.*, as the result of sink effects) were ignored; thus, the computed values were net rates. Emission factors (μg m⁻² h⁻¹) were calculated using the floor areas of the zones. Seven of the 28 samples were excluded from this analysis because the interval between the change in airflow rate and the initiation of sampling was insufficiently long to establish near steady-state conditions.

The emission factors of predominant, indoor-derived VOCs in samples collected at steady state were analyzed by principal component (PC) analysis as a means to categorize and identify emission sources. PC analysis is a multivariate statistical tool for reducing the dimensionality of a data set consisting of a number of interrelated variables. The technique converts highly correlated variables to a reduced number of uncorrelated vectors, which are linearized sums (PCs) of standardized individual variables (*i.e.*, normalized to mean = 0 and standard deviation = 1). It is hypothesized that correlated compounds will tend to group on a single PC because they have common or closely linked emission sources. Compounds originating from more than one source will be associated with more than one PC. The software was StatView for Windows (Ver. 5.0.1, SAS Institute Inc.). A cutoff criterion for correlation matrix eigenvalues of ≥1.0 was

used to determine which PCs were kept in the analysis. The varimax rotation method was employed.

Results

The total OA flow rate for the building ranged from 19,100 to 48,6000 m³ h⁻¹, a 2.5-fold difference, over the seven sampling days (Table 2). This was equivalent to a building average ventilation rate range of 1.35 to 3.4 h⁻¹. The numbers of RNs and TSRs logged into work were highest in the morning hours and typically declined towards the ends of the sampling intervals. Variations in occupancy between 8:00 and 15:00 typically were about 25% or less. The average numbers of RNs, TSRs and an assumed 40 administrative and support staff who were present in the building during the 8:00-15:00 interval ranged from 211 to 273 over the seven sampling days (Table 2). There were approximately ten fewer occupants averaged over the 5-h sampling interval on each day.

Normalized airflow rates (L s⁻¹/100 m²) for each of the AHU zone on the seven sampling days are presented in Fig. 1. By design, AHU 2-2 flow rates remained relatively constant (<25% variation). There were approximate 5-, 7- and 3-fold variations over the seven days between the low and high rates in AHUs 1-1, 2-1 and 2-3, respectively. The ventilation conditions in these three zone on the sampling days of weeks 8 and 13 were intended to approximate the code-minimum OA supply rate of 76 L s⁻¹/100 m². Conditions on the sampling days in weeks 3 and 7 were intended to be twice the minimum OA supply rate, but AHU 2-1 was operating at the lowest setting in week 3. Conditions on the sampling days in weeks 2, 6 and 11 were intended to be four times the minimum, but generally fell short of this goal.

About ten of the target VOCs were not detected in any samples and a number of other compounds, including chlorinated hydrocarbon solvents, occurred at very low concentrations. The 21 VOCs with geometric mean indoor concentrations of ~ 0.2 ppb or higher and indoor/outdoor concentration ratios predominantly above unity are listed in Table 3. They are ordered in this and subsequent tables by chemical class (*i.e.*, alcohols, ketones, aldehydes, esters, aromatic hydrocarbons, terpene hydrocarbons and misc.) and then by decreasing volatility within class. Indoor and outdoor concentrations and indoor/outdoor concentration ratios are summarized as geometric means and ranges. VOC concentrations less than lower limits of quantitation (based on a 0.5-2 ng compound-dependent instrumental limit) were averaged as one half the quantitation limit. Indoor geometric mean VOC concentrations were below 5 ppb, with the exceptions of ethanol, isopropanol, acetone, and formaldehyde. Outdoor geometric mean concentrations were below 1 ppb, with the exceptions of the same compounds plus acetaldehyde. For approximately half the reported VOCs, concentrations in the majority of outdoor samples were below quantitation limits.

Whole building net emission factors for the week 2, 6, 7 and 13 sampling days in which all samples were collected near steady-state conditions were calculated as the sums of the zonal emission rates divided by the total building area. Emission factors for 20 VOCs in $\mu\text{g m}^{-2} \text{h}^{-1}$ and CO_2 in $\text{g m}^{-2} \text{h}^{-1}$ are presented in Table 3. *m/p*-Xylene was excluded because more than one-half of its In-Out concentrations were below the limit of quantitation. The sums of the VOC emission factors on the four sampling days ranged from 1.65 to 2.7 $\text{mg m}^{-2} \text{h}^{-1}$. Much of this mass was accounted for by a few compounds including ethanol, isopropanol, acetone, decamethylcyclopentasiloxane (d5 siloxane) and, in some weeks, 2-butoxyethanol.

Zonal average emission factors were calculated as the averages of the 21 zonal measurements made near steady-state conditions. These are summarized in Table 3 as geometric mean concentrations and ranges. The individually measured CO₂ emission factors, which varied 2.3-fold, exhibited the least variability by time and zone. VOCs which varied by ~5-fold or less by time and zone, included ethanol, acetaldehyde, hexanal, isoprene, α -pinene, and d5 siloxane. Isopropanol, 2-butoxyethanol, methyl isobutyl ketone (MIBK), ethyl acetate and butyl acetate exhibited the most variability with a 25-fold or more difference between minimum and maximum values.

The results of the PC analysis of the emission factors for 16 predominant VOCs measured in the 21 samples collected at steady state are presented in Table 5. CO₂, which is solely produced from breath, was included in the analysis as an indicator of occupant related sources. Ethanol, an abundant compound, was excluded because of the relatively high uncertainty in its measurement. The first five rotated PCs of the analysis of VOC and CO₂ emission factors accounted for 83% of the total variance. Coefficients between 0.29 and -0.29 have been omitted from the table to improve readability and facilitate the identification of sources.

Discussion

The composition and concentrations of VOCs in the study building were generally consistent with data reported in the literature for North American office buildings studied since 1990 (Daisey *et al.*, 1994, Girman *et al.*, 1999, Shields *et al.*, 1996). Oxidized solvents such as ethanol, isopropanol, acetone and 2-butoxyethanol often dominate the mixture in office buildings. A notable difference for the study building is the virtual absence of chlorinated

hydrocarbon solvents. This may, in part, reflect reductions over recent years in the production and use of environmentally harmful and toxic halocarbons.

Through our selection process, most the VOCs listed in Table 1 predominantly derive from indoor sources in this building. Indoor/outdoor ratios below about 1.35, calculated by propagation of uncertainty assuming a typical measurement precision of 25% for individual VOC, are indicative of an outdoor source. Two compounds, toluene and m/p-xylene have geometric mean indoor/outdoor ratios near this value indicating they have strong outdoor source contributions, likely motor vehicle emissions (Daisey *et al.*, 1994). Acetaldehyde is another compound whose indoor concentrations are strongly influenced by outdoor sources.

Occupants were the likely exclusive source of CO₂ in the building. The per occupant CO₂ generation rates calculated for the sampling days when the building was at near steady-state conditions are in the range of 0.0068-0.0092 L s⁻¹ (Table 5). These values are elevated over a generation rate of 0.0052 L s⁻¹ calculated for an average-sized adult engaged in office work but within the upper bound of 0.010 L s⁻¹ for office workers (Persily, 1997).

Principal component analysis previously has been applied to VOC concentrations measured in cross-sectional studies of office buildings and residences in attempts to ascertain sources (Apte and Daisey, 1999; Apte and Erdmann, 2002; Edward *et al.*, 2001; Ten Brinke *et al.*, 1998). It was anticipated that PC analysis of emission factors in a single building might produce more specific source information. In fact, the loadings of the predominant indoor-derived VOCs on the PC vectors demonstrated that the emission factors of many compounds were interrelated (Table 4). The observed groupings likely were due to commonalties among the emission sources. However, as observed here, there were inconsistencies that are difficult to explain based on the known sources of some compounds. Furthermore, differences in the physical and

chemical behaviors of compounds in a building may serve to obscure associations based on source similarities. With these limitations in mind, the following tentative source identifications were made based on the groups of highly correlated VOCs and on available information from the literature supporting the indicated associations.

PC1 with high loadings of 2-ethyl-1-hexanol, 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (TMPD-MIB, combined isomers), formaldehyde, CO₂ and d5 siloxane likely is indicative of occupant-related sources. CO₂ is a direct indicator of occupancy. The d5 siloxane is used as a major ingredient in personal deodorants and previously has been associated with occupancy in office buildings (Shields *et al.*, 1996). If all of the d5 siloxane is attributed to this source, the average per occupant generation rates are in the range of ~3-6 mg h⁻¹ (Table 5). TMPD-MIB is used as a coalescing aid in latex paints but also is used in cosmetic nail care products (Eastman Chemical Co., 2003), providing a possible link to occupants as a source. Formaldehyde can derive from many sources potentially present in office buildings including composite wood products, architectural finishes, thermal and acoustical insulation, fabrics, paper, and nail care products (Kelly *et al.*, 1999). In addition, formaldehyde is present in some cosmetic lotions and shampoos (Rastogi, 1992). Thus, an occupant association might occur due to formaldehyde emissions from workstation components, office supplies, clothing or cosmetics. 2-Ethyl-1-hexanol is an industrial solvent with numerous uses; however, a link with occupancy has not been documented to our knowledge. Unexplainably, isoprene is negatively correlated with PC1, although isoprene is a predominant VOC in breath (Fenske and Paulson, 1999).

PC2 with high loadings of MIBK, butyl acetate, acetaldehyde, pentanal, and hexanal possibly is indicative of a material source, such as furnishings. A similar compound association was produced as the first PC in an analysis of the concentrations of 19 VOCs measured in 41 U.S.

office buildings (Apte and Erdmann, 2002). Acetaldehyde, pentanal, and hexanal are all emitted by composite wood products (Hodgson *et al.*, 2002). However, wood products typically emit hexanal at much higher rates than acetaldehyde rather than the similar rates seen here. A possible source of MIBK and butyl acetate is furniture coatings (Salthammer, 1997).

PC3 with high loadings of acetone, isopropanol, 2-butoxyethanol, and 1-butanol possibly represents the emissions of solvents from cleaning solutions. A PC analysis of VOC concentrations in 12 California office buildings produced a similar high correlation between isopropanol and 2-butoxyethanol (Ten Brinke *et al.*, 1998). Commonly used glass and surface cleaners and some general-purpose cleaners contain 2-butoxyethanol but not necessarily acetone or isopropanol (Zhu *et al.*, 2001). In addition, products in these same categories frequently contain d-limonene (*ibid.*). These observations suggest that PC3 may be indicative of solutions used to clean office equipment for which we were unable to find published data.

PC4 with high loadings of d5 siloxane, toluene, and isoprene also may be associated with occupants. This is indicated by multiple factors. CO₂ is a secondary contributor. The d-5 siloxane has a documented occupant source. Despite the negative correlation between isoprene and CO₂ in PC1, the isoprene concentrations in the building are consistent with an occupant source. The per occupant isoprene generation rates calculated for the sampling days when the building was operating at near steady-state conditions, are in the range of ~0.2-0.3 mg h⁻¹ (Table 5). These values are consistent with an adult isoprene generation rate of 0.27 mg h⁻¹ calculated from breath concentration and exhalation rate (Fenske and Paulson, 1999). Finally, toluene is a major constituent of at least some nail enamel removers (Zhu *et al.*, 2001).

d-Limonene, which is the sole highly loaded compound on PC4, is used in air fresheners and as an odorant and active ingredient in cleaning products (*ibid.*). The occupant related

compounds CO₂ and d5 siloxane are secondary contributors. In a Nordic study, PC analysis of VOC concentrations in smoke-free workplace environments also produced a vector dominated solely by d-limonene (Edwards *et al.*, 2001). Cleaning products, air fresheners and personal fragrances were indicted as the likely source.

The ability of ventilation to control the concentrations of a range of air pollutants deriving from different sources was examined qualitatively. In-Out concentrations were used in this assessment in order to focus solely on pollutant sources associated with the building and occupants. In-Out concentrations of eight VOCs variously identified with different source categories are plotted in Fig. 2 versus normalized airflow rate (L s⁻¹/100 m²). These range from very volatile compounds (*e.g.*, formaldehyde, acetaldehyde and isopropanol), with low removal rates due to sorption on surfaces, through lower volatility compounds (*e.g.*, TMPD-MIB) that are more likely to have substantial sink effects. Only steady state data are included in the plots. The concentrations of isopropanol and 2-butoxyethanol, two compounds with cleaning product sources (PC3), showed little relationship with ventilation; although, the two highest isopropanol values occurred at the lowest airflow rates. Formaldehyde concentrations, which had an indicated association with occupant sources (PC1), also were not apparently associated with ventilation as the concentrations in the zones served by AHUs 2-2 and 2-3 were nearly identical and constant throughout the study. Formaldehyde concentrations in the zones served by AHUs 1-1 and 2-1 were mostly higher possibly indicating a localized source; but, they were not associated with ventilation as the higher concentrations occurred at the higher airflow rates. Concentrations of acetaldehyde and hexanal with possible material sources (PC2) exhibited general trends of higher concentrations at lower flow rates in zones served by AHUs 1-1, 2-1 and 2-3. Concentrations of d-limonene with a probable air freshener and/or cleaning product source

(PC5) were not associated strongly with ventilation in any zone. One relatively high outlying d-limonene value occurred on a single day in one location. TMDP-MIB concentrations were elevated on three days in the zone served by AHU 2-2. All of the other TMDP-MIB values were low and relatively constant. This may have been due to re-emission from sinks at higher airflow rates. The concentrations of d5 siloxane exhibited trends of higher concentrations at lower flow rates in zones served by AHUs 1-1 and 2-1.

These results illustrate that the efficacy of ventilation for controlling VOC concentrations can vary considerably depending upon the operation of the building, the pollutant sources and the physical and chemical processes affecting the pollutants. These factors combine to obscure a direct inverse relationship between concentration and ventilation for some VOCs.

In large buildings with multiple air handling zones, the degree of air mixing among zones may vary depending upon the operation of the ventilation system. For the purposes of this study, the building's air inlet dampers were manipulated to achieve periods of controlled, relatively constant ventilation. Consequently, normalized OA flow rates between several adjoining zones varied considerably during the study (Fig. 1), possibly affecting air mixing among these zones. In many cases, a large building's ventilation system does not operate at steady-state conditions. The effects attributable to air mixing may be amplified when, for example, variable air volume systems continually adjust the supply rates of cool or warm air to maintain desired indoor temperatures in various zones.

Many common VOCs are likely to be multiple sources of in a building. These sources, such as building materials and cosmetics, can have very different emission characteristics. For a given source, there may be overriding temporal and spatial variations in generation rates that are unassociated with ventilation. As a primary example, concentrations of compounds that are

solvent constituents of products used intermittently or sporadically in a building would not necessarily be expected to exhibit strong inverse relationships with ventilation. This was apparently the case for acetone, isopropanol and 2-butoxyethanol, which likely derived from the use of cleaning products/solutions. The sources of compounds that are strongly linked with occupancy also can vary spatially and temporally in association with the occupants' work and personal activities.

Physical and chemical processes affect the temporal pattern of pollutant net emission rates. Sink effects are indicated to be important for some VOCs based on these results. The sorption of VOCs onto surfaces in the building and their later release when bulk air concentrations decline directly links VOC emissions with ventilation to at least partially negate the benefit of increased ventilation. For some common VOC source profiles and VOC/material combinations, this effect is predicted to be relatively large (Zhao *et al.*, 2002). In a study of a single large office building, the source strengths of C₁₀-C₁₁ of isoparaffinic hydrocarbons emitted by wet-process photocopiers were quantified. The emission rates of these compounds measured over the weekend with very few occupants were about 20% of the weekday values likely due to re-emission from indoor surfaces (Hodgson *et al.*, 1991). In simulated room experiments, strongly sorbing VOCs emitted by a habitual intermittent source (environmental tobacco smoke) were lost quickly to surfaces and then released at slow rates over long periods (Singer *et al.*, submitted). Indoor air chemistry involving the reaction of ozone with unsaturated compounds such as d-limonene is linked to ventilation since the concentrations of products are greater at low ventilation rate due to increased reaction times as shown by modeling and experiments (Weschler and Shields, 2000). All of these processes serve to reduce the general effectiveness of ventilation for controlling VOC sources.

Conclusions

Adequate ventilation is required to remove indoor-generated pollutants from buildings. However, differences in the concentrations of most of the abundant VOCs in the study building on seven days of sampling could not easily be predicted by the differences in ventilation rates on those days. A number of compounds likely had multiple sources with different emission characteristics. Temporal and spatial variations in cleaning products probably obscured the relationship between concentration and ventilation for some solvents. For other compounds, it is likely that net emission rates increased with ventilation due to their re-emission from sinks. These results emphasize the importance of employing source control measures to limit the concentrations of VOCs in office buildings. Source control should target the VOCs of most concern with respect to potential occupant health and comfort effects. Control procedures most readily can be applied to the products and materials that are used or consumed in buildings. They are less applicable to sources associated with personal activities such as the use of cosmetics, which were implicated as the possible source of several VOCs. Several potentially effective control procedures are use of low emitting materials to finish and furnish interiors, use of low-emitting cleaning products, and reduced usage of products containing chemicals that are highly reactive with ozone.

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Table 1. Summary of indoor concentrations, outdoor concentrations and indoor/outdoor ratios of VOCs measured in 4 AHU zones on 7 sampling days (n = 28).

Compound	Concentration (ppb)					
	Indoor		Outdoor		Indoor/Outdoor Ratio	
	Geomean	Range	Geomean	Range	Geomean	Range
Ethanol	38	14.8-126	9.5	7.8-14.2	4.0	1.90-9.8
Isopropanol	44	18.7-250	9.7	9.1-10.1	4.6	1.86-27
1-Butanol	0.46	0.25-1.13	<0.11	<0.11-0.21	Nm ^a	3.0->50
2-Ethyl-1-hexanol	0.41	0.19-1.07	0.07	<0.06-0.17	nm	1.46->50
2-Butoxyethanol	3.9	1.31-19.1	0.46	<0.07-1.46	8.3	1.53->50
Acetone	14.0	4.0-41	2.5	0.28-10.0	5.6	1.41-60
MIBK ^b	0.17	<0.08-2.2	<0.08	<0.08-0.15	nm	5.1->50
Formaldehyde	11.9	5.4-25	3.4	1.64-7.1	3.4	1.44-10.7
Acetaldehyde	3.0	1.4-7.1	1.68	0.81-3.9	1.79	0.91-3.2
Pentanal	0.48	0.21-0.87	0.21	0.15-0.31	2.3	0.88-5.2
Hexanal	1.15	0.61-2.2	0.29	0.21-0.36	4.0	1.88-10.1
Heptanal	0.27	0.14-0.54	0.14	0.10-0.18	1.90	0.77-4.7
Ethyl acetate	0.25	<0.09-2.5	<0.09	<0.09-0.17	nm	5.1->50
Butyl acetate	0.22	0.09-1.31	<0.07	<0.07-0.17	nm	1.73->50
TMPD-MIB ^b	0.17	<0.08-0.42	--	<0.08	nm	>50
Toluene	1.23	0.75-2.9	0.94	0.47-2.1	1.30	0.80-3.0
m/p-Xylene	0.50	0.31-1.12	0.40	0.24-0.78	1.25	0.80-2.2
Isoprene	0.76	<0.12-2.6	0.13	<0.12-0.44	nm	1.96->50
α -Pinene	0.38	0.09-0.87	<0.06	<0.06-0.11	nm	3.6->50
d-Limonene	0.83	0.22-4.9	--	<0.06	nm	>50
d5 Siloxane ^b	2.5	1.1-7.4	0.05	0.03-0.08	52	13.3->50

a. Not meaningful; concentration for majority of outdoor samples below lower LOQ

b. MIBK = 4-Methyl-2-pentanone; TMDP-MIB = 2,2,4-Trimethyl-1,3-pentenediol monoisobutyrate (combined isomers); d5 siloxane = Decamethylcyclopentasiloxane

Table 2. Numbers of occupants and whole-building ventilation parameters on 7 sampling days.

Parameter	Units	Wk 2	Wk 3	Wk 6	Wk 7	Wk 8	Wk 11	Wk 13
Occupants ^a	Persons	217	211	215	243	226	217	273
Total OA ^b flow rate	1,000 m ³ h ⁻¹	48.6	22.8	46.2	25.5	21.4	46.1	19.1
Area specific OA flow rate	L s ⁻¹ /100 m ²	292	137	277	153	128	277	115
Ventilation rate	h ⁻¹	3.4	1.62	3.3	1.81	1.51	3.3	1.35

a. Average number of occupants from 8:00-15:00

b. Outdoor air

Table 3. Whole-building emission factors of VOCs and CO₂ on 4 sampling days when building was operating at near steady-state conditions, and zonal average emission factors when AHU zones were operating near steady-state conditions (n = 21).

Compound	Emission Factor ($\mu\text{g m}^{-2} \text{h}^{-1}$)					
	Whole Building				Zonal Average	
	Wk 2	Wk 6	Wk 7	Wk 13	Geomean	Range
Ethanol	290	480	280	380	320	153-780
Isopropanol	1,160	740	580	850	500	94-2,400
1-Butanol	20	8.7	5.8	4.9	8.1	3.0-31
2-Ethyl-1-hexanol	12.3	18.1	10.6	3.2	9.6	<1.43-22
2-Butoxyethanol	520	192	132	29	88	14.7-990
Acetone	260	136	183	187	144	29-410
MIBK ^a	4.5	3.8	2.2	2.4	4.2	1.60-70
Formaldehyde	121	111	58	25	54	20-220
Acetaldehyde	11.9	8.4	19.5	13.7	12.4	<8.7-30
Pentanal	2.4	3.2	8.6	6.8	4.6	<2.4-20
Hexanal	16.7	19.9	24	23	21	11.9-48
Heptanal	<3.5	3.1	6.3	3.7	3.3	<2.4-17.8
Ethyl acetate	6.8	3.3	12.2	2.9	6.2	0.67-25
Butyl acetate	8.7	5.8	1.98	3.0	5.4	<1.70-42
TMPD-MIB ^a	16.4	15.5	9.0	4.2	8.8	3.6-23
Toluene	<1.75	9.9	4.9	9.6	5.3	<1.23-17.4
Isoprene	8.8	11.2	13.1	18.5	11.7	5.5-28
α -Pinene	14.9	13.6	12.5	12.1	13.0	5.2-23
d-Limonene	56	26	55	22	31	12.6-150
d5 siloxane ^a	206	260	230	200	220	114-330
CO ₂ ^b	2.7	2.8	2.6	2.2	2.5	1.59-3.6

a. Defined in Table 1

b. Emission factor in $\text{g m}^{-2} \text{h}^{-1}$

Table 4. Loadings of the first five rotated principal components for analysis of emission factors of VOCs and CO₂. Compounds are sorted by loading from first to last principal components. Compounds with coefficients >0.5 are indicated in bold.

Compound	Principal Component					Commun- ality
	1	2	3	4	5	
2-Ethyl-1-hexanol	0.86					0.75
TMPD-MIB	0.83		0.34			0.95
Formaldehyde	0.73	-0.33	0.40			0.91
CO ₂	0.68			0.37	0.34	0.81
d5 Siloxane	0.56			0.71	0.48	0.80
MIBK	0.37	0.86			-0.32	0.87
Butyl acetate	0.47	0.82		-0.38	-0.33	0.89
Acetaldehyde		0.81				0.72
Pentanal		0.79				0.87
Hexanal		0.75				0.78
Acetone			0.92			0.87
Isopropanol			0.90			0.88
2-Butoxyethanol	0.40		0.84			0.95
1-Butanol	0.44		0.66	-0.36		0.78
Toluene			-0.31	0.84		0.65
Isoprene				0.71		0.82
d-Limonene					0.88	0.87
Variance (%)	30	22	13	11	7	83 Total

Table 5. Whole building emission rates (ERs) and average per-occupant generation rates of isoprene, decamethylcyclopentasiloxane (d5 siloxane), and CO₂ on 4 sampling days when building was operating at near steady-state conditions. Occupants were assumed to be primary source of isoprene and d5 siloxane.

Parameter	Units	Wk 2	Wk 6	Wk 7	Wk 13
Isoprene ER	mg h ⁻¹	41	52	61	86
Isoprene generation rate	mg h ⁻¹ occup ⁻¹	0.188	0.24	0.25	0.31
d5 Siloxane ER	mg h ⁻¹	950	1,210	1,060	940
d5 Siloxane generation rate	mg h ⁻¹ occup ⁻¹	4.4	5.6	4.4	3.4
CO ₂ ER	L s ⁻¹	1.98	1.97	1.99	1.85
CO ₂ generation rate	L s ⁻¹ occup ⁻¹	0.0091	0.0092	0.0082	0.0068

Figure 1. Normalized airflow rates in four AHUs on 7 sampling days. Arrows indicated non-steady state conditions.

Figure 2. Indoor minus outdoor concentrations of 8 VOCs at near steady-state conditions in four AHUs on 7 sampling days versus normalized AHU airflow rates.



