

THE EFFECT OF VENTILATION ON THE INDOOR CONCENTRATIONS OF VAPOR PHASE ORGANIC COMPOUNDS

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ABSTRACT

Volatile organic compounds are a potential threat to the proper operation of modern electronic equipment. The concentrations of numerous vapor-phase organic compounds within a telephone switching office have been measured during a period of minimal ventilation and during subsequent periods of moderate ventilation. These measurements were made using passive samplers to collect the organic compounds. The compounds were then identified and quantified using standard gas chromatographic/mass spectrometric procedures. For the first sampling period (June 9–July 16, 1987) the amount of outdoor air used for ventilation averaged less than 3% of the total amount of air circulated through the air-handling system. The concentrations measured under these conditions were quite high; 13 compounds had values greater than 20 $\mu\text{g}/\text{m}^3$. For the subsequent sampling periods, the amount of outdoor air was increased to between 10% and 15% of the circulated air. The concentrations measured under these conditions were frequently an order of magnitude lower than those measured during the first interval. For many compounds, the indoor concentrations were comparable to, or only slightly larger than, the outdoor concentrations. These results demonstrate the importance of adequate ventilation in modern office buildings.

INTRODUCTION

Due to rising energy costs, many buildings in the U.S. have implemented energy conservation programs. These measures frequently include reductions in the amount of outdoor air used for building ventilation. However, a reduction in outdoor air can lead to increased levels of volatile organic compounds (VOC), which have indoor sources.

Within telephone switching offices there are many sources of VOC. Examples include cabling, floor tiles, carpet, wall coverings, furniture, building materials, floor wax, cleaning products, paints, and lubricants. High concentrations of volatile organic compounds are most frequently associated with "sick building syndrome" (Noma et al. 1988). However, they can also pose a threat to the proper operation of modern electronic equipment. They can promote arcing between relay contacts leading to increased contact erosion. Polymeric films derived from airborne organics can produce unacceptably high resistances between contact surfaces. Airborne organics can condense on read-write heads, increasing the likelihood of fine particles sticking to the heads, which can subsequently lead to head crashes and disc drive failures. In short, money saved on energy by reducing ventilation with outdoor air might be lost to increased costs associated with diagnosing and repairing failures of electronic equipment caused by elevated levels of VOC.

The Sheboygan Falls, WI, office is a new building that

contains a digital telephone switch. It was installed during the period from December, 1986 to March, 1987, although cutover to the switch did not occur until July, 1987. Based on recommendations from the manufacturer, the switch is on a raised floor which is used as an air distribution plenum. Cool air flows directly from this false floor into and through the digital switch. Wisconsin Bell personnel were concerned that such an arrangement might lead to increased concentrations of contaminants within the Sheboygan Falls office, which, in turn, might adversely affect the operation of the switch. They requested that the authors evaluate the indoor air quality at this site.

Sampling for VOC with organic vapor monitors began on June 9, 1987. Throughout the first sampling period the office was poorly ventilated (less than 3% outdoor air). Since then, the amount of outdoor air used for ventilation has been increased, and three additional sets of VOC samples have been collected. This paper documents the reduction in VOC concentrations resulting from increased ventilation with outdoor air at the Sheboygan Falls office.

EXPERIMENTAL

The Sheboygan Falls office is a 1493 ft^2 (139 m^2) single-story building. This includes the main switch area, the power room, the lavatory, and the janitor's closet. The total volume is 14,200 ft^3 (402 m^3). The power room and the janitor's closet have exhaust fans that run continuously. The former operates at 80 cfm (2.3 m^3/min) and the latter at 155 cfm (4.4 m^3/min). There is also an 85-cfm (2.4 m^3/min) exhaust fan in the lavatory that operates only when the lights are on. Air in the building is circulated by two fan systems. Fan system 1 is rated at 1500 cfm (42.5 m^3/min) and runs continuously. Fan system 2 is rated at 1650 cfm (46.7 m^3/min) and runs "on demand." Fan system 2 comes on if the room temperature is greater than 76°F or if the room relative humidity is greater than 53%. During the first sampling interval in this study both fans were operating (reflecting the warm mid-summer temperatures outside). During the subsequent sampling intervals fan 2 was off for the majority of the time. During the first sampling period the outside air dampers were closed and the building was not pressurized. During the subsequent sampling periods the outside air damper for fan 1 was set for a minimum 20% outdoor air, and the building was under positive pressure.

The sampling device used in this study is an organic vapor monitor or passive sampler. The collection procedure depends on molecular diffusion for eventual contact between vapor phase compounds and the charcoal sorbent. This method has been validated for low-level sampling over extended time intervals and is applicable for concentrations spanning six orders of magnitude; reproducibility averages 13% of the mean value; and the sensitivity is excellent (0.06 $\mu\text{g}/\text{m}^3$ —Shields and Weschler 1987).

TABLE 1

Concentrations ($\mu\text{g}/\text{m}^3$) of volatile organic compounds detected within the Sheboygan Falls, WI office (1987).

Compound	DLU 0050		
	6/9-7/16 < 3% OA	8/19-9/23 10-15% OA	11/3-12/9 10-15% OA
Trichloroethylene	0.83	ND	ND
Toluene	8.57	5.17	2.28
Perchloroethylene	3.13	1.33	0.77
Octane	3.18	ND	1.00
D3	0.78	ND	ND
Ethyl Benzene	8.76	7.08	2.73
Xylene (M&P)	23.72	19.75	7.80
Styrene	4.22	ND	ND
Xylene (O)	8.06	5.44	2.84
Butoxyethanol-2 (N)	3.04	ND	ND
Nonane	7.42	1.24	ND
Alpha-Pinene	20.96	ND	ND
n-Propyl Benzene	5.83	1.62	0.79
C3-Alkyl Benzene	18.04	ND	3.03
C3-Alkyl Benzene	9.06	ND	1.12
C3-Alkyl Benzene/Br. C10/B-Pinene	23.49	ND	ND
Trimethyl Benzene (1, 2, 4)	ND	2.63	3.07
Trimethyl Benzene (1, 2, 4)/ Br. C10	22.73	ND	ND
Branched Decane	4.61	ND	ND
Decane & C3-Alkyl Benzene	39.20	5.44	2.60
Branched C11	15.87	ND	ND
Branched C11	8.01	ND	ND
C4-Alkyl Benzene/Br. C11	19.93	ND	ND
C4-Alkyl Benzene/Br. C11	24.15	ND	ND
C4-Alkyl Benzene/Br. C11	17.42	ND	ND
Branched C11	8.41	ND	ND
Undecane & C4-Alkyl Benzene	51.04	5.18	4.03
D5	45.45	ND	ND
Dodecane	38.58	3.90	1.25
Tridecane	45.30	4.16	0.47
D6	30.01	ND	ND
Tetradecane	27.19	10.39	1.83
Pentadecane	24.90	6.48	1.65
Diethyl Phthalate	15.48	5.78	ND
Hexadecane	4.82	6.32	5.16
Heptadecane	2.94	ND	ND
Octadecane	4.08	ND	ND

Prior to analysis each badge is spiked with an internal standard, typically 5 μl of a 20 $\mu\text{l}/10\text{ ml}$ cyclooctane/carbon disulfide solution. The badge is then extracted with 1.5 ml of carbon disulfide. Organic compounds contained in the extract are separated and identified using standard gas chromatographic/mass spectrometric (GC/MS) procedures.

Analyses were conducted on a gas chromatograph/mass spectrometer containing a 12 m by 0.2 mm narrow bore, cross-linked dimethyl silicone, fused silica capillary column (split operation, He column flow 1 ml/min). The injection port is held at 240°C while the temperature is programmed from 0°C to 220°C at a rate of 8°C/min. An autotune with perfluorotributylamine (PFTBA) is performed daily to calibrate the mass spectrometer.

Both laboratory blanks (unexposed monitors that remained in the laboratory during sampling) and field blanks (unexposed monitors sent into the field along with sample monitors) have been analyzed; for badges from the same production lot, the results are indistinguishable. Blank corrections were only necessary for n-alkanes between dodecane and hexadecane. Other compounds did not require corrections.

TABLE 2

Concentrations ($\mu\text{g}/\text{m}^3$) of volatile organic compounds detected within the Sheboygan Falls, WI office (1987).

Compound	RR0100.01 6/9-7/16 < 3% OA	RR0100.02 8/19-9/23 10-15% OA	RR0100.02 11/3-12/9 10-15% OA
Trichloroethylene	1.84	ND	ND
Toluene	9.85	7.58	2.45
Branched Octane	0.93	ND	ND
Perchloroethylene	2.34	0.97	0.83
Octane	3.42	ND	1.38
D3	0.80	ND	ND
Ethyl Benzene	8.68	7.73	2.50
Xylene (M&P)	23.85	23.32	7.77
Styrene	4.02	ND	ND
Xylene (O)	7.98	6.69	2.04
Butoxyethanol-2 (N)	2.88	ND	ND
Nonane	6.59	1.51	ND
Alpha-Pinene	19.73	ND	ND
n-Propyl Benzene	5.59	2.58	0.56
C3-Alkyl Benzene	17.54	ND	1.50
C3-Alkyl Benzene	9.56	ND	0.68
C3-Alkyl Benzene/Br. C10/B-Pinene	20.89	ND	ND
Trimethyl Benzene (1, 2, 4)	15.35	4.52	1.30
Decane & C3-Alkyl Benzene	38.85	4.00	2.10
Branched Alkane/D4	ND	ND	10.84
Branched C11	14.49	ND	ND
Branched C11/C4-Alkyl Benzene/?	8.08	ND	ND
Branched C11/C4-Alkyl Benzene/?	9.99	ND	ND
C4-Alkyl Benzene/Br. C11	13.33	ND	ND
C4-Alkyl Benzene/Br. C11	22.91	ND	ND
C4-Alkyl Benzene/Br. C11	16.17	ND	ND
Branched C11	7.95	ND	ND
Undecane & C4-Alkyl Benzene	51.98	5.29	1.72
D5	44.02	ND	ND
Dodecane	33.58	4.40	0.51
Tridecane	31.50	4.05	0.19
D6	25.49	ND	ND
Tetradecane	19.27	2.59	0.86
Pentadecane	20.50	1.16	0.22
Diethyl Phthalate	8.69	4.80	ND
Hexadecane	4.38	ND	0.51
Heptadecane	3.81	ND	ND
Octadecane	2.50	ND	ND

RESULTS AND DISCUSSION

Table 1 presents concentrations for more than 35 volatile organic compounds detected at frame location DLU 0050 within the Sheboygan Falls office. Values are listed for three different sampling intervals—June 9 to July 16, 1987; August 19 to September 23, 1987; and November 3 to December 9, 1987. During the first sampling interval the amount of outdoor air introduced averaged less than 3% of the total amount of air being circulated through the air-handling system (< 0.4 air changes per hour). For the subsequent two intervals the amount of outdoor air was significantly increased and averaged between 10% and 15% of the circulated air (~1.3 air changes per hour). Table 2 presents information analogous to that contained in Table 1 (same three sampling intervals), but the VOC were collected at a different location in the office. The first set of samples was collected at frame location RR0100.01 and the next two sets of samples were collected at the adjacent frame, RR0100.02. For a given sampling interval the concentrations in Tables 1 and 2 are similar, indicating that the air within the office is relatively well mixed. A more striking comparison is that between different

TABLE 3

Indoor concentrations, outdoor concentrations, and indoor/outdoor ratios (I/O) for volatile organic compounds at Sheboygan Falls, WI from 8/19-9/23/87 ($\mu\text{g}/\text{m}^3$).

Compound	RR100.02		DLU 0050		Outdoors
	Indoors	I/O	Indoors	I/O	
Toluene	7.58	1.2	5.17	0.8	6.39
Perchloroethylene	0.97	0.8	1.33	1.1	1.25
Ethyl Benzene	7.73	0.9	7.08	0.8	8.54
Xylene (M&P)	23.32	0.9	19.75	0.8	25.42
Xylene (O)	6.69	0.9	5.44	0.8	7.19
Nonane	1.51	≥ 1	1.24	≥ 1	ND
n-Propyl Benzene	2.58	2.5	1.62	1.5	1.05
Trimethyl Benzene (1, 2, 4)	4.52	1.9	2.63	1.1	2.39
Decane & C3-Alkyl Benzene	4.00	1.1	5.44	1.5	3.66
Undecane & C4-Alkyl Benzene	5.29	1.8	5.18	1.8	2.88
Dodecane	4.40	1.0	3.90	0.9	4.46
Tridecane	4.05	1.1	4.16	1.1	3.67
Diethyl Phthalate	4.80	≥ 1	5.78	≥ 1	ND

sampling intervals in either Table 1 or 2. The increase in ventilation air from the first sampling interval to the subsequent sampling intervals has dramatically reduced the concentrations of many of the volatile organic compounds. Indeed, a large number of compounds detected during the first sampling period are below detection levels during subsequent sampling periods. These include trichloroethylene, hexamethylcyclotrisiloxane (D3), styrene, 2-butoxyethanol, alpha-pinene, an isomer of C₃-alkyl benzene, several branched decane isomers, beta-pinene, several branched undecane isomers, several C₄-alkyl benzene isomers, decamethylcyclopentasiloxane (D5), dodecamethylcyclohexasiloxane (D6), n-heptadecane, and n-octadecane. Other compounds show significantly reduced concentrations; they include perchloroethylene, the n-alkanes from octane to pentadecane, n-propyl benzene, several C₃-alkyl benzene isomers, and diethyl phthalate. On the other hand, there are

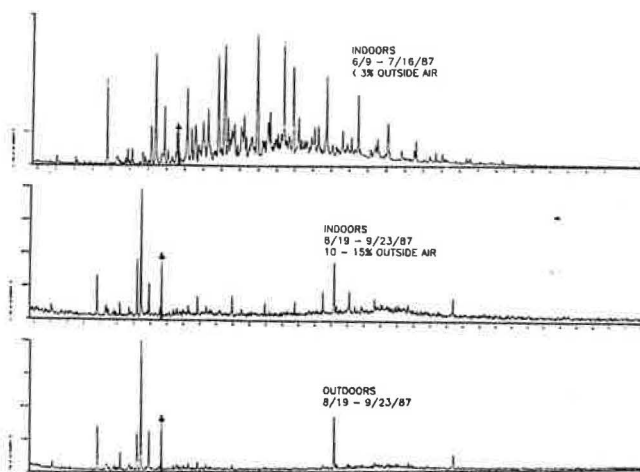


Figure 1 Total ion chromatograms for samples collected indoors (< 3% outdoor air and 10%-15% outdoor air) and outdoors at the Sheboygan Falls office. In each chromatogram the internal standard is shaded and has a small arrow above it. Many of the volatile organic compounds associated with the individual peaks are listed in Tables 1-4.

TABLE 4

Indoor concentrations, outdoor concentrations, and indoor/outdoor ratios (I/O) for volatile organic compounds at Sheboygan Falls, WI from 11/3-12/9/87 ($\mu\text{g}/\text{m}^3$).

Compound	RR100.02		DLU 0050		Outdoors
	Indoors	I/O	Indoors	I/O	
Toluene	2.45	1.7	2.27	1.5	1.47
Perchloroethylene	0.83	5.5	0.77	5.1	0.15
Octane	1.37	2.6	1.00	1.9	0.53
Ethyl Benzene	2.50	1.1	2.72	1.2	2.36
Xylene (M&P)	7.77	1.0	7.80	1.0	7.60
Xylene (O)	2.04	0.9	2.83	1.2	2.28
n-Propyl Benzene	0.55	0.8	0.79	1.1	0.70
C3-Alkyl Benzene	1.50	0.5	3.03	1.0	2.91
C3-Alkyl Benzene	0.68	0.6	1.12	0.9	1.22
Trimethyl Benzene (1, 2, 4)	1.30	0.5	3.06	1.3	2.42
Decane & C3-Alkyl Benzene	2.09	0.9	2.59	1.1	2.43
Undecane & C4-Alkyl Benzene	1.71	1.0	4.03	2.2	1.80
Dodecane	0.50	≥ 1	1.24	≥ 1	ND
Tridecane	0.18	≥ 1	0.47	≥ 1	ND

compounds which show only small concentration reductions from the first to subsequent sampling periods. These include toluene, ethyl benzene, m&p-xylene, and o-xylene. More will be said about this group of compounds below.

Figure 1 compares a total ion chromatogram (TIC) for an indoor sample collected during the "low ventilation air period" with a TIC for an indoor sample collected during an "increased ventilation air period" (August 19-September 23, 1987) and a TIC for an outdoor sample (August 19-September 23, 1987). In each TIC the peak associated with the internal standard is darkened and has a small arrow above it. The amount of internal standard is identical in each run; hence, for quantitative comparisons, the top TIC should be enlarged by a factor of 1.5. The top and middle chromatograms reveal that there is a marked reduction in indoor concentrations for many of the VOC as the ventilation air is increased. What is further apparent, comparing the middle and bottom chromatograms, is that most of the compounds that remain elevated indoors after the ventilation air has been increased are compounds with dominant outdoor sources. This point is amplified in Tables 3 and 4.

Table 3 contrasts indoor VOC concentrations measured at RR0100.02 and DLU 0050 with outdoor VOC concentrations measured at the building's air intake. Table 3 is for the period August 19-September 23, 1987, while Table 4 presents an analogous comparison for the period November 3-December 9, 1987. Each table also includes indoor/outdoor (I/O) ratios for the measured VOC. Such ratios indicate if there is a significant indoor source of an organic compound in addition to the amount of that compound that enters the building from outdoors. In Table 3 the compounds with I/O ratios greater than unity include n-nonane, n-propyl benzene, 1,2,4-trimethyl benzene, n-decane and C₃-alkyl benzene, n-undecane and C₄-alkyl benzene, and diethyl phthalate. These compounds are among the compounds in Tables 1 and 2 that decrease dramatically with an increase in outdoor air. In Table 4, fewer compounds have I/O ratios greater than 1. These include perchloroethylene, n-octane, n-undecane, and C₄-alkyl benzene. This suggests that, on average, indoor source strengths are decreasing with time. However, activities within the office do change from sampling interval to sampling interval, and some of the compounds in Table 4 with elevated

TABLE 5

Concentrations ($\mu\text{g}/\text{m}^3$) of volatile organic compounds detected outdoors at the Sheboygan Falls, WI office (1987).

Compound	Air Intake		
	8/19-9/23	10/6-11/3	11/3-12/9
Toluene	6.39	1.89	1.47
Perchloroethylene	1.25	Ref. as IS	0.15
Octane	ND	0.75	0.53
Ethyl Benzene	8.54	3.21	2.36
Xylene (M&P)	25.42	8.46	7.60
Xylene (O)	7.19	2.76	2.28
n-Propyl Benzene	1.05	0.61	0.70
C3-Alkyl Benzene	ND	2.34	2.91
C3-Alkyl Benzene	ND	0.96	1.22
Trimethyl Benzene (1, 2, 4)	2.39	1.95	2.42
Decane & C3-Alkyl Benzene	3.66	2.61	2.43
Undecane & C4-Alkyl Benzene	2.88	1.55	1.80
Dodecane	4.46	0.98	ND
Tridecane	3.67	ND	ND
Tetradecane	1.31	ND	1.26
Hexadecane	5.41	8.37	1.74

TABLE 7

Concentrations ($\mu\text{g}/\text{m}^3$) of volatile organic compounds detected in various locations outside the Sheboygan Falls, WI office (1987).

Compound	10/6-11/3/87		
	Diesel Stack Air Intake Fr. of Bldg		
Toluene	1.61	1.89	1.78
Perchloroethylene	0.80	Ref. As IS	0.86
Octane	0.70	0.75	0.80
Ethyl Benzene	2.71	3.21	3.12
Xylene (M&P)	7.88	8.46	9.24
Xylene (O)	2.35	2.76	2.57
n-Propyl Benzene	0.52	0.61	0.73
C3-Alkyl Benzene	1.97	2.34	2.58
C3-Alkyl Benzene	0.80	0.96	1.11
Trimethyl Benzene (1, 2, 4)	1.56	1.95	2.51
Decane & C3-Alkyl Benzene	1.96	2.61	2.62
Undecane & C4-Alkyl Benzene	1.33	1.55	2.20
Dodecane	0.89	0.98	1.27

I/O ratios do not have elevated I/O ratios in Table 3.

In contrast to the compounds with elevated I/O ratios, the compounds in Tables 3 and 4 that have I/O ratios close to 1 show minimal change in their concentrations in Tables 1 and 2. These include toluene, ethyl benzene, m&p-xylene, and o-xylene. The major source of these compounds within the Sheboygan Falls office is infiltration from outdoors and, consequently, ventilation will have little effect on their concentrations (see the middle and bottom chromatograms in Figure 1).

Table 5 lists outdoor concentrations of volatile organic compounds detected during three separate sampling periods at the Sheboygan Falls office. These samples were collected at the air intake. Table 6 lists outdoor concentrations of volatile organic compounds at a similar location in Neenah, WI (Weschler and Shields 1989). The outdoor concentrations for several of the compounds, including ethyl benzene and the xylene isomers, are significantly higher at the Sheboygan Falls site than at the Neenah site. Initially, a source on the grounds of the Sheboygan Falls office was suspected. One possibility

TABLE 6

Concentrations ($\mu\text{g}/\text{m}^3$) of volatile organic compounds detected at a telephone office in Neenah, WI.

Compound	4/14-6/15/87	
	Indoors	Outdoors
Toluene	2.29	1.64
Perchloroethylene	0.34	0.21
Octane	0.20	ND
D3	0.49	ND
Ethyl Benzene	0.59	0.49
Xylene (M&P)	1.61	1.11
Xylene (O)	0.40	0.43
Nonane	ND	0.18
n-Propyl Benzene	0.78	0.60
C3-Alkyl Benzene	0.78	0.95
C3-Alkyl Benzene	0.85	0.89
Trimethyl Benzene (1, 2, 4)	1.67	0.99
Decane & C3-Alkyl Benzene	1.47	0.90
D4	10.85	5.43
C4-Alkyl Benzene	0.93	0.57
Undecane & C4-Alkyl Benzene	1.46	1.29
Trichlorobenzene	1.91	ND
Dodecane	1.19	1.79
Tridecane	1.25	ND
Tetradecane	ND	0.65
Dimethyl Phthalate	0.96	ND
Pentadecane	0.60	1.18
Diethyl Phthalate	0.77	ND
Hexadecane	1.30	ND
Heptadecane	1.75	ND

was the exhaust stack for the diesel generators (emergency power), which are exercised twice a month. This stack is on the roof, set back about 10 ft from the outdoor wall that contains the air intake. To test this hypothesis, outdoor samples were collected at three different locations: next to the diesel stack, at the back of the building by the outdoor air intake, and at the front of the building. The results are presented in Table 7. The concentrations measured at the three different outdoor locations are very similar, including those for ethyl benzene and the xylene isomers. These results indicate that the elevated levels are not due to a point source on the office grounds, but instead reflect outdoor air levels in the greater Sheboygan Falls area. Discussions with local residents suggested that outdoor VOC levels may be influenced by a large coal-fired power plant located about six miles east in Sheboygan, WI. Lake-effect winds could bring the power plant plume into the Sheboygan Falls area. The higher (relative to Neenah, WI) values of ethyl benzene and the xylene isomers are consistent with such a source. Furthermore, the higher summer concentrations of these compounds, compared with middle and late fall (see Table 5), are consistent with seasonal weather patterns and perhaps an inversion layer during part of the summer sampling interval (Seinfeld 1986).

The above discussion of outdoor concentrations should not deflect attention from the central observation of this study: the very high concentrations of indoor VOC at low ventilation rates. To underscore this point, it is useful to compare indoor concentrations from the Sheboygan Falls office with indoor concentrations from the Neenah site. Indoor values at Sheboygan Falls during the first sampling interval (less than 3% outdoor air, Tables 1 and 2) are frequently 20 to 30 times larger than indoor values for the same compounds at Neenah (Table 6). For example, undecane and C₄-alkyl benzene, coeluting peaks, had a combined concentration of ~50 $\mu\text{g}/\text{m}^3$ at Sheboygan Falls, compared with 1.5 $\mu\text{g}/\text{m}^3$ at

Neenah; similarly, dodecane had contrasting concentrations of $\sim 35 \mu\text{g}/\text{m}^3$ and $1.2 \mu\text{g}/\text{m}^3$; and pentadecane had contrasting concentrations of $\sim 22 \mu\text{g}/\text{m}^3$ and $0.6 \mu\text{g}/\text{m}^3$. The sampling period at Neenah was 62 days—from April 14 to June 15, 1987. During this period the amount of outdoor air introduced averaged close to 60% of the circulated air (Weschler and Shields 1988). This reflects the air-handling system at Neenah, which has been designed to maximize the use of outdoor air. The use of such large amounts of outdoor air keeps indoor concentrations comparable to outdoor concentrations, even for compounds with significant indoor sources.

Figure 2 further amplifies the above point. The steady-state concentrations of a hypothetical vapor-phase organic compound are plotted as a function of the amount of outdoor air (percent of circulated air). These concentrations have been calculated using a mass-balance model presented in earlier studies (Weschler et al. 1988; Weschler and Shields 1989) and applied to the Sheboygan Falls office. The calculations assume that fan 1 is on and fan 2 is off (i.e., a flow rate in the plenum of $42.4 \text{ m}^3/\text{min}$), that the building is under slight positive pressure, that the hypothetical compound has an internal generation rate of $20 \text{ g}/\text{min}$, and that the hypothetical compound is not present outdoors. Figure 2 indicates an indoor concentration less than $2 \mu\text{g}/\text{m}^3$ at 25% outdoor air. At 12.5% outdoor air, the concentration, $3.8 \mu\text{g}/\text{m}^3$, is still acceptable. However, the curve shows that the concentration is rising rapidly as the percent outdoor air decreases. At 1.6% outdoor air, the calculated concentration is up to $30 \mu\text{g}/\text{m}^3$ and climbing rapidly. Figure 2 clearly illustrates the consequences of inadequate ventilation when indoor sources of VOC are present.

Figure 3 is also derived from the mass-balance model. In this figure the steady-state concentrations of a hypothetical organic compound are plotted as a function of the rate at which this compound is emitted indoors. There are actually two lines corresponding to two different ventilation strategies, 1.5% outdoor air and 15% outdoor air. The other parameters in the model are identical to those used in deriving

Figure 2. At 15% outdoor air, even for a source rate of $40 \mu\text{g}/\text{min}$ (very large), the calculated concentration is still less than $7 \mu\text{g}/\text{m}^3$. In contrast, at 1.5% outdoor air and the same emission rate, the calculated concentration is more than $60 \mu\text{g}/\text{m}^3$. It is evident from Figure 3 that for an office similar to that in Sheboygan Falls, 15% outdoor air provides adequate dilution of indoor pollutants even at high indoor emission rates.

These studies were initiated as a result of concern over a design feature in the air-handling system at the Sheboygan Falls office. This building uses a raised floor as an air distribution plenum (see Introduction). Cool air flows directly out of this false floor into the digital switch. Such an arrangement makes the office especially sensitive to inadequate ventilation. The concern was warranted because there are major potential sources of organic emissions in a "raised floor plenum." These include both the tiles associated with the raised floor (plasticizers) and concrete sealer or paint used on the actual floor (solvents, plasticizers, other additives). These sources have very large surface areas, and the ventilation air passes directly over them. Such an arrangement actually facilitates mass transport of outgassing organic compounds from the surface of the emitting materials. Emission rates for certain pollutants can be larger than those encountered in a building with a more traditional air-handling system. Consequently, if there is inadequate ventilation, steady-state indoor concentrations of selected contaminants can reach very high levels.

CONCLUSIONS

When the Sheboygan Falls switching office was poorly ventilated, the concentrations of numerous vapor-phase organic compounds were unacceptably high. Eighteen of the monitored compounds had concentrations in excess of $10 \mu\text{g}/\text{m}^3$. Such high concentrations can lead to failures in the sensitive electronic equipment housed within this office. For example, organic compounds can cause contact activation, or

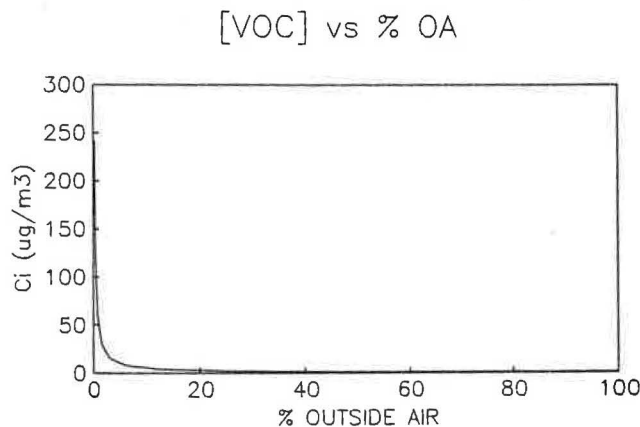


Figure 2 Plot of indoor steady-state concentration (C_i) of a hypothetical volatile organic compound vs. the amount of outdoor air used for ventilation (percent of circulated air). This plot is derived from a mass-balance expression presented elsewhere (Weschler and Shields 1989). It has been calculated assuming a flow rate in the plenum of $42.5 \text{ m}^3/\text{min}$, an indoor emission rate of $20 \text{ g}/\text{min}$, and an outdoor concentration of zero.

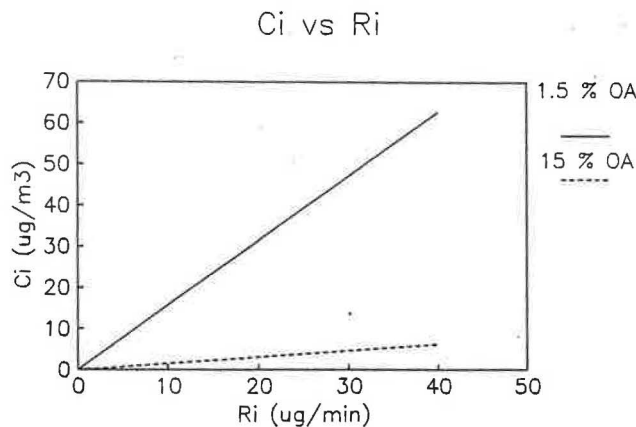


Figure 3 Plots of indoor steady-state concentrations (C_i) of a hypothetical volatile organic compound vs. its indoor emission rate (R_i). The solid line has been plotted assuming that 1.5% of the circulated air is outdoor air. The dashed line has been plotted assuming that 15% of the circulated air is outdoor air. These plots have been derived from a mass-balance model presented elsewhere (Weschler and Shields 1989). They have been calculated assuming a flow rate in the plenum of $42.5 \text{ m}^3/\text{min}$ and an outdoor concentration of zero.

the enhancement of arc duration, in telephone switching systems. For activation processes, Gray (1978) has reported a value of roughly $500 \mu\text{g}/\text{m}^3$ as the lower critical exposure to unsaturated organic species with 10 carbon atoms. A "good housekeeping" value is one to two orders of magnitude lower than this value. Such concentrations have been achieved at the Sheboygan Falls office by increasing the amount of ventilation air to a moderate level. None of the monitored compounds currently exceeds a concentration of $10 \mu\text{g}/\text{m}^3$. As expected, those compounds with the highest I/O ratios (i.e., those compounds with dominant indoor sources) are most affected by the ventilation rate.

The results from the Sheboygan Falls office can be explained in the context of a mass-balance model that has been presented in earlier studies (Weschler et al. 1988; Weschler and Shields 1989). Plots derived from the model illustrate the consequences of inadequate ventilation when there are indoor sources of vapor-phase contaminants. Their indoor concentrations increase sharply when the rate at which they are exhausted from the building becomes small compared to the rate at which they are emitted within the building. The model also shows that, at a building such as Sheboygan Falls, 15% outdoor air provides adequate dilution of indoor pollutants even when their emission rates are as large as $40 \mu\text{g}/\text{min}$.

The results of this study demonstrate that, through the judicious use of outdoor air, indoor concentrations of volatile organic compounds can be maintained at levels close to outdoor concentrations. This is true even for species with significant indoor sources.

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DISCUSSION

William A. Turner, Harriman Associates, Auburn, ME: Could you clarify the air exchange rates at 3% and 10% to 15% outdoor air in your study buildings? Are they typical of office building air turnover rates?

H.C. Shields and C.J. Weschler, Bell Communications Research, Red Bank, NJ: As noted in the manuscript, when the amount of outside air used for ventilation averaged less than 3% of the total air being circulated in the air-handling system, the air turnover rate in the building was less than 0.4 air changes per hour. When 10% to 15% of the air being circulated through the air-handling system was outside air, the air turnover rate was approximately 1.3 air changes per hour. The latter value is slightly larger than might typically be encountered in this type of commercial building.