

in the open air. However, the velocity of the airstream through the chamber has considerable influence on the yields of individual compounds in SS (Klus and Kuhn 1982).

To collect the particulate phase of MS and SS, the smoke aerosols are passed through a glass fiber filter (a Cambridge filter with a diameter of 45 mm) that traps more than 99 percent of all particles with a diameter of at least 0.1 μm (Wartman et al. 1959). The portion of the smoke that passes through the glass fiber filter is arbitrarily designated as vapor phase, although it is realized that this separation does not fully reflect the actual physicochemical conditions prevailing in MS and SS. For the analysis of individual components or a group of components, specific trapping devices and methods have been developed (Dube and Green 1982).

Human Smoking

The standardized machine-smoking conditions used in the tobacco laboratory were set up to simulate the parameters of human smoking as practiced 30 years ago. The examination of current smoking practices suggests that machine-smoking conditions no longer reflect current practices. Human smoking patterns depend on a number of factors, one of which is the delivery of nicotine. Dosimetry of smoke constituents has shown that low nicotine delivery (<0.6 to 1.0 mg/cigarette) generally induces the smoker to draw larger puff volumes (up to 55 mL per puff), to puff more frequently (three to five times a minute), and to inhale more deeply (Herning et al. 1981). Furthermore, many smokers of cigarettes with perforated filter tips tend to obstruct the holes in these tips by pressing their lips around them; thus, they inhale more smoke than would be expected according to the machine-smoking data (Kozlowski et al. 1980). Smokers of cigarettes with a longitudinal air channel in the filter tip compress the tip in a similar manner so that the mainstream smoke delivery is increased over that measured with the laboratory methodology (Hoffmann et al. 1983).

These deviations from machine-smoking patterns cause a greater amount of tobacco to be consumed during MS generation. Consequently, the quantity of tobacco burned between puffs is diminished, and lower amounts of combustion products are released as SS. Because of the proximity to the burning tobacco product, the active smoker usually inhales more of the SS and ETS than a nonsmoker.

It is not known to what extent the different constituents of inhaled ETS aerosols can be retained in the respiratory tract of nonsmokers. Studies with MS have shown that more than 90 percent of the volatile, hydrophilic components are retained by the smoker (Dalhamn et al. 1968a) and that less than 50 percent of the volatile, hydrophobic MS components are retained by the smoker (Dalhamn et al. 1968b). On the basis of these data, it may be assumed that the

passive smoker retains a high percentage of the vapor phase components of ETS and significantly less of its hydrophobic volatiles.

Sidestream Smoke

Formation and Physicochemical Nature

When nonfilter cigarettes are being smoked under standardized conditions, approximately 45 percent of the tobacco column is consumed during the generation of MS (puff-drawing), whereas the remainder is burned between puffs and under conditions of a strongly reducing atmosphere. In addition, MS and SS is generated at distinctly higher temperatures than SS (Wynder and Hoffmann 1967). Thus, undiluted SS contains more tobacco-derived combustion products than does MS, and contains especially greater quantities of those combustion products that are formed by nitrosation or amination. Consequently, the composition of SS differs from that of MS.

The SS of a smoldering cigarette enters the surrounding atmosphere about 3 mm in front of the paper burn line, at about 350° C (Baker 1984). In Table 1, the MS and the SS from nonfilter cigarettes are compared. Under standardized conditions, the formation of the MS of a nonfilter cigarette (80 mm, 1,230 mg) is completed during 10 puffs, requires 20 seconds, and consumes 347 mg of tobacco. The formation of SS from the same cigarette during smoldering requires 550 seconds and consumes 411 mg of tobacco (Neurath and Horstmann 1963).

The pH of the MS of a blended U.S. cigarette ranges from 6.0 to 6.2 and the pH of SS, from 6.7 to 7.5. Above pH 6, the proportion of unprotonated nicotine in undiluted smoke rises; at pH 7.9, about 50 percent is unprotonated. Therefore, SS contains more free nicotine in the vapor phase than MS. The reported measurements of the pH of cigars were 6.5 to 8.5 for MS and 7.5 to 8.7 for SS; measurements for the pH of SS from pipes have not been published (Brunnemann and Hoffmann 1974).

Chemical Analysis

In order to establish reproducible chemical-analytical data, cigarette SS is generated in a special chamber. This assures that the cigarettes burn evenly during puff intervals when an airstream at a velocity of 25 mL per second is drawn through the chamber. At this flow rate in the chamber, MS generation is quantitatively similar to that measured without the SS chamber (Neurath and Ehmke 1964; Brunnemann and Hoffmann 1974; Dube and Green 1982). Throughout this chapter the data refer primarily to MS, SS, and ETS deriving from cigarettes and not from cigars or pipes, because

TABLE 1.—Comparison of mainstream smoke (MS) and sidestream smoke (SS) of a nonfilter cigarette: Some physicochemical data

Study	Parameters	MS	SS
Neurath and Horstmann (1963)	Duration of smoke production (sec)	20	550
	Tobacco burned (mg)	347	411
Wynder and Hoffmann (1967)	Peak temperature during formation (°C)	≈900	≈600
Brunnemann and Hoffmann (1974)	pH of total aerosol	6.0–6.2	6.7–7.5
Scassellati-Sforzolini and Savino (1968)	Number of particles per cigarette ¹	10.5 x 10 ¹²	3.5 x 10 ¹²
Carter and Hasegawa (1975); Hiller et al. (1982)	Particle sizes (nm) ¹	0.1–1.0	0.01–0.8
	Particle mean diameter (nm) ¹	0.4	0.32
Wynder and Hoffmann (1967); Keith and Derrick (1960); Baker (1984); Hoffmann, Brunnemann et al. (1984)	Smoke dilution (vol %) ²		
	Carbon monoxide	3–5	2–3
	Carbon dioxide	8–11	4–6
	Oxygen	12–16	1.5–2
	Hydrogen	3–15	0.8–1.0

NOTE: Data obtained under standard laboratory smoking conditions of 1 puff per minute of 2-second duration and 35 mL volume.

¹Fresh and undiluted mainstream smoke and sidestream smoke.

²Four mm distant from the burning cone (gas temperature, 350° C).

cigarette smoke is the major source of ETS in public places. Few data are available on the SS and ETS from cigars and pipes.

About 300 to 400 of the several thousand individual compounds identified in tobacco smoke have been quantitatively determined in both mainstream and sidestream smoke. A listing of selected agents in the MS of nonfilter cigarettes with their reported range of concentration and their relative ratio of distribution in SS compared with MS is presented in Table 2. Values greater than 1.0 reflect the greater release of a given compound into SS than into MS. The grouping of the compounds in Table 2 into vapor phase components and particulate phase constituents refers to the makeup of MS, but does not represent the physicochemical distribution of these compounds in SS. Some of the volatile compounds in MS and SS are compared. On the basis of the amount of tobacco burned in the MS and SS of a nonfilter cigarette (see Table 1), the ratio of SS to MS should be 1.2 to 1.5 if the combustion conditions during both phases of smoke generation were comparable. However, this is not the case,

as is indicated by the higher SS to MS ratios for carbon monoxide (2.5-4.7), carbon dioxide (8-11), acrolein (8-15), benzene (10), and other smoke constituents.

The high yield of carbon monoxide and carbon dioxide in SS indicates that more carbon monoxide is generated during smoldering than during puff-drawing. After passing very briefly through the hot cone, most of the carbon monoxide gas in both MS and SS is oxidized to carbon dioxide, most likely owing to the high temperature gradient and the sudden exposure to environmental oxygen upon emission.

The higher yields of volatile pyridines in SS compared with MS are probably caused by the preferred formation of these compounds from the alkaloids during smoldering (Schmeltz et al. 1979). In contrast, hydrogen cyanide (HCN) is primarily formed from protein at temperatures above 700° C (Johnson and Kang 1971), and the smoldering of tobacco at about 600° C does not yield the pyrosynthesis of HCN to the extent that it occurs at the higher temperatures present during MS generation. The very high levels of ammonia, nitrogen oxide, and the volatile N-nitrosamines in SS compared with the levels in MS is striking. Studies with ¹⁵N-nitrate have underscored that the burning of tobacco results in the reduction of nitrate to ammonia, and that the latter is released to a greater extent during SS formation than during puff-drawing (Johnson et al. 1973). In a blended cigarette, this higher level of ammonia in SS causes its elevated pH to reach levels of 6.7 to 7.5, while the pH of MS is about 6 (Brunnemann and Hoffmann 1974).

The increased release of the highly carcinogenic volatile N-nitrosamines into SS (20 to 100 times greater than into MS) has been well established (Brunnemann et al. 1977). The carcinogenic potential of SS may also be affected by the levels of the oxides of nitrogen (NO_x). Four to ten times more nitrogen oxide (NO) is released into the environment in sidestream smoke than is inhaled with the mainstream smoke. The smoker inhales more than 95 percent of the NO_x in the form of NO, and only a small portion is oxidized to the powerful nitrosating agent nitrogen dioxide (NO₂). Only a fraction of NO is expected to be retained in the respiratory system of smokers by being bound to hemoglobin. The NO_x gases released into the environment are partially oxidized to NO₂ (Vilcins and Lephardt 1975). Therefore, sidestream smoke-polluted environments are expected to contain the hydrophilic nitrosating agent NO₂.

Data for particulate matter and some of its constituents in MS and SS are also listed in Table 2. The release of tobacco-specific N-nitrosamines into SS is up to four times higher than that into MS. Whether the distribution of these agents in the vapor phase and the particulate phase of SS is of major consequence with respect to the carcinogenic potential of SS needs to be determined. It is equally

TABLE 2.—Distribution of constituents in mainstream smoke (MS) and the ratio of sidestream smoke (SS) to MS of nonfilter cigarettes

Vapor phase constituents ¹	MS range	SS/MS ratio	Particulate phase constituents ¹	MS range	SS/MS ratio
Carbon monoxide	10-23 mg	2.5-4.7	Particulate matter ²	15-40 mg	1.3-1.9
Carbon dioxide	20-40 mg	8-11	Nicotine	1-2.5 mg	2.6-3.3
Carbonyl sulfide	18-42 µg	0.03-0.13	Anatabine	2-20 µg	<0.1-0.5
Benzene ¹	12-48 µg	10	Phenol	60-140 µg	1.6-3.0
Toluene	160 µg	6	Catechol	100-360 µg	0.6-0.9
Formaldehyde	70-100 µg	0.1-50	Hydroquinone	110-300 µg	0.7-0.9
Acrolein	60-100 µg	8-15	Aniline	360 ng	30
Acetone	100-250 µg	2-5	2-Toluidine	160 ng	19
Pyridine	16-40 µg	6.5-20	2-Naphthylamine ²	1.7 ng	30
3-Methylpyridine	12-36 µg	3-13	4-Aminobiphenyl ²	4.6 ng	31
3-Vinylpyridine	11-30 µg	20-40	Benz[a]anthracene ⁴	20-70 ng	2-4
Hydrogen cyanide	400-500 µg	0.1-0.25	Benzo[a]pyrene ³	20-40 ng	2.5-3.5
Hydrazine ³	32 ng	3	Cholesterol	22 µg	0.9
Ammonia	50-130 µg	40-170	γ-Butyrolactone ⁴	10-22 µg	3.6-5.0
Methylamine	11.5-28.7 µg	4.2-6.4	Quinoline	0.5-2 µg	8-11
Dimethylamine	7.8-10 µg	3.7-5.1	Harman	1.7-3.1 µg	0.7-1.7
Nitrogen oxide	100-600 µg	4-10	N'-Nitrosornicotine ⁴	200-3,000 ng	0.5-3

TABLE 2.—Continued

Vapor phase constituents ¹	MS range	SS/MS ratio	Particulate phase constituents ¹	MS range	SS/MS ratio
N-Nitrosodimethylamine ⁴	10–40 ng	20–100	NNK ⁴	100–1,000 ng	1–4
N-Nitrosopyrrolidine ⁴	6–30 ng	6–30	N-Nitrosodienthanolamine ⁴	20–70 ng	1.2
Formic acid	210–490 µg	1.4–1.6	Cadmium	100 ng	7.2
Acetic acid	330–810 µg	1.9–3.6	Nickel ³	20–80 ng	13–30
			Zinc	60 ng	6.7
			Polonium-210 ³	0.04–0.1 pCi	1.0–4.0
			Benzoic acid	14–28 µg	0.67–0.95
			Lactic acid	63–174 µg	0.5–0.7
			Glycolic acid	37–126 µg	0.6–0.95
			Succinic acid	110–140 µg	0.43–0.62

¹ Values are given for fresh and undiluted MS and SS.

² Human carcinogen (IARC 1986).

³ Suspected human carcinogen (IARC 1986).

⁴ Animal carcinogen (IARC 1986).

SOURCE: Elliott and Rowe (1975); Hoffmann et al. (1983); Klus and Kuhn (1982); Sakuma et al. (1983); Sakuma, Kusama, Yamaguchi, Matsuki et al. (1984); Sakuma, Kusama, Yamaguchi, Sugawara (1984); Schmeltz et al. (1975).

important to examine the significance of the abundant release of amines into SS (levels are up to 30 times higher than in MS), indicated by the data for aniline, 2-toluidine, and the alkaloids. This is of concern because certain amines are readily nitrosated to N-nitrosamines. However, analytical data on secondary reactions of amines in polluted environments are lacking.

For a meaningful interpretation of the data on the distribution of the compounds in cigarette smoke presented in Table 2, certain aspects of the methodology should be emphasized. First, the data are based on analyses of nonfilter cigarettes that were smoked under standardized laboratory conditions. Second, the standardized machine-smoking conditions were established according to human smoking patterns observed three decades ago and do not reflect the smoking behavior of contemporary smokers. This caveat applies particularly to smoking patterns observed with filter cigarettes designed for low smoke yields. Most consumers of these cigarettes inhale the smoke more intensely than smokers of nonfilter cigarettes (Herning et al. 1981; Hill et al. 1983). This change in smoking intensity affects the delivery of the sidestream smoke. The conventional filter tips of cigarettes influence primarily the yield of MS and have little impact on SS yield. However, in the case of cigarettes with specially designed filter tips such as perforations, the yield of SS is also affected (Table 3) (Adams et al. 1985).

Radioactivity of Tobacco Smoke

Naturally occurring decay products of radon are found in tobacco and, therefore, also in tobacco smoke. These include the isotopes of lead (Pb-210), bismuth (Bi-210), polonium (Po-210), and radon, which originates from the decay of uranium through radium (Radford and Hunt 1964; Martell 1975). Radon and its short-lived daughters (Po-218, Pb-214, Bi-214, Po-214), which precede long-lived daughters in the decay chain, are ubiquitous in indoor air and are largely derived from sources other than tobacco smoke. Most of the radon daughters are attached to particles in the air, but a small proportion, referred to as the unattached fraction, is not (Raabe 1969; Kruger and Nöthling 1979; Bergman and Axelson 1983).

It has been suggested that the presence of Pb-210 and subsequent decay products in tobacco is dependent upon an absorption of short-lived radon daughters on the leaves of the tobacco plant, especially where phosphate fertilizers that are rich in radium have been used and have caused increased leakage of radon from the ground. These attached short-lived radon daughters then decay to long-lived Pb-210 and subsequent nuclides found in the tobacco (Fleischer and Parungo 1974; Martell 1975). However, the origin of these decay products may

TABLE 3.—Distribution of selected components in the sidestream smoke (SS) and the ratio of SS to mainstream smoke (MS) of four U.S. commercial cigarettes

Components	Cigarette A 85 mm NF		Cigarette B 85 mm F		Cigarette C 85 mm F		Cigarette D 85 mm PF	
	SS	SS/MS	SS	SS/MS	SS	SS/MS	SS	SS/MS
Tar (mg/g)	22.6	1.1	24.4	1.6	20.0	2.9	14.1	15.6
Nicotine (mg/g)	4.6	2.2	4.0	2.7	3.4	4.2	3.0	20.0
Carbon monoxide (mg/g)	28.3	2.1	36.6	2.7	33.2	3.5	26.8	14.9
Ammonia (mg/g)	524	7.0	893	46	213.1	6.3	236	5.8
Catechol (µg/g)	58.2	1.4	89.8	1.3	69.5	2.6	117	12.9
Benzo(a)pyrene (ng/g)	67	2.6	45.7	2.6	51.7	4.2	448	20.4
N-Nitrosodimethylamine (ng/g)	735	23.6	597	139	611	50.4	685	167
N-Nitrosopyrrolidine (ng/g)	177	2.7	139	13.6	233	7.1	234	17.7
N'-Nitrosornicotine (ng/g)	857	0.85	307	0.63	185	0.68	338	5.1

NOTE: NF, nonfilter cigarette; F, filter cigarette; PF, cigarette with perforated filter tip; values given are for fresh and undiluted sidestream and mainstream smoke.
SOURCE: Adams et al. (1985).

also depend on the general occurrence of radon in the atmosphere and not on the local emanation of radon (Hill 1982).

In recent years, it has been shown that relatively high levels of radon and short-lived radon daughters may occur in indoor air, and consistent observations in this regard have been made in several countries (Nero et al. 1985). In the air with a very low concentration of particles, the proportion of unattached radon daughters is increased beyond that found with a higher concentration of particles. The unattached daughters are removed more rapidly than those that are attached by plating out on walls and fixtures. The addition of an aerosol, such as tobacco smoke, increases the attached fraction, elevates the concentration of radon daughters, and reduces the rate of removal of radon daughters (Bergman and Axelson 1983). The dose of α radiation received by the airway epithelium depends not only on the concentration of radon daughters but also on the unattached fraction and on the size distribution of the inhaled particles. The interplay among these factors as they are modified by ETS has not yet been fully examined.

Environmental Tobacco Smoke

The air dilution of sidestream smoke, and of other contributors to ETS, causes several physicochemical changes in the aerosol. The concentration of particles in ETS depends on the degree of air dilution and may range from 300 to 500 mg/m³ to a few μ g/m³. At the same time, the median diameter of particles may decrease as undiluted SS is diluted to form ETS (Keith and Derrick 1960; Wynder and Hoffmann 1967; Ingebrethsen and Sears 1986). Furthermore, nicotine volatilizes during air dilution of SS, so that in ETS it occurs almost exclusively in the vapor phase (Eudy et al. 1985). This is reflected in the fairly rapid occurrence of relatively high concentrations of nicotine in the saliva of people entering a smoke-polluted room (Hoffmann, Haley et al. 1984). Most likely there are also redistributions between the vapor phase and the particulate phase of other constituents in SS due to air dilution, which may account for the presence of other semivolatiles in the vapor phase of ETS. However, evidence of such effects needs to be established.

Comparison of Toxic and Carcinogenic Agents in Mainstream Smoke and in Environmental Tobacco Smoke

The combustion products of cigarettes are the source of both environmental tobacco smoke and mainstream smoke. Therefore, comparisons of the levels of specific toxins and carcinogens in ETS with the corresponding levels in the mainstream smoke are relevant to an estimation of the risk of ETS exposure. Although ETS is a far

less concentrated aerosol than undiluted MS, both inhalants contain the same volatile and nonvolatile toxic agents and carcinogens. This fact and the current knowledge about the quantitative relationships between dose and effect that are commonly observed from exposure to carcinogens have led to the conclusion that the inhalation of ETS gives rise to some risk of cancer (IARC 1986).

However, comparisons of MS and ETS should include the consideration of the differences between the two aerosols with regard to their chemical composition, including pH levels, and their physicochemical nature (particle size, air dilution factors, and distribution of agents between vapor phase and particulate phase). Another important consideration pertains to the differences between inhaling ambient air and inhaling a concentrated smoke aerosol during puff-drawing. Finally, chemical and physicochemical data established by the analysis of smoke generated by machine-smoking are certainly not fully comparable to the levels and characteristics of compounds generated when a smoker inhales cigarette smoke. This caveat applies particularly to the smoking of low-yield cigarettes, for which the yields of smoke constituents in machine-generated smoking and human smoking activities may be most divergent (Herning et al. 1981).

The levels of certain smoke constituents in the mainstream smoke of one cigarette compared with the amounts of such compounds inhaled as constituents of ETS in 1 hour at a respiratory rate of 10 L per minute are presented in Table 4. Unaged MS does not contain nitrogen dioxide ($\text{NO}_2 < 5 \mu\text{g}/\text{cigarette}$) because the nitrogen oxides generated during tobacco combustion in the reducing atmosphere of the burning cone are transported in the smoke stream ($\approx 10 \text{ vol } \% \text{ O}_2$) to the exit of the cigarette mouthpiece in less than 0.2 seconds, and it takes 500 seconds for half of the nitrogen oxide in MS to oxidize to nitrogen dioxide (Neurath 1972). The relatively low values for nicotine reported in ETS may be explained, in part, by the inefficiency of the trapping devices for collecting all of the available nicotine; the alkaloid is predominantly in the vapor phase, which escapes retention by the filters of such devices.

The assignment of benzene as a "human carcinogen," benzo[a]pyrene as a "suspected human carcinogen," and N-nitrosodimethylamine and N-nitrosodiethylamine as "animal carcinogens" is based on definitions by the International Agency for Research on Cancer (1986). Accordingly, a human carcinogen is an agent for which "sufficient evidence of carcinogenicity indicates that there is a causal relationship between exposure and human cancer." A suspected human carcinogen is an agent for which "limited evidence of carcinogenicity indicates that a causal interpretation is credible, but that alternate explanations, such as chance, bias, or confounding, could not adequately be excluded." An animal carcinogen is an agent

TABLE 4.—Concentrations of toxic and carcinogenic agents in nonfilter cigarette mainstream smoke and in environmental tobacco smoke (ETS) in indoor environments

Agent	Mainstream Smoke		Inhaled as ETS constituents during 1 hour			
	Weight	Concentration	Range		Episodic high values ¹	
			Weight	Concentration	Weight	Concentration
Carbon monoxide	10-23 mg	24,9000-57,300 ppm	1.2-22 mg	1-18.5 ppm	37 mg	32 ppm
Nitrogen oxide	100-600 µg	230,000-1,400,000 ppb	7-90 µg	9-120 ppb	146 µg	195 ppb
Nitrogen dioxide	<5 µg	<7,600 ppb	24-87 µg	21-76 ppb	120 µg	105 ppb
Acrolein	60-100 µg	75,000-125,000 ppb	8-72 µg	6-50 ppb	110 µg	80 ppb
Acetone	100-250 µg	120,000-300,000 ppb	210-720 µg	150-500 ppb	3,500 µg	2,400 ppb
Benzene ²	12-48 µg	11,000-43,000 ppb	12-190 µg	6-98 ppb	190 µg	98 ppb
N-Nitrosodimethylamine ³	10-40 ng	9-38 ppb	6-140 ng	0.003-0.072 ppb	140 ng	0.072 ppb
N-Nitrosodiethylamine ³	4-25 ng	3-17 ppb	<6-120 ng	<0.002-0.05 ppb	120 ng	0.05 ppb
Nicotine	1,000-2,500 µg	430,000-1,080,000 ppb	0.6-30 µg	0.15-7.5 ppb	300 µg	75 ppb
Benzo[a]pyrene ⁴	20-40 ng	5-11 ppb	1.7-460 ng	0.0002-0.04 ppb	460 ng	0.04 ppb

NOTE: Values for inhaled mainstream smoke components were calculated from values in Table 2 and on a respiratory rate of 10 L per minute. Values for carbon monoxide and nicotine represent the range in mainstream smoke of U.S. nonfilter cigarettes as reported by the U.S. Federal Trade Commission (1985). Data under ETS are derived from Tables 8 through 15, with data from the unventilated interior compartments of automobiles excluded (Badre et al. 1978).

¹The designation "episodic high values" was chosen to classify those data in the literature that require confirmation.

²Human carcinogen according to the IARC (Vainio et al. 1985) and suspected carcinogen according to the ACGIH (1985).

³Animal carcinogen according to the IARC (Vainio et al. 1985).

⁴Suspected human carcinogen, according to the IARC (Vainio et al. 1985) and according to the ACGIH (1985).

“for which there is sufficient evidence of carcinogenicity in animals but for which no data on humans are available.”

Polonium-210 is not listed in Table 4 because there are no data on the concentration of this isotope in ETS, although it is a component of both MS and SS. Whereas in clean air the short-lived radon daughters tend to plate out on room surfaces, in the presence of an aerosol such as ETS, some of the short-lived radon daughters become attached to particles and consequently remain available for inhalation. Radon daughter background concentration may more than double in the presence of ETS (Bergman and Axelson 1983).

Number and Size Distribution of Particles in Environmental Tobacco Smoke

Environmental tobacco smoke consists of the combined products of both fresh and aged sidestream smoke and exhaled mainstream smoke. Coagulation, evaporation, and particle removal on surfaces occur simultaneously to modify the physical characteristics of the ETS particles; as a result, the “typical” particle size and chemical composition of ETS may vary with the age of the smoke and the characteristics of the environment. Other factors such as relative humidity, particle concentration, and temperature may also affect the characteristics of ETS.

The rapid dilution of SS smoke as it is emitted into a room leads to a number of physical and chemical changes. For example, the evaporation of volatile species as the ETS ages reduces the median diameter of the smoke particles. Several studies have measured the particle distribution of SS under controlled conditions (Table 5), and indicate that the mass median diameter (MMD) of ETS is between approximately 0.2 μm and 0.4 μm . The differences among the studies reflect the varying analytical methods. ETS particles are in the diffusion-controlled regime for particle removal and therefore will tend to follow stream lines, remain airborne for long periods of time, and rapidly disperse through open volumes.

As indicated, a number of factors can produce variation in the mean size of the particles in ETS; however, in considering transport, deposition, and removal in the human lung, it is useful to assume that the particle sizes of aged ETS will generally be between 0.1 and 0.4 μm . Although the results presented in Table 5 do not permit the assignment of a single value for the diameter of sidestream smoke particles, the difference in deposition efficiency in the human respiratory tract of 0.2 μm particles and 0.4 μm particles is negligible (Chan and Lippmann 1980). Particles in this size range are not efficiently removed by sedimentation or impaction. Although diffusion is the major removal mechanism for particles of this size, it is minimally efficient in the 0.2 to 0.4 μm range. The relatively low

TABLE 5.—Summary of sidestream smoke size distribution studies

Study	Cigarette	Method	Chamber concentration ($\mu\text{g}/\text{m}^3$)	Count median diameter	Mass median diameter	Geometric standard deviation	Number per cm^3
Keith and Derrick (1960)	Blended	"Conifuge"	Not reported	0.15	Not reported	Not reported	3.8×10^{11}
Porstendorfer and Schraub (1972)	Not reported	CNC/diffusion tube	Not reported	0.24	Not reported	Not reported	3.3×10^{12}
Hiller et al. (1982)	Not reported	SPART analyzer	50-100	0.32	0.41	1.5	Not reported
Leaderer et al. (1984)	Commercial	EAA	700	Not reported	0.225	2.1	Not reported
Ingebretsen and Sears (1986)		MC/CNC			0.2	1.5	

NOTE: CNC = Condensation nucleus counter; SPART = Single particle aerodynamic relaxation time analyzer; EAA = Electrical aerosol analyzer; MC = Mobility classifier.

particle deposition efficiency for SS particles in human volunteers observed by Hiller and colleagues (1982) is consistent with particles in this size range.

Several investigators have measured the size distribution of MS smoke (Table 6). As is the case with SS smoke, the different instruments and methodologies employed yielded differing results.

For purposes of comparison, only two sets of studies utilizing similar instruments are discussed. McCusker and colleagues (1983), using a single particle aerodynamic relaxation time (SPART) analyzer to study highly diluted MS smoke particles, found a mass median diameter of 0.42 μm with a geometric standard deviation (GSD) of 1.38. Hiller and colleagues (1982) used the SPART analyzer on SS smoke particles and found a mass median diameter of 0.41 μm and GSD of 1.5. Chang and colleagues (1985) used an electrical aerosol analyzer (EAA) to measure MS for various dilution ratios and reported a MMD of 0.27 μm (GSD 1.26) for the highest dilution. Leaderer and colleagues (1984) used an EAA to determine the size distribution for SS smoke particles in an environmental chamber and determined an MMD of 0.23 μm (GSD 2.08). These results also show that studies utilizing similar instruments provide similar results for the size distribution of both SS and MS particles. As discussed in an earlier section, however, the chemical composition of the MS and ETS particles can be quite different because of the very different conditions of their generation and the subsequent dilution and aging ETS undergoes before inhalation.

Estimating Human Exposure to Environmental Tobacco Smoke

Human exposure to ETS can be estimated using approaches similar to those used for other airborne pollutants. The concentration of ETS to which an individual is exposed depends on factors such as the type and number of cigarettes burned, the volume of the room, the ventilation rate, and the proximity to the source. These factors, along with the duration of exposure and individual characteristics such as ventilatory rate and breathing pattern, dictate the dosage received by an individual.

Ideally, the health effects of exposures to ETS might be assessed by quantifying the time-dependent exposure dose for each of the several thousand compounds in cigarette smoke and defining the dose-response relationships for these compounds in producing disease, both as isolated compounds and in various combinations. The magnitude of this task, given the number of compounds in smoke, and the limited knowledge of the precise mechanisms by which these compounds cause disease have led to a simpler approach, one that attempts to use measures of exposure to individual smoke constituents as estimates of whole smoke exposure. The accuracy with which

TABLE 6.—Summary of mainstream smoke size distribution studies

Study	Cigarette	Method	Dilution ratio	Count median diameter (μm)	Mass median diameter (μm)	Geometric standard deviation	Concentration (number/cm ³)
Keith and Derrick (1960)	Blended	"Conifuge"	295	0.23	Not reported	1.6	5.3×10^8
Porstendörfer and Schraub (1972)	Not reported	CNC/diffusion tube	Not reported	0.22	Not reported	Not reported	Not reported
Okada and Matsunama (1974)	Blended	Light scattering	1500	0.18	0.29	1.5	3×10^{10}
Hinds (1978)	Commercial	Cascade impactor	10	Not reported	0.52	1.35	Not reported
		Cascade impactor	50	Not reported	0.44	1.44	Not reported
		Cascade impactor	100	Not reported	0.39	1.43	Not reported
		Aerosol certifuge	100	Not reported	0.38	1.33	Not reported
		Aerosol certifuge	320	Not reported	0.38	1.37	Not reported
		Aerosol certifuge	500	Not reported	0.38	1.35	Not reported
		Aerosol certifuge	700	Not reported	0.37	1.31	Not reported
McCusker et al. (1983)	2R1	SPART analyzer	1.26×10^4	0.36	0.42	1.38	4.2×10^8
Chang et al. (1985)	2R1	EAA	6	0.25	0.30	1.27	4.2×10^8
			10	0.24	0.26	1.18	3.6×10^8
			18	0.22	0.26	1.26	7×10^8

NOTE: CNC = Condensation nucleus counter; SPART = Single particle aerodynamic relaxation time analyzer; EAA = Electrical aerosol analyzer.

measurements of a single compound reflect exposure to whole smoke is limited by the changes in the composition of ETS with time and the conditions of exposure. For this reason, exposures to ETS are often assessed using several measures as markers, including markers of the vapor phase and the particulate phase as well as reactive and nonreactive constituents. Although biological markers show promise as measures of exposure because they measure the absorption of smoke constituents, they too have limitations (discussed in Chapter 4). An individual's exposure is a dynamic integration of the concentration in various environments and the time that the individual spends in those environments.

In specifying an individual's exposure to specific components of ETS, consideration must be given to the time scale of exposure appropriate for the response of interest. Immediate exposures of seconds or hours would be most relevant for irritant and acute allergic responses. Time-averaged exposures, of hours or days, may be important for acute contemporary effects such as upper and lower respiratory tract symptoms or infections; chronic exposures occurring over a year or a lifetime might be associated with increased prevalence of chronic diseases and risk of cancer.

The spatial dimensions or the proximity of the individual to the source of smoke is important in assessing that individual's exposure to ETS. ETS is a complex, dynamic system that changes rapidly once emitted from a cigarette. Physical processes such as evaporation and dilution of the particles, scavenging of vapors on surfaces, and chemical reactions of reactive compounds are continuously occurring and modify the mixture referred to as ETS. An individual located a few centimeters or a meter from a burning cigarette may be exposed to a high concentration of ETS, ranging from 200 to 300 mg/m³, and may inhale components of the mostly undiluted smoke plume and of the exhaled mainstream smoke. Ayer and Yeager (1982) reported cigarette plume concentrations of formaldehyde and acrolein in the core smoke stream emitted from the cigarette of up to 100 times higher than known irritation levels. Hirayama, as reported by Lehnert (1984), cites the importance of this "proximity effect" in assessing exposure. Distances on the order of a meter to tens of meters from a burning cigarette are relevant for exposures in offices, restaurants, a room in a house, a car, or the cabin of a commercial aircraft. At these distances, the mixing of ETS throughout the airspace and the factors that affect concentration are of importance in determining exposure for people in the space. In many rooms, mixing is not completely uniform throughout the volume, and significant concentration gradients can be demonstrated (Ishizu 1980). These concentration gradients will affect an individual's exposure by modifying the effectiveness of ventilation in diluting or removing pollutants. The airborne mass concentration may vary by

a factor of 10 or more within a room. Short-term measurements in rooms with smokers can yield respirable particulate concentrations of 100 to 1,000 $\mu\text{g}/\text{m}^3$ (Repace and Lowrey 1980). Multihour measurements average out variations in smoking, mixing, and ventilation and yield concentrations in the range of 20 to 200 $\mu\text{g}/\text{m}^3$ (Spengler et al. 1981, 1985, 1986). Finally, on a systems scale, as in a house or building, concentrations are influenced by dispersion and dilution through the volume. Most time-integrated samples are taken on this larger scale.

Using a piezobalance, Lebret (1985) found significant variation in respirable suspended particulate (RSP) levels between the living room, kitchen, and bedroom in homes in the Netherlands during smoking or within one-half hour of smoking. Ju and Spengler (1981) studied the room-to-room variation in 24-hour average concentrations of respirable particles in various residences. Although differences between some rooms were statistically significant, absolute differences were relatively small, with a maximum difference of a factor of 2.

Moschandreas and colleagues (1978) released sulfur hexafluoride, a tracer gas, in the living rooms of several residences and observed uniform concentrations in adjacent rooms within 30 to 90 minutes. RSP, which is slightly reactive, and nonreactive gases would be expected to rapidly migrate through adjacent rooms. Therefore, in a setting such as the work environment, where the duration of exposure is several hours or more, ETS would be expected to disseminate throughout the airspace in which smoking is occurring. Smoke dissemination may be reduced when air exchange rates are low, as may occur when internal doors are closed.

Time-Activity Patterns

Individual time-activity patterns are a major determinant of exposure to ETS. The population of the United States is mobile, spending variable amounts of time in different microenvironments. Individual activity patterns depend on age, occupation, season, social class, and sex. For example, Letz and colleagues (1984) surveyed the time-activity patterns of 332 residents of Roane County, Tennessee, and found that 75 percent of the person-hours were spent at home, 10.8 percent at work, 8.5 percent in public places, 2.9 percent in travel, and 2.8 percent in various other places. As expected, occupation and age were strong determinants of time-activity patterns. Housewives and unemployed or retired individuals spent 84.9 percent of their time at home, and occupational groups worked 21 to 24 percent of the hours. Students tended to spend the largest percentage of their time in public places, presumably schools, ranging from 14.7 percent for the youngest group to 19.17 percent for the oldest group of students.

TABLE 7.—Mean percent and standard deviation of time allocation in various locations by work or school classification subgroup

Location	Homemaker	Student	Outdoor worker	Office/Service	Industrial/Construction	Total, all participants
Home	84.34 (2.02) ¹	60.91 (13.92)	49.97 (12.24)	68.74 (8.72)	57.28 (7.05)	64.21 (13.99)
Outside	5.52 (3.27)	8.62 (5.53)	19.81 (8.55)	2.47 (2.49)	10.59 (10.74)	8.08 (7.07)
Motor vehicle	4.28 (3.19)	5.11 (3.74)	8.67 (6.15)	4.69 (2.33)	7.64 (7.52)	5.51 (4.29)
Other indoors	6.01 (3.27)	23.61 (10.61)	21.55 (5.32)	24.99 (10.24)	24.80 (12.86)	21.58 (11.37)
Cooking	4.69 (1.88)	0.34 (0.79)	0.00 (0.00)	2.32 (2.30)	0.52 (0.86)	1.24 (1.98)
Near smokers	2.84 (4.32)	5.20 (7.88)	2.75 (3.38)	11.73 (15.19)	12.03 (10.05)	6.89 (9.71)
Number	8	32	4	12	8	66 ²

¹ Numbers in parentheses are the standard deviation.

² Two unemployed participants were included in the total, but not given a separate category.

SOURCE: Data from Quackenboss et al. (1982).

The time allocations for various population subgroups in Portage, Wisconsin, are summarized in Table 7 (Quackenboss et al. 1982). The data are consistent with the findings of Letz and colleagues (1984) and show that the variability of individual nonsmokers' exposure to smokers can be quite marked between the various occupational subgroups.

Infants have unique time-activity patterns; their mobility is limited and the locations where they spend their time depend primarily on their caretakers. The time-location patterns for 46 infants is illustrated in half-hour segments in Figure 1 (Harlos et al. in press). Although infants spend most of their time in their bedrooms, they are in contact with a caretaker while traveling or in the living room or the kitchen for approximately half of the day. These infant time-activity patterns presumably correspond to the family patterns and may significantly influence the infants' potential exposure.

Although most people spend approximately 90 percent of their time in just two microenvironments (home and work) (Szalai 1972), important exposures can be encountered in other environments. For instance, commuting or being "in transit" accounts for about 0.5 to 1.5 hours per day for most people. Therefore, additional information

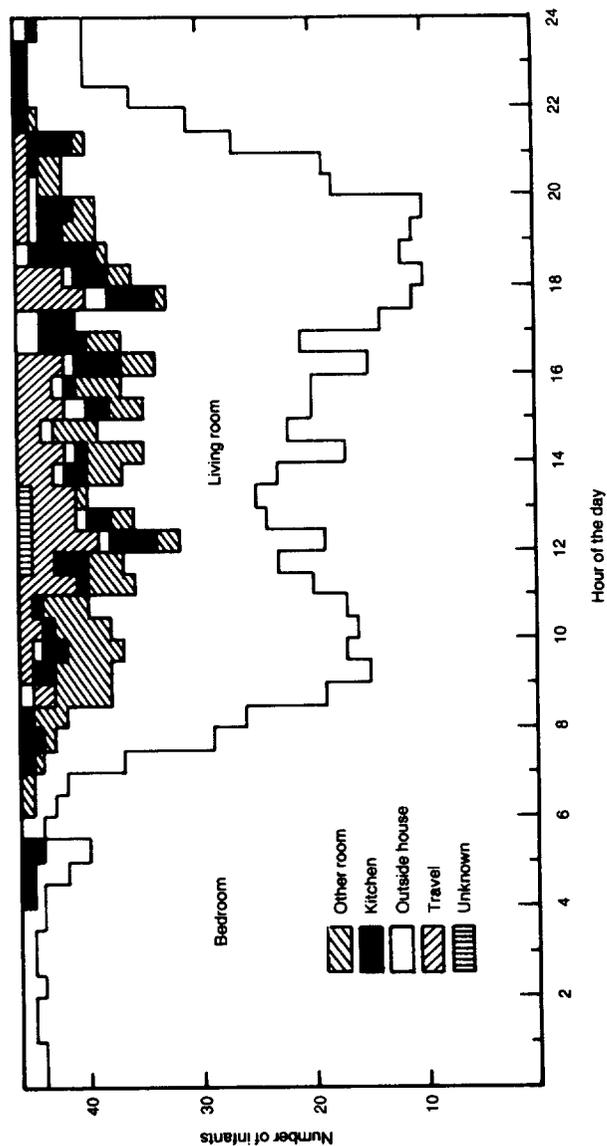


FIGURE 1.—Time location patterns for 46 infants
 SOURCE: Harlos et al. (in press).

on the time spent and the ETS concentration in various microenvironments may be useful in defining exposure. This exposure information can be obtained by questionnaire and validated by personal monitoring programs. The characterization of concentra-

tions or exposures or both in microenvironments should use time scales appropriate for the health effect of interest. These variations in location and time-activity patterns can make the reconstruction of detailed ETS exposure difficult in studies of long-term health effects.

The limitations in utilizing this time-activity approach in characterizing exposures to other environmental pollutants also apply for ETS exposures. They include the following: the extent to which overall population estimates can be generalized to individual patterns is poorly understood; concentrations in various microenvironments are only partially characterized; the variation in time and activity patterns and their effects on concentration levels are not established; extrapolation to longer time scales either prospectively or retrospectively has not been validated; the differences within structures, i.e., room to room variations, are not well established.

Temporal and Spatial Distribution of Smokers

Exposure to ETS can occur in a wide variety of public and private locations. Approximately 30 percent of the U.S. adult population currently are cigarette smokers. Nationwide, 40 percent of homes have one or more smokers (Bureau of the Census 1985). In a survey of more than 10,000 children in six U.S. cities, the percentage of children living with one or more smoking adults varied from a low of 60 percent to a high of 75 percent (Ferris et al. 1979). Lebowitz and Burrows (1976) reported that 54 percent of children in a study in Tucson had at least one smoker in the home; Schilling and colleagues (1977) reported that 63 percent of homes in a Connecticut study had a smoker in the home. These data indicate that the population potentially exposed to ETS in the home is greater than might be inferred from aggregated national statistics on the prevalence of smoking. A variation in the percentage of homes with smokers may be observed among different regions. Furthermore, within households, smoking does not take place uniformly in time or space. Smoking patterns may change with activity, location, and time of day. These variables all serve to modify a nonsmoker's exposure to ETS.

Exposure to ETS at home may also correlate with ETS exposures outside the home, possibly because nonsmokers married to smokers may have a greater tolerance for ETS-polluted environments or may be in the company of more smokers because of the spouses' tendency to associate with other smokers. Wald and Ritchie (1984) used a biological marker and questionnaires to show that nonsmokers married to smokers reported a duration of exposure to ETS greater outside the home than was reported by nonsmokers married to nonsmokers (10.7 hours and 6.0 hours, respectively).

Smoking prevalence varies widely among different groups (e.g., teenage girls, nonworking adults, and adults employed in various

occupations); this variation modifies the exposure of nonsmokers to ETS. Smokers are present in nearly all environments, including most workplaces, restaurants, and transit vehicles, making it almost impossible for a nonsmoker to avoid some exposure to ETS. The number of cigarettes consumed per hour by the smoker may vary at different times in the day, and the rate and density of smoking will also differ by the type of indoor environment and activity in such locales as schools, autos, planes, offices, shops, and bars.

Although there have been numerous measurements of ETS concentrations in various indoor settings, these data do not represent a comprehensive description of the actual distribution of ETS exposures in the U.S. population. Spengler and colleagues (1985) and Sexton and colleagues (1984) demonstrated by the personal monitoring of respirable particles and the use of time-activity questionnaires that exposures to ETS both at home and at work are significant contributors to personal exposures. However, additional data on the distribution of smokers in the nonsmokers' environment, as well as the distribution of ETS levels in that environment, are needed in order to characterize the actual ETS exposure of the U.S. population.

Determinations of Concentration of Environmental Tobacco Smoke

Environmental tobacco smoke is a complex mixture of chemical compounds that individually may be in the particulate phase, the vapor phase, or both. ETS concentration varies with the generation rate of its tobacco-derived constituents, usually given as micrometer per hour. The generation rate for ETS has been approximated by the number of cigarettes smoked or the number of people present in a room who are actively smoking. Room-specific characteristics such as ventilation rate, decay rate, mixing rate, and room volume also modify the concentration. Because ETS particles have MMDs in the 0.2 to 0.4 μm range, convective flows dominate their movement in air, they remain airborne for long periods of time, and they are rapidly distributed through a room by advection and a variety of mixing forces. Under many conditions, the ventilation rate of a space will dominate chemical or physical removal mechanisms in determining the levels of ETS particles.

Nonreactive ETS components distribute rapidly through an air-space volume, and their elimination depends almost solely on the ventilation rate. For example, Wade and colleagues (1975) simultaneously measured carbon monoxide, a nonreactive gas, and nitrogen dioxide, a reactive gas, in a house and determined their half-lives to be 2.1 and 0.6 hours, respectively. This study demonstrates the need for caution in extrapolating from one vapor phase compound to another. Reactive gases and vapors may be rapidly lost to surfaces or

may react with other chemical species. Their removal may be dominated by their reaction or absorption rates. Furthermore, the decay of ETS-derived substances can be a function of the chemical as well as the physical characteristics of room surfaces. For example, Walsh and colleagues (1977) found that sulfur dioxide removal was greater for rooms with neutral and alkaline carpets than for rooms having carpets with acidic pH. Reactions with furnishings and other materials may occur for some ETS components as well.

Microenvironmental Measurements of Concentration

As was discussed earlier, the complex chemical makeup of ETS makes the measurements of individual levels for each compound present in ETS impossible with existing resources; thus, some individual constituents have been measured as markers of overall smoke exposure. Because many of these constituents are also emitted from other sources in the environment, the contribution of ETS to the levels of these constituents is quantified by determining the enrichment of specific compounds found in smoke-polluted environments relative to the concentration measured in nonsmoking areas. Various ETS components have been measured for this purpose, including acrolein, aldehydes, aromatic hydrocarbons, carbon monoxide, nicotine, nitrogen oxides, nitrosamines, phenols, and respirable particulate matter. A summary of the levels found and the conditions of measurement are presented in Tables 8 through 15. The major limitation of using most of these gases, vapors, and particles is their lack of specificity for ETS. The presence of sources, other than tobacco smoke, of these compounds may limit their utility for determining the absolute contribution made by ETS to room concentrations. Levels of nicotine and tobacco-specific nitrosamines, however, are specific for ETS exposure.

Obviously, no single measurement can completely characterize the nonsmoker's exposure to ETS, and many studies have measured several of these components in order to characterize the exposure. Markers should be chosen both because of their accuracy in estimating exposure and because of their relevance for the health outcome of interest.

One widely reported marker of ETS is respirable suspended particulate (RSP) matter. Although lacking specificity for tobacco smoke, the prevalence and number of smokers correlates well with RSP levels in homes and other enclosed areas.

A study of the RSP levels in 80 homes in six cities (Figure 2) (Spengler et al. 1981) showed that indoor concentrations were higher on average and had a greater range than the outdoor concentrations. From these data, it is evident that even one smoker can significantly elevate indoor RSP levels.

TABLE 8.—Acrolein measured under realistic conditions.

Study	Type of premises	Occupancy	Ventilation	Monitoring conditions	Levels	
					Mean	Range
Badre et al. (1978)	Cafes	Varied	Not given	100 mL samples		0.03-0.10 mg/m ³
	Room	18 smokers	Not given	100 mL samples	0.185 mg/m ³	
	Hospital lobby	12 to 30 smokers	Not given	100 mL samples	0.02 mg/m ³	
	2 train compartments	2 to 3 smokers	Not given	100 mL samples		0.02-0.12 mg/m ³
	Car	3 smokers	Natural, open	100 mL samples	0.03 mg/m ³	
		2 smokers	Natural, closed	100 mL samples	0.30 mg/m ³	
Fischer et al. (1978) and	Restaurant	50-80/470 m ³	Mechanical	27 × 30 min samples	7 ppb	
Weber et al. (1979)	Restaurant	60-100/440 m ³	Natural	29 × 30 min samples	8 ppb	
	Bar	30 -40/50 m ³	Natural, open	28 × 30 min samples	10 ppb	
	Cafeteria	80-150/574 m ³	11 changes/hr	24 × 30 min samples	6 ppb (5 ppb nonsmoking section)	

TABLE 9.—Aromatic hydrocarbons measured under realistic conditions

Study	Type of premises	Occupancy	Ventilation	Monitoring conditions	Levels		Nonsmoking controls	
					Mean	Range	Mean	Range
Benzene (mg/m³)								
Badre et al. (1978)	Cafe	Varied	Not given	100 mL samples		0.05-0.15		
	Room	18 smokers	Not given	100 mL samples	0.109			
	Train compartments	2 to 3 smokers	Not given	100 mL samples		0.02-0.10		
	Car	3 smokers 2 smokers	Natural, open Natural, closed	100 mL samples 100 mL samples	0.04 0.15			
Toluene (mg/m³)								
	Cafe	Varied	Not given	100 mL samples		0.04-1.04		
	Room	18 smokers	Not given	100 mL samples	0.215			
	Train compartments	2 to 3 smokers	Not given	100 mL samples	1.87			
	Car	2 smokers	Natural, closed	100 mL samples	0.50			
Benzo(a)pyrene (ng/m³)								
Elliott and Rowe (1975)	Arena	8,647-10,786 people	Mechanical	Not given	7.1			
		12,000-12,844 people	Mechanical	Not given	9.9			
		13,000-14,277 people	Mechanical	Not given	21.7			
				Separate non-activity days			0.69	
Galuskinova (1964)	Restaurant	Not given	Not given	20 days in summer	6.2			
				18 days in the fall		28.2-144		

TABLE 9.—Continued

Study	Type of premises	Occupancy	Ventilation	Monitoring conditions	Levels		Nonsmoking controls	
					Mean	Range	Mean	Range
Just et al. (1972)	Coffee houses	Not given	Not given	6 hr continuous	0.25-10.1		4.0-9.3 (outdoors)	
					<u>Benzo[el]pyrene (ng/m³)</u>			
					3.3-23.4		3.0-5.1 (outdoors)	
					<u>Benzo[ghi]perylene (ng/m³)</u>			
					5.9-10.5		6.9-13.8 (outdoors)	
					<u>Perylene (ng/m³)</u>			
					0.7-1.3		0.1-1.7 (outdoors)	
					<u>Pyrene (ng/m³)</u>			
					4.1-9.4		2.8-7.0 (outdoors)	
					<u>Anthanthrene (ng/m³)</u>			
					0.5-1.9		0.5-1.8 (outdoors)	
					<u>Coronene (ng/m³)</u>			
0.5-1.2		1.0-2.8						
<u>Phenols (μ/m³)</u>								
7.4-11.5								
<u>Benzo[a]pyrene (ng/m³)</u>								
Perry (1973) ¹	14 public places	Not given	Not given	Samples, 5 outdoor locations	<20-760		<20-43	

¹The correctness of the data is doubtful (Grimmer et al. 1977).