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**SOURCE STRENGTHS AND SOURCES OF VOLATILE ORGANIC COMPOUNDS
IN A NEW OFFICE BUILDING**

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ABSTRACT: This study was conducted at a newly constructed office building in Portland, OR. The primary objectives were to identify the major sources of volatile organic compounds (VOC) in the building and to measure both long-term (one year) and short-term (several day) variations in source strengths. Samples for VOC were collected on four occasions over a period of 14 months starting with the first month of occupancy. During the final sampling period, samples were collected over four days (Friday - Monday). The primary source of VOC in the building was liquid-process photocopiers and plotters which emitted a characteristic mixture of C₁₀-C₁₁ branched alkanes. Motor vehicles in the below-ground parking garage probably were also a major source of hydrocarbons. The source strength of total organic carbon, which was dominated by the office-machine emissions, remained relatively constant over the course of the study. Short-term variations in the source strengths of many compounds were related to occupant activities.

INTRODUCTION

Conditioning of ventilation air for office buildings consumes considerable energy. Consequently, recent construction practices have attempted to minimize the amount of conditioned air used for ventilation while still maintaining adequate indoor air quality. At the same time, there have been an increasing number of complaints among workers about nonspecific health problems associated with office environments. Although the etiological agents responsible for these complaints remain largely unknown, it is suspected that volatile organic compounds (VOC) may play a role in producing symptoms such as mucous membrane irritation, headache, nausea, and dizziness which are characteristic of this "sick building syndrome".

There are many potential sources of VOC in office buildings. The concentrations of those VOC which are generated within a building during the work day can be controlled to some extent by increasing the ventilation rate. However, in many cases, source control would be a more effective and energy-efficient strategy. The major impediment to implementing source control measures is that it is first necessary to identify and understand the significant sources of VOC in a building.

This paper presents results from a detailed study of a large, newly constructed, office building. The primary objectives of this portion of the study were to identify the major sources of VOC in the building and to measure both long-term (one year) and short-term (several day) variations in concentrations and source strengths in order to define the emission patterns of those sources.

EXPERIMENTAL

Description of the Building

The study was conducted at a new, federal office building in Portland, OR. The building was constructed during 1986-1987 and first occupied in August, 1987. The building has seven above-ground office floors and three basement levels. The basement contains a loading dock and two and one-half floors of parking garage. The building has about 46,000 m² of occupied floor space with approximately 2000 employees.

A penthouse on the roof of the building houses the air intakes, exhausts and mechanical equipment for the seven office floors. There are three main HVAC systems which serve the east, center and west cores of the building. Each of these systems has a vertical return air shaft connected to the ceiling plenums on all floors. The interior plan is generally open architecture with work spaces enclosed by low partitions. The ventilated volume of the office

floors is approximately 134,000 m³. The basement floors have their own mechanical systems with air intakes and exhausts at ground level. The basement floors are connected to the office floors by several elevator shafts and stairwells.

Air-sampling locations for measurements of tracer gas, carbon dioxide, carbon monoxide (CO), respirable particles and humidity were established throughout the building and in the mechanical systems during the final construction stage and connected by tubing to a diagnostic center on the first basement floor. Temperature sensors were also located throughout the building. Continuous ventilation rate measurements were made using an automated tracer-gas decay system. This system injects sulfur hexafluoride into the building supply fans every two or three hours, allows the tracer gas to mix and then typically monitors the decay in tracer-gas concentrations on each office floor and in the return-air shafts. Average ventilation rates calculated for the building had coefficients of variation of about 10 %.

Sampling and Analysis for VOC

Samples for VOC in indoor and outdoor air were collected on four occasions over a period of 14 months. The first samples were collected in August, 1987 as the building was being occupied. Subsequent samples were collected in October, 1987, January, 1988 and October, 1988. In October, 1988, samples were periodically collected over a four-day period from Friday through Monday.

The details of the sampling and analysis methods for VOC have been previously described.^{1,2} In brief, air samples for VOC analysis were collected on multisorbent samplers (Part No. ST032, Envirochem, Inc., Kemblesville, PA) which are packed in series with Tenax-TA, Amborsorb XE-340 and activated charcoal. These samples were collected in duplicate or triplicate from the return air shafts at the penthouse level, from office spaces and from outdoor air on the roof of the building. The volumes of indoor samples were typically 1-3 L collected at a rate of 100 cm min⁻¹.

For analysis, a sample is thermally desorbed from a sampler and introduced into a capillary gas chromatograph (GC) with a UNACON Model 810A (Envirochem, Inc.) sample concentrating and inletting system. The GC is connected via a direct interface to a Series 5970B Mass Selective Detector (MSD, Hewlett Packard Co.). For quantitative analyses, the MSD is operated to monitor multiple, individually selected ions. Following thermal desorption, a portion of the sample (~8 %) is split off and analyzed directly by a flame ionization detector to give a measure of the total of C₄ and higher molecular weight hydrocarbons in the sample. This measure has been termed total organic carbon (TOC), and results are given as mass of carbon per m³. Coefficients of variation for the quantitative measures of individual compounds and TOC in this study were typically better than 10 %.

Source Strengths of VOC

Apparent source strengths of VOC were calculated using a single-equation, mass-balance model.² This model assumes perfect mixing of air in an enclosed volume. It was also assumed that removal processes other than ventilation were negligible. At near steady-state conditions, the source strength, S (mg h⁻¹), of a pollutant reduces to the product of the ventilated volume, V, and the ventilation rate times the difference between the indoor and outdoor concentrations. To facilitate comparison between this and other buildings, results have been expressed as specific source strengths, S/V (mg/m³-h).

MAJOR SOURCES

The dominant source of VOC in the building was liquid-process photocopiers and plotters. On a walk-through survey conducted in October, 1988, 26 of these copiers and three of these plotters were observed throughout the building with three or more machines on each of the seven floors. Some of the machines were located in small rooms in the core of the building. Many, however, were located in open office areas.

Both the copiers and the plotters use a common solvent as a clear dispersant and in their toner premixes. The tradename of this solvent is Isopar G (Exxon Corp.). It is a manufactured product consisting of a mixture of C_{10} and C_{11} branched alkanes with a specific gravity of 0.75 and a boiling point range of 155-176°C. The GC-MS scan analysis of plotter dispersant presented in Figure 1 shows that this product contains at least 20 major compounds. The figure also compares the composition of a portion of an indoor air sample collected in the building to the composition of the dispersant. All of the peaks in the air sample between 33.8 and 37.2 minutes correspond to the peaks in the dispersant based on matching retention times and mass spectra. There is, however, an unexplained difference in the ratios of the peak areas of the individual compounds to the total area in the two samples.

An inventory indicated that 147 L of copier dispersant and toner premix were used in the building over a period of about 55 working days. This suggests that the average solvent usage for copiers was approximately 2.7 L day⁻¹ or 2 kg day⁻¹.

In general, the light hydrocarbons such as those contained in Isopar G are considered to have low toxicity. For example, the occupational threshold limit values for exposures to nonane and gasoline are 200 ppm (1050 mg m⁻³) and 300 ppm (900 mg m⁻³), respectively.³ The manufacturer recommends an exposure limit to Isopar G of 300 ppm (~1850 mg m⁻³).

Motor vehicles were another likely source of the VOC in the office levels. The basement loading dock and parking garage levels are served by their own air-handling systems. However, during the fall and winter of 1987-1988, occasional incidents of significantly elevated CO concentrations (>10 ppm) from vehicle exhaust were measured in the upper building due to the flow of air from the basement levels up the elevator shafts and stairwells. Subsequently, control of the garage exhaust fans was modified so that the fans operated continuously during occupied hours rather than intermittently as before. This reduced, but did not completely eliminate, the transport of CO to the upper building.

This study identified and quantified a number of light hydrocarbons in the building which are characteristic components of vehicle exhaust.⁴⁻⁶ Table I shows that the relative composition of C_5 - C_8 aliphatic hydrocarbons and aromatic hydrocarbons in indoor air in the building remained approximately constant throughout the study. The indoor composition of these compounds was similar to the composition in outdoor air sampled on the roof, although indoor concentrations were distinctly higher (Table II). Since vehicles are typically the dominant source of these compounds in urban environments, the similarity in relative composition between indoor and outdoor air suggests that vehicles in the basement levels were the primary indoor source.

Other possible sources of VOC in the building were building and interior finish materials; furnishings; and office, cleaning and personal-care products. However, the contribution of these source categories to TOC appeared to be minor compared to liquid-process office machines and motor vehicles.

LONG-TERM TEMPORAL VARIATIONS

Variations in indoor concentrations and specific source strengths of individual compounds on the four sampling occasions over the 14-month study are presented in Table I. Since the major sources of VOC were related to occupant activities, concentrations in those samples which were collected after the regular work day may be less than the maximum values for those days. Temporal variations in the concentrations and specific source strengths of TOC are shown in Figure 2, and temporal variations in the major classes of compounds are shown in Figure 3.

There was a generally inverse relationship between concentrations and ventilation rate with the highest concentrations of individual compounds, classes of compounds and TOC most often occurring in January, 1988 when the ventilation rate was the lowest (0.24 h^{-1}). The concentration of TOC on this date was 11 mg m^{-3} which was relatively high for an office building. In addition, the concentration of the $\text{C}_9\text{-C}_{14}$ aliphatic hydrocarbon group was significantly elevated. The source of these latter compounds has not been identified. It was not, however, dominated by liquid-process office machines since only one of the more than 20 Isopar compounds was quantified and included in the group.

Specific source strengths of TOC were nearly identical for the first three sampling periods and increased somewhat in the final sampling period. Since the chromatograms clearly showed that TOC was dominated by the Isopar compounds, this similarity suggests fairly uniform use of copiers and plotters over the course of the study. Assuming that these values were typical for the entire work day, the range of source strengths would be 2.6 to 4.6 kg day^{-1} which is consistent with the estimated solvent usage rate for copiers alone of 2 kg day^{-1} . The $\text{C}_5\text{-C}_8$ aliphatic hydrocarbons and the aromatic hydrocarbons had higher specific source strengths in the two October sampling periods when the ventilation rates were highest. It is possible that this was due to an increased flow of air from the basement levels into the office levels at this ventilation condition. As noted above, the source strength of $\text{C}_9\text{-C}_{14}$ aliphatic hydrocarbons was highest in January, 1988 for unknown reasons. The elevated source strengths of oxygenated and chlorinated compounds in the final sampling period were due to three compounds (2-propanol, 2-propanone and trichloroethylene) whose sources may have been cleaning products. With the exception of 2-butanone and dichloromethane, there was no general decrease in source strengths with increased building age as would be expected if building and interior finish materials and furnishings were the dominant sources of VOC.

SHORT-TERM TEMPORAL VARIATIONS

The variation in the average ventilation rate over the a four-day period (Friday - Monday) from 28-31 October, 1988 is shown in Figure 4. The maximum ventilation rate was approximately 2 h^{-1} , which is near the maximum design value for the building. When the ventilation system and other exhaust fans were off at night, the ventilation rate decreased to about 0.2 h^{-1} , which represents infiltration through the building shell. During this period, the ventilation system was operated on Friday evening until midnight and for 6-8 hours during the day on Saturday and Sunday which was atypical.

The variations in the specific source strengths of TOC, the sum of the individual compounds, and the sum of four Isopar compounds over the four-day period are shown in Figure 5. These source strengths were calculated using concentrations measured in the central return-air shaft and on the roof. Since the chromatograms were dominated by Isopar compounds and the concentrations of only four of these compounds were estimated (Table II), much of the difference in source strengths between TOC and the sum of the individual compounds was probably due to the more than 16 Isopar compounds which were not quantified. The data show that the source strengths on Friday were at a maximum and approx-

imately equal in mid-morning and mid-afternoon. On the following Monday, the mid-morning source strengths significantly exceeded the afternoon values. Source strengths were lowest at night and during the weekend reflecting the low level of occupancy and activity in the building at these times. The specific source strength of TOC during the weekend averaged about $1 \text{ mg/m}^3\text{-h}$ which is equal to a source strength of about $3 \text{ kg}\cdot\text{day}^{-1}$. This compares to an estimated source strength on Friday of about $9 \text{ kg}\cdot\text{day}^{-1}$ and suggests that the major sources of VOC were associated with occupant activities.

Variations in the specific source strengths of the other major classes of compounds over the four-day period are shown in Figure 6. The $\text{C}_9\text{-C}_{14}$ aliphatic hydrocarbons and the chlorinated hydrocarbons had emission profiles which were similar to TOC, suggesting that their sources were also related to occupant activities. The source strengths of the $\text{C}_5\text{-C}_8$ aliphatic hydrocarbons and the aromatic hydrocarbons had somewhat different profiles with elevated mid-morning and low mid-afternoon values on both Friday and Monday. Since it is hypothesized that motor vehicles were the primary source of these compounds, the temporal variations can perhaps be explained by vehicular traffic, the operating cycle of the garage-level exhaust fans and the way the upper and basement levels interact at different ventilation conditions. The mechanisms involved in the interaction of the upper and garage levels are currently being investigated. The high source strength of oxygenated compounds on Sunday was due solely to 2-propanone which may have been used in a maintenance activity.

SPATIAL VARIATIONS

Spatial variations in the concentrations of individual compounds and TOC in the building on Friday, October 28, 1988 are shown in Table II. Samples were collected in the three return-air shafts and in an office cubicle on the fifth floor over a period of about one hour with the building operating at a ventilation rate of 2 h^{-1} . Coefficients of variation for concentrations of individual compounds in the three air shafts were, with several exceptions, less than 10%. Coefficients of variation for the sum of the compounds and TOC were 7 and 8%, respectively. Concentrations in the office were in good agreement with average concentrations in the air shafts. This uniformity of concentrations indicates that the air in the building was well mixed at this ventilation condition. This mixing was aided by the mechanical recirculation of air among the office floors. Mixing at lower ventilation rates with more recirculation of air would be expected to be as good or better.

CONCLUSIONS

The major sources of VOC in this building were related to occupant activities. The predominant compounds were $\text{C}_{10}\text{-C}_{11}$ branched alkanes emitted by liquid-process photocopiers and plotters. Additional predominant compounds were other aliphatic hydrocarbons and aromatic hydrocarbons, many of which may have been emitted by vehicles in the basement levels. Although the concentrations of these compounds as estimated by TOC were relatively high, they were two to three orders of magnitude below occupational threshold limit values for exposures to light hydrocarbons. The potential for the measured concentrations of this mixture of compounds to produce health symptoms characteristic of the "sick building syndrome" is not known since the requisite animal and human studies on low-level sensory irritation and central nervous system effects have not been conducted.

Identification of the sources of VOC is the necessary first step in developing control strategies for VOC in a building. If, for example, it was desired to limit the concentration of TOC in this building to several milligrams per m^3 without modifying source activities, it would be necessary to maintain a ventilation rate in excess of 1 h^{-1} during occupied hours. A more energy-efficient strategy for maintaining low concentrations would be to modify the way

the building's systems handle sources. Since the air in the building is well mixed, this might mean establishing enclosed locations for essential liquid-process office machines with exhaust ventilation directly to the outside. The feasibility and cost of such a retrofit approach has not been studied. When the conditions which allow air from the basement levels to flow into the upper office levels are better understood, strategies to prevent vehicle emissions from impacting air quality can perhaps be devised.

ACKNOWLEDGMENTS

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Table 1. Long-term variations in the concentrations and specific source strengths of individual VOC.

COMPOUND	CONCENTRATION (ug/m3) *				SP. SOURCE STRENGTH (ug/m3-h)				
	Date	8/4/87	10/14/87	1/13/88	10/28/88	8/4/87	10/14/87	1/13/88	10/28/88
	Time	20:00	17-19:00	15-17:00	15-17:00	20:00	17-19:00	15-17:00	15-17:00
Vent. Rate	0.5	1.36	0.24	1.99	0.5	1.36	0.24	1.99	
Oxygenated									
2-Propanol (acetone)	14.8	20.2	137.2	26.5	5.8	21.9	31.6	52.6	
2-Propanone	50.1	28.8	66.6	32.4	22.1	27.0	14.9	49.7	
2-Butanone	40.9	6.2	15.3	5.7	19.0	2.5	2.0	7.6	
Chlorinated									
Dichloromethane	32.4	2.6	13.4	2.7	15.9	1.3	2.7	5.4	
1,1,1-Trichloroethane	13.5	13.8	119.7	17.1	5.4	13.6	27.5	27.0	
Trichloroethene	16.4	7.2	58.2	14.8	8.2	9.7	11.0	27.6	
Aliphatic									
2-Methylbutane	31.9	53.8	81.6	26.2	13.1	31.7	16.1	44.7	
n-Hexane	11.3	10.0	24.0	9.2	5.7	6.7	3.7	14.6	
Cyclohexane	5.7			2.7	2.4			4.2	
n-Heptane	4.8	3.1	12.6	3.6	2.0	2.7	0.2	5.5	
3-Methylhexane	6.0	4.0	14.7	3.5	2.4	3.1	0.0	5.2	
Methylcyclohexane	5.1			1.7	2.4			2.5	
2,2,4-Trimethylpentane	2.4	1.8	8.0	3.0	1.0	1.3	0.7	6.0	
1,4-Dimethylcyclohexane	3.1				1.6				
n-Nonane	39.6	10.6	149.1	33.9	19.7	11.4	35.3	63.0	
2,2,5-Trimethylhexane	2.4				1.2				
Isopar 2 **	147.0	82.5	638.7	95.4	72.8	104.2	151.7	179.7	
n-Undecane	115.6	57.3	831.3	48.3	55.2	71.3	196.8	85.7	
n-Dodecane	49.1	10.6	280.8	10.9	21.8	5.9	67.0	17.6	
n-Tridecane		6.0	111.9	8.5		5.8	26.2	13.8	
n-Tetradecane		36.1	245.3	27.0		43.0	57.9	49.5	
Aromatic									
Toluene	60.4	81.3	91.0	33.1	22.7	80.9	13.7	50.2	
Ethylbenzene	11.8	7.0	18.7	7.5	5.3	4.9	2.3	11.4	
1,2-Dimethylbenzene	17.2	8.7	25.8	8.1	7.6	5.8	4.1	12.0	
1,3-,1,4-Dimethylbenzene		18.1	54.5	18.3		11.7	8.8	26.6	
1,3,5-Trimethylbenzene	4.1				1.6				
TOTALS									
Sum of Individual VOC	685	470	2998	440	315	466	674	762	
Total Organic Carbon	5200	1900	11000	2300	2500	2400	2500	4300	

* Average concentration for return-air shafts

** Estimated concentration using n-decane as standard

Table II. Concentrations of VOC in mechanical system air, indoor air and outdoor air on October 28, 1988.

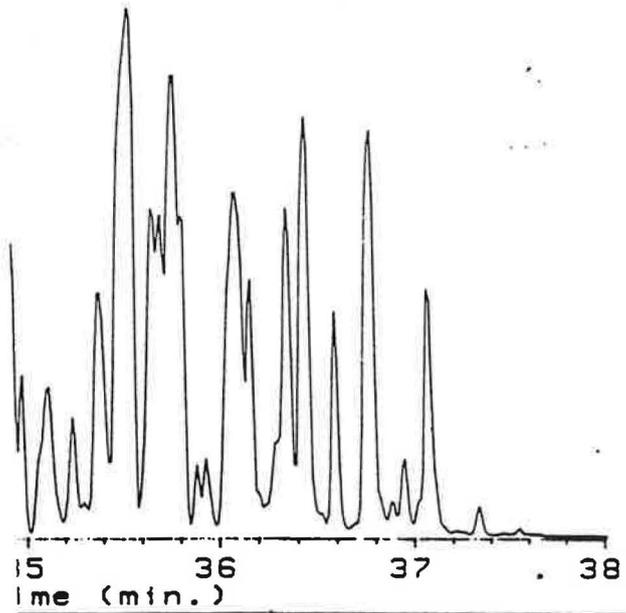
COMPOUND	Time	CONCENTRATION (ug/m ³)				Floor 5 15:38	Roof 14:42
		Return Fans East 15:51	Center 15:16	West 16:25	Return Fan Average		
Oxygenated							
2-Propanol		38.8	19.1	21.5	26.5	13.1	0.0
2-Propanone (acetone)		33.9	31.2	32.2	32.4	27.9	7.4
2-Butanone		5.2	5.3	6.6	5.7	5.0	1.9
Chlorinated							
Dichloromethane		2.8	2.7	2.6	2.7	2.0	0.0
1,1,1-Trichloroethane		15.8	18.3	17.2	17.1	15.0	3.5
Trichloroethene		16.0	15.4	13.1	14.8	15.9	0.9
Aliphatic							
2-Methylbutane		30.2	30.2	18.3	26.2	35.8	3.8
n-Pentane		13.2	17.8	11.5	14.2	21.1	2.7
n-Hexane		9.4	9.7	8.4	9.2	10.9	1.8
Cyclohexane		2.8	2.8	2.4	2.7	3.2	0.6
n-Heptane		3.7	3.8	3.3	3.6	3.6	0.8
3-Methylhexane		3.6	3.5	3.3	3.5	5.1	0.9
Methylcyclohexane		1.8	1.8	1.6	1.7	2.0	0.4
2,2,4-Trimethylpentane		3.1	3.1	2.8	3.0	4.4	0.0
n-Nonane		33.2	40.4	28.0	33.9	37.2	2.2
Isopar 1 *		133.6	155.4	134.3	141.1	139.5	7.7
Isopar 2 *		94.5	110.5	81.1	95.4	98.0	5.1
Isopar 3 *		221.1	240.9	198.2	220.1	250.6	11.1
Isopar 4 *		278.5	297.6	248.1	274.8	306.1	13.9
n-Undecane		52.9	47.7	44.5	48.3	56.2	5.3
n-Dodecane		9.9	12.2	10.6	10.9	13.3	2.0
n-Tridecane		7.3	7.6	10.5	8.5	9.5	1.6
n-Tetradecane		28.3	27.4	25.2	27.0	62.3	2.1
Aromatic							
Benzene		15.3	15.0	15.0	15.1	18.7	4.7
Toluene		33.4	34.8	31.1	33.1	41.0	7.9
Ethylbenzene		7.3	7.8	7.3	7.5	7.8	1.8
1,2-Dimethylbenzene		8.2	8.2	7.9	8.1	10.0	2.1
1,3-,1,4-Dimethylbenzene		18.7	18.2	18.0	18.3	24.0	4.9
Methylethylbenzene		11.4	11.1	11.2	11.2	13.6	2.9
1,2,4-Trimethylbenzene		10.6	10.7	10.5	10.6	12.6	2.7
1,4-Diethylbenzene		8.6	8.7	8.5	8.6	9.1	2.1
TOTALS							
Sum of Individual VOC		1153	1219	1035	1136	1275	105
Total Organic Carbon		2348	2537	2061	2315	2163	143

* Estimated concentration using n-decane or n-undecane as standards

1.4
15.6
11.7
4.9

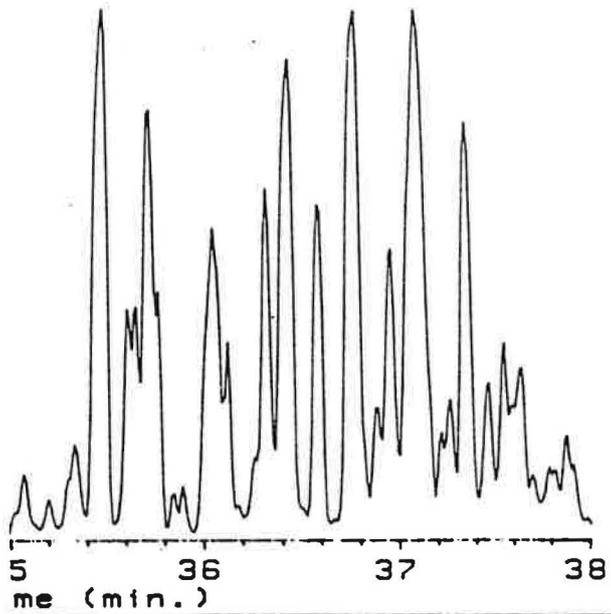
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a



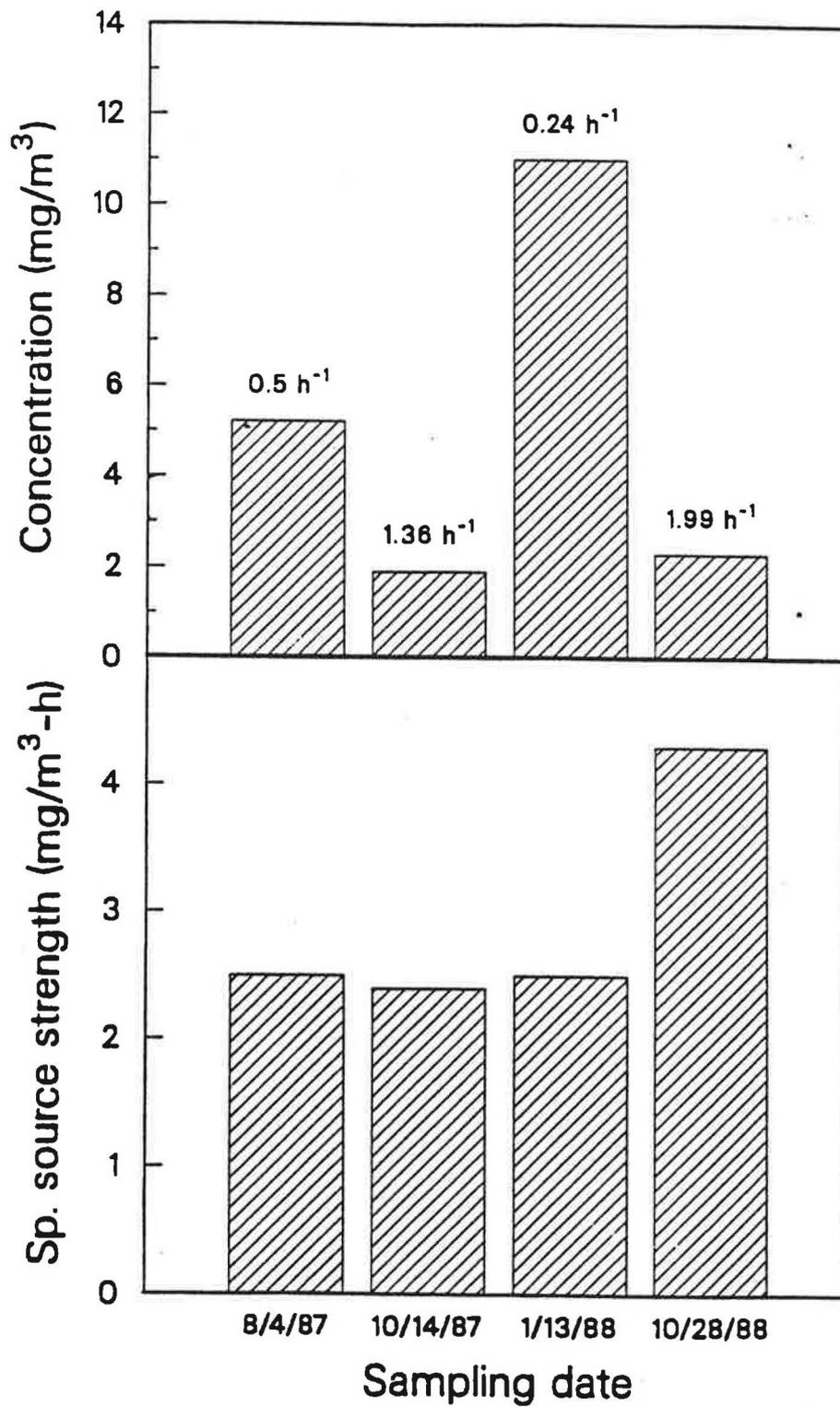
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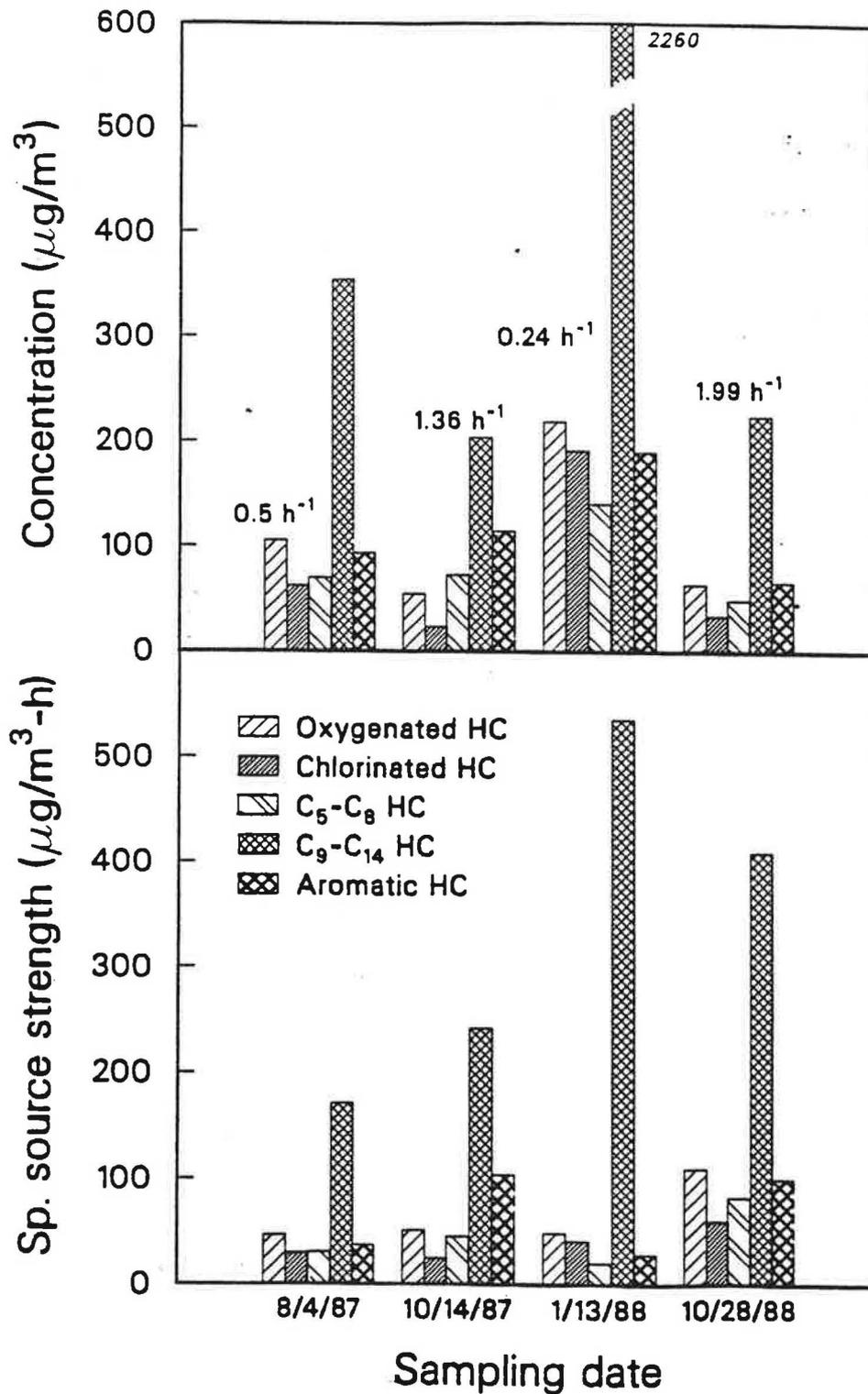
XBL 895-1701

Chromatograms for a dispersant from a liquid-responding portion of an indoor air sample (b).



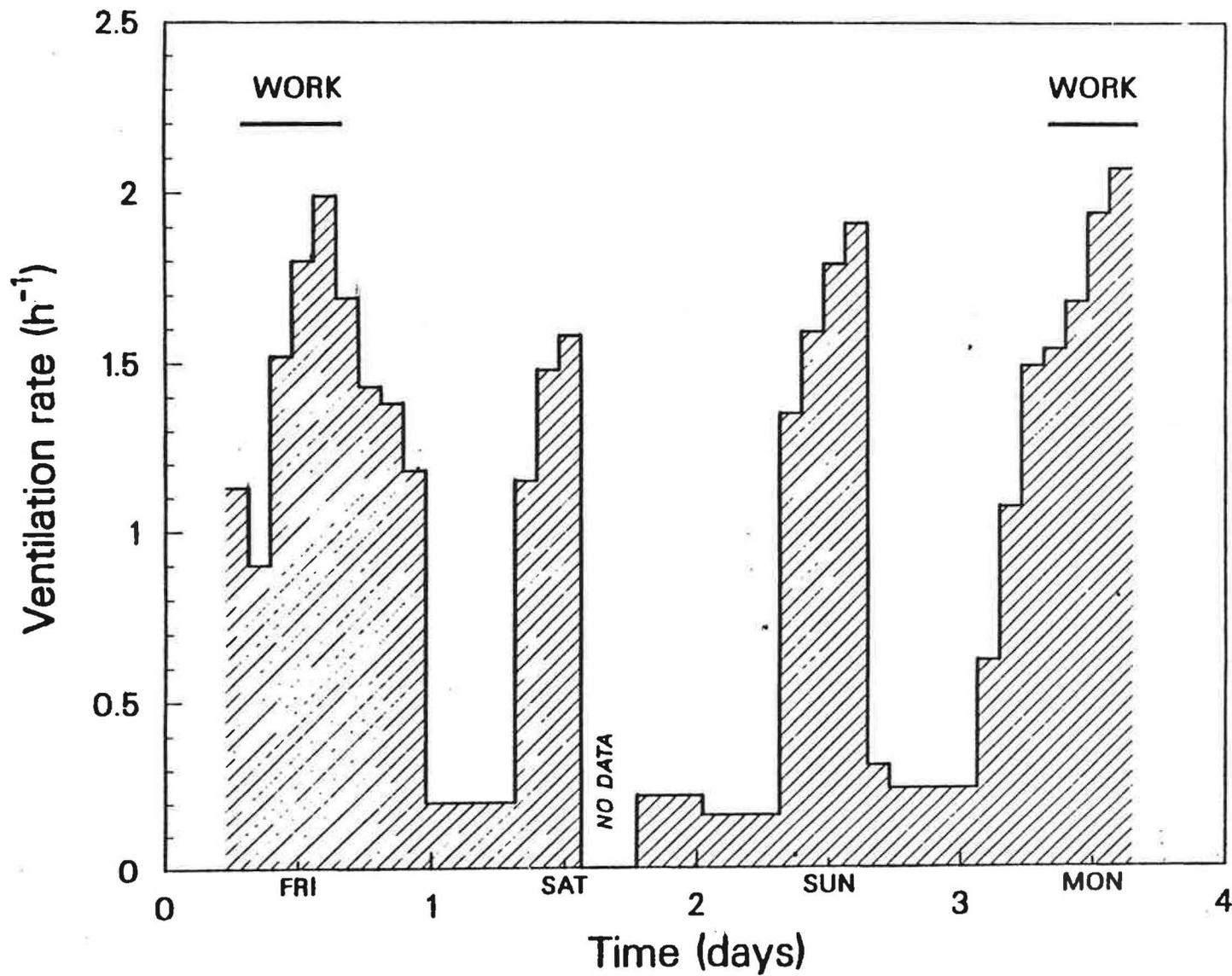
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Figure 2. Long-term variations in the concentration and specific source strength of TOC. Ventilation rates are shown above the concentration bars.



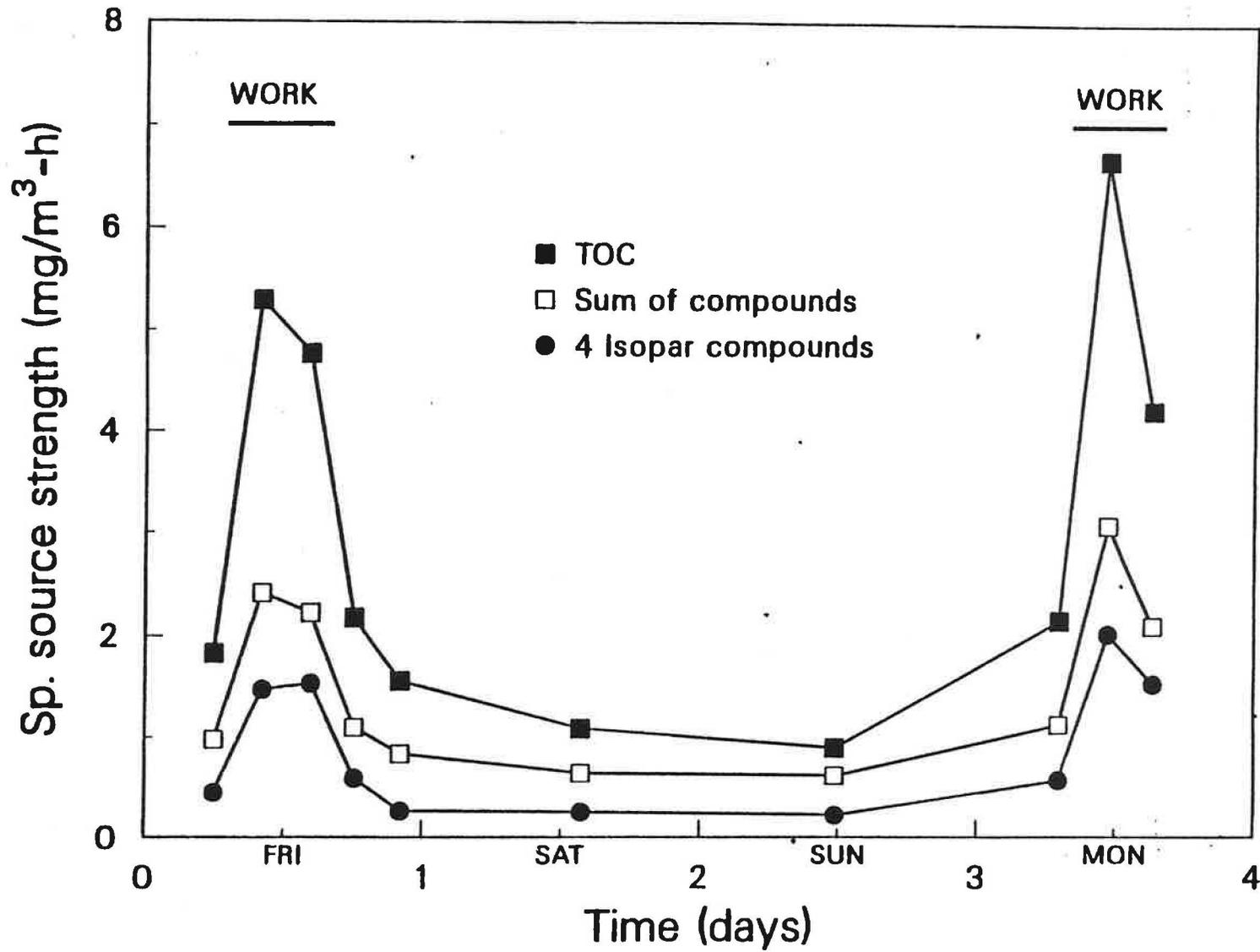
XCG 895-4652

Figure 3. Long-term variations in the concentrations and specific source strengths of the major classes of VOC. Ventilation rates are shown above the concentration bars.



XCG 895-4653

Figure 4. Average ventilation rate over a four-day period (Friday - Monday). Work-day durations are shown as horizontal bars.



XCG 895-4654

Figure 5. Variations in the specific source strengths of TOC, the sum of the individual VOC, and four Isopar compounds over a four-day period. Work-day durations are shown as horizontal bars.