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Project Summary

Indoor Air Quality in Public Buildings: Volume I

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This report documents the first of two studies of indoor air quality in public buildings carried out by the U.S. Environmental Protection Agency in response to public and Congressional concern. A total of 10 buildings were studied in the program. A report on the last six buildings studied (Sheldon 1988) is being published simultaneously with this report, which deals with the first four buildings investigated.

This Project Summary was developed by EPA's Office of Acid Deposition, Environmental Monitoring and Quality Assurance, Washington, DC, to announce key findings of the research project that is fully documented in a separate report of the same title. (See Project Report ordering information at back).

Introduction

In 1982, Congress mandated that the U.S. Environmental Protection Agency (EPA) carry out a study of indoor air quality. Because very little was known at that time about volatile organic chemicals (VOCs) in indoor air, it was decided to concentrate the study on this class of compounds, which includes a number of carcinogenic and mutagenic species (benzene, tetrachloroethylene, etc.).

These compounds were being extensively studied in private homes in EPA's ongoing Total Exposure Assessment Methodology (TEAM) Study (Wallace 1987); therefore it was decided to concentrate on buildings rather than homes. Buildings where people spend long periods of time were selected for study: schools, homes for the elderly, and office buildings. These buildings also contain populations (children, the elderly) that may be more sensitive to air pollutants.

Study Design

The goals of the study were the following:

1) Identify all VOCs collected by the available methodology (Tenax absorbent, GC-MS detection) on a subset of samples, both outdoor and indoor.

2) Quantify a set of target VOCs, selected on the basis of their potential health effects, production volume, and amenability to collection on Tenax, in all samples.

3) Determine the effect of aging on the concentrations of VOCs within a newly constructed building.

4) Measure emissions of VOCs from building materials and processes.

5) Measure concentrations of inhalable particles, including metals, and air exchange rates in all buildings.

Four buildings were selected for study: two homes for the elderly in Washington, DC; an elementary school in Washington DC; and an office building scheduled to be constructed in Research Triangle Park, NC. The first three buildings were monitored once only, but the new office building was monitored three times: immediately following completion of construction; two months later (after the occupants moved in); and again five months after completion of construction.

Each monitoring visit lasted two or three days. From three to five indoor sites were selected and one outdoor site (near the air intake for the building) was monitored over consecutive 12-hour periods. Air exchange rates were determined for each 12-hour period by injecting sulfur hexafluoride (SF_6)

into the building ventilation system and measuring the decay in concentration.

Measurement Methods

Measurement methods are described fully in the report. Following is a brief description.

1) *Volatile organics.* Air samples were collected in cartridges containing 1.5 g of 35/60 mesh Tenax™. 20 liters of air were sampled over each 12-hour period. Thermal desorption was followed by GC-MS analysis.

2) Particles. Inhalable particles including both the fine (<2.5μ) and coarse (2.5-10μ) fractions were collected on dichotomous samplers (using virtual impaction) and on samplers designed for EPA by the National Bureau of Standards (using stack filters). The filters were weighed by microbalance and analyzed for metals by proton-induced x-ray emission (PIXE).

Near-real-time particle measurements using the Piezobalance™ were made at some buildings to document short-term variations in particles caused by sources such as smoking.

3) *Emissions from materials.* Headspace vapors from heated materials in belljars were collected on Tenax cartridges and analyzed by GC-MS for the target compounds. Several materials (paints, wallpaper, carpet, adhesives) were then selected for analysis of emissions in a room-size chamber (Pierce Foundation, Yale Univ.). Materials were aged for one week, placed in the chamber and allowed to equilibrate for 24 hours, and their organic emissions were then collected on triplicate Tenax cartridges and analyzed by GC-MS. One chamber experiment used cleaning materials and an insecticide collected from the supplies in the office building. A technician applied detergent, chlorine bleach scouring powder, and the spray insecticide at intervals during the sampling period in the chamber.

Quality Assurance

Three blank Tenax cartridges from each Tenax batch employed in the six monitoring visits were analyzed for the target pollutants. Three additional cartridges were spiked with known amounts of the target compounds and carried to the field and returned unexposed; these were then analyzed to determine recovery efficiencies. Deuterated compounds were loaded on some cartridges as a further check on recovery efficiency. Ten percent of exposed cartridges were collected in duplicate to determine sampling precision.

Results

Quality Assurance

Blank levels were low for all chemicals except benzene. Median recovery efficiencies averaged 102% for all chemicals. Precision of duplicate samples averaged ± 25% (Table 1).

Qualitative Identifications

A total of 16 samples (12 indoor, 4 outdoor) were analyzed to identify a broad spectrum of VOCs occurring in the four buildings. More than 500 chemicals were identified. Those appearing most often include aliphatic, aromatic, and chlorinated compounds (Table 2).

A typical air sample contained 100-200 compounds. Of these, about 50 compounds per sample were unique to that sample. Indoor samples were normally more complex than outdoor samples.

Quantitative Results

A total of 165 Tenax samples were collected. All four buildings had higher concentrations of VOCs indoors than outdoors. For the three older buildings, the indoor-outdoor ratio of total organics was about 2 or 3 to 1. However, this ratio was nearly 50 to 1 for the new office building immediately following construction. After two months, this ratio dropped to about 10 to 1 and after an additional three months, the ratio was about 5 to 1. Chemicals at elevated levels in the new building included aromatic compounds such as xylenes and ethylbenzene, and aliphatic compounds such as decane and undecane (Table 3).

Emissions from 16 materials collected from the new office building were measured on a semiquantitative basis using headspace analysis. Between 13 and 111 organic chemicals were identified from each material. Common emissions included xylenes, ethylbenzene, decane and undecane, and 1,1,1-trichloroethane. All but one of the 15 target chemicals were emitted by one or more of the materials. (The one exception was tetrachloroethylene.)

Emission rates determined from the chamber studies are displayed in Table 4. The mixture of cleaning agents (liquid detergent and a chlorine bleach scouring powder) and a spray pesticide produced large quantities of chlorinated compounds, whereas the paint, carpet, and adhesives produced primarily aromatic and aliphatic compounds.

Fine particle mass averaged over 24-hour periods ranged from 30-100 $\mu g/m^3$ in smoking areas, compared to 10$\mu g/m^3$ in nonsmoking areas, (Table 5). Short-term measurements using the Piezobalance™ documented much higher concentrations (nearly 300 $\mu g/m^3$) during smoking episodes in a smoking lounge (Figure 1).

Air exchange measurements showed typical ranges of 0.5 to 1 air change per hour for two buildings (Table 6). One building, a home for the elderly, had consistently high air exchange rates due to high negative pressures created by excessive heating and very cold winter temperatures.

Table 1: *Recoveries, Blank Levels, and Precision for Target Volatile Organics*

Chemical	*Recoveries[a] (%)*	*Blank Levels[a] (ng/cartridge)*	*Median RSD[b] (%)*
Chlorinated			
Chloroform	*96*	*5*	*31*
1,2-Dichloroethane	*102*	*ND[c]*	*7*
1,1,1-Trichloroethane	*104*	*12*	*31*
Trichloroethylene	*99*	*2*	*20*
Tetrachloroethylene	*95*	*ND*	*16*
p-Dichlorobenzene	*109*	*2*	*20*
Carbon Tetrachloride	*97*	*ND*	*23*
Aromatic			
Benzene	*80*	*36*	*35*
Styrene	*109*	*6*	*40*
Ethylbenzene	*111*	*2*	*23*
o-Xylene	*104*	*1*	*25*
m+p-Xylene	*104*	*4*	*25*
Aliphatic			
Decane	*120*	*ND*	*30*
Undecane	*105*	*4*	*22*
Dodecane	*98*	*2*	*22*
Mean for all Chemicals	*102 ± 9*	*5 ± 9*	*25 ± 8*

[a] *Median of 18 triplicate determinations.*
[b] *Relative standard deviation (N = 17 duplicates)*
[c] *Not detected.*

Table 2: *Most Common Organic Compounds at Four Buildings*

Class/Compound	n[a]		N[b]
Aromatic Hydrocarbons		Aliphatics	
benzene	16	*undecane*	10
toluene	16	*2-methylhexane*	9
xylenes	16	*2-methylpentane*	9
styrene	16	*3-methylhexane*	9
ethylbenzene	16	*3-methylpentane*	9
ethyl methyl benzenes	16	*octane*	9
trimethyl benzenes	16	*nonane*	9
dimethylethylbenzenes	15	*decane*	9
naphthalene	15	*dodecane*	9
methyl naphthalenes	15	*tridecane*	9
propylmethylbenzenes	14	*methylcyclohexane*	9
n-propyl benzene	13	*heptane*	8
diethyl benzenes	12	*tetradecane*	8
		2-methylheptane	8
Halogenated Hydrobarbons		*cyclohexane*	8
Tetrachloroethylene	16	*pentadecane*	7
1,1,1-trichloroethane	15	*4-methyldecane*	7
trichloroethylene	14	*2,4-dimethylhexane*	7
dichlorobenzenes	12	*pentane*	6
trichlorofluoromethane	12	*hexane*	6
dichloromethane	11	*eicosane*	6
chloroform	10	*3-methylnonane*	6
		1,3-dimethyl-cyclopentane	6
Esters			
ethyl acetate	8		
m-hexyl butanoate	4		
Alcohols			
2-ethyl-1-hexanol	9		
n-hexanol	8		
2-butyloctanol	7		
n-dodecanol	6		
Aldehydes			
n-nonanal	13		
n-devanal	10		
Miscellaneous			
acetone	16		
acetic acid	10		
dimethylphenols	6		
ethylene oxide	4		

[a] *Number of samples (of 16) with compound present.*
[b] *Number of samples (of 10) with compound present.*

Discussion

Of the 500 chemicals identified in the four buildings, about half were found only once, suggesting the presence of many small sources rather than a few dominant ones. Aliphatic hydrocarbons formed the most populous category of chemicals, with aromatic hydrocarbons and chlorinated hydrocarbons forming the next most populous categories. Alcohols, acids, ketones, aldehydes, and esters were also prevalent. It should be noted that the observed chemicals did not include organics more volatile than hexane or less volatile than dodecane. Moreover, most polar compounds were also not collected by the methodology employed. Thus the observed VOCs were only a portion of the total VOCs present.

As observed in the TEAM Study of individual homes (Wallace, 1987a), indoor concentrations of VOCs in buildings exceed outdoor concentrations for all of the prevalent target chemicals. The TEAM Study findings implied that the source of the higher indoor concentrations might be emissions from building materials, consumer products, or indoor processes such as cleaning or smoking. The present study documents that the 19 materials and several processes studied emit essentially all of the observed target chemicals. The question of what *proportion* of the observed concentrations might be attributed to the materials and processes tested has been treated more fully in Wallace, 1985. That paper concludes that many of the target chemicals are emitted by a very large number of materials and processes, and that therefore the observed concentrations may often be due to small contributions from many sources. These findings are in good agreement with the later more extensive studies of 31 building materials carried out in the EPA companion study of six buildings (Sheldon, 1987; Wallace, 1987b; Jungers, 1987.)

The new office building had concentrations of five aromatic and aliphatic hydrocarbons that were two orders of magnitude greater than the concentrations observed 5 months later. Half-lives of the five chemicals ranged from 2-8 weeks (Pellizzari, 1984; Wallace *et al.*, 1987). Thus the time required for this building to approach the outdoor concentrations would range from 3-12 months. This finding supports the Scandinavian decision to require 100% outdoor air as makeup air for the first 6 months of a new building's life.

Fine particle mass was strongly affected by smoking. Levels in smoking lounges and apartments ranged from 20-90 $\mu g/m^3$ greater than in nonsmoking areas. One apartment with with two heavy smokers had 24-hour-average levels of up to 100 $\mu g/m^3$. These findings are similar to those in the extensive series of studies carried out by Spengler and coworkers in the Harvard 6-City Study (Spengler, 1985; Ware, 1984), in which the average contribution of each smoker to the household concentration of fine particles has been 25-30 $\mu g/m^3$. The observed short-term concentration of 300 $\mu g/m^3$ in a smoking lounge with nine smokers present was also in close agreement with the model of Repace (1980).

Two types of health effects may be associated with the elevated concentrations of organic gases and particles reported here. First, chronic health effects, including cancer, may be caused by long-term exposure to some of these compounds. Benzene is a recognized human carcinogen; chloroform, trichloroethylene, tetrachloroethylene, carbon tetrachloride, and p-dichlorobenzene are animal carcinogens and therefore possible human carcinogens. The elevated particle loadings associated with the smoking areas of these buildings supplements earlier work (Repace, 1980; Spengler, 1985) indicating increased exposure to environmental tobacco smoke (ETS), a probable human carcinogen, in these buildings, which house children, the sick and the elderly. Risk assessments have been carried out for VOCs (Wallace, 1986; Tancrede, 1987) and for ETS (Repace and Lowrey, 1985; NAS, 1986) in the home environment and have concluded that risks are

Table 3: *Volatile Organics in a New Office Building*

*Chemical	Concentration (μg/m³) Indoors[a] July	Sept.	Dec	Outdoors[b] all Trips
Aliphatics				
Decane	380	38	4	2
Undecane	170	48	13	1
Dodecane	47	19	5	0.2
Aromatics				
m+p-Xylene	140	19	9	2
o-Xylene	74	8	4	1
Ethylbenzene	84	6	5	1
Benzene	5	7	7	3
Styrene	8	7	4	1
Halocarbons				
1,1,1-Trichloroethane	380	100	49	6
Tetrachloroethylene	7	2	3	1
Trichloroethylene	1	38	27	0.3
Carbon Tetrachloride	1	1	1	1
Chloroform	1	2	18	6
p-Dichlorobenzene	1	1	1	ND
Total of 14 Organics	1300	326	150	25

[a] *Mean of six 12-hour averages at five indoor locations.*
[b] *Mean of 18 12-hour averages at one outdoor location.*

Table 4: *Emission Rates From Various Selected Sources*

Chemical	Emission Rate (ng/min/m²) Cleaning Agents and Insecticides	Painted Sheetrock	Glued Wallpaper	Glued Carpet
Chloroform	15,000 ± 250 (1.5)[a]	ND[b]	ND	ND
1,2-Dichloroethane	12,000	ND	310 ± 46 (15)	180 ± 12 (7)
1,1,1-Trichloroethane	37,000 ± 15,000 (42)	31 ± 15 (47)	84 ± 48 (57)	260 ± 31 (12)
Benzene	ND	120 ± 29 (25)	ND	ND
Carbon Tetrachloride	71,000 ± 5,300 (7.5)	ND	ND	ND
Trichloroethylene	370±47 (3.8)	ND	ND	ND
Tetrachloroethylene	ND	ND	ND	ND
Chlorobenzene	ND	ND	ND	ND
Ethylbenzene	ND	ND	ND	77 ± 39 (50)
p-Xylene	ND	ND	26 ± 6.5 (25)	150 ± 24 (16)
Styrene	ND	ND	ND	98 ± 14 (15)
o-Xylene	ND	ND	6.5 ± 3.1 (50)	98 ± 26 (27)
m-Dichlorobenzene	560 ± 20 (3.6)	ND	ND	ND
p-Dichlorobenzene	440 ± 5 (1.2)	ND	ND	41 ± 14 (36)
n-Decane	170 ± 27 (16)	240 ± 29 (12)	190 ± 77 (40)	545 ± 150 (28)
o-Dichlorobenzene	ND	ND	ND	ND
n-Undecane	1,100 ± 0 (0)	1500 ± 350 (24)	300 ± 110 (36)	500 ± 150 (30)

[a] *Coefficient of variance (%). N = 3 observations. ± SD (CV), N = 3 observations.*
[b] *ND = not detected (values are in ng/min/m²).*

Table 5: *Respirable Particles at Two Homes for the Elderly*

Location	Concentration (μg/m³)[a] Home #2	Home#1
Smoker's Apartment	89	39
Commons Area	16[b]	30[c]
Nonsmoker's Apartment	9	9
Outdoors	4[d]	10

[a] *Mean of three consecutive 24-hour samples.*
[b] *Some smoking observed*
[c] *Specified smoking lounge*
[d] *One 24-hour sample*

considerably greater for these chemicals in indoor air than in outdoor air or, (except for chloroform), in drinking water. The risks associated with the type of buildings studied here would be smaller by the ratio of the time spent in them to the time spent in homes.

The second type of health effect is acute, consisting of eye, nose and throat irritation, headaches, neurotoxic symptoms such as depression, irritability, and forgetfulness, and general malaise—a group of symptoms often described as "Sick Building Syndrome" (SBS). Although the cause or causes of SBS are unknown, several hypotheses implicate low-level concentrations of VOCs as a possible cause (Berglund, 1982; Molhave, 1984).

The economic effect of SBS may be considerable, if a large proportion of workplaces are affected. One nationwide survey has reported that 25% of American workers feel the quality of air at their workplace affects their work adversely. If so, economic productivity may be lowered by a significant amount.

Conclusions

At least 500 volatile organic compounds have been identified in indoor air in four buildings. These indoor air samples contained from 100 to 200 VOCs, often at levels that were several times the outdoor concentration. The sources of these elevated indoor air concentrations included building materials, consumer products, and processes such as cleaning and smoking. The materials tested emitted between 18 and 111 VOCs at rates ranging up to 1000 μg/m²/h.

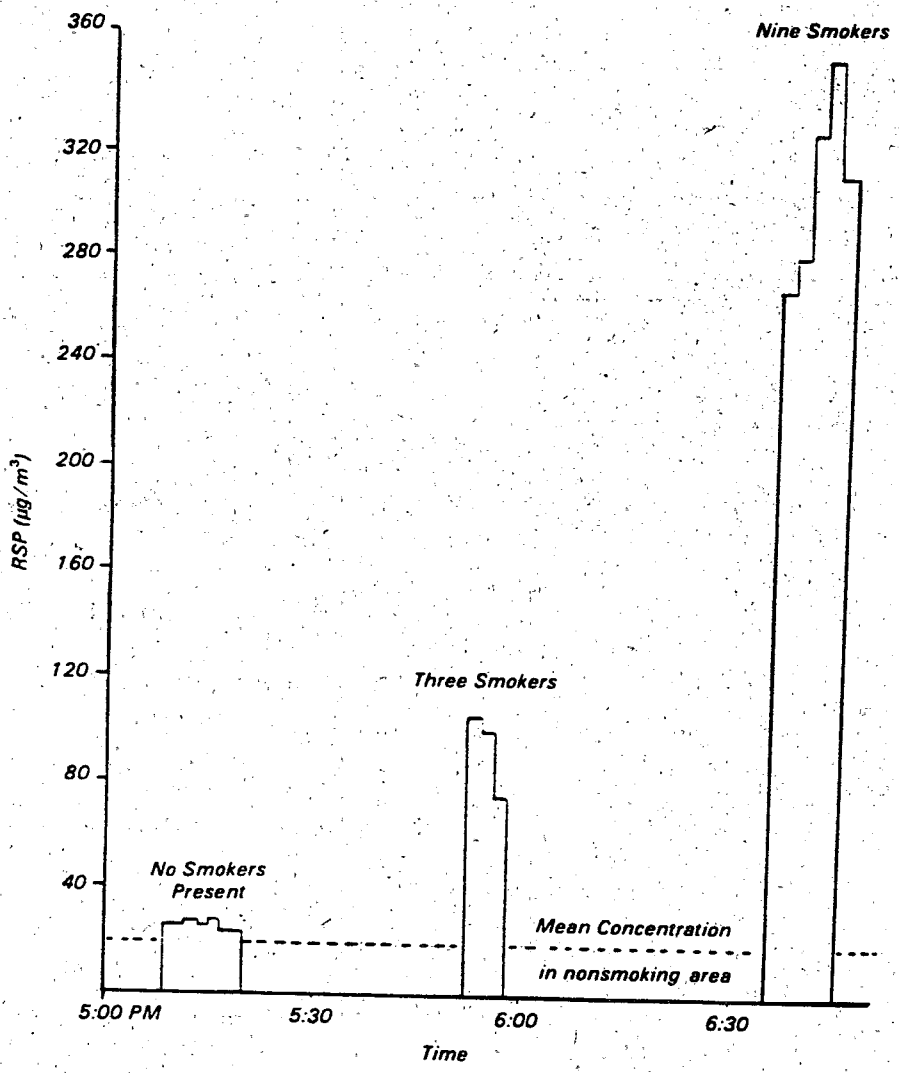
Concentrations of individual aromatic and aliphatic compounds such as xylenes and decane were elevated over outdoor levels by factors of 100 in the new building studied. Half-lives of these compounds ranged from 2-8 weeks. The time to reach concentrations comparable with outdoor levels was estimated at 3-12 months.

Concentrations of fine particulates were elevated by 20-70 μg/m³ in smoking areas.

Recommendations

This study has indicated that concentrations of certain target VOCs are elevated in buildings due to emissions from certain building materials. Only four buildings were monitored and only 16 building materials were tested for emissions. Considering that the building stock in the U.S. is more than 3 million, and that building materials and consumer products probably number in the hundreds of thousands, it is clear that only the surface has been scratched in this study. Many more buildings of various types (hospitals, enclosed shopping malls, etc.) where people spend a considerable fraction of their time should be monitored before it will be possible to estimate the frequency

Figure 1. *Respirable particulates in smoking lounge of the elderly home #1 (3/24/83).*



distribution of VOC concentrations in such buildings. Many more building materials should be tested to determine their rates of emission of chemicals of concern before a trustworthy estimate of the range of emission rates can be achieved.

Table 6: *Air Exchange Rates at Three Buildings*

Building	Air Exchange Rate[a] (ach)
Elderly Home #1	1.72 ± 0.41
School	0.85 ± 0.31
Office (July)	0.61 ± 0.32
Office (September)	0.52 ± 0.25

[a] *Mean of 4-6 measurements over consecutive 12-hour periods at each of 3-4 indoor locations in each building.*

An economic study of the effects of indoor air quality on productivity would help to clarify the magnitude of the indoor air quality problem in the office and workplace environment.

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