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VOLATILE ORGANIC COMPOUNDS

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In the 1970s, a sharp increase in nonspecific complaints by office workers and schoolchildren was noted in several countries. Because the symptoms seemed to result from exposure in schools or office buildings, the term *sick-building syndrome* was applied to them. Although the cause of sick-building syndrome remains unknown, organic chemicals are highly suspect. Many chlorinated solvents, light aromatic hydrocarbons, and pesticides (Table 11.1) are known to have effects, at high concentrations, similar to sick building syndrome. Since some of the organic compounds are known or suspected human carcinogens, cancer is also a potential consequence of low-level chronic exposures to organic chemicals in indoor air. Thus, recent concern over both acute and chronic health effects has sparked interest in organics in indoor air.

During the 1970s, advances in synthetic sorbents, miniaturized pumps and data loggers, and analytical techniques facilitated the measurement of indoor concentrations and personal exposures to many organics at environmental concentrations. As a result, substantial data are now available on personal exposures and on concentrations of organics in indoor air. These data show that personal exposures are largely determined by indoor sources and that indoor air concentrations of scores of organic compounds are considerably greater than outdoor concentrations, even in urban-industrial or petrochemical manufacturing centers. Furthermore, the sources of the higher concentrations indoors are primarily consumer products, building materials, and personal activities.

These findings have profound implications for regulation and research. If indoor concentrations indeed exceed outdoor levels, then increased attention and resources should be directed to organics in indoor air. Protection of public health may require actions to reduce indoor concentrations of organics through such approaches as building codes, product labeling, component substitutions, and

Table 11.1 Common Organic Chemicals and Their Sources

Chemicals	Measured Peak Nonoccupational Exposure ($\mu g/m^3$)	Major Sources of Exposure
Volatile Chemicals		
Benzene	1,000	Smoking, auto exhaust, passive smoking, driving, pumping gas
Tetrachloroethylene	1,000	Wearing or storing dry-cleaned clothes; visiting dry cleaners
p-Dichlorobenzene	1,000	Room deodorizers, moth cakes
Chloroform	250	Showering (10-min average)
Methylene chloride	50	Washing clothes, dishes
1,1,1-Trichloroethane	500,000	Paint stripping, solvent usage
Trichloroethylene	1,000	Wearing or storing dry-cleaned clothes, aerosol sprays, fabric protectors
Carbon tetrachloride	100	Unknown (cosmetics, electronic parts)
Aromatic hydrocarbons (toluene, xylenes, ethylbenzene, trimethylbenzenes)	100 1,000	Industrial-strength cleansers Paints, adhesives, gasoline, combustion sources
Aliphatic hydrocarbons (octane, decane, undecane)	1,000	Paints, adhesives, gasoline, combustion sources
Terpenes (limonene, α-pinene)	1,000	Scented deodorizers, polishes, fabrics, fabric softeners, cigarettes, food, and beverages
Semivolatile Chemicals		
Chlorpyrifos (Dursban), insecticides	10	Household
Chlordane, heptachlor	100	Termiticide
Diazinon	100	
Polychlorinated biphenyls (PCBs)		Transformers, fluorescent ballasts, ceiling tiles
Polycyclic aromatic hydrocarbons (PAHs)	1	Combustion products (smoking, wood burning, kerosene heaters)

individual consumer actions. Many questions remain concerning health effects of organics, and both laboratory and epidemiologic research are needed. Epidemiologic studies will be facilitated by the personal monitors and sensitive analytical techniques now available.

IDENTIFICATION AND CHARACTERIZATION

Organic gases are found in all indoor locations. More than five hundred volatile organic compounds (VOCs) were identified in four buildings in Washington, D.C., and Research Triangle Park, North Carolina (Sheldon et al. 1988a). Several

thousand organics have been identified in environmental tobacco smoke, which contaminates about 60 percent of all U.S. homes and workplaces (Repace and Lowrey 1980, 1985); and about 90 percent of U.S. homes use household pesticides (Immerman and Drummond 1984).

Early studies of organics indoors were carried out in the 1970s in the Scandinavian countries (Johansson 1978; Molhave and Moller 1979; Berglund, Johansson, and Lindvall 1982a, 1982b). Molhave (1982) showed that many common building materials used in Scandinavian buildings emitted organic gases. Seifert and Abraham (1982) found benzene and toluene associated with storage of magazines and newspapers in German homes. Early U.S. measurements were made in thirty-four Chicago homes (Jarke and Gordon, 1981); in nine Love Canal residences (Pellizzari, Erickson, and Zweidinger 1979); on two college campuses (Wallace et al. 1982); in twelve New Jersey and North Carolina homes (Pellizzari et al. 1981); and in several buildings (Hollowell and Miksch 1981; Miksch, Hollowell, and Schmidt 1982).

SOURCES AND SINKS

Early studies of VOC sources concentrated on emissions from building materials (Molhave 1982) and adhesives (Girman et al. 1986). Later studies also investigated building materials (Wallace 1987a; Sheldon et al. 1988a, 1988b) but added cleaning materials and activities such as scrubbing with chlorine bleach, spraying insecticides (Wallace et al. 1987a), and using paint removers (Girman and Hodgson 1987). Knoppel and Schauenburg (1987) studied VOC emissions from ten household products (waxes, polishes, and detergents); nineteen different alkanes, alkenes, alcohols, esters, and terpenes were among the three chemicals emitted at the highest rates from the ten products. All of these studies employed either headspace analysis or chambers to measure emission rates.

Other studies estimated emission rates from measurements in homes or buildings. For example, Wallace and co-workers (1987a) estimated emissions from a number of personal activities (such as visiting a dry cleaners and pumping gas) by regressing measurements of exposure or breath levels against the specified activities. Girman and Hodgson (1987) extended their chamber studies of paint removers to a residence, finding similar concentrations of methylene chloride in this more realistic situation.

One study (Wallace et al. 1990) involved seven volunteers undertaking about twenty-five activities suspected of causing increased VOC exposures; a number of these activities (using bathroom deodorizers, washing dishes, cleaning an automobile carburetor) resulted in ten- to one-thousandfold increases in eight-hour exposures to specific VOCs.

The U.S. National Aeronautics and Space Agency (NASA) has carried out an extensive program of measuring organic emissions from materials used in space capsules and the shuttle (Nuchia 1986). Data on about five thousand materials are available; perhaps three thousand of these materials are in use in general commerce

(Ozkaynak et al. 1987). The chemicals emitted from the largest number of materials included toluene (1,896 materials), methyl ethyl ketone (1,261 materials), and xylenes (1,111 materials).

Only recently has research been directed at sinks for VOCs. It is clear from the long-lasting odor that clothes impregnated with dry-cleaning fluids or moth-control agents are capable of absorbing and reemitting these VOCs. If other household fabrics also have this property, then accurate estimates of exposure will require some knowledge of the strength of absorption. In calculating indoor concentrations, the quantitative measure of sink strength is often expressed as a *decay factor* (units of air changes per hour) to be added to the actual air exchange.

A recent forty-one-day chamber study (Berglund, Johansson, and Lindvall 1987) of aged building materials taken from a "sick" preschool more than five years old indicated clearly that the materials had absorbed about thirty VOCs, which they reemitted to the chamber during the first thirty days of the study. Only thirteen of the VOCs originally present in the first days of the study continued to be emitted in the final days, indicating that these thirteen were the only true components of the materials. This finding has significant implications for remediating sick buildings. Even if the source material is identified and removed, weeks may be needed before reemission of organics from sinks in the building stops.

Another study (Seifert and Schmahl 1987) of sorption of VOCs and semivolatile organic compounds (SVOCs) on materials such as plywood and textiles concluded that sorption was small for the VOCs studied but significant for lindane on muslin curtains and wool carpets.

MEASUREMENT METHODS

VOCs

For many years, the most widely used method for sampling volatile organics at *occupational* levels (ppm) was collection on activated charcoal followed by solvent (CS_2) desorption. However, at *environmental* levels (ppb), this method lacks sensitivity unless high volumes or long sampling times are employed.

In the mid-1970s, synthetic sorbents were developed which could be heated to high temperatures without degradation. This property permitted the use of thermal rather than solvent desorption to recover the collected organics. Thermal desorption has several advantages over solvent desorption, including fewer analytical operations, shorter operating time, and recovery of the entire collected sample for analysis rather than only the rediluted portion.

Tenax, the most popular synthetic sorbent for sampling indoor air, has a number of advantageous properties, including being hydrophobic (so that sampling under high relative humidities is possible), being stable under very high desorption temperatures, and being reusable. Its disadvantages include reduced ability to capture very volatile chemicals such as vinyl chloride and methylene chloride; formation of reaction products, including mainly acetophenone, benzaldehyde, and phenol (Pellizzari 1977, 1979); and high background levels of benzene,

styrene, and possibly toluene. Since 1979, Tenax has been used widely in studies of personal exposure to organics (Pellizzari, Erickson and Zweidinger 1979; Pellizzari et al. 1984b, 1987a, 1987b; Wallace et al. 1984, 1985, 1990; Handy et al. 1987; Wallace 1987b) and of concentrations in indoor air (De Bortoli et al. 1984, 1986; Gammage, White, and Gupta 1984; Pellizzari et al. 1984a; Wallace et al. 1987b; Sheldon et al. 1988a, 1988b).

Other synthetic sorbents occasionally used to measure volatile organics in indoor air include Porapak Q (Berglund, Johannson, and Lindvall 1982a, 1982b) and XAD-2 resin. Composite sampling trains employing several different sorbents in series can be used (Hodgson, Girman, and Binenboym 1986; De Bortoli et al. 1987) to compensate for each sorbent's limitations. For example, Tenax may be used in series with activated charcoal to allow collection of very volatile compounds such as vinyl chloride.

Although activated charcoal was occasionally used in early studies of indoor air (Lebret et al. 1986) the development in the late 1970s of passive sampling devices—primarily designed for occupational sampling—permitted collection of extended-time samples without much effort or technician time (Seifert and Abraham 1983). The sampling time of one to two weeks provides enough material to overcome the twin problems of high background concentrations on the badge due to manufacturing conditions and loss of sensitivity from solvent desorption due to redilution of the collected sample. Studies of this type include a major study of VOCs in German homes (Krause et al. 1987; Mailahn, Seifert, and Ullrich 1987; Seifert et al. 1987). Passive sampling devices employing Tenax have also been developed in the United States (Coutant, Lewis, and Mulik 1985, 1986; Lewis et al. 1985) and in Europe (De Bortoli et al. 1987).

Collection of atmospheric samples in evacuated metallic containers (McClenny et al. 1986; Oliver, Pleil, and McClenny 1986) followed by direct injection into a gas chromatograph for analysis has several advantages over the sorption methods discussed previously. Since a sorption/desorption process is not involved, chemical reactions on the sorbent and low recoveries due to breakthrough or incomplete desorption can be avoided. Consequently, a wider range of compounds can be studied. Disadvantages of the method include analysis of only a small portion, about 1 ml, of the collected whole-air sample of 1–10 liters and the potential for contamination of the sample by the pump, sampling tubes, and fittings. Also, the canister may not be amenable to miniaturization to the degree necessary to provide personal air samples.

Thus, no single method of sampling VOCs in the atmosphere or indoors has become a standard or reference method. In the United States, the two preferred methods are Tenax and evacuated canisters. These two methods were compared under controlled conditions in an unoccupied house (Spicer 1986). Ten chemicals were injected at nominal levels of about 3, 9, and 27 $\mu g/m^3$. Two sets of four Tenax cartridges operating at different flow rates (Walling 1984) were compared with two evacuated canisters. The results showed that the two methods were in excellent agreement, with precisions of better than 10 percent for all chemicals at all spiked levels.

Several researchers (Gammage, White, and Gupta 1984; Sheldon et al. 1987) have attempted to use a portable gas chromatograph as a means of obtaining real-time indicators of major household sources such as gasoline fumes from attached garages. However, the sensitivity and the resolution of the instruments have limited their usefulness to date. Another approach to obtaining higher time resolution has been to use small whole-air samples collected sequentially over short (e.g., two-minute) periods. This approach has been used to study short-term peaks in automobiles and in showers (Pleil, Oliver, and McClenny 1987). Wolkoff (1987) obtained forty-minute resolution using sequential Tenax sampling in Danish town halls.

SVOCs

Some SVOCs exist primarily in the vapor phase at room temperature whereas others are primarily bound to airborne particles. Determination of the phase is important because the appropriate method of sampling depends on whether the target compound is a gas or is bound to particles. Only recently, for example, was nicotine found to be in the vapor phase (Eudy et al. 1986; Hammond 1986), a finding that calls into question many previous studies involving quantification of nicotine on filtered samples.

Currently, the most widely used sorbent for sampling a broad spectrum of airborne pesticides is polyurethane foam (PUF) (Lewis and MacLeod 1982). Samples are usually collected at 4 liters/min for twelve to twenty-four hours. Solvent desorption (gas chromatography) followed by electron capture detection (GC-ECD) or mass spectrometry (GC-MS) analysis can detect concentrations of 10 ng/m^3. Approximately fifty to sixty pesticides (including organochlorines, organophosphates, and pyrethroids) have been tested successfully in laboratories using PUF.

A sorbent often used for the termiticide chlordane is Chromosorb 102 (Thomas and Seiber 1974). This sorbent was used by the U.S. armed forces in studying more than ten thousand homes on military bases (Lillie and Barnes 1987; Olds 1987).

Other SVOCs include polyaromatic hydrocarbons (PAHs), which are produced in indoor combustion processes—smoking, wood burning (Daisey, Spengler, and Kaarakka 1987), and space heating with kerosene. The mutagenic activity of PAHs is high, especially in cigarette smoke (Lewtas, Claxton, and Mumford 1987). Therefore, even though PAH concentrations are normally low (approximately 1 ng/m^3), it may be important to develop systems to monitor their levels in homes. At present, fully satisfactory systems do not exist. Criteria for a satisfactory indoor collection system include flow rate sufficiently low not to affect the air exchange characteristics of the home, sensitivity at the 1 ng/m^3 level, and separate collection of PAHs in both particle and vapor phases. This last requirement is

difficult to meet because PAHs exist in both the particle and vapor phases simultaneously, in relative proportions determined by their molecular characteristics and environmental conditions. Usual methods of collection (filter followed by sorbent) may result in "blow-off" of the molecules from the material on the filter so that the vapor phase concentration is overestimated, and the particle-bound fractions are underestimated. Denuders, which collect the vapor phase *before* the particle phase, have been developed to allow better determination of the vapor particle distribution for PAHs and acid aerosols (Koutrakis, Wolfson, and Spengler 1988).

Although PUF has been used as a sorbent with good collection efficiencies and good sample recoveries for PAHs having three or more rings, side-by-side studies using XAD-2 indicate that it is preferable to PUF for PAHs with three rings or fewer (Chuang 1987).

STUDIES OF EXPOSURE TO ORGANICS

Two types of studies involving measurement of organics indoors may be distinguished: personal exposure studies, in which subjects carry or wear personal air monitors, and indoor air studies, in which samples are taken at fixed locations within a building. Personal exposure studies require small, light, quiet personal monitors (Wallace and Ott 1982); indoor air studies can employ larger and heavier monitors.

Examples of personal exposure studies include the total exposure assessment methodology (TEAM) study of VOCs (Pellizzari et al. 1983, 1987a, 1987b; Handy et al. 1987; Wallace 1987b) and the nonoccupational pesticide exposure (NOPES) study of SVOCs (mostly pesticides) (Lewis and Bond 1987; Immerman et al. 1988).

CONCENTRATIONS

Three large studies of VOCs, involving more than one hundred homes each, have been carried out in the United States (Wallace et al. 1985, 1988), The Netherlands (Lebret et al. 1986), and West Germany (Krause, Englert, and Dube 1987). Observed concentrations were remarkably similar for most chemicals (Table 11.2), indicating similar sources in these countries. One exception is chloroform, typically present at levels of 1–4 $\mu g/m^3$ in the United States but not found in European homes. This geographic contrast is to be expected, since the likely source is volatilization from chlorinated water (Wallace et al. 1982; Andelman 1985a, 1985b; Andelman, Wilder, and Myers 1987; McKone 1987); the two European countries do not chlorinate their water.

In the United States, indoor concentrations of many VOCs greatly exceed outdoor concentrations. Mean values of indoor levels range from two to ten times the outdoor levels. Maximum twelve-hour values indoors are often one hundred or one thousand times ambient concentrations because of personal activities.

For most organics, differences among houses are far greater than differences among cities. This observation has considerable implications for both regulatory

Table 11.2 Volatile Organic Concentrations in Indoor Air in Germany and The Netherlands Compared with Personal Exposures in the United States

	Concentration ($\mu g/m^3$)					
	Arithmetic Mean		Median	Maximum		
Compound/Class	West Germany[a]	United States[b]	in The Netherlands[c]	West Germany	United States[d]	The Netherlands
Chlorinated						
Chloroform	NM[e]	3	NM	NM	210	NM
1,1,1-Trichloroethane	9	52	NM	260	8,300	NM
Trichloroethylene	11	6	<2	120	350	106
Tetrachloroethylene	14	16	<2	810	250	205
p-Dichlorobenzene	14	25	1	1,260	1,600	299
Aromatic						
Benzene	10	16	6	90	510	148
Styrene	2	3	NM	41	76	NM
Ethylbenzene	10	9	2	160	380	138
o-Xylene	7	9	10[f]	45	750	753[f]
m + *p*-Xylene	23	26			300	3,100
Toluene	84	NM	35	1,710	NM	2,252
Aliphatic						
Octane	5	4[g]	1	92	122	533
Nonane	10	12[g]	4	140	177	407
Decane	15	6[g]	10	240	161	905
Undecane	10	8[g]	6	120	385	445
Dodecane	6	4[g]	2	72	72	118
Terpenes						
α-Pinene	10	4[g]	NM	120	208	NM
Limonene	28	43[g]	30	320	2,530	773

[a]Seifert and Schmalhl (1987): two-week averages; 488 West German homes.
[b]Wallace (1987a): twenty-four-hour averages; 526 persons in New Jersey and California.
[c]Lebret et al. (1986): one-week averages; 319 homes in The Netherlands.
[d]Wallace (unpublished): twelve-hour averages; overnight maxima in 666 homes in New Jersey, California, and Maryland.
[e]Not measured.
[f]*o* + *m* + *p*-Isomers.
[g]Wallace (unpublished): twenty-four-hour averages; 315 persons in California and Maryland.

policy and scientific research. If exposure to air toxics is only weakly affected by outdoor concentrations, then the maintenance of large outdoor sampling networks and/or the establishment of outdoor ambient or emission standards will have little relevance to protecting public health. Similarly, future environmental epidemiology studies will require direct measurement of personal exposure of all study subjects and cannot rely on simply comparing a "high-exposure" geographic area with a "low-exposure" one.

SELECTED VOCS IDENTIFIED IN INDOOR AIR

Although more than five hundred VOCs have been identified in indoor air—of which approximately two dozen are carcinogenic or mutagenic (Sheldon et al. 1988a)—the list of commonly found VOCs is smaller, on the order of fifty com-

pounds (Table 11.3). Of these, an even smaller number—perhaps ten—may have serious health effects such as cancer. These compounds are discussed individually below.

Benzene Benzene (C_6H_6) is one of the few VOCs recognized as a human carcinogen (International Agency for Research on Cancer 1982), largely on the basis of studies of occupationally exposed persons. The main source of exposure to benzene for about fifty million American smokers has been identified recently as mainstream cigarette smoke (Higgins, Greist, and Olerich 1983). Cigarette smokers take in about 2 mg/day, compared with less than 0.2 mg for most nonsmokers (Wallace et al. 1987b). Passive smokers are also exposed to higher levels of benzene (Jermini, Weber, and Grandjean 1976; Higgins 1987). Median levels in homes without smokers were 6.5 and 7.0 $\mu g/m^3$ in West Germany and the United States, respectively, compared with levels of 11 and 10.5 $\mu g/m^3$ in homes with smokers in the two countries (Krause et al. 1987; Wallace et al. 1987b). Benzene is also found in gasoline, at a concentration of about 1–2 percent; however, the total personal exposure due to driving or filling gas tanks is less than from passive smoking (Bond 1986; Wallace et al. 1990). Two recent studies (Sandler et al. 1985; Stjernfeldt et al. 1986) have shown higher mortality from leukemia in children of smoking parents compared with children of nonsmokers. This association may be attributable to the approximately tenfold increase in benzene levels in the pregnant smoker's bloodstream.

Vinyl Chloride This VOC, like benzene, is a human carcinogen (International Agency for Research on Cancer 1982). Unlike benzene, however, few indoor concentrations have been measured, due in part to its low breakthrough volume on Tenax. Since vinyl chloride may be created by chemical reactions at landfills, nearby homes might be contaminated. One study of indoor air in homes near a landfill has indeed documented increased concentrations (Stephens, Ball, and Mar 1986).

p-*Dichlorobenzene* This chemical has two main uses, as a moth-control agent and as a deodorizer. Both uses require that an elevated concentration be maintained indoors for weeks or months. Thus homes with these sources may have indoor concentrations of 10–1,000 $\mu g/m^3$ compared with typical outdoor levels of < 1 $\mu g/m^3$ (Wallace et al. 1987a). *p*-Dichlorobenzene was found recently to cause cancer in both rats and mice (National Toxicology Program 1987) and is thus a possible human carcinogen.

Chloroform This chemical ($CHCl_3$) is created by chlorination of drinking water supplies. Despite the regulation of trihalomethanes in drinking water, levels exceed the standard (100 μg/liter for all trihalomethanes together) in a substantial portion of drinking water supplies. The main source of airborne chloroform in homes is volatilization from household use of water, such as washing clothes or

Table 11.3 Most Common Organic Compounds Found at Four Buildings

Class/Compound	N^a	Class/Compound	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
Ethylmethyl benzenes	16	Octane	9
Trimethyl benzenes	16	Nonane	9
Dimethylethyl benzenes	15	Decane	9
Naphthalene	15	Dodecane	9
Methylnaphthalenes	15	Tridecane	9
Propylmethyl benzenes	14	Methylcyclohexane	9
n-Propyl benzenes	13	Heptane	8
Diethylbenzenes	12	Tetradecane	8
Halogenated Hydrocarbons		2-Methylheptane	8
Tetrachloroethylene	16	Cyclohexane	8
1,1,1-Trichloroethane	15	Pentadecane	7
Trichloroethylene	14	4-Methyldecane	7
Dichlorobenzenes	12	2,4-Dimethylhexane	7
Trichlorofluoromethane	12	Pentane	6
Dichloromethane	11	Hexane	6
Chloroform	10	Eicosane	6
Esters		3-Methylnonane	6
Ethyl acetate	8	1,3-Dimethylcyclopentane	6
m-Hexyl butanoate	4		
Alcohols			
2-Ethyl-1-hexanol	9		
n-Hexanol	8		
2-Butyloctanol	7		
n-Dodecanol	6		
Aldehydes			
n-Nonanal	13		
n-Decanal	10		
Miscellaneous			
Acetone	16		
Acetic acid	10		
Dimethylphenols	6		
Ethylene oxide	4		

[a]Number of samples (of sixteen) with compound present.
[b]Number of samples (of ten) with compound present.

dishes. Recent studies (Andelman, Wilder, and Myers 1987; McKone 1987) indicate that exposure from inhaling chloroform volatilized from household use of water (particularly hot showers) is comparable with the exposure from ingesting household tap water.

Tetrachloroethylene This chemical is used in a majority of U.S. dry-cleaning shops. The main avenue of exposure appears to be wearing or storing dry-cleaned clothes (Howie 1981; Wallace et al. 1984) although a single visit to a dry-cleaning

shop can elevate body burden levels for a number of hours afterward (Wallace et al. 1984; Gordon et al. 1988). Dry-cleaning workers are exposed to ppm levels (Pellizzari et al. 1984b), and several studies (Blair, Decoufle, and Grauman 1979) have found elevated cancer mortality in laundry and dry-cleaning workers.

Methylene Chloride This common solvent was found in more than 50 percent of 1,200 products tested by the U.S. Environmental Protection Agency (U.S. EPA 1987). Best known as a paint stripper, it has been measured at levels of 100 ppm in chamber and room experiments (Girman and Hodgson 1987). Normal indoor concentrations are unknown since it cannot be measured by Tenax; however, if concentrations of methylene chloride are comparable to other VOCs, a 100-ppm exposure for eight hours while stripping paint would be equivalent to a lifetime's normal exposure.

1,1,1-Trichloroethane This chemical is used widely in hundreds of consumer products as a sorbent or propellant. It is also used in about 15 percent of U.S. dry-cleaning shops. It does not appear to be an animal carcinogen although few adequate animal studies have been completed.

Aromatic Compounds (Particularly Toluene, Xylenes, Ethylbenzene, and Styrene) These aromatic chemicals are found in gasoline, combustion products (including cigarettes), and paints, adhesives, and solvents. Concentrations in buildings may be elevated by factors of about one hundred immediately following painting or renovation (Pellizzari et al. 1984a; Sheldon et al. 1988a, 1988b). Little evidence of carcinogenicity has been noted for these compounds (National Toxicology Program 1987), although recent results indicate that toluene and xylenes may each be carcinogenic to both rats and mice (C. Maltoni, personal communication, March 1989). Neurotoxic effects have been noted at high (50–100 ppm) concentrations. As common indoor chemicals, this class of compounds may be implicated in sick-building syndrome (Molhave, Bach, and Pedersen 1986).

Aliphatic Hydrocarbons Aliphatic hydrocarbons are found in petroleum products, including gasoline, paint, and adhesives. Like the aromatics mentioned above, aliphatics such as decane and undecane can be found at one hundredfold elevated concentrations in newly painted or renovated buildings (Sheldon et al. 1988a, 1988b). Little evidence of health effects is available, although some of these chemicals are classified as promoters or co-carcinogens (International Agency for Research on Cancer 1982). They may also be implicated in sick-building syndrome (Molhave, Bach, and Pedersen 1986).

Terpenes This class of compounds includes several of the most popular scents used in room air fresheners, cleansers, polishes, and bathroom deodorants. Limonene (lemon scent) and α-pinene (pine scent) are emitted naturally from citrus fruit and trees but are also added to many products (including, in the case of limonene, foods and beverages). Indoor concentrations of limonene are among the highest for any VOC (Pellizzari et al. 1989).

SVOCs The armed forces studies (Lillie and Barnes 1987; Olds 1987) of chlordane in more than ten thousand homes showed that 237 of 5,038 air force homes and 39 of 4,368 army homes exceeded the 5 μg/m³ guidelines established by the National Academy of Sciences (1979).

Another large study of over two hundred homes has been carried out in the United States (Lewis and Bond 1987; Immerman et al. 1988). Preliminary results show that in the two cities studied (Jacksonville, Florida, and Springfield, Massachusetts), chlorpyrifos (Dursban) is the most frequently used pesticide and is found at the highest concentrations, with chlordane and heptachlor (termiticides) and diazinon and propoxur following (Table 11.4). Mean concentrations were below 1 μg/m³ for most pesticides. A few homes tested for household dust accumulations showed elevated levels of pesticides. Ingestion of house dust could be an important route of exposure for toddlers (Roberts, Ruby, and Warren 1987).

European studies of SVOCs have concentrated on wood preservatives containing pentachlorophenol and lindane (γ-hexachlorocyclohexane) (Krause, Englert, and Dube 1987; Zsolnay, Gebefugi, and Korte 1987). One study of 104 West German homes (Krause, Englert, and Dube 1987) showed indoor air levels of pentachlorophenol averaging about 6 μg/m³. Household dust had high concentrations of both lindane and pentachlorophenol. Persons reporting exposure (N = 989) averaged 44 μg/liter pentachlorophenol in their urine, compared with 12.7 μg/liter in controls (N = 207). These results led to the banning of pentachlorophenol in wood preservatives in West Germany in 1987.

A series of studies in telephone company buildings containing mostly equip-

Table 11.4 Common Pesticides Found in Indoor Air in the EPA Nonoccupational Pesticides Exposure Study (ng/m³)[a]

Pesticide	Jacksonville, Florida	Springfield, Massachusetts
Chlorpyrifos	230	7
Chlordane	260	120
Heptachlor	130	17
Diazinon	210	25
Propoxur	300	22
O-Phenylphenol	75	33
Lindane	13	5
Dichlorvos	82	3
Bendiocarb	32	0.3
Aldrin	15	0.2
Dieldrin	10	3

Source: Adapted from Immerman and Firestone (1989).
[a]Values are averages of several weighted mean concentrations.

ment showed that heavier organics (C_{12}–C_{30}) were present at ng/m³ levels and could be traced to janitorial use of floor waxes and polishes (Weschler 1978).

CONCENTRATIONS IN THE BODY

Most of the VOCs measured in indoor air have also been identified in human exhaled breath (Krotoszynski, Gabriel, and O'Neill 1977; Krotoszynski, Bruneau, and O'Neill 1979; Wallace et al. 1986; Gordon et al. 1988). Thus, breath measurements may be used to replace or supplement indoor air measurements to determine exposure. Breath measurements of VOCs have several advantages as compared with air measurements. They represent previous exposures integrated across time and also across all routes of exposure (ingestion, inhalation, and skin absorption). For at least two common indoor air chemicals—chloroform and limonene—exposure through ingestion of food and beverages may be equally as important as inhalation. Breath measurements can detect exposures from active smoking. In fact, the finding that cigarette smoking is a major source of benzene exposure followed from the observation that the mean benzene level in the breath of smokers was nearly an order of magnitude larger than in nonsmokers (Wallace et al. 1984, 1987b). Finally, comparison of breath measurements with personal air exposures provides an indication of both body burden and metabolism of the organics. For example, breath levels of tetrachloroethylene are comparable to personal air exposures, indicating little metabolism, whereas breath levels of xylenes are only 10 percent of exposures, indicating considerable metabolism. In addition, biological half-lives of several chemicals have been measured at environmental (ppb) exposures and have been found to range between five and twenty-one hours (Gordon et al. 1988).

Organics have also been measured in other biologic samples. Brugnone and co-workers (1987) have measured benzene in the breath and blood of cigarette smokers and in occupationally exposed workers in Italy. Breast milk has also been studied extensively for SVOCs, particularly pesticides and polychlorinated biphenyls (World Health Organization 1983; Rogan et al. 1986). VOCs, especially *p*-dichlorobenzene and tetrachloroethylene, have also been found in mothers' milk (Sheldon et al. 1985). Adipose tissue has also been studied for both VOC and SVOC levels (U.S. EPA 1986).

ACTIONS TO REDUCE EXPOSURES

In many cases, the major source of exposure to organic chemicals has been identified—in the words of Pogo, "We have met the enemy, and he is us." People smoke, use air deodorizers, store pesticides in their homes, and otherwise expose themselves, their spouses, and their children to a variety of toxins. The remedy is implied in identifying the source: stop smoking or limit it to a room in the house with its own ventilation system; eliminate or reduce use of air deodorizers or switch to those with less carcinogenic constituents; throw away or store outside the house unused or little-used pesticides, solvents, and spray cans. Children may be protected from ingesting house dust by having hardwood surfaces instead of carpets and by removing shoes at the front door to avoid tracking in pesticides.

Outside the home, individuals may have less control. Organics in offices and schools may be emitted by new building materials, renovations, janitorial cleaning, regular pesticide applications, and other activities. Adequate ventilation may help but cannot overcome strong intermittent sources. Cleaning, renovating, or pesticide application may be scheduled in the evenings or weekends to reduce exposure. Additional ventilation and activated charcoal filtration to supplement the building ventilation system have been implemented in a few offices although rigorous studies of the effectiveness of these measures are lacking.

Organizations such as the American Society for Testing and Materials (ASTM) may be able to establish consensus guidelines on the amount of organic emissions allowable from building materials. Manufacturers may voluntarily limit emissions or substitute less harmful chemicals on receipt of animal test data. A novel idea—"baking out" new buildings by elevating interior temperatures prior to occupancy—has been tried several times (Girman et al. 1987) with moderate success.

SUMMARY

Organic chemicals found indoors may be implicated in either acute health effects (sick-building syndrome) or in chronic effects (cancer). However, the mechanisms of action are largely unknown and must await further research in neurobehavioral or immune system response, pharmacokinetics, and mutagenicity studies of complex mixtures.

We have good knowledge of indoor concentrations and major sources of most VOCs, particularly nonpolar VOCs that are not extremely volatile. Nearly all of these are usually at higher concentrations indoors than outdoors, with short-term indoor peaks one hundred to one thousand times greater than outdoors. Preliminary data on SVOCs indicate that 80 percent or more of personal exposure to pesticides is from indoor sources. Little is known concerning concentrations and major sources of polar organics (oxygenated compounds), high-volatility nonpolar organics (vinyl chloride, methylene chloride, and others), or particle-bound organics (PAHs, dioxin, and furans).

Major sources of indoor organics include consumer products (deodorizers, solvents, and others), personal activities (smoking, cleaning, using hot water, wearing dry-cleaned clothes, and others), and building-related products and processes (paints, adhesives, caulking, fabrics, custodial cleaning, and pest control). Few details are known regarding emission rates of organics from the myriad different consumer products.

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