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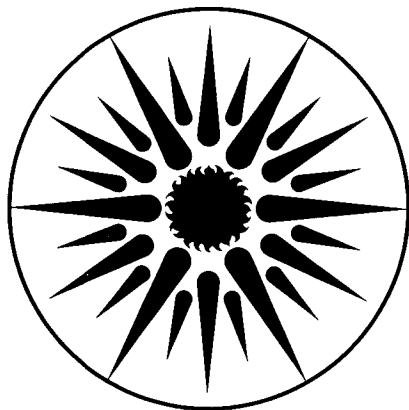
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APPLICATION OF A MULTISORBENT SAMPLING TECHNIQUE FOR INVESTIGATIONS

OF VOLATILE ORGANIC COMPOUNDS IN BUILDINGS

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ABSTRACT: An analytical method for volatile organic compounds (VOC) which employs a multisorbent sampler containing, in series, Tenax-TA, Ambersorb XE-340, and activated charcoal is described. The method was evaluated in the laboratory and was used to measure concentrations of VOC at a school and an office building. The sampler quantitatively collects compounds spanning a broad range of boiling points, including highly volatile solvents. The overall precision of the method is better than ten percent and often better than five percent. The composition and concentrations of VOC in the two, approximately five-month old, non-residential buildings were similar and also similar to the composition and concentrations in typical residential indoor air. Concentrations of VOC were measured at two ventilation rates in both non-residential buildings, and the data were applied to a single-equation mass-balance model. Apparent specific source strengths for VOC approximately doubled with a six-fold increase in ventilation rate.

Introduction

Interest is expanding in measuring concentrations of volatile organic compounds (VOC) in buildings since it is now recognized that many peoples' dominant exposures to these compounds occur in the indoor environment *[1]*. Nevertheless, the data on indoor concentrations of VOC are still limited, and considerably more data are needed before anything more than rudimentary assessments of population exposures can be made. One area of recent concern is that of acute health problems such as mucous-membrane irritation, headache, nausea, and dizziness experienced by some occupants of buildings and hypothesized to be the result of exposures to elevated concentrations of VOC *[2]*. The increasing incidence of this "sick-building syndrome" may possibly be due to the coincidence of several factors such as: 1) the recent high rate of construction of office buildings; 2) efforts to conserve energy usage in buildings by reducing ventilation rates; and 3) the evolution of building practices which now incorporate many synthetic materials such as adhesives, caulks, and fabrics into interiors.

Surveys of concentrations of VOC in indoor air are useful because they contribute to the small but growing data base and provide us with frequency distributions which are necessary for evaluating population exposures *[1]*. Of equal importance to surveys, are detailed studies conducted in single or small groups of buildings in which it is possible to investigate the factors which contribute to concentrations of VOC. There are only a few examples of detailed studies such as investigations of changes in concentrations during the first few months of a building's occupancy *[3,4]*.

A variety of tools are needed to perform both surveys and detailed studies. Most important are quantitative methods for VOC which are rapid, reliable, and relatively inexpensive. In this paper, we describe an analytical method for VOC in ambient and indoor air which employs a commercially available, multisorbent sampler containing, in series, Tenax-

TA, Ambersorb XE-340, and activated charcoal. The method 1) quantitatively collects VOC over a broad range of boiling points, 2) has the high accuracy and precision necessary for detecting small spatial and temporal changes in concentration, and 3) requires relatively low sample volumes making it adaptable to a variety of applications. The method was evaluated in the laboratory and was used to measure concentrations of VOC at a school and an office building in which some occupants had complained of symptoms characteristic of the sick-building syndrome. At both sites, we investigated the effect of ventilation rate on concentrations of VOC.

Experimental

Materials and Methods

All sorbent tube samplers are constructed of glass tubing, 203 mm in length and 6 mm O.D. Multisorbent samplers (Part No. ST032, Envirochem, Inc., Kemblesville, PA) are packed in series with glass beads at the inlet followed by Tenax-TA, Ambersorb XE-340 and activated charcoal in order of increasing affinity for low-boiling compounds. Similar samplers without the charcoal layer were used in some laboratory experiments. The average weights of the sorbent layers are: glass beads - 294 mg; Tenax - 85.5 mg; Ambersorb - 167 mg; and charcoal - 48.0 mg. Tenax samplers (Part No. ST023, Envirochem, Inc.) are packed with glass beads at the inlet followed by ~170 mg of Tenax-TA.

Prior to use, samplers are conditioned by heating to 300°C for 10 min with a helium purge flowing in the reverse direction of gas flow during sample collection. Samplers are sealed at each end with nylon tube caps and Teflon ferrules. Capped samplers are stored at -10°C in elongated culture tubes.

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

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concentrating and inletting system. This instrument passes the sample through dual, sequential traps of decreasing internal diameter to concentrate the sample.

Chromatographic peak shape, peak resolution and peak area response for low-boiling compounds are enhanced with an on-column cryogenic focusing attachment [5]. This device sprays liquid nitrogen directly on a 5-mm section of the capillary column to further concentrate the sample.

The GC is connected via a direct capillary interface to a 5970B series Mass Selective Detector (MSD, Hewlett Packard Co.). For quantitative analyses, the MSD is operated to monitor multiple, individually-selected ions. For each compound of interest, an ion with high relative intensity is chosen as the quantitative ion, and a characteristic ion is chosen as a qualifying ion for confirmation of compound identity.

A standard gas mixture for qualitative or quantitative analyses is prepared by injecting an aliquot of a liquid mixture of the analytes of interest into a helium-filled 2-L flask with a septum cap which is then heated and maintained at 65°C [6].

Air-sampling flow rate in both laboratory and field experiments is typically ~100 cm^3 min^{-1} (20°C, 760 mm Hg). The vacuum source for field samples is provided by a diaphragm pump. Sample flow rates are regulated with electronic mass-flow controllers placed between samplers and the pump. Sample volumes are varied according to estimates of expected analyte concentrations. Typical sample volumes for urban outdoor air are 5 or 10 L. Sample volumes for indoor air are generally lower.

New one-gallon (4 L) paint cans are used as source-isolation and small-volume chambers. Before use they are cleaned by rinsing with acetone and methanol and heating in an oven. Source-isolation chambers are used without lids. They are placed with their open end over the

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source material and are held in place with weights if used in a vertical position or with a clamp and a ring stand if used in a horizontal position. After being held in place for several hours, a sample of chamber air is collected with the multisorbent sampler through a fitting on the bottom of the can. Cans are used with lids equipped with two fittings when employed as dynamic small-volume chambers. The fitting used as an inlet has a tubing extension so that clean air is introduced at the bottom of the chamber near the material being investigated. Air exits the other fitting and can be sampled with the multisorbent sampler.

Laboratory and Field Evaluation

Laboratory experiments for the determination of precision, accuracy, and sample breakthrough volumes were conducted using a 20-m^3 environmental chamber. Prior to an experiment, the chamber was ventilated, then sealed. Samples for the determination of chamber background were collected, and the chamber was spiked to known concentrations with the analytes of interest. Experimental samples were then collected. Breakthrough volumes were determined from the analysis of backup samplers which were placed in series with the samplers being investigated and which were exchanged at predetermined volume intervals.

Field samples were collected at the sites of two relatively new, non-residential buildings. The interior finish work at both buildings had been substantially completed approximately five months prior to sampling. During that period, some occupants of both buildings had complained of symptoms characteristic of the sick-building syndrome including mucous-membrane irritation, headache, nausea, and dizziness. One of these buildings was a small school to which several classrooms had been added. The classroom, which we investigated, had a ventilated volume of 295 m^3. Ventilation rates were determined by tracer-gas decay with the air handling system both on and off. On a single day, air samples for VOC were collected in an adjacent outdoor courtyard and in the classroom at conditions near steady state (i.e., operated at constant ventilation rate for > 3h) with the air handling system both on and off. The other building was a six-story office building with a ventilated volume of

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~36700 m^3. Ventilation rates were calculated for the entire building from air velocity measurements made with a hot-wire anemometer at the building's air inlet vents on the roof. On a single day, air samples for VOC were collected on the roof and indoors in open office spaces at conditions near steady state with the ventilation system drawing in 100 percent outside air and in recirculation mode with ~16 percent outside air.

Results and Discussion

Validation of the Method

The results of the laboratory validation of the analytical method for VOC that employs the multisorbent sampler have been reported in detail [5]. Here we summarize the results pertaining to sample breakthrough volumes, precision, and accuracy.

Breakthrough volume has been defined as the volume at which a significant amount of a constant atmosphere of an adsorbate drawn through a sorbent tube appears in the tube effluent [7]. For this study, significant breakthrough was defined as a loss of more than one percent. The method of direct measurement of breakthrough volume using backup samplers collected at various volume intervals was used because important field sampling parameters such as air temperature, presence of other compounds, and water vapor concentration can be simulated. Breakthrough volumes were only measured for representative low-boiling compounds. Breakthrough volumes of higher boiling compounds can be estimated since, for most compounds, there is a good correlation between breakthrough volume and boiling point [7].

In Table 1, breakthrough volumes for ten low-boiling compounds on samplers with Tenax plus Ambersorb and on samplers with only Tenax are compared at conditions of 21°C, ~50 percent relative humidity and a sample flowrate of 100 cm^3 min^{-1}. Concentrations of the

individual compounds in the chamber were ~240 μg m^{-3}. Trichlorofluoromethane and, to a smaller extent, dichloromethane were the only compounds not quantitatively collected in a 10-L sample by the samplers with Tenax plus Ambersorb. The addition of a charcoal layer in multisorbent samplers increased the breakthrough volume for trichlorofluoromethane to >5 L, while breakthrough volumes for the other compounds exceeded 10 L. Retention of the ten compounds on Tenax alone was considerably smaller, with half of the compounds having breakthrough volumes of less than one liter. Larger amounts of Tenax could be used to increase breakthrough volumes, in which case, proportionally more rigorous cleanup procedures would be required to ensure acceptable sampler blanks. With a sample volume of 10 L and no breakthrough, the limit of quantitation for the method using the multisorbent sampler is expected to be 10 to 50 ng m^{-3} for most compounds. However, for this study, no attempt was made to quantify concentrations much below 0.4 μg m^{-3} with a 5-L sample volume.

The precision and accuracy of the method for the analysis of the same ten compounds is demonstrated in Table 2. Three replicate samples were collected with the multisorbent sampler from the environmental chamber before and after the addition of known concentrations of the compounds. At background concentrations, the precision of the method was better than five percent, with the exception of the analysis of pentanal which was more variable. At concentrations of 194-330 μg m^{-3}, the precision for all compounds was better than 3.5 percent. Comparison of prepared and measured chamber concentrations indicates that the accuracy of the method for seven of the ten compounds was five percent or better. The indicated accuracies for benzene and pentanal were 107 and 88 percent, respectively, for undetermined reasons. The indicated accuracy for trichlorofluoromethane of 119 percent was probably caused by the offgassing of this compound from the polyurethane foam used to insulate the chamber.

Application of the Method

The applicability of the method for the quantitation of a broad range of VOC is

demonstrated by the samples collected indoors and outdoors at the two buildings. Twenty-seven and 42 individual compounds were detected in samples obtained from the classroom site and the office-building site, respectively. Many of the detected compounds were tentatively identified from their mass spectra. Twenty of the compounds, whose identity was confirmed by their retention times, were quantified in selected-ion monitoring mode using multipoint calibration curves. The concentrations at the two sites of 19 of these compounds are presented in Table 3. Data for benzaldehyde were not included since it is a known decomposition product of Tenax [8]. The 19 compounds are ubiquitous components of urban outdoor and indoor air. Alkanes and alkylbenzenes, which derive from petroleum distillate fractions, form the dominant groups. Many of the compounds were detected and occurred in similar concentrations at both sites. The samples include low-boiling solvents such as *n*-pentane with a boiling point of 36°C. Methods which employ Tenax as the only sorbent typically do not quantitatively collect compounds with boiling points below 70-80°C [9,10]

The precision obtained with duplicate samples at both buildings (Table 3) was comparable to, although not quite as good as that obtained in the laboratory. With the exception of analyses for two compounds, precision was better than ten percent. For samples collected at the office building, where sample volumes were more accurately measured than at the school, precision was generally five percent or better. This improvement suggests that precision depends a great deal on the accurate measurement of sample volume. In this study, accurate measurements of volume were achieved by the use of electronic mass-flow controllers.

The existing data on concentrations of VOC in buildings are quite limited, and the majority of these data are for residences rather than for larger buildings. In Table 4, the range of concentrations of the individual compounds measured in the two non-residential buildings are compared to summary data from three surveys of residential indoor air [1,3,9]. Data from at least one survey exist for all but two compounds, acetone and *n*-pentane. Median concentrations for newer Dutch houses and for houses in New Jersey (samples of

overnight air) are used in the comparison. Range data are used for Italian houses since median values were not provided. The indoor air concentrations measured in this study are comparable to the median values and the low range values from the Italian survey. This comparison suggests that concentrations in the classroom and the office building, at the time measured, may be typical for the indoor environment.

The concentrations of VOC when the buildings were first occupied and health complaints started, however, may have been considerably higher than the concentrations measured at the time of this study. Results of measurements of VOC concentrations in 11 Dutch houses before and during the first three months of occupancy showed that hydrocarbons as a class increased dramatically in concentration just after interior finish work was completed to geometric mean concentrations of >7500 μg m^{-3} [3]. After only one month of occupancy, geometric mean concentrations were similar to typical indoor concentrations. The maximum concentrations fall within the range of concentrations that have been shown to have significant irritant effects in sensitive but otherwise healthy individuals [2].

Ratios of indoor (I) concentrations to outdoor (O) concentrations of VOC at the two buildings are calculated in Table 3. These I/O ratios are generally greater than one and in a number of cases approach or exceed ten. These values are typical for indoor environments and indicate contributions from indoor sources for most compounds [3,9]. Two compounds, isopropyl alcohol and dichlorobenzene, have very high ratios reflecting their virtual absence in outdoor air.

High I/O ratios are often indicative of compounds with high source strengths. Therefore, it is instructive to attempt to identify the sources of these compounds. The two major broad categories of sources are consumer products and materials used to finish interiors of buildings [11,12,13]. From experience, we know that aliphatic and aromatic hydrocarbons are emitted by a variety of interior-finish materials and that chlorinated hydrocarbons and terpenes are

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often emitted by consumer products. In the classroom, a bathroom deodorizer was suspected as the primary source of α-pinene and dichlorobenzene, although this was not confirmed by analysis of the deodorizer. Wood products used in the construction of the building were also a possible source of α-pinene. The possible indoor sources of isopropyl alcohol and acetone, two compounds which also had high I/O ratios in this building, were less obvious.

The apparent sources of these two compounds were identified from the analysis of samples collected from source-isolation chambers. Samples of air were drawn from chambers that had been placed over the carpet and over the vinyl base cove for five hours. Concentrations of VOC in these samples are compared to concentrations in room air obtained at the low ventilation rate in Fig. 1. To facilitate comparison, concentrations in each sample have been normalized to the concentration of m,p-xylene in that sample. The figure suggests that the carpet assembly was a source of acetone and that the base cove assembly was a strong source of isopropyl alcohol as well as a possible source of acetone and *n*-pentane.

It is important to investigate concentrations of VOC as a function of ventilation rate in large buildings since ventilation system failures are often implicated in cases of poor indoor air quality in these buildings and ventilation rate is the primary operating parameter available for controlling concentrations of airborne contaminants. Both the classroom and the office building were sampled at conditions near steady state at two different ventilation rates. The high and low ventilation rates varied by a factor of six for both buildings. Concentrations as a function of ventilation rate are presented in Table 3 and Figs. 2 and 3. Since the precision of the method is typically better than ten percent, many of the observed differences are significant. As expected, concentrations of most compounds were highest at the low ventilation rate. However, concentrations only varied by a factor of two to three between the two ventilation rates, not by a factor of six as would be predicted assuming constant source strengths.

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Apparent specific source strengths were calculated for all compounds with indoor concentrations $\geq 1\mu g/m^{-3}$ using a single-equation, mass-balance model. The model, which describes the average volume concentration of a pollutant in an enclosed space, has been used in a variety of indoor air pollution studies [14,15,16]. It assumes perfect mixing so that exfiltrating air and indoor air have the same average pollutant concentrations. The mathematical expression for the change in indoor pollutant concentration is

$$dC = PaC_o dt + \frac{S}{V} dt - (a + k) C dt \qquad (1)$$

where

C = indoor pollutant concentration ($\mu g\ m^{-3}$),

C_o = outdoor pollutant concentration ($\mu g\ m^{-3}$),

P = fraction of the outdoor pollutant level that penetrates the enclosed space (unitless),

a = ventilation rate in air changes per hour (h^{-1}),

S = indoor pollutant source strength ($\mu g\ h^{-1}$),

V = volume (m^3),

k = net rate of removal processes other than ventilation (h^{-1}),

t = time (h).

Assuming that P equals one for gases, that removal processes other than ventilation, k, are negligible, and that C_o and a are constant over the time period, Equation 1 can be integrated between times zero and t to give

$$C(t) = \frac{aC_o + S/V}{a} (1 - e^{-at}) + C(0) e^{-at} \qquad (2)$$

Rearranging (2) to isolate a non-zero source strength gives

$$S = Va\ \frac{C(t) - C(0)e^{-at}}{1 - e^{-at}} - VaC_o \qquad (3)$$

Model results have been expressed as specific source strengths (S/V, μg m^{-3} h^{-1}) to facilitate comparisons between the two buildings.

Provided the essential parameters are known or can be estimated, the mass-balance model is a much more powerful tool for examining the indoor sources of VOC than the simplistic I/O ratio. A different picture of the relative source strengths of the compounds emerges from the model (Figs. 2 and 3) than from the I/O ratio (Table 3). The model reveals that the indoor sources of acetone were relatively higher in each building than the I/O ratios for this compound suggest and that the sources of dichlorobenzene and 1,1,1-trichloroethane were relatively lower. Also, it is apparent that specific source strengths for individual compounds were generally much higher in the office building than in the classroom.

For many compounds in both buildings, the apparent specific source strengths were highest at the high ventilation rate. The dependence of source strengths on ventilation rate might be expected for compounds emitted from materials in which most of the resistance to mass transfer is in the air above the materials rather than in the materials themselves. Decreases in the concentrations of the compounds in the bulk air and possible decreases in the thicknesses of boundary layers over the materials at high ventilation rates could result in increased source strengths. Such a dependence of source strength on bulk air concentration has been observed for formaldehyde emitted from particle board [17]. However, for many compounds and materials, it is more plausible that the majority of the resistance to mass transfer is in the materials rather than in the air. In this case, ventilation rate should have little or no effect on source strengths. Therefore, an alternate explanation for the observed dependence of source strengths on ventilation rate in the two buildings might be that ventilation efficiency within the spaces was low at the high ventilation rate.

Source strengths are perhaps best defined in laboratory studies where the important parameters affecting emissions can be controlled. Source strengths of VOC from materials and

material assemblages can be determined in small-volume (4 L) chambers if small representative samples of the materials can be prepared. There remains, of course, the problems of translating results obtained in chambers to actual in buildings due to differences in loading factors, mixing, and other parameters. In this study, we measured emissions from a water-based carpet adhesive and from an assemblage consisting of the same adhesive and a two-year-old carpet. These materials were prepared on aluminum plates and were allowed to age in a fume hood for nine days before being transferred to chambers supplied with clean air. Material loading in the chambers was 2.5 m^2 m^{-3}. Samples for VOC were collected from the chambers with the multisorbent sampler at conditions near steady state at ventilation rates of 0.2, 1, and 5 h^{-1}. The emissions from the materials consisted of aliphatic, alicyclic and aromatic hydrocarbons as well as a group of unidentified compounds. Source strengths were calculated for the identified compounds using the mass-balance model. Since actual concentrations were not available for all compounds, the data for each compound were normalized to the source strength of that compound for the adhesive alone at a ventilation rate of 0.2 h^{-1} (Fig. 4). For the adhesive alone, there was a definite increase in source strengths for all but the aromatic compounds with increasing ventilation rate and decreasing chamber concentration. Source strengths increased by a factor of roughly 1.5 when ventilation rate changed from 0.2 to 1 h^{-1} and by a factor of almost two when ventilation rate changed from 1 to 5 h^{-1}. This suggests that for the adhesive without an overlying material, the source strengths of the compounds were largely determined by mass-transfer resistance in the air. The source strengths at 0.2 h^{-1} for eight of the twelve compounds were lower for the assemblage of adhesive and carpet than for the adhesive alone. In addition, the effect of ventilation rate on source strengths was much less pronounced for the assemblage presumably because mass-transfer resistance was greater in the carpet than in the air.

Conclusions

The analytical method for VOC employing the multisorbent sampler is well suited for detailed investigations of VOC in buildings. The method was successfully used to measure concentrations of VOC in ambient air, indoor air, and small-volume chambers. The multisorbent sampler quantitatively collects compounds spanning a large boiling-point range, including highly volatile solvents with boiling points as low as 36°C. In comparison, samplers employing Tenax alone typically do not quantitatively collect compounds with boiling points below 70-80°C. The analytical method is inherently precise, and when sample volumes are carefully controlled and measured, the precision of the overall method is better than ten percent and often better than five percent. This level of precision is necessary in order to measure temporal and spatial variations in VOC concentrations that are often of interest in chamber studies and in detailed investigations of buildings. Since a sample collected on the multisorbent sampler is concentrated and injected in almost its entirety onto the chromatographic column, only relatively small sample volumes are required (typically 1-5 L). This makes the sampler well suited for chamber studies where the volume of chamber effluent to be sampled may be limited. In addition, sampling times are correspondingly short which is useful for characterizing temporal variations in concentrations.

Using the multisorbent sampler, we were able to characterize concentrations of VOC in two buildings, identify compounds which had high indoor source strengths, determine *in-situ* the source of several of these compounds, and investigate changes in apparent specific source strengths with ventilation rate. In both a classroom and an office building, an increase in the apparent specific source strengths of many VOC was observed with an increase in ventilation rate. In general, these source strengths approximately doubled with a six-fold increase in ventilation rate. The cause of the changes in source strengths was undetermined and is a topic for further investigation. The implication of the non-linear response of concentrations of VOC to ventilation rate is that increased ventilation may not be as effective in reducing at

least short-term concentrations as would be predicted by a simple mass-balance model which assumes perfect mixing and constant source strengths. On the other hand, sources might be depleted faster at higher ventilation rates.

Acknowledgments

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TABLE 1 — *Breakthrough volumes for low-boiling compounds.*

Compound	Boiling Point, deg C	Breakthrough Volume[a], L	
		Tenax Sampler	TA[b] Sampler
Trichloroflouromethane	24	<0.5	<4
n-Pentane	36	<0.5	>10
Dichloromethane	40	<0.5	8-10
n-Hexane	69	1-2	>10
2-Butanone	80	1-2	>10
Chloroform	62	1-2	>10
Ethyl acetate	77	>4	>10
1,1,1-Trichloroethane	74	<0.5	>10
Benzene	80	2-4	>10
Pentanal	102	0.5-1	>10

[a]Breakthrough is loss of >1% of analyte.
[b]Sampler with Tenax plus Ambersorb.

TABLE 2 — *Precision and accuracy for low-boiling compounds using a sampler containing Tenax plus Ambersorb.*

| Compound | Concentration in Chamber, μg m^{-3} | | | Accuracy, % |
	Background	Prepared	Measured	
Trichlorofluoromethane	9.9 (0.1)[a]	277	330 (1.1)[a]	119
n-Pentane	4.6 (1.5)	229	223 (2.5)	97
Dichloromethane	3.3 (1.5)	240	228 (2.3)	95
n-Hexane	2.0 (2.5)	238	246 (3.2)	103
2-Butanone	2.2 (3.2)	218	218 (3.4)	100
Chloroform	---[b]	265	257 (3.1)	97
Ethyl acetate	0.4 (7.5)	241	246 (2.5)	102
1,1,1-Trichloroethane	6.1 (4.8)	245	255 (1.0)	104
Benzene	3.6 (4.4)	239	256 (3.0)	107
Pentanal	3.2 (4.0)	220	194 (3.0)	88

[a]Mean and (relative standard deviation, %) for triplicate samples.
[b]Below limit of quantitation.

TABLE 3 —*Comparison of indoor and outdoor concentrations of VOC at the site of a classroom and an office building. Indoor concentrations were measured at two ventiatlion rates.*

	CLASSROOM Concentration, μg m^{-3}				OFFICE BUILDING Concentration, μg m^{-3}			
Compound	Outdoor	Indoor 1.55h^{-1}	0.26h^{-1}	I/O[a]	Outdoor	Indoor 4.52h^{-1}	0.75h^{-1}	I/O
Isopropyl alcohol	---[b]	23.3(6.0)[c]	73.0	>73	---	---	---	
Acetone	6.5	23.8(9.8)	36.3	6	5.2	16.9(5.4)	30.5	6
Methylethylketone	---	---	---		5.0	20.1(0.7)	63.5	13
1,1,1-Trichloroethane	---	---	---		1.0	5.5(1.3)	12.6	13
Trichloroethylene	---	---	---		---	---	7.2	>7
m,p-Dichlorobenzene	---	3.1(4.5)	9.2	>9	---	---	---	
n-Pentane	4.9	5.6(8.8)	11.7	2	0.9	3.5(2.0)	1.8	4
n-Hexane	3.1	3.4(14)	4.8	2	---	2.1(3.3)	---	>2
3-Methylhexane	2.0	2.1(6.7)	3.9	2	0.4	1.4(5.0)	---	4
n-Heptane	2.0	1.6(4.4)	8.0	4	---	---	---	
n-Decane	---	---	---		2.4	2.4(2.9)	3.6	2
n-Undecane	---	---	---		---	5.0(0)	5.5	>6
Methylcyclohexane	1.4	1.4(5.0)	---	1	0.6	---	---	<1
Benzene	5.8	6.0(5.8)	12.0	2	6.7	6.9(3.0)	2.8	1
Toluene	13.2	15.0(4.3)	27.0	2	4.3	11.4(2.5)	12.0	3
Ethylbenzene	2.7	3.0(4.7)	4.2	2	0.9	4.3(3.3)	10.1	11
m,p-Xylene	10.0	11.2(4.4)	20.6	2	3.2	17.1(1.6)	43.0	13
o-Xylene	3.7	4.1(3.4)	6.6	2	2.4	6.0(2.3)	15.2	6
α-Pinene	---	12.1(13)	33.9	>34	---	---	---	
TOTAL	55	116	251	5	33	103	208	6

[a]Ratio of highest indoor concentration to outdoor concentration.
[b]Not detected or less than ~0.4 μg m^{-3}.
[c]Mean and (relative standard deviation, %) for duplicate samples.

TABLE 4 — *Comparison of the range of indoor concentrations of VOC measured in a classroom and an office building to summary statistics for concentrations measured in three surveys of residences.*

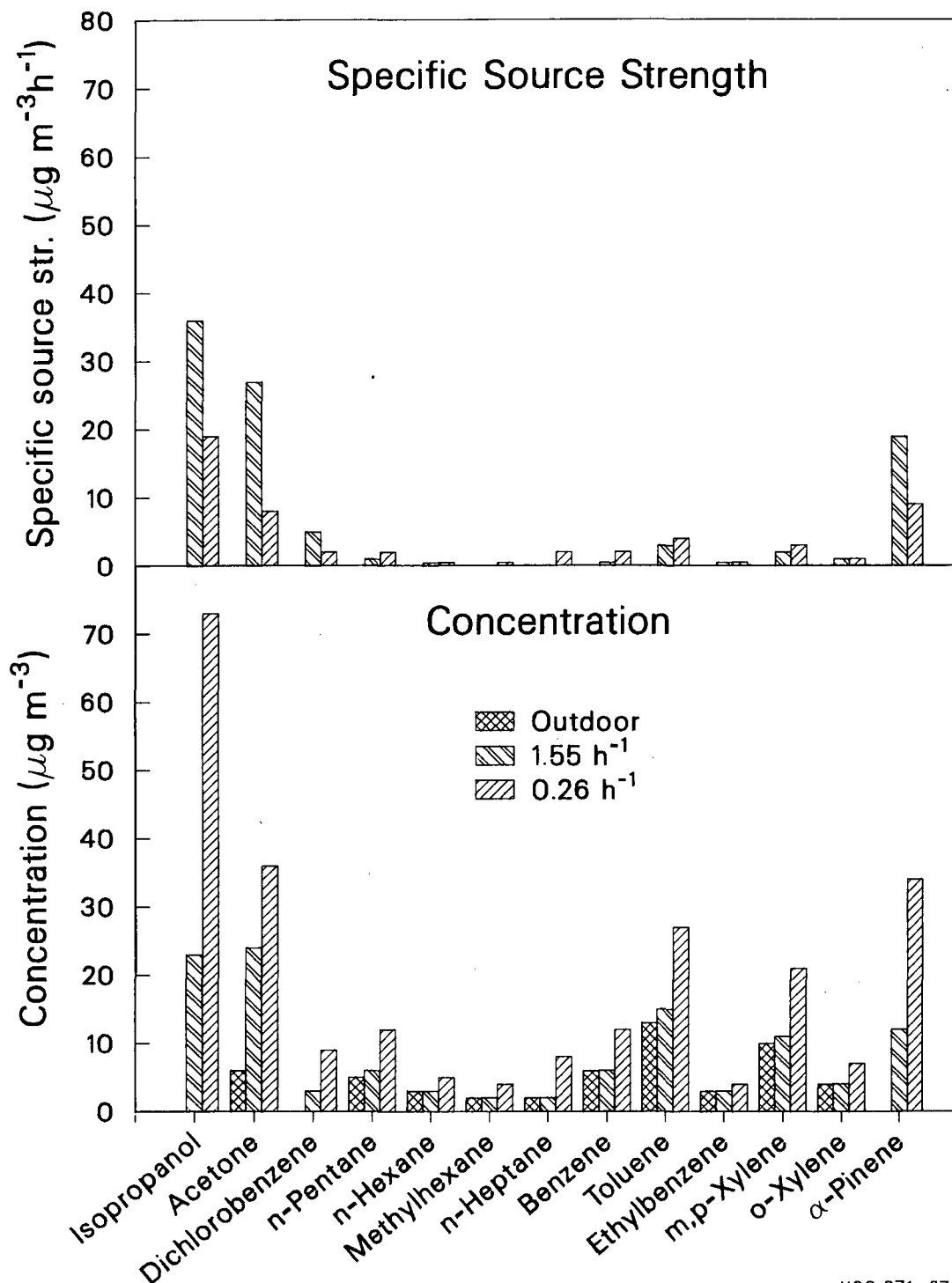|	Indoor Concentration, μg m^{-3}			
	This Study, 2 Buildings Range	15 Italian Houses[a] Range	96 Dutch Houses, <6 yr[b] Median	348 Persons, Overnight Air[c] Median
Acetone	17–36	3–157		
Methylethylketone	<1–64	<2–38		
1,1,1-Trichlorethane	<1–13	4–60		16
Trichloroethylene	<1–7	1–86	<2	2
m,p-Dichlorobenzene	<1–9	<5–230	<1	3
n-Hexane	<1–5	3–590	3	
3-Methylhexane	<1–4		1	
n-Heptane	<1–8	1–76	2	
n-Decane	<1–4	2–1100	14	
n-Undecane	<1–6	<1–950	9	
Methylcyclohexane	<1–1		1	
Benzene	3–12	5–204	5	13
Toluene	11–27	17–378	43	
Ethylbenzene	3–10	<2–109	2	6
m,p-Xylene	11–43	6–390	10	16
o-Xylene	4–15	4–132		5
α-Pinene	<1–34	<1–605		

[a]DeBortoli, *et al.* *[Ref. 9]*.
[b]Lebret, *et al.* *[Ref. 3]*.
[c]Wallace, *et al.* *[Ref. 1]*.
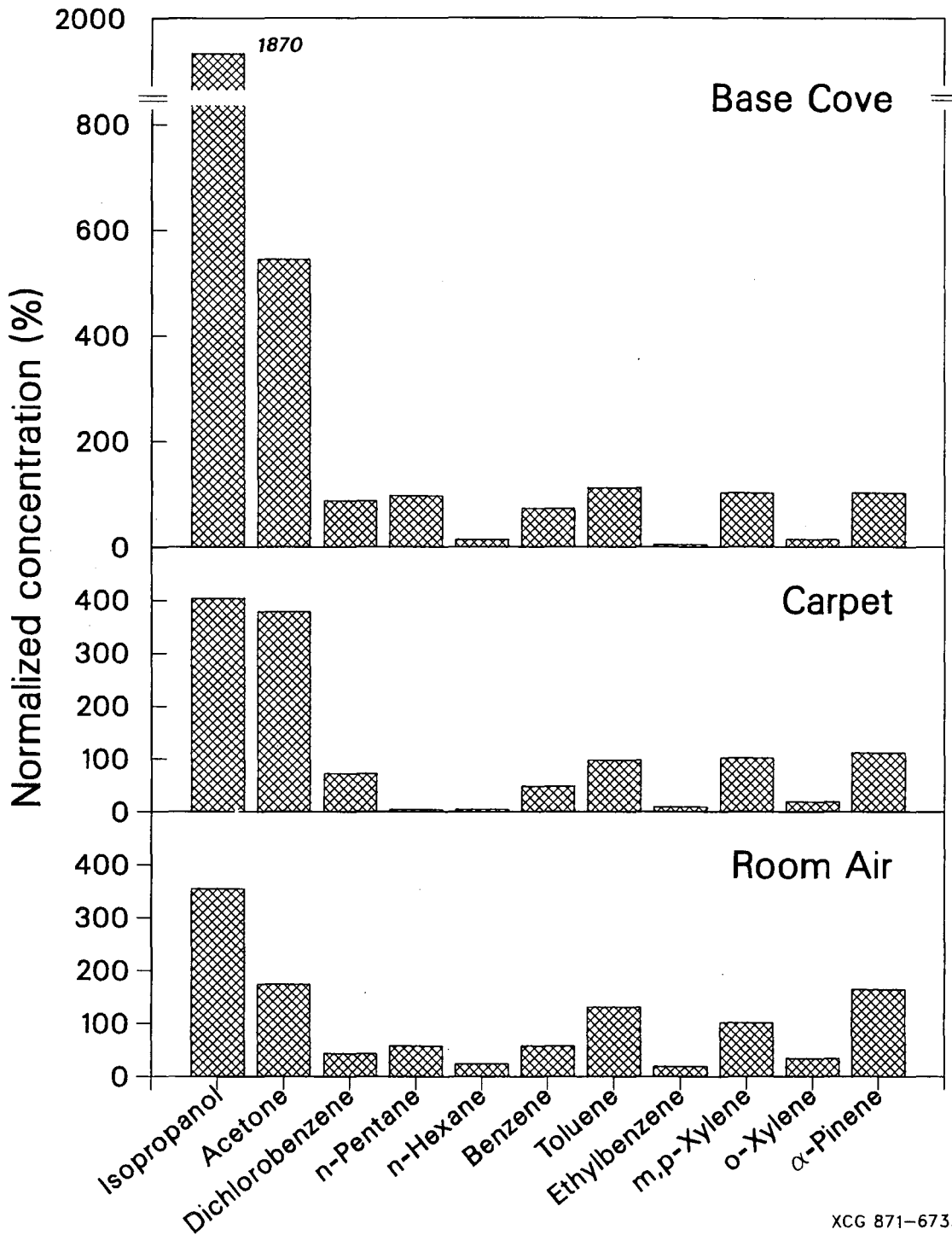
FIG. 1 — *Comparison of concentrations of VOC in room air and in source-isolation chambers placed over the carpet and the vinyl base cove in a classroom. Concentrations in each sample are normalized to concentrations of m,p-xylene in that sample.*

FIG. 2 — *Concentrations of VOC in outdoor air and in indoor air at two ventilation rates at a classroom. Apparent specific source strengths for VOC were calculated for the two ventilation rate conditions using a mass-balance model.*
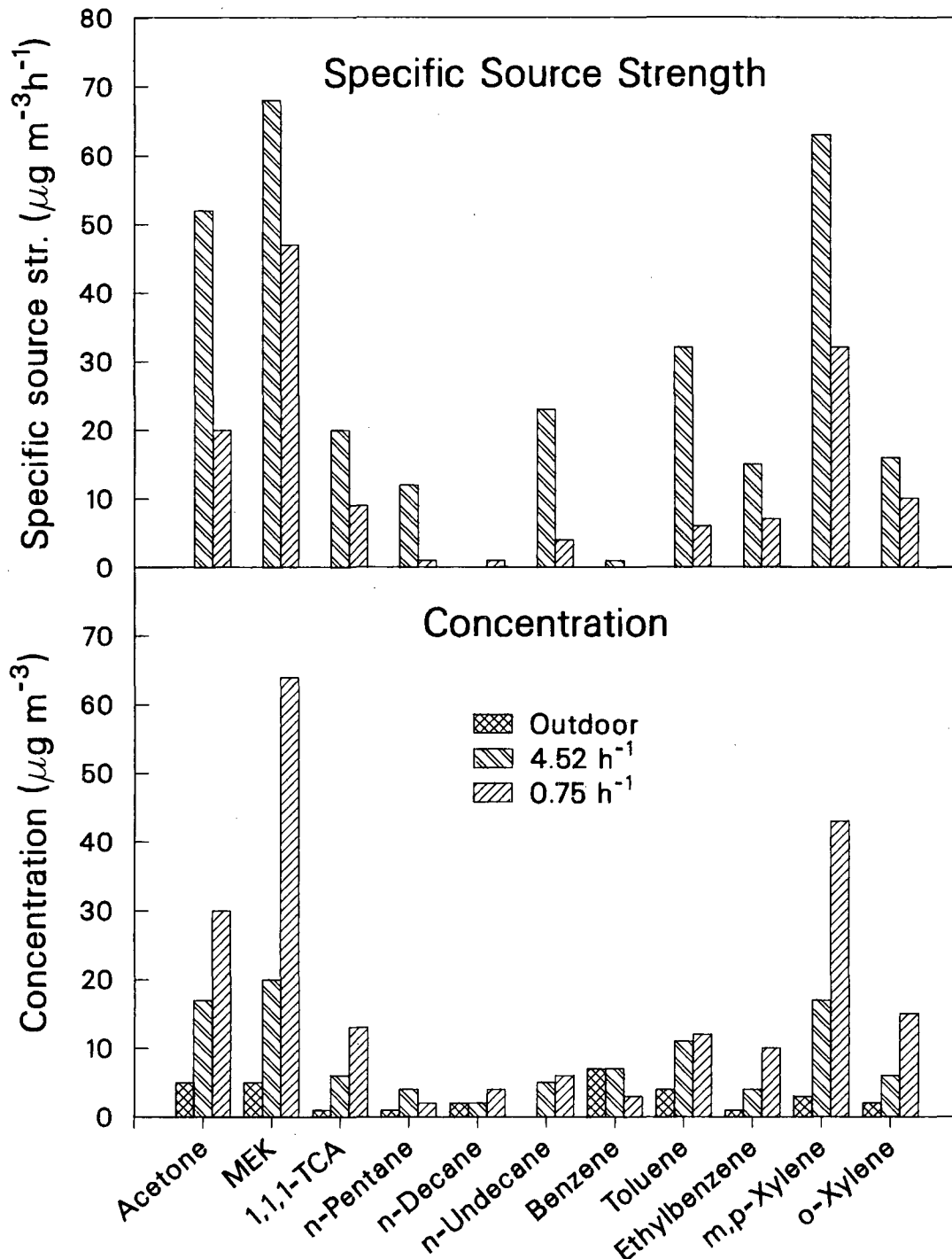
FIG. 3 — *Concentrations of VOC in outdoor air and in indoor air at two ventilation rates at an office building. Apparent specific source strengths for VOC were calculated for the two ventilation rate conditions using a mass-balance model.*
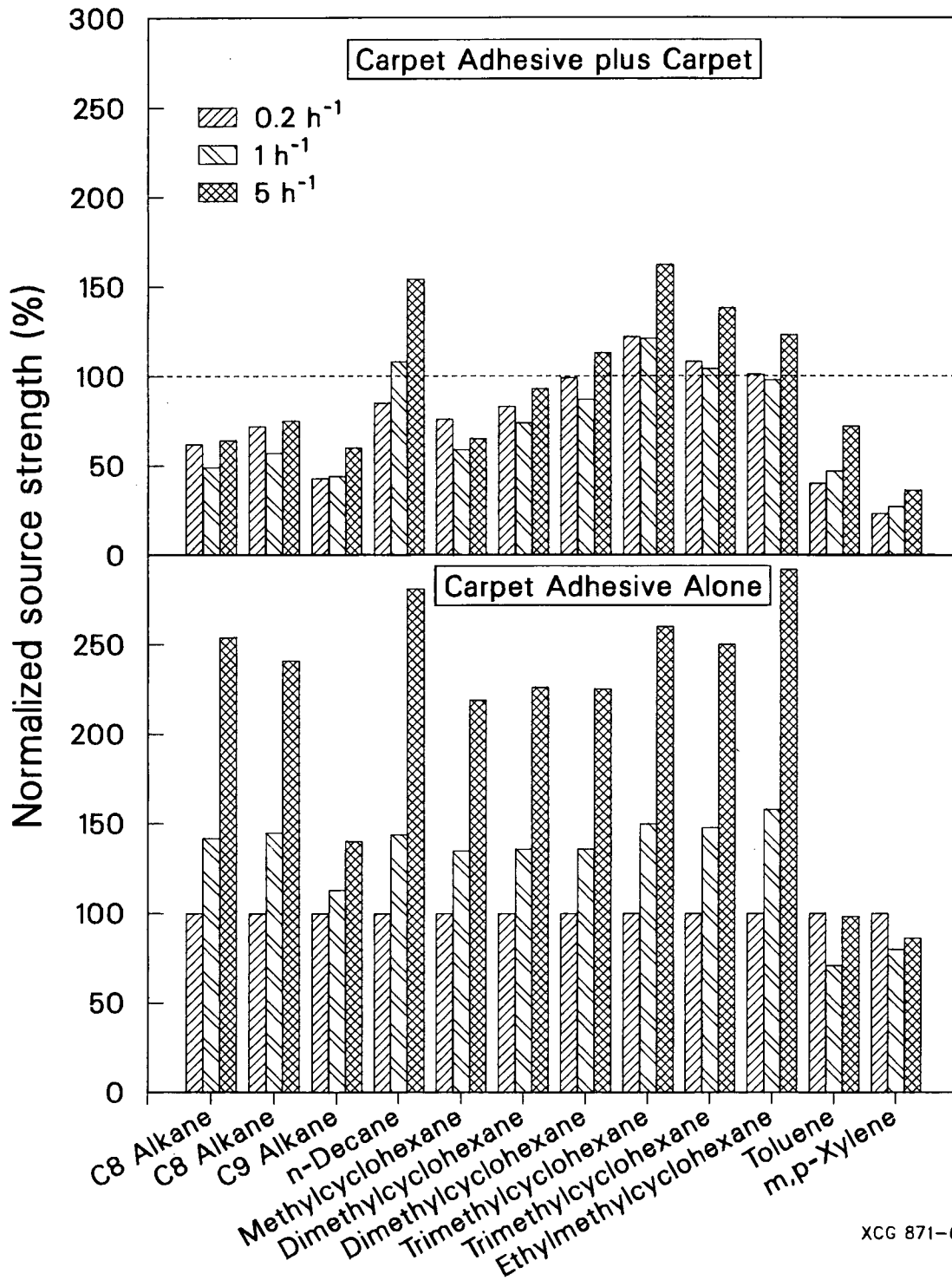
FIG. 4 — *Source strengths of VOC emitted by a carpet adhesive and by an assemblage of the adhesive plus carpet at three ventilation rates. Source strengths for each compound are normalized to the source strength of that compound for the adhesive alone at 0.2 h^{-1}.*

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