FORMALDEHYDE

This substance was considered by previous working groups in October 1981 (IARC, 1982), March 1987 (IARC, 1987a) and October 1994 (IARC, 1995). Since that time, new data have become available, and these have been incorporated in the monograph and taken into consideration in the evaluation.

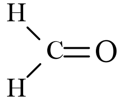
1. Exposure Data

1.1 Chemical and physical data

1.1.1 *Nomenclature*

Chem. Abstr. Serv. Reg. No.: 50-00-0
Deleted CAS Reg. Nos.: 8005-38-7; 8006-07-3; 8013-13-6; 112068-71-0
Chem. Abstr. Name: Formaldehyde
IUPAC Systematic Name: Methanal
Synonyms: Formaldehyde, gas; formic aldehyde; methaldehyde; methyl aldehyde; methylene oxide; oxomethane; oxymethylene

1.1.2 *Structural and molecular formulae and relative molecular mass*



CH_2O Relative molecular mass: 30.03

1.1.3 *Chemical and physical properties of the pure substance*

From Lide (2003), unless otherwise specified
(*a*) *Description*: Colourless gas with a pungent odour (Reuss *et al.*, 2003)
(*b*) *Boiling-point*: –19.1 °C
(*c*) *Melting-point*: –92 °C
(*d*) *Density*: 0.815 at –20 °C

(*e*) *Spectroscopy data*: Infrared [prism, 2538], ultraviolet [3.1] and mass spectral data have been reported (Weast & Astle, 1985; Sadtler Research Laboratories, 1991).

(*f*) *Solubility*: Soluble in water, ethanol and chloroform; miscible with acetone, benzene and diethyl ether

(*g*) *Stability*: Commercial formaldehyde–alcohol solutions are stable; the gas is stable in the absence of water; incompatible with oxidizers, alkalis, acids, phenols and urea (IARC, 1995; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

(*h*) *Reactivity*: Reacts explosively with peroxide, nitrogen oxide and performic acid; can react with hydrogen chloride or other inorganic chlorides to form bis(chloromethyl) ether (see IARC, 1987b) (IARC, 1995; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

(*i*) *Octanol/water partition coefficient (P)*: log P = 0.35 (Hansch *et al.*, 1995)

(*j*) *Conversion factor*: $mg/m^3 = 1.23 \times ppm$[1]

1.1.4 *Technical products and impurities*

Trade names: BFV; FA; Fannoform; Floguard 1015; FM 282; Formalin; Formalin 40; Formalith; Formol; FYDE; Hoch; Ivalon; Karsan; Lysoform; Morbicid; Paraform; Superlysoform

Formaldehyde is most commonly available commercially as a 30–50% (by weight) aqueous solution, commonly referred to as ‘formalin’. In dilute aqueous solution, the predominant form of formaldehyde is its monomeric hydrate, methylene glycol. In more concentrated aqueous solutions, oligomers and polymers that are mainly polyoxymethylene glycols are formed and may predominate. Methanol and other substances (e.g. various amine derivatives) are usually added to the solutions as stabilizers, in order to reduce intrinsic polymerization. The concentration of methanol can be as high as 15%, while that of other stabilizers is of the order of several hundred milligrams per litre. Concentrated liquid formaldehyde–water systems that contain up to 95% formaldehyde are also available, but the temperature necessary to maintain the solution and prevent separation of the polymer increases from room temperature to 120 °C as the concentration in solution increases. Impurities include formic acid, iron and copper (Cosmetic Ingredient Review Expert Panel, 1984).

Formaldehyde is marketed in solid form as its cyclic trimer, trioxane ($(CH_2O)_3$), and its polymer, paraformaldehyde, with 8–100 units of formaldehyde (WHO, 1991; IARC, 1995; Reuss *et al.*, 2003).

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[1] Calculated from: $mg/m^3 = (\text{relative molecular mass}/24.45) \times ppm$, assuming normal temperature (25 °C) and pressure (103.5 kPa)

1.1.5 *Analysis*

Selected methods for the determination of formaldehyde in various matrices are presented in Table 1.

The most widely used methods for the determination of the concentration of formaldehyde in air are based on spectrophotometry, with which sensitivities of 0.01–0.03 mg/m^3 can be achieved. Other methods include colorimetry, fluorimetry, high-performance liquid chromatography (HPLC), polarography, gas chromatography (GC), infrared detection and gas detector tubes. Most methods require the formation of a derivative for separation and detection.

HPLC is the most sensitive method (limit of detection, 2 μg/m^3 or less). Gas detector tubes (Draeger Safety, undated; Sensidyne, undated; WHO, 1989; MSA, 1998; Matheson Tri-Gas®, 2004; Sensidyne, 2004; SKC®, 2005) that have sensitivities of about 0.05–0.12 mg/m^3 [0.04–0.1 ppm] and infrared analysers (Interscan Corporation, undated; Environmental Protection Agency, 1999a,b; MKS Instruments, 2004a,b; Thermo Electron Corporation, 2005) that have sensitivities of about 1.2–230 μg/m^3 [1–110 ppb] are often used to monitor workplace atmospheres.

Based on these methods, several standards have been established to determine levels of formaldehyde emissions from wood products (European Commission, 1989; ASTM International, 1990; Groah *et al.*, 1991; Jann, 1991; Deutsche Norm, 1992, 1994, 1996; Standardiseringen i Sverige, 1996; Composite Panel Association, 1999; ASTM International, 2000; Japanese Standards Association, 2001; ASTM International, 2002a,b; Composite Panel Association, 2002).

Sandner *et al.* (2001) reported a modification of the existing method 1 of the Deutsche Forschungsgemeinschaft (1993) to monitor formaldehyde in the workplace that uses adsorption to 2,4-dinitrophenylhydrazine-coated sorbents followed by HPLC with ultraviolet (UV)/diode array detection. The detection limit decreased from approximately 15 μg/m^3 for the original method to 0.07 μg/m^3 for the modified method.

In the development of new methods to monitor formaldehyde in air, emphasis has been on direct optical sensors and on increased sensitivity (Friedfeld *et al.*, 2000; Lancaster *et al.*, 2000; Chan *et al.*, 2001; Mathew *et al.*, 2001; Alves Pereira *et al.*, 2002; Werle *et al.*, 2002).

Methods for the analysis of formaldehyde in biological matrices (e.g. blood and urine) have been reviewed (ATSDR, 1999), and new methods continue to be reported (Carraro *et al.*, 1999; Spanel *et al.*, 1999; Luo *et al.*, 2001; Kato *et al.*, 2001). Formaldehyde has been measured in blood by gas chromatography–mass spectrometry (GC–MS) after derivatization to pentafluorophenylhydrazone (Heck *et al.*, 1982, 1985). Formic acid or formate is produced from formaldehyde and can be measured in blood and urine (Baumann & Angerer, 1979). However, biological monitoring of exposure to formaldehyde is not common practice.

Table 1. Methods for the analysis of formaldehyde in air and food

Sample matrix	Sample preparation	Assay procedure	Limit of detection	Reference
Air	Draw air through impinger containing aqueous pararosaniline; treat with acidic pararosaniline and sodium sulfite	Spectrometry	10 µg/m^3	Georghiou *et al.* (1993)
	Draw air through PTFE filter and impingers, each treated with sodium bisulfite solution; develop colour with chromotropic acid and sulfuric acid; read absorbance at 580 nm	Spectrometry	0.5 µg/sample	NIOSH (1994a) [Method 3500]
	Draw air through solid sorbent tube treated with 10% 2-(hydroxymethyl) piperidine on XAD-2; desorb with toluene	GC/FID GC/FID & GC/MS GC/NSD	1 µg/sample 2 µg/sample 20 µg/m^3	NIOSH (1994b) [Method 2541] NIOSH (1994c) [Method 2539] Occupational Safety and Health Administration (1990a) [Method 52]
	Draw air through impinger containing hydrochloric acid/2,4-dinitrophenylhydrazine reagent and isooctane; extract with hexane/dichloromethane	HPLC/UV	2 µg/m^3	Environmental Protection Agency (1988) [Method TO5]
	Draw air through a glassfibre filter impregnated with 2,4-dinitrophenylhydrazine; extract with acetonitrile	HPLC/UV	15 µg/m^3	Deutsche Forschungsgemeinschaft (1993) [Method 1]
	Draw air through silica gel coated with acidified 2,4-dinitrophenylhydrazine reagent	HPLC/UV	2 µg/m^3 (0.6–123 µg/m^3)	Environmental Protection Agency (1999c); INRS (2003) [Method TO11A]
	Draw air through a cartridge containing silica gel coated with 2,4-dinitrophenylhydrazine; extract with acetonitrile	HPLC/UV	0.07 µg/m^3	Sandner *et al.* (2001)
	Draw air through a cartridge containing silica gel coated with 2,4-dinitrophenylhydrazine; extract with acetonitrile	HPLC/UV	0.07 µg/sample	NIOSH (2003a) [Method 2016]

Table 1 (contd)

Sample matrix	Sample preparation	Assay procedure	Limit of detection	Reference
	Expose passive monitor containing bisulfite-impregnated paper; desorb with deionized water; acidify; add chromotropic acid; read absorbance at 580 nm	Chromotropic acid test	0.14 μg/m^3	Occupational Safety and Health Administration (1990b) [Method ID-205]
	Collect gases with portable direct-reading instrument; compare spectra with references	FTIRS	0.49 μg/m^3	NIOSH (2003b) [Method 3800]
Dust (textile or wood)	Draw air through inhalable dust sampler containing a PVC filter; extract with distilled water and 2,4-dinitrophenylhydrazine/acetonitrile	HPLC/UV	0.08 μg/ sample	NIOSH (1994d) [Method 5700]
Food	Distil sample; add 1,8-dihydroxy-naphthalene-3,6-disulfonic acid in sulfuric acid; purple colour indicates presence of formaldehyde	Chromotropic acid test	NR	AOAC (2003) [Method 931.08]
	Distil sample; add to cold sulfuric acid; add aldehyde-free milk; add bromine hydrate solution; purplish-pink colour indicates presence of formaldehyde	Hehner-Fulton test	NR	AOAC (2003) [Method 931.08]

FTIRS, Fourier transform infrared spectrometry; GC/FID, gas chromatography/flame ionization detection; GC/MS, gas chromatography/mass spectrometry; GC/NSD, gas chromatography/nitrogen selective detection; HPLC/UV, high-performance liquid chromatography/ultraviolet detection; NR, not reported; PTFE, polytetrafluoroethylene; PVC, polyvinyl chloride

1.2 Production and use

1.2.1 *Production*

Formaldehyde has been produced commercially since 1889 by the catalytic oxidation of methanol. Various specific methods were used in the past, but only two are widely used currently: the silver catalyst process and the metal oxide catalyst process (Bizzari, 2000; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

The silver catalyst process is conducted in one of two ways: (i) partial oxidation and dehydrogenation with air in the presence of silver crystals, steam and excess methanol at 680–720 °C and at atmospheric pressure (also called the BASF process; methanol conversion, 97–98%); and (ii) partial oxidation and dehydrogenation with air in the presence of crystalline silver or silver gauze, steam and excess methanol at 600–650 °C (primary conversion of methanol, 77–87%); the conversion is completed by distilling the product and recycling the unreacted methanol. Carbon monoxide, carbon dioxide, methyl formate and formic acid are by-products (Bizzari, 2000; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

In the metal oxide (Formox) process, methanol is oxidized with excess air in the presence of a modified iron–molybdenum–vanadium oxide catalyst at 250–400 °C and atmospheric pressure (methanol conversion, 98–99%). By-products are carbon monoxide, dimethyl ether and small amounts of carbon dioxide and formic acid (Bizzari, 2000; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

Paraformaldehyde, a solid polymer of formaldehyde, consists of a mixture of poly(oxymethylene) glycols [$HO–(CH_2O)_n–H$; $n = 8–100$]. The formaldehyde content is 90–99%, depending on the degree of polymerization, the value of n and product specifications; the remainder is bound or free water. As a convenient source of formaldehyde for certain applications, paraformaldehyde is prepared commercially by the concentration of aqueous formaldehyde solutions under vacuum in the presence of small amounts of formic acid and metal formates. An alternative solid source of formaldehyde is the cyclic trimer of formaldehyde, 1,3,5-trioxane, which is prepared commercially by strong acid-catalysed condensation of formaldehyde in a continuous process (Bizzari, 2000; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

Available information indicates that formaldehyde was produced by 104 companies in China, 19 companies in India, 18 companies in the USA, 15 companies each in Italy and Mexico, 14 companies in Russia, 11 companies each in Brazil and Japan, eight companies each in Canada and Germany, seven companies each in China (Province of Taiwan), Malaysia and the United Kingdom, six companies each in Argentina and Spain, five companies in Belgium, four companies each in Colombia, France, Iran, the Netherlands and Thailand, three companies each in Chile, Israel, Poland, Portugal, the Republic of Korea, Sweden, Turkey and the Ukraine, two companies each in Australia, Austria, Ecuador, Egypt, Pakistan, Peru, Romania and Serbia and Montenegro, and one company each in Algeria, Azerbaijan, Bulgaria, Denmark, Estonia, Finland, Greece, Hungary, Indonesia, Ireland, Lithuania, Norway, Saudi Arabia, Singapore, Slovakia, Slovenia, South Africa, Switzerland, Uzbekistan and Venezuela (Chemical Information Services, 2004).

Available information indicates that paraformaldehyde was produced by eight companies in China, four companies each in Germany and India, three companies each in Russia and the USA, two companies each in China (Province of Taiwan), Iran, Mexico and Spain and one company each in Canada, Egypt, Israel, Italy, Japan, the Netherlands, the Republic of Korea, Romania, Saudi Arabia and the United Kingdom (Chemical Information Services, 2004).

Available information indicates that 1,3,5-trioxane was produced by three companies in Germany, two companies each in China, India and the USA and one company in Poland (Chemical Information Services, 2004).

Production of formaldehyde in selected years from 1983 to 2000 and in selected countries is shown in Table 2. Worldwide capacity, production and consumption of formaldehyde in 2000 are shown in Table 3.

Table 2. Production of 37% formaldehyde in selected regions (thousand tonnes)

Country or region	1983	1985	1990	1995	2000
North America					
Canada	256	288	288	521	675
Mexico	79	106	118	139	136
USA	2520[a]	2663	3402	3946	4650
Western Europe[b]	3757	3991	4899	5596	6846[c]
Japan	1089	1202	1444	1351	1396

From Bizzari (2000)

[a] Data for 1980

[b] Includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom

[c] Data for 1999

1.2.2 *Use*

Worldwide patterns of use for formaldehyde in 2000 are shown in Table 4. The most extensive use of formaldehyde is in the production of resins with urea, phenol and melamine, and of polyacetal resins. Formaldehyde-based resins are used as adhesives and impregnating resins in the manufacture of particle-board, plywood, furniture and other wood products; for the production of curable moulding materials (appliances, electric controls, telephones, wiring services); and as raw materials for surface coatings and controlled-release nitrogen fertilizers. They are also used in the textile, leather, rubber and cement industries. Further uses are as binders for foundry sand, stonewool and glasswool mats in insulating materials, abrasive paper and brake linings (WHO, 1989; IARC, 1995; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

Another major use of formaldehyde is as an intermediate in the synthesis of other industrial chemical compounds, such as 1,4-butanediol, trimethylolpropane and neopentyl glycol, that are used in the manufacture of polyurethane and polyester plastics, synthetic resin coatings, synthetic lubricating oils and plasticizers. Other compounds produced from formaldehyde include pentaerythritol, which is used primarily in raw materials for surface coatings and explosives, and hexamethylenetetramine, which is used as a cross-linking agent for phenol–formaldehyde resins and explosives. The complexing agents, nitrilotriacetic acid (see IARC, 1990a) and ethylenediaminetetraacetic acid, are derived from formaldehyde and are components of some detergents. Formaldehyde is used for the production of 4,4′-methylenediphenyl diisocyanate (see IARC, 1979), which is a constituent of polyurethanes that are used in the production of soft and rigid foams, as adhesives and to bond particle-board (WHO, 1989; IARC, 1995; Reuss *et al.*, 2003; Gerberich & Seaman, 2004).

Polyacetal plastics produced by the polymerization of formaldehyde are incorporated into automobiles to reduce weight and fuel consumption, and are used to make functional

Table 3. World supply and demand for 37% formaldehyde in 2000 (thousand tonnes)

Country/region	Production	Consumption
North America		
Canada	675	620
Mexico	136	137
USA	4 650	4 459
South and Central America[a]	638	636
Western Europe[b]	7 100	7 054
Eastern Europe[c]	1 582	1 577
Middle East[d]	454	438
Japan	1 396	1 395
Africa[e]	102	102
Asia		
China	1 750	1 752
Indonesia	891	892
Malaysia	350	350
Republic of Korea	580	580
Other[f]	789	795
Australia and New Zealand	304	304
Total	21 547	21 091

From Bizzari (2000)

[a] Includes Argentina, Brazil, Chile, Colombia, Ecuador, Peru, Uruguay and Venezuela

[b] Includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom

[c] Includes Bulgaria, the Czech Republic, Hungary, Lithuania, Poland, Romania, Russia, Slovakia, Slovenia, the Ukraine and Yugoslavia

[d] Includes Iran, Israel, Saudi Arabia and Turkey

[e] Includes Algeria, Nigeria, South Africa and Tunisia

[f] Includes Bangladesh, Cambodia, China (Province of Taiwan), Democratic People's Republic of Korea, India, Laos, Myanmar, Pakistan, the Philippines, Singapore, Sri Lanka, Thailand and Viet Nam

components of audio and video electronic equipment. Formaldehyde is also the basis for products that are used to manufacture dyes, tanning agents, precursors of dispersion and plastics, extraction agents, crop protection agents, animal feeds, perfumes, vitamins, flavourings and drugs (WHO, 1989; Reuss *et al*., 2003).

Formaldehyde itself is used to preserve and disinfect, for example, human and veterinary drugs and biological materials (viral vaccines contain 0.05% formalin as an inactivating agent), to disinfect hospital wards and to preserve and embalm biological specimens. Formaldehyde and medications that contain formaldehyde are also used in dentistry (Lewis, 1998). Formaldehyde is used as an antimicrobial agent in many cosmetics products,

Table 4. Worldwide use patterns (%) of formaldehyde in 2000

Region or country	Use (million tonnes)	UFR	PFR	PAR	MFR	BDO	MDI	PE	HMTA	TMP	Other[a]
USA	4.5	24.2	16.6	12.7	3.1	11.2	6.8	5.0	2.6		17.8[b]
Canada	0.62	51.3	32.3		3.2			12.9			
Mexico	0.14	70.8	11.7		5.1				11.7		0.7
South and Central America[c]	0.64	55.8	18.9		7.9		1.6	10.8			5.0
Western Europe[d]	7.1	44.4	8.6	7.1	7.5	6.7	5.4	5.4	2.0	2.1	10.9
Eastern Europe[e]	1.6	71.5	5.1		3.2			4.4	8.8		6.9
Africa[f]	0.10	70.6	14.7		7.8						6.9
Middle East[g]	0.43	75.1	4.6		14.8						5.5
Japan	1.4	12.3	7.7	32.9	4.8	2.1	8.4	6.7	2.2	2.2	20.7[h]
Asia[i]	4.4	54.2	9.8	8.4	8.7			5.8	2.9		10.2
Oceania[j]	0.30	67.4	12.2		20.4						

From Bizzari (2000)

UFR, urea–formaldehyde resins; PFR, phenol–formaldehyde resins; PAR, polyacetal resins; MFR, melamine–formaldehyde resins; BDO, 1,4-butanediol; MDI, 4,4′-diphenylmethane diisocyanate; PE, pentaerythritol; HMTA, hexamethylenetetramine; TMP, trimethylolpropane

[a] Not defined

[b] Including chelating agents, trimethylolpropane, trimethylolethane, paraformaldehyde, herbicides, neopentyl glycol, pyridine chemicals, nitroparaffin derivatives, textile treating and controlled-release fertilizer

[c] Includes Argentina, Brazil, Chile, Colombia, Ecuador, Peru, Uruguay and Venezuela

[d] Includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom

[e] Includes Bulgaria, the Czech Republic, Hungary, Lithuania, Poland, Romania, Russia, Slovakia, Slovenia, the Ukraine and Yugoslavia

[f] Includes Algeria, Nigeria, South Africa and Tunisia

[g] Includes Iran, Israel, Saudi Arabia and Turkey

[h] Including 6.4% for paraformaldehyde

[i] Includes Bangladesh, Cambodia, China, China (Province of Taiwan), Democratic People's Republic of Korea, India, Indonesia, Laos, Malaysia, Myanmar, Pakistan, the Philippines, Republic of Korea, Singapore, Sri Lanka, Thailand and Viet Nam

[j] Includes Australia and New Zealand

including soaps, shampoos, hair preparations, deodorants, lotions, make-up, mouthwashes and nail products (Cosmetic Ingredient Review Expert Panel, 1984; Reuss *et al.*, 2003).

Formaldehyde is also used directly to inhibit corrosion, in mirror finishing and electroplating, in the electrodeposition of printed circuits and in the development of photographic films (Reuss *et al.*, 2003).

Paraformaldehyde is used in place of aqueous solutions of formaldehyde, especially when the presence of water interferes, e.g. in the plastics industry for the preparation of phenol, urea and melamine resins, varnish resins, thermosets and foundry resins. Other uses include the synthesis of chemical and pharmaceutical products (e.g. Prins reaction, chloromethylation, Mannich reaction), the production of textile products (e.g. for crease-resistant finishes), the preparation of disinfectants and deodorants (Reuss *et al.*, 2003) and in selected pesticide applications (Environmental Protection Agency, 1993).

1.3 Occurrence

Formaldehyde is a gaseous pollutant from many outdoor and indoor sources. Outdoors, major sources of formaldehyde include power plants, manufacturing facilities, incinerators and automobile exhaust emissions. Forest fires and other natural sources of combustion also introduce formaldehyde into the ambient air. Other than in occupational settings, the highest levels of airborne formaldehyde have been detected indoors where it is released from various building materials, consumer products and tobacco smoke. Formaldehyde may be present in food, either naturally or as a result of contamination (Suh *et al.*, 2000).

Natural and anthropogenic sources of formaldehyde in the environment, and environmental levels in indoor and outdoor air, water, soil and food have been reviewed (WHO, 1989; IARC, 1995; ATSDR, 1999).

1.3.1 *Natural occurrence*

Formaldehyde is ubiquitous in the environment; it is an endogenous chemical that occurs in most life forms, including humans. It is formed naturally in the troposphere during the oxidation of hydrocarbons, which react with hydroxyl radicals and ozone to form formaldehyde and other aldehydes as intermediates in a series of reactions that ultimately lead to the formation of carbon monoxide and dioxide, hydrogen and water. Of the hydrocarbons found in the troposphere, methane is the single most important source of formaldehyde. Terpenes and isoprene that are emitted by foliage react with hydroxyl radicals to form formaldehyde as an intermediate product. Because of their short half-life, these sources of formaldehyde are important only in the vicinity of vegetation. Formaldehyde is one of the volatile compounds that are formed in the early stages of decomposition of plant residues in the soil, and occurs naturally in fruit and other foods (WHO, 1989; IARC, 1995).

An overview of the formation and occurrence of formaldehyde in living organisms has been reported (Kalász, 2003). The reader is referred to Section 4.1 for a discussion of blood levels of endogenously formed formaldehyde in humans.

1.3.2 *Occupational exposure*

Estimates of the number of persons who are occupationally exposed to formaldehyde worldwide are not available. However, an estimate of the number of people who were exposed in the European Union in the early 1990s is available from the International Information System on Occupational Exposure to Carcinogens (more commonly referred to as CAREX) (Kauppinen *et al*., 2000). Approximate numbers of persons who were exposed to levels of formaldehyde above 0.1 ppm [0.12 mg/m^3] are presented by major industry sector in Table 5. While these are not precise estimates, they do indicate that exposure to formaldehyde, at least at low levels, may occur in a wide variety of industries.

Three main sets of circumstances may lead to occupational exposure to formaldehyde. The first is related to the production of aqueous solutions of formaldehyde (formalin) and their use in the chemical industry, e.g. for the synthesis of various resins, as a preservative in medical laboratories and embalming fluids and as a disinfectant. A second set is related to its release from formaldehyde-based resins in which it is present as a residue and/or through their hydrolysis and decomposition by heat, e.g. during the manufacture of wood products, textiles, synthetic vitreous insulation products and plastics. In general, the use of phenol–formaldehyde resins results in much lower emissions of formaldehyde than that of urea- and melamine-based resins. A third set of circumstances is related to the pyrolysis or combustion of organic matter, e.g. in engine exhaust gases or during firefighting.

(*a*) *Manufacture of formaldehyde, formaldehyde-based resins and other chemical products*

Concentrations of formaldehyde measured in the 1980s during the manufacture of formaldehyde and formaldehyde-based resins are summarized in Table 6. More recent data were not available to the Working Group.

Mean levels during the manufacture of formaldehyde were below 1 ppm [1.2 mg/m^3]. These workers may also be exposed to methanol (starting material), carbon monoxide, carbon dioxide and hydrogen (process gases) (Stewart *et al*., 1987).

The reported mean concentrations in the air of factories that produce formaldehyde-based resins vary from < 1 to > 10 ppm [< 1.2 to > 12.3 mg/m^3]. There are obvious differences between factories (the earliest measurements date from 1979) but no consistent seasonal variation. Chemicals other than formaldehyde to which exposure may occur depend on the types of resin manufactured: urea, phenol, melamine and furfural alcohol are the chemicals most commonly reacted with liquid formaldehyde (formalin). Some processes require the addition of ammonia, and alcohols are used as solvents in the production of liquid resins (Stewart *et al*., 1987).

Table 5. Approximate number of workers exposed to formaldehyde above background levels (0.1 ppm) in the European Union, 1990–93

Industry	Estimate
Manufacture of furniture and fixtures, except primarily of metal	179 000
Medical, dental, other health and veterinary services	174 000
Manufacture of wearing apparel, except footwear	94 000
Manufacture of wood and wood and cork products, except furniture	70 000
Personal and household services	62 000
Construction	60 000
Manufacture of textiles	37 000
Iron and steel basic industries	29 000
Manufacture of fabricated metal products, except machinery	29 000
Manufacture of other non-metallic mineral products	23 000
Manufacture of machinery, except electrical	20 000
Manufacture of industrial chemicals	17 000
Manufacture of other chemical products	17 000
Manufacture of plastic products not classified elsewhere	16 000
Agriculture and hunting	16 000
Manufacture of paper and paper products	13 000
Printing, publishing and allied industries	13 000
Wholesale and retail trade and restaurants and hotels	13 000
Manufacture of transport equipment	11 000
Manufacture of electrical machinery, apparatus and appliances	10 000
Manufacture of footwear	9 000
Manufacture of glass and glass products	8 000
Research and scientific institutes	7 000
Non-ferrous metal basic industries	6 000
Manufacture of leather and products of leather or of its substitutes	6 000
Beverage industries	4 000
Manufacture of instruments, photographic and optical	4 000
Other manufacturing industries	3 000
Food manufacturing	3 000
Crude petroleum and natural gas production	2 000
Manufacture of rubber products	4 000
Financing, insurance, real estate and business services	3 000
Education services	2 000
Sanitary and similar services	2 000
Services allied to transport	2 000
Manufacture of miscellaneous products of petroleum and coal	1 000
Other industries	2 000
Total (all industries)	971 000

From Kauppinen *et al*. (2000); CAREX (2003)

Table 6. Concentrations of formaldehyde in the workroom air in formaldehyde and resin manufacturing plants

Industry and operation	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Special chemical manufacturing plant (USA)	8	NR	< 0.03–1.6 [0.04–2.0]	NR	Blade (1983)
Production of formaldehyde (Sweden)	9	0.3 [0.3]	NR	1980s	Rosén *et al.* (1984)
Resin manufacture (Sweden)	22	0.5 [0.6]	NR	1980s	Rosén *et al.* (1984)
Formaldehyde manufacture (USA)				1983	Stewart *et al.* (1987)
Plant no. 2, summer	15	0.6[b] [0.7]	0.03–1.9 [0.04–2.3]		
Plant no. 10, summer	9	0.7[b] [0.9]	0.6–0.8 [0.7–1.0]		
Resin manufacture (USA)				1983–84	Stewart *et al.* (1987)
Plant no. 1, summer	24	3.4[b] [4.2]	0.2–13.2 [0.3–16.2]		
Plant no. 6, summer[c]	6	0.2[b] [0.3]	0.1–0.2 [0.1–0.3]		
Plant no. 7, summer	9	0.2[b] [0.3]	0.1–0.3 [0.1–0.4]		
Plant no. 7, winter	9	0.6[b] [0.7]	0.4–0.9 [0.5–1.1]		
Plant no. 8, summer[c,d]	13	0.4[b] [0.7]	0.2–0.8 [0.3–1.0]		
Plant no. 8, winter[c,d]	9	0.1[b] [0.1]	0.1–0.2 [0.1–0.3]		
Plant no. 9, summer[c,d]	8	14.2[b] [17.5]	4.1–30.5 [5.0–37.5]		
Plant no. 9, winter	9	1.7[b] [2.1]	1.1–2.5 [1.4–3.1]		
Plant no. 10, summer[d]	23	0.7[b] [0.9]	0.3–1.2 [0.4–1.5]		
Chemical factory producing formaldehyde and formaldehyde resins (Sweden)	62	0.2 [0.3]	0.04–0.4 [0.05–0.5]	1979–85	Holmström *et al.* (1989a)
Resin plant (Finland)					Heikkilä *et al.* (1991)
Furan resin production	3	2.3 [2.9]	1.0–3.4 [1.3–4.2]	1982	
Maintenance	4	2.9 [3.6]	1.4–5.5 [1.8–6.9]	1981	
Urea–formaldehyde resin production	7	0.7 [0.9]	0.6–0.8 [0.7–1.1]	1981	

NR, not reported

[a] Arithmetic mean unless otherwise specified

[b] Mean and range of geometric means

Some of the results were affected by the simultaneous occurrence in the samples (Stewart *et al.*, 1987) of:

[c] phenol (leading to low values)

[d] particulates that contained nascent formaldehyde (leading to high values).

No measurements of exposure to formaldehyde in other chemical plants where it is used, e.g. in the production of pentaerythritol, hexamethylenetetramine or ethylene glycol, were available to the Working Group.

(*b*) *Histopathology and disinfection in hospitals*

Formalin is commonly used to preserve tissue samples in histopathology laboratories. Concentrations of formaldehyde are sometimes high, e.g. during tissue disposal, preparation of formalin and changing of tissue processor solutions (Belanger & Kilburn, 1981). The usual mean concentration during exposure is approximately 0.5 ppm [0.6 mg/m^3]. Other agents to which pathologists and histology technicians may be exposed include xylene (see IARC, 1989a), toluene (see IARC, 1989b), chloroform (see IARC, 1987c) and methyl methacrylate (see IARC, 1994a) (Belanger & Kilburn, 1981). Concentrations of airborne formaldehyde in histopathology laboratories and during disinfection in hospitals are presented in Table 7.

Levels of formaldehyde were measured in 10 histology laboratories using area samplers for 1–4 h for a study of neurobehavioural and respiratory symptoms. Concentrations of formaldehyde in areas where tissue specimens were prepared and sampled were 0.25–2.3 mg/m^3 (Kilburn *et al.*, 1985). In two studies in Israel, pathology staff were divided into two groups: those who had low exposure (mean, 0.5 mg/m^3), which included laboratory assistants and technicians, and those who had high exposure (mean, 2.8 mg/m^3), which included physicians and hospital orderlies, based on 15-min samples (Shaham *et al.*, 2002, 2003). Another study by the same group [it is not clear whether these are the same data or not] reported 15-min area measurements of 1.7–2.0 mg/m^3 and personal measurements of 3.4–3.8 mg/m^3 during exposure (Shaham *et al.*, 1996a,b).

Formaldehyde has also been used extensively in hospitals for disinfection (IARC, 1995; see Table 7).

(*c*) *Embalming and anatomy laboratories*

Formaldehyde is used as a tissue preservative and disinfectant in embalming fluids (Table 7). Some parts of bodies that are to be embalmed are also cauterized and sealed with a hardening compound that contains paraformaldehyde powder. The concentration of formaldehyde in the air during embalming depends on its content in the embalming fluid, the type of body, ventilation and work practices; mean levels are approximately 1 ppm [1.2 mg/m^3]. Embalming of a normal intact body usually takes approximately 1 h. Disinfectant sprays are occasionally used, and these may release small amounts of solvent, such as isopropanol (Williams *et al.*, 1984). Methanol is used as a stabilizer in embalming fluids, and concentrations of 0.5–22 ppm [0.7–28.4 mg/m^3] have been measured during embalming. Low levels of phenol have also been detected in embalming rooms (Stewart *et al.*, 1992).

Skisak (1983) measured levels of formaldehyde in the breathing zone at dissecting tables and in the ambient air in a medical school in the USA for 12 weeks. Concentrations of > 1.2 mg/m^3 formaldehyde were found in 44% of the breathing zone samples and

Table 7. Concentrations of formaldehyde in the workroom air of mortuaries, hospitals and laboratories

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Histopathology laboratories					
Pathology laboratory (Sweden)	13	0.5 [0.7]	NR	1980s	Rosén *et al.* (1984)
Histology laboratory, tissue specimen preparation and sampling (USA)	NR	NR	0.2–1.9 [0.25–2.3]	NR	Kilburn *et al*. (1985)
Pathology laboratories (Germany)	21	0.5[b] [0.6]	< 0.01–1.2 [< 0.01–1.6]	1980–88	Triebig *et al.* (1989)
Hospital laboratories (Finland)	80	0.5 [0.6]	0.01–7.3 [0.01–9.1]	1981–86	Heikkilä *et al.* (1991)
Histology laboratory (Israel)					
Area samples	NR	NR	1.4–1.6 [1.7–2.0]	NR	Shaham *et al.* (1996a,b)
Personal samples	NR	NR	2.8–3.1 [3.4–3.8]		
Teaching laboratory (USA)	16	0.3 [0.4]		NR	Tan *et al*. (1999)
Pathology laboratories (Turkey)	10	NR	max., < 2 [< 2.5]	NR	Burgaz *et al*. (2001)
Histology laboratory (Israel)	NR			NR	Shaham *et al*. (2002)
Laboratory assistants/technicians (15 min)		0.4 [0.5]	0.04–0.7 [0.05–0.9]		
Physicians and orderlies (15 min)		2.2 [2.8]	0.7–5.6 [0.9–7.0]		
Disinfection in hospitals					
Cleaning hospital floors with detergent containing formaldehyde (Italy)	4	0.18 [0.22]	0.15–0.21 [0.18–0.26]	NR	Bernardini *et al.* (1983)
Personal samples (38–74 min)					
Disinfection of dialysis clinic (USA)	7	0.6 [0.8]	0.09–1.8 [0.12–2.2]	1983	Salisbury (1983)
Personal samples (37–63 min)					
Disinfecting operating theatres (Germany)	43	0.4[c] [0.5]	0.04–1.4 [0.05–1.7]	NR	Elias (1987)
Bedrooms in hospital (Germany)	14	0.05 [0.06]	< 0.01–0.7 [< 0.01–0.9]	1980–88	Triebig *et al.* (1989)
Disinfecting operating theatres (Germany)[d]				NR	Binding & Witting (1990)
3% cleaning solution	43	0.8 [1.1]	0.01–5.1 [0.01–6.3]		
0.5 % cleaning solution	26	0.2 [0.2]	0.01–0.4 [0.01–0.5]		
Disinfection in hospitals (Finland)	18	0.1 [0.1]	0.03–0.2 [0.04–0.3]	1981–86	Heikkilä *et al.* (1991)

Table 7 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Embalming					
Embalming, six funeral homes (USA)	NR	0.7 [0.9]	0.09–5.3 [0.1–6.5]	NR	Kerfoot & Mooney (1975)
Autopsy service (USA)[d]				NR	Coldiron *et al.* (1983)
Personal samples	27	1.3[c] [1.7]	0.4–3.3 [0.5–4.0]		
Area samples	23	4.2 [5]	0.1–13.6 [0.1–16.7]		
Museum, taxidermy (Sweden)	8	0.2 [0.3]	NR	1980s	Rosén *et al.* (1984)
Embalming, seven funeral homes				1980	Williams *et al.* (1984)
Intact bodies (personal samples)	8	0.3 [0.4]	0.18–0.3 [0.2–0.4]		
Autopsied bodies (personal samples)	15	0.9 [1.1]	0–2.1 [0–2.6]		
Embalming, 23 mortuaries (USA)	NR	1.1 [1.4]	0.03–3.2 [0.04–3.9]	NR	Lamont Moore & Ogrodnik (1986)
8-h TWA		0.2 [0.2]	0.01–0.5 [0.01–0.6]		
Autopsy (Finland)	5	0.7 [0.8]	< 0.1–1.4 [< 0.1–1.7]	1981–86	Heikkilä *et al.* (1991)
Embalming (USA)				NR	Stewart *et al.* (1992)
Personal samples	25	2.6 [3.2]	0.3–8.7 [0.4–10.7]		
Area 1	25	2.0 [3.0]	0.2–7.5 [0.3–9.2]		
Area 2	25	2.2 [2.7]	0.3–8.2 [0.3–10.0]		
Embalming (Canada)				NR	Korczynski (1994)
Intact bodies (personal samples)	24	0.6 [0.8]	0.1–4.6 [0.1–5.6]		
Autopsied bodies (personal samples)	24	0.6 [0.8]	0.09–3.3 [0.1–4.1]		
Area samples	72	0.5 [0.6]	0.04–6.8 [0.05–8.4]		
Funeral home, embalming (USA)				NR	Korczynski (1996)
Area samples	4	NR	< 0.1–0.15 [< 0.1–0.19]		
Personal samples	4	0.16 [0.19]	NR		
Anatomy laboratories					
Anatomy laboratory, dissecting (USA) Personal samples	54	NR	0.3–2.6 [0.4–3.2]	NR	Skisak (1983)

Table 7 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Anatomy laboratory, dissecting (USA)				1982–83	Korky (1987)
Laboratory	NR	NR	7–16.5 [8.6–20.3]		
Stock room	NR	NR	2.0–2.6 [2.4–3.2]		
Public hallway	NR	NR	max., < 1 [< 1.2]		
Anatomical theatre (Germany)	29	1.1[b] [1.4]	0.7–1.7 [0.9–2.2]	1980–88	Triebig *et al.* (1989)
Anatomy laboratory, dissecting (USA)				NR	Akbar-Khanzadeh *et al.* (1994)
Personal samples (1.2–3.1 h)	32	1.2 [1.5]	0.07–2.9 [0.09–3.6]		
Personal samples (TWA)	NR	0.4 [0.5]	0.09–0.95 [0.11–1.17]		
Area samples (2.5 min)	13	1.4 [1.7]	0.9–1.8 [1.1–2.2]		
Area samples (TWA)	2	1.7 [2.0]	1.0–2.3 [1.2–2.8]		
Anatomy laboratory, dissecting (USA)				NR	Akbar-Kahnzadeh & Mlynek (1997)
Personal samples	44	1.9 [2.3]	0.3–4.5 [0.4–5.5]		
Area samples	76	1.0 [1.2]	0.6–1.7 [0.7–2.1]		
Anatomy laboratory, dissecting (China)	25	0.4 [0.5]	0.06–1.04 [0.07–1.28]	NR	Ying *et al*. (1997, 1999)
Anatomy laboratory, dissecting (China)	NR	2.4 [2.9]	NR	NR	He *et al*. (1998)
Anatomy/histology laboratory, dissecting	48	3.0 [3.7]	0.2–9.1 [0.2–11.2]	NR	Kim *et al.* (1999)
Anatomy laboratory, dissecting (Austria)	NR	0.22 [0.27]	0.11–0.33 [0.13–0.41]	NR	Wantke *et al*. (2000)
Two locations in a room over 4 weeks	NR	0.12 [0.15]	0.06–0.22 [0.07–0.27]	NR	Wantke *et al*. (1996b)
Anatomy laboratory, dissecting (Turkey)	NR	NR	max., < 4 [< 5]	NR	Burgaz *et al*. (2001)
Anatomy laboratory, dissecting (USA)	15	0.9 [1.1]	0.3–2.6 [0.3–3.1]	NR	Keil *et al*. (2001)
Biology laboratory, dissecting (Canada)				NR	Dufresne *et al*. (2002)
Laboratory 1	18	0.20 [0.25]	0.08–0.62 [0.11–0.76]		
Laboratory 2	18	0.51 [0.63]	0.3–1.2 [0.3–1.5]		
Anatomy laboratory, dissecting (Japan)	NR	NR	0.11–0.62 [0.14–0.76]	NR	Tanaka *et al*. (2003)

NR, not reported; TWA, time-weighted average

[a] Arithmetic means unless otherwise specified

[b] Median

[c] Mean of arithmetic means

[d] 8-h TWA

11 ambient air samples; the levels in breathing zone samples were in the range of 0.4–3.2 mg/m^3, and 50% of the samples contained 0.7–1.2 mg/m^3.

Korky *et al*. (1987) studied the dissecting facilities at a university in the USA during the 1982–83 academic year. Airborne concentrations of formaldehyde were 7–16.5 ppm [8.6–20.3 mg/m^3] in the laboratory, 1.97–2.62 ppm [2.4–3.2 mg/m^3] in the stockroom and < 1 ppm [< 1.2 mg/m^3] in the public hallway.

Concentrations of formaldehyde in the breathing zone of two embalmers in the USA were measured during the embalming of an autopsied body, which generally results in higher exposures than that of non-autopsied bodies. The average was 0.19 mg/m^3 [duration of measurement not provided] (Korczynski, 1996).

Samples (1–2-h) taken in an anatomy/histology laboratory in the Republic of Korea for a cross-sectional study of serum antibodies showed concentrations of formaldehyde that ranged from 0.19 to 11.25 mg/m^3 with a mean of 3.74 mg/m^3 (Kim *et al*., 1999).

In a cross-sectional study of immunoglobulin (Ig)E sensitization in Austria, concentrations of formaldehyde were measured in two locations in a dissection room for the full period that students were present. The mean level was 0.15 mg/m^3 (Wantke *et al*., 1996a,b). The windows were open and the ventilation was working continuously. In a second study in the same laboratories, medical students were exposed to an average indoor concentration of 0.27 mg/m^3 formaldehyde (Wantke *et al*., 2000).

Levels of formaldehyde measured in anatomy laboratories in China for a cytogenetic study averaged 0.51 mg/m^3 over a 3-h period; the peak occurred while cadavers were being dissected (Ying *et al*., 1997, 1999).

A cross-sectional study on the cytogenetic effects of formaldehyde on anatomy students in China found personal exposures of 2.92 mg/m^3 (He *et al*., 1998).

In a study of respiratory function, 34 personal samples and short-term area samples were collected in a gross anatomy laboratory in the USA. The mean concentration of formaldehyde in the room was 1.53 mg/m^3 during the 1.2–3.1-h dissecting period. The direct-reading short-term area samples (2.5-min) averaged 1.68 mg/m^3. Eight-hour time-weighted average (TWA) personal exposures ranged from 0.11 to 1.17 mg/m^3, with a mean of 0.52 mg/m^3 (96% of subjects were exposed to levels of formaldehyde above the 0.38 mg/m^3 ceiling, and the 8-h TWA exposure of 3% of them was above 0.94 mg/m^3) (Akbar-Khanzadeh *et al.*, 1994). A subsequent study of respiratory function was conducted in the same laboratory because, among other reasons, the concentration of formaldehyde in the embalming solution was increased. The mean concentration of formaldehyde in the personal samples was 2.31 mg/m^3 (duration, 2.5 h) (Akbar-Khanzadeh & Mlynek, 1997). In the same laboratory, area measurements were taken in the centre of and at various locations in the room over a 16-week period; each measurement lasted for the time the students were active during a session (3–4 h per day). The average concentration in the centre of the room was 1.13 mg/m^3 (15 measurements) (Keil *et al*., 2001). Breathing zone concentrations were expected to be higher because of the proximity of the students to the cadaver during dissection. Although the room had mechanical air supply and exhaust systems, the ventilation system served the entire building and intake air was contaminated with formaldehyde.

The concentration of formaldehyde in the air in pathology and anatomy laboratories in Turkey did not exceed 2 and 4 mg/m^3, respectively [no other information available], when measured in a study of cytogenetic responses (Burgaz *et al*., 2001).

In a study of two biological laboratories in Canada where dissection of animal specimens was performed, 3-h personal samples showed mean concentrations of 0.25 mg/m^3 and 0.63 mg/m^3 formaldehyde, respectively (Dufresne *et al*., 2002). The first laboratory had a general mechanical ventilation system, whereas the second had no ventilation system.

Measurements in an anatomy class in Japan rose to 0.76 mg/m^3 after 10 min of class; 30 min later, the formaldehyde concentration had decreased to 0.14 mg/m^3 (Tanaka *et al*., 2003).

(*d*) *Manufacture of wood products and paper*

Exposure to formaldehyde may occur in several sectors of the wood-related industries because of the use of formaldehyde-based resins. Table 8 summarizes the concentrations of formaldehyde observed in the wood product and pulp and paper industries.

Exposure to formaldehyde is typically monitored by measuring its gaseous form; slight additional exposure may occur through the inhalation of formaldehyde bound to wood dust, although this was considered to be negligible in one study (Gosselin *et al*., 2003). For example, at a plant in the USA that constructed products made of particle-board, measurements were taken for 4.5 h at the sawing operation. A back-up impinger was positioned behind an inhalable dust sampler or a closed-face cassette to capture both dust-bound and gaseous formaldehyde. Levels of formaldehyde gas behind the inhalable dust sampler averaged [132 μg/m^3 (standard deviation [SD], 14 μg/m^3; four samples)] and those of bound formaldehyde from inhalable dust averaged [11 μg/m^3 (SD, 4 μg/m^3; 12 samples)]. Respective measurements for the closed cassettes averaged [147 μg/m^3 (SD, 9 μg/m^3; four samples)] and [8 μg/m^3 (SD, 2 μg/m^3; 12 samples)] (Kennedy *et al*., 1992).

(i) *Veneer and plywood mills*

Plywood consists of three or more veneers glued together or a core of solid wood strips or particle-board with veneered top and bottom surfaces. The dried panels may also be patched or spliced by applying a liquid formaldehyde-based adhesive to the edges, pressing the edges together and applying heat to cure the resin. To produce panels, veneers are roller- or spray-coated with formaldehyde-based resins, then placed between unglued veneers. The plywood industry has used formaldehyde-based glues in assembling of plywood for over 50 years. Before the introduction of formaldehyde-based resins in the 1940s, soya bean and blood–albumen adhesives were used, and cold pressing of panels was common. Exposure to formaldehyde from resins may occur among workers during the preparation of glue, during splicing, patching, sanding and hot-pressing operations and among nearby workers. Urea-based resins release formaldehyde more readily during curing than phenol-based resins; however, improvements in the formulation of resins have reduced exposures.

Table 8. Concentrations of formaldehyde in the workroom air of plywood mills, particle-board mills, furniture factories, other wood product plants, paper mills and the construction industry

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m³])	Range (ppm [mg/m³])	Year	Reference
Plywood mills					
Plywood production (Sweden)	47	0.3 [0.4]	NR	1980s	Rosén *et al.* (1984)
Plywood mills (Finland)					Kauppinen (1986)
Glue preparation, short-term	15	2.2 [2.7]	0.6–5.0 [0.7–6.2]	1965–74	
Glue preparation, short-term	19	0.7 [0.9]	0.1–2.3 [0.1–2.8]	1975–84	
Assembling	32	1.5 [1.9]	< 0.1–4.4 [< 0.1–5.4]	1965–74	
Assembling	55	0.6 [0.7]	0.02–6.8 [0.03–8.3]	1975–84	
Hot pressing	41	2.0 [2.5]	< 0.1–7.7 [< 0.1–9.5]	1965–74	
Hot pressing	43	0.5 [0.6]	0.06–2.1 [0.07–2.6]	1975–84	
Sawing of plywood	5	0.5 [0.6]	0.3–0.8 [0.4–1.0]	1965–74	
Sawing of plywood	12	0.1 [0.1]	0.02–0.2 [0.03–0.3]	1975–84	
Coating of plywood	7	1.0 [1.2]	0.5–1.8 [0.6–2.2]	1965–74	
Coating of plywood	28	0.3 [0.4]	0.02–0.6 [0.03–0.7]	1975–84	
Plywood panelling manufacture (USA)				1983–84	Stewart *et al.* (1987)
Plant no. 3, winter	27	0.2[b] [0.3]	0.08–0.4 [1.0–0.5]		
Plant no. 3, summer	26	0.1[b] [0.1]	0.01–0.5 [0.01–0.6]		
Plywood mill (Indonesia)	40	0.6 [0.8]	0.2–2.3 [0.3–2.8]	NR	Malaka & Kodama (1990)
Plywood factory (Italy)				NR	Ballarin *et al.* (1992)
Warehouse	3	0.3 [0.4]	0.1–0.5 [0.2–0.6]		
Shearing press	8	0.08 [0.1]	0.06–0.11 [0.08–0.14]		
Plywood mill (Finland)				1996–97	Mäkinen *et al.* (1999)
Personal samples					
Patching	6	0.06 [0.07]	0.02–0.08 [0.03–0.10]		
Feeding of drying machine	6	0.05 [0.06]	0.01–0.12 [0.01–0.15]		
Forklift driving	6	0.06 [0.07]	0.02–0.16 [0.02–0.20]		
Scaring	6	0.11 [0.14]	0.06–0.20 [0.07–0.24]		
Assembly (machine I)	4	0.24 [0.30]	0.08–0.66 [0.10–0.81]		
Assembly (machine II)	6	0.12 [0.15]	0.08–0.22 [0.10–0.27]		
Hot pressing (machine I)	5	0.11 [0.13]	0.07–0.19 [0.08–0.23]		

Table 8 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Glue preparation	2	0.12 [0.15]	0.06–0.19 [0.07–0.23]		
Finishing (puttying)	4	0.07 [0.09]	0.06–0.11 [0.07–0.14]		
Carrying plywood piles	2	0.05 [0.06]	0.04–0.06 [0.05–0.07]		
Finishing (sanding)	2	0.04 [0.05]	0.01–0.06 [0.01–0.07]		
Plywood mill (New Zealand)				[2000]	Fransman *et al.* (2003)
Dryers	14	0.06[b] [0.07]	GSD, [3.2]		
Composers	2	0.02[b] [0.03]	GSD, [1.0]		
Pressing	5	0.13[b] [0.16]	GSD, [2.7]		
Finishing end	1	0.03[b] [0.04]	NA		
Particle- and other board mills					
Particle-board production (Sweden)	21	0.3 [0.4]	NR	1980s	Rosén *et al.* (1984)
Medium-density fibre board (Sweden)	19	0.2 [0.3]	NR	1980s	Rosén *et al.* (1984)
Particle-board mills (Finland)					Kauppinen & Niemelä (1985)
Glue preparation	10	2.2 [2.7]	0.3–4.9 [0.4–6.0]	1975–84	
Blending	10	1.0 [1.2]	0.1–2.0 [0.1–2.5]	1965–74	
Blending	8	0.7 [0.9]	< 0.1–1.4 [< 0.1–1.7]	1975–84	
Forming	26	1.7 [2.1]	< 0.5–4.6 [< 0.6–5.7]	1965–74	
Forming	32	1.4 [1.7]	0.1–4.8 [0.1–5.9]	1975–84	
Hot pressing	35	3.4 [4.2]	1.1–9.5 [1.4–11.7]	1965–74	
Hot pressing	61	1.7 [2.1]	0.2–4.6 [0.25–5.7]	1975–84	
Sawing	17	4.8 [5.9]	0.7–9.2 [0.9–11.3]	1965–74	
Sawing	36	1.0 [1.2]	< 0.1–3.3 [< 0.1–4.1]	1975–84	
Coating	7	1.0 [1.2]	0.5–1.8 [0.6–2.2]	1965–74	
Coating	12	0.4 [0.5]	0.1–1.2 [0.1–1.5]	1975–84	
Chip-board production (Germany)	24	1.5 [1.9]	< 0.01–8.4 [< 0.01–10]	1980–88	Triebig *et al.* (1989)
Particle-board mill (Indonesia)	9	2.4 [3.0]	1.2–3.5 [1.5–4.3]	NR	Malaka & Kodama (1990)
Block-board mill (Indonesia)	6	0.5 [0.6]	0.4–0.6 [0.5–0.7]	NR	Malaka & Kodama (1990)

Table 8 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Oriented strand board plant (Canada)				1990s	Herbert *et al.* (1995)
Debarking	5	≤ 0.05 [0.06]	NR		
Pre-heat conveyor	5	≤ 0.05 [0.06]	NR		
Post-heat press conveyor	5	≤ 0.05 [0.06]	NR		
Packaging/storage	5	≤ 0.05 [0.06]	NR		
Fibreboard, sawing and sanding (United Kingdom)				1990s	Chung *et al.* (2000)
Standard MDF (Caberwood)					
Gaseous form	5	0.06 [0.07]	0.04–0.07 [0.05–0.09]		
Extracted from dust	6	0.08 [0.10]	0.06–0.11 [0.07–0.13]		
Moisture resistant (Medite MR)					
Gaseous form	5	0.05 [0.06]	0.01–0.10 [0.01–0.12]		
Extracted from dust	6	0.10 [0.13]	0.04–0.14 [0.05–0.17]		
Zero added formaldehyde (Medite ZF)					
Gaseous form	6	0.04 [0.04]	0.02–0.06 [0.03–0.07]		
Extracted from dust	6	0.03 [0.04]	0.02–0.06 [0.03–0.07]		
Medite exterior grade (Medex)					
Gaseous form	6	0.03 [0.04]	0.01–0.07 [0.01–0.08]		
Extracted from dust	6	0.04 [0.05]	0.04–0.06 [0.05–0.07]		
Furniture factories					
Furniture factories (Sweden)				1980s	Rosén *et al.* (1984)
Varnishing with acid-cured varnishes	32	0.7 [0.9]	NR		
Furniture factories (Finland)					
Feeding painting machine	14	1.1 [1.4]	0.3–2.7 [0.4–3.3]	1975–84	Priha *et al.* (1986)
Spray painting	60	1.0 [1.2]	0.2–4.0 [0.3–5.0]		
Spray painting assistance	10	1.0 [1.2]	0.2–1.6 [0.3–2.0]		
Curtain painting	18	1.1 [1.4]	0.2–6.1 [0.3–7.5]		
Before drying of varnished furniture	34	1.5 [1.8]	0.1–4.2 [0.1–5.2]		
After drying of varnished furniture	14	1.4 [1.7]	0.2–5.4 [0.3–6.6]		

Table 8 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Cabinet-making (Canada)	48	NR	max., < 0.1 [< 0.1]	NR	Sass-Kortsak *et al.* (1986)
Furniture factories, surface finishing with acid curing paints (Sweden)				NR	Alexandersson & Hedenstierna (1988)
Paint mixer/supervisor	6	0.2 [0.3]	0.1–0.4 [0.2–0.5]		
Mixed duties on the line	5	0.4 [0.5]	0.3–0.5 [0.3–0.6]		
Assistant painters	3	0.5 [0.6]	0.2–0.7 [0.2–0.9]		
Spray painters	10	0.4 [0.5]	0.1–1.1 [0.2–1.3]		
Feeder/receiver	13	0.2 [0.3]	0.1–0.8 [0.1–0.9]		
Furniture factories (Finland)				1981–86	Heikkilä *et al.* (1991)
Glueing	73	0.3 [0.4]	0.07–1.0 [0.09–1.2]		
Machining in finishing department	9	0.3 [0.4]	0.1–0.9 [0.1–1.1]		
Varnishing	150	1.1 [1.4]	0.1–6.3 [0.1–7.9]		
Manufacture of furniture (Denmark)				NR	Vinzents & Laursen (1993)
Painting	43	0.16 [0.20][b]	GSD, [2.25]		
Glueing	68	0.12 [0.15][b]	GSD, [2.87]		
Wood-working shops (Egypt)				1990s	Abdel Hameed *et al.* (2000)
Ventilated workshop	14	0.42 [0.52]	0.28–0.54 [0.34–0.66]		
Unventilated workshop	14	0.64 [0.79]	0.48–0.84 [0.59–1.03]		
Other wood product plants					
Glueing in wood industry (Sweden)	65	0.2 [0.3]	NR	1980s	Rosén *et al.* (1984)
Parquet plant (Finland)				1981	Heikkilä *et al.* (1991)
Machining	3	0.3 [0.4]	0.16–0.5 [0.2–0.6]		
Varnishing	5	0.8 [1.0]	0.2–1.4 [0.3–1.7]		
Production of wooden structures (Finland)				1981–86	Heikkilä *et al.* (1991)
Glueing	36	0.7 [0.8]	0.07–1.8 [0.1–2.2]		
Machining	19	0.4 [0.4]	0.1–0.8 [0.1–0.9]		
Manufacture of wooden bars (Finland)				1983	Heikkilä *et al.* (1991)
Glueing	33	0.6 [0.7]	0.2–1.9 [0.2–2.4]		
Machining	7	1.2 [1.5]	0.2–2.2 [0.3–2.7]		

Table 8 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Match mill, impregnation of matchbox parts (Finland) Short-term	2	2.0 [2.5]	1.9–2.1 [2.3–2.6]	1963	Finnish Institute of Occupational Health (1994)
Wooden container mill, glueing and sawing (Finland)	6	0.3 [0.4]	0.2–0.4 [0.3–0.5]	1961	Finnish Institute of Occupational Health (1994)
Paper mills					
Laminated paper production (Sweden)	23	0.3 [0.4]	NR	1980s	Rosén *et al.* (1984)
Manufacture of offset paper (Sweden)	8	0.2 [0.2]	NR	1980s	Rosén *et al.* (1984)
Lamination and impregnation of paper with melamine and phenol resins (USA)				1983	Stewart *et al.* (1987)
Plant no. 6, summer[c,d]	53	0.7[b] [0.9]	< 0.01–7.4 [< 0.01–9.1]		
Plant no. 6, winter[d]	39	0.3[b] [0.4]	0.05–0.7 [0.06–0.9]		
Paper mill (Finland)				1975–84	Heikkilä *et al.* (1991)
Coating of paper	30	0.7 [0.9]	0.4–31 [0.5–39]		
Gum paper production	4	0.4 [0.5]	0.3–0.6 [0.3–0.8]		
Impregnation of paper with amino resin	6	3.1 [3.9]	0.5–13 [0.6–16]		
Impregnation of paper with phenol resin	20	0.1 [0.1]	0.05–0.3 [0.06–0.4]		
Paper mill (Finland)					Finnish Institute of Occupational Health (1994)
Glueing, hardening, lamination and rolling of special paper	12	0.9 [1.1]	0.3–2.5 [0.4–3.1]	1971–73	
Impregnation of paper with phenol resin, partly short-term	38	7.4 [9.1]	< 1.0–33.0 [< 1.1–40.6]	1968–69	
Paper storage, diesel truck traffic	5	0.3 [0.4]	0.2–0.4 [0.25–0.5]	1969	
Pulp and paper industries (12 countries)				1950–94	Korhonen *et al.* (2004)
Pulping, refining of stock (8 mills)	25	0.5 [0.6]	0–3.1 [0–3.8]		
Newsprint and uncoated paper machine (2 mills)	7	0.15 [0.18]	0.04–0.46 [0.05–0.57]		
Fine and coated paper machine (6 mills)	51	1.1 [1.4]	0.01–9.9 [0.01–12.2]		

Table 8 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Paperboard machine (1 mill)	8	0.5 [0.6]	0.2–2.2 [0.2–2.7]		
Paper/paperboard machine from more than one of above categories (24 mills)	228	0.4 [0.5]	0–6.6 [0–8.1]		
Calendering or on-machine coating (10 mills)	166	4.2 [5.2]	0–50 [0–61.5]		
Winding, cutting and grading (17 mills)	111	0.2 [0.3]	0–1.1 [0–1.4]		
Recycled paper industry (12 countries)					
Re-pulping of waste paper (2 mills)	8	0.2 [0.3]	0.05–0.4 [0.06–0.5]		
Construction industry					
Insulating buildings with urea–formaldehyde foam (Sweden)	6	0.1 [0.2]	NR	1980s	Rosén *et al.* (1984)
Insulating buildings with urea–formaldehyde foam (USA)	66	1.3[e] [1.6]	0.3–3.1 [0.4–3.8]	NR	WHO (1989)
Varnishing parquet with urea–formaldehyde varnish (Finland)	10	2.9 [3.6]	0.3–6.6 [0.4–8.1]	1976	Heikkilä *et al.* (1991)
Varnishing parquet with urea–formaldehyde varnish (Finland)	6	4.3 [5.3]	2.6–6.1 [3.2–7.5]	1987	Riala & Riihimäki (1991)
Sawing particle-board at construction site (Finland)	5	< 0.5 [< 0.6]	NR	1967	Finnish Institute of Occupational Health (1994)

GSD, geometric standard deviation; NA, not applicable; NR, not reported

[a] Arithmetic mean unless otherwise specified

[b] Geometric mean

Some of the results in the Stewart *et al.* (1987) study were affected by the simultaneous occurrence in the samples of:

[c] phenol (leading to low values)

[d] particulates that contained nascent formaldehyde (leading to high values).

[e] Mean of arithmetic means

Recent studies conducted in these industries in Finland and New Zealand (Mäkinen *et al.*, 1999; Fransman *et al.*, 2003) found mean concentrations of formaldehyde to be less than 0.5 mg/m^3. In contrast, mean levels of 2 ppm [2.5 mg/m^3] have been observed historically in some operations in the Finnish industry (Kauppinen, 1986).

(ii) *Manufactured board mills*

Both phenol–formaldehyde and urea–formaldehyde resins are used in mills that produce particle- and other manufactured boards, including oriented strand boards and medium-density fibre boards. Phenolic resins are more liable to be used for panels that are destined for applications that require durability under adverse conditions, while urea-based resins are used for less demanding, interior applications. Melamine–formaldehyde resins may also be used to increase durability, but rarely are because they are more expensive. Exposure to formaldehyde and other resin constituents is possible during the mixing of glues, the laying of mat and hot-pressing operations.

Herbert *et al.* (1995) and Chung *et al.* (2000) found levels of formaldehyde below 0.2 mg/m^3 in recent studies in Canada and the United Kingdom, respectively, in oriented strand-board and fibre-board plants. Mean exposures greater than 1 ppm [1.2 mg/m^3] have been observed in the past in particle- and chip-board mills (Kauppinen & Niemelä, 1985; Triebig *et al.*, 1989; Malaka & Kodama, 1990).

(iii) *Furniture factories*

Furniture varnishes may contain acid-cured urea–formaldehyde resins dissolved in organic solvents. In Finland, workers were exposed to an average level of about 1 ppm [1.23 mg/m^3] formaldehyde in most facilities (Priha *et al.*, 1986; Heikkilä *et al.*, 1991).

In a recent study in wood-working shops in Egypt, the levels of formaldehyde were found to average 0.42 and 0.64 ppm [0.52 and 0.79 mg/m^3] in ventilated and unventilated workplaces, respectively (Abdel Hameed *et al.*, 2000). [The origin of the formaldehyde was not stated.]

(iv) *Paper mills*

Some paper mills produce special products that are coated with formaldehyde-based phenol, urea or melamine resins. Coating agents and other chemicals used in paper mills may also contain formaldehyde as a bactericide.

As part of an IARC international epidemiological study of workers in the pulp and paper industry, measurements were carried out in the production departments of paper and paperboard mills and recycling plants in 12 countries. The highest exposures were observed during calendering or on-machine coating (Korhonen *et al.*, 2004).

(*e*) *Building and construction industry*

Exposure to formaldehyde may also occur in the construction industry (Table 8). Specialized construction workers who varnish wooden parquet floors may have relatively high exposure. The mean levels of formaldehyde in the air during varnishing with urea–formaldehyde varnishes ranged between 2 and 5 ppm [2.5–6.2 mg/m^3]. One coat of varnish takes only about 30 min to apply (Riala & Riihimäki, 1991), but the same worker may apply five or even 10 coats per day. Other chemical agents to which parquetry workers are usually exposed include wood dust from sanding (see IARC, 1995) and solvent vapours from varnishes, putties and adhesives. Operations that may have resulted in exposure to formaldehyde in the building trades are insulation with urea–formaldehyde foam and machining of particle-board, but these have now largely been discontinued. Various levels of formaldehyde have been measured during insulation with urea–formaldehyde foam, but exposure during handling and sawing of particle-board seems to be consistently low. Formaldehyde may be released when synthetic vitreous fibre-based insulation is applied to hot surfaces, i.e. high-temperature insulation in power plants, due to decomposition of the phenol–formaldehyde binder at temperatures > 150 °C (International Labour Office, 2001) (see also under (*f*)).

(*f*) *Manufacture of textiles and garments*

The use of formaldehyde-based resins to produce crease-resistant fabrics began in the 1950s. The early resins contained substantial amounts of extractable formaldehyde: over 0.4% by weight of fabric. The introduction of dimethyloldihydroxyethyleneurea resins in 1970 reduced the levels of free formaldehyde in fabrics to 0.15–0.2%. Since then, methylation of dimethyloldihydroxyethyleneurea and other modifications of the resin have decreased the level of formaldehyde gradually to 0.01–0.02% (Elliott *et al.*, 1987). Some flame-retardants contain agents that release formaldehyde (Heikkilä *et al.*, 1991). The cutting and sewing of fabrics release low levels of textile dust, and small amounts of chlorinated organic solvents are used to clean spots. Pattern copying machines may emit ammonia and dimethylthiourea in some plants (Elliott *et al.*, 1987). Finishing workers in textile mills may also be exposed to textile dyes, flame-retardants, carrier agents, textile-finishing agents and solvents (see IARC, 1990b).

Measurements of formaldehyde in the air of textile mills are summarized in Table 9. In the late 1970s and 1980s, levels of formaldehyde in the garment industry averaged 0.2–2 ppm [0.25–2.5 mg/m^3]. However, exposures in the past were generally higher, probably because of the higher content of free formaldehyde in fabrics. For example, the concentrations of formaldehyde were reported to have been 0.9–2.7 ppm [1.1–3.3 mg/m^3] in a post-cure garment manufacturing plant and 0.3–2.7 ppm [0.4–3.3 mg/m^3] in eight other garment manufacturing plants in the USA in 1966 (Elliott *et al.*, 1987). Goldstein (1973) reported that concentrations of formaldehyde in cutting rooms decreased from over 10 ppm [12 mg/m^3] in 1968 to less than 2 ppm [2.4 mg/m^3] in 1973 as a result of improvements in the processes of resin treatment. The mean formaldehyde concentration in air increased from 0.1 to 1.0 ppm [0.12 to 1.23 mg/m^3] in a study in the USA when the formaldehyde content of the fabric increased from 0.015 to 0.04% (Luker & Van Houten, 1990). Measurements from the late 1980s onwards indicate lower levels, usually averaging 0.1–0.2 ppm [0.12–0.25 mg/m^3].

Full-shift personal (for 5.7–6.4 h; eight samples) and area (for 6.3–7.3 h; 12 samples) measurements were taken at a pre-cured permanent-press garment manufacturing plant in

Table 9. Concentrations of formaldehyde in the workroom air of textile mills and garment factories

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range or SD in ppm [mg/m^3]	Year	Reference
Textile mills					
Textile plants (Finland)				1975–78	Nousiainen & Lindqvist (1979)
Finishing department, mixing	8	0.8 [1.1]	< 0.2–>5 [< 0.2–> 6]		
Crease-resistant treatment	52	0.4 [0.5]	< 0.2–>3 [< 0.2–> 4]		
Finishing department (excluding crease-resistant and flame-retardant treatment)	17	0.3 [0.4]	max., 1.3 [1.5]		
Flame-retardant treatment	67	1.9 [2.5]	< 0.2–>10 [< 0.2–> 11]		
Fabric store	6	0.8 [1.1]	0.1–1.3 [0.1–1.6]		
Textile mills (Sweden)				1980s	Rosén *et al.* (1984)
Crease-resistant treatment	29	0.2 [0.2]	NR		
Flame-retardant treatment	2	1.2 [1.5]	NR		
Garment factories					
Manufacture from crease-resistant cloth (USA)	181	NR	< 0.1–0.9 [< 0.1–1.1]	NR	Blade (1983)
Manufacture of shirts from fabric treated with formaldehyde-based resins (USA)	326	~0.2 [~0.25]	< 0.1–0.4 [< 0.1–0.5]	1980s	Elliott *et al.* (1987)
Garment industry (Finland)				1981–86	Heikkilä *et al.* (1991)
Handling of leather	3	0.1 [0.1]	0.02–0.1 [0.03–0.1]		
Pressing	32	0.2 [0.3]	0.02–0.7 [0.03–0.9]		
Sewing	15	0.1 [0.1]	0.02–0.3 [0.03–0.3]		
Sewing plant (USA)				NR	Luker & Van Houten (1990)
Processing of 0.04% formaldehyde fabric	9	1.0 [1.2]	0.5–1.1 [0.6–1.4]		
Processing of 0.015% formaldehyde fabric	9	0.1 [0.1]	< 0.1–0.2 [< 0.1–0.3]		
Garment manufacturing (USA)				NR	Echt & Burr (1997)
Sewers, cutters and bundlers					
Personal samples					
8-h TWA	8	0.21 [0.26]	0.18–0.23 [0.22–0.28]		
Area samples	8	0.16 [0.19]	0.14–0.17 [0.17–0.21]		
8-h TWA	8	0.24 [0.30]	0.17–0.30 [0.21–0.37]		
	8	0.21 [0.26]	0.16–0.25 [0.20–0.31]		

Table 9 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range or SD in ppm [mg/m^3]	Year	Reference
Cut and spread				NR	Kennedy *et al.* (1992)
Formaldehyde gas (inhalable dust)	6	0.03	SD, 0.01		
Bound formaldehyde (inhalable dust)	6	< 0.01	SD, < 0.01		
Formaldehyde gas (total dust)	6	0.04	SD, 0.01		
Bound formaldehyde (total dust)	6	< 0.01[b]	SD, < 0.01		
Turn and ticket					
Formaldehyde gas (inhalable dust)	6	< 0.01	SD, < 0.01		
Bound formaldehyde (inhalable dust)	6	< 0.01	SD, < 0.01		
Formaldehyde gas (total dust)	6	0.03	SD, 0.01		
Bound formaldehyde (total dust)	6	< 0.01	SD, < 0.01		
Retail dress shops (USA)	NR	NR	0.1–0.5 [0.1–0.6]	1959	Elliott *et al.* (1987)
Fabric shops (Finland)	3	0.17 [0.21]	0.12–0.24 [0.15–0.30]	1985–87	Priha *et al.* (1988)
Fabric stores (USA)	77	0.14 [0.17]	0.03–0.28 [0.04–0.34]	NR	McGuire *et al.* (1992)
24-h area samples					
Independent stores	33	0.10 [0.13]	0.03–0.28 [0.04–0.34]		
Chain stores	44	0.19 [0.24]	0.09–0.27 [0.11–0.33]		

NR, not reported; SD, standard deviation

[a] Arithmetic mean

[b] Five samples with non-detectable levels

the USA. Levels of exposure to formaldehyde for sewers, cutters and bundlers ranged from 0.22 to 0.28 mg/m^3 (8-h TWA, 0.17–0.21 mg/m^3). Area measurements of formaldehyde at cutting, sewing, pressing, spreading and receiving (storage) locations ranged from 0.21 to 0.37 mg/m^3 (8-h TWA; 0.20–0.31 mg/m^3). Full-shift (for 5.8–6.4 h; eight samples) personal measurements of formaldehyde in inhalable dust showed levels of up to 29 µg/mg dust; settled dust samples showed concentrations of 0.7 and 0.8 µg/mg dust (Echt & Burr, 1997). In another garment production facility in the USA, formaldehyde gas and formaldehyde bound to dust were detected at levels of 26–36 µg/m^3 and 0.2–0.7 µg/m^3, respectively (Kennedy *et al.*, 1992).

The use of formaldehyde-based resin to finish textiles and some garments may also result in exposure in retail shops. Measurements in dress shops in the USA in the 1950s showed levels up to 0.5 ppm [0.62 mg/m^3] (Elliott *et al.*, 1987). The air in three Finnish fabric shops in the 1980s contained 0.15–0.3 mg/m^3 formaldehyde (Priha *et al.*, 1988). In fabric stores in the USA that were monitored by placing samplers on a shelf in the store for 24 h, the average concentration of formaldehyde was 0.17 mg/m^3 (McGuire *et al.*, 1992).

(*g*) *Foundries*

Formaldehyde-based resins are commonly used as core binders in foundries (Table 10). Urea–formaldehyde resin is usually blended with oleoresin or phenol–formaldehyde resin and mixed with sand to form a core, which is then cured by baking in an oven or by heating from inside the core box (hot-box method). The original hot-box binder was a mixture of urea–formaldehyde resin and furfuryl alcohol (commonly referred to as furan resin). Furan resins were then modified with phenol to produce urea–formaldehyde/furfuryl alcohol, phenol–formaldehyde/furfuryl alcohol and phenol–formaldehyde/urea–formaldehyde resins.

The mean concentrations of formaldehyde measured during core-making and operations following core-making in the 1980s in Sweden and Finland were usually below 1 ppm [1.2 mg/m^3]; however, measurements made before 1975 suggest that past exposures may have been considerably higher (Heikkilä *et al.*, 1991). Many other chemicals occur in foundries, e.g. silica (see IARC, 1987d) and other mineral dusts, polycyclic aromatic hydrocarbons (see IARC, 1983), asbestos (see IARC, 1987e), metal fumes and dusts, carbon monoxide, isocyanates (see IARC, 1986), phenols (see IARC, 1989c), organic solvents and amines (see IARC, 1999). These exposures have been described in a previous monograph (IARC, 1984).

(*h*) *Synthetic vitreous fibre production*

Formaldehyde resins are commonly used to bind man-made vitreous fibre products. Measurements of formaldehyde in the air of plants manufacturing synthetic vitreous fibres are summarized in Table 10.

Measurements in glasswool and stonewool plants in the 1980s showed mean concentrations of 0.1–0.2 ppm [0.12–0.25 mg/m^3] formaldehyde. Very high levels were measured

Table 10. Concentrations of formaldehyde in the workroom air of foundries and during the manufacture of synthetic vitreous fibres and plastics

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Foundries					
Foundry (Sweden)				1980s	Rosén *et al.*
Hot-box method	5	1.5 [1.9]	NR		(1984)
Moulding	17	0.1 [0.1]	NR		
Foundries (Sweden)					Åhman *et al.*
Moulders and core-maker handling furan resin sand 8-h TWA	36	0.1 [0.1]	0.02–0.22 [0.02–0.27]	NR	(1991)
Foundries (Finland)				Before 1975	Heikkilä *et al.*
Core-making	43	2.8 [3.4]	< 0.1–> 10 [< 0.1–> 11]		(1991)
Core-making	17	0.3 [0.4]	0.02–1.4 [0.03–1.8]	1981–86	
Casting	10	0.2 [0.2]	0.02–0.2 [0.03–0.8]	1981–86	
Moulding	25	0.3 [0.4]	0.04–2.0 [0.05–2.5]	1981–86	
Synthetic vitreous fibre plants					
(Sweden)				1980s	Rosén *et al.*
Production	16	0.15 [0.19]	NR		(1984)
Form pressing	4	0.16 [0.20]	NR		
(Finland)				1981–86	Heikkilä *et al.*
Production	36	0.20 [0.25]	0.02–1.5 [0.03–1.7]		(1991)
Form pressing	24	0.09 [0.11]	0.01–0.3 [0.01–0.4]		
Fibrous glass manufacturing plant (USA)				NR	Milton *et al.*
Fixed location workers (*n* = 17)	97	0.07; 0.05[b]	GSD, 4.0		(1996)
Forming attendant (*n* = 2)	11	0.07; 0.03[b]	GSD, 8.2		
Forming attendant leader (*n* = 3)	18	0.09; 0.07[b]	GSD, 1.9		
Binder water leader (*n* = 1)	4	0.05; 0.01[b]	GSD, 10.9		
Binder water operator (*n* = 1)	6	0.06; 0.05[b]	GSD, 2.1		
Pipefitter (*n* = 1)	5	0.05; 0.05[b]	GSD, 1.4		
Forehearth operator (*n* = 6)	35	0.07; 0.05[b]	GSD, 4.4		
Curing oven machine operator (*n* = 3)	18	0.08; 0.07[b]	GSD, 1.7		

Table 10 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Mobile workers (*n* = 20)	< 100	0.03; 0.02[b]	GSD, 3.1		
Crew (packaging) (*n* = 2)	12	0.02; 0.01[b]	GSD, 4.1		
Washwater tender (*n* = 1)	3	0.04; 0.04[b]	GSD, 1.5		
Mechanical repair (*n* = 7)	35	0.02; 0.01[b]	GSD, 3.4		
Electrician (*n* = 5)	25	0.03; 0.02[b]	GSD, 3.1		
Sheet metal worker (*n* = 2)	10	0.03; 0.02[b]	GSD, 2.7		
Welder (*n* = 2)	10	0.04; 0.03[b]	GSD, 2.6		
Pipefitter (*n* = 1)	5	0.03; 0.02[b]	GSD, 1.9		
Plastics production					
Production of moulded plastic products (USA)				1983–84	Stewart *et al.* (1987)
Plant no. 8, phenol resin, summer	10	0.5[b] [0.6]	0.1–0.9 [0.1–1.1]		
Plant no. 9, melamine resin, summer	13	9.2[b] [11.3]	< 0.01–26.5 [< 0.01–32.6]		
Moulding compound manufacture (USA)					
Plant no. 9, winter	9	2.8[b] [3.4]	0.04–6.7 [0.05–8.2]		
Plant no. 9, summer[c]	18	38.2[b] [47.0]	9.5–60.8 [11.7–74.8]		
Plant no. 1, winter	12	1.5[b] [1.8]	0.9–2.0 [1.1–2.1]		
Plant no. 1, summer	24	9.7[b] [11.9]	3.8–14.4 [4.7–17.7]		
Plant no. 8, winter	13	0.3[b] [0.4]	0.07–0.7 [0.09–0.9]		
Plant no. 7, summer	43	0.3[b] [0.4]	0.05–0.6 [0.06–0.8]		
Plant no. 2, summer	15	6.5[b] [8.0]	0.3–20.6 [0.4–25.3]		
Plastics production (Finland)				1981–86	Heikkilä *et al.* (1991)
Casting of polyacetal resin	10	0.3 [0.4]	0.06–0.7 [0.08–0.8]		
Casting of urea–formaldehyde resin	4	0.4 [0.5]	0.2–0.5 [0.3–0.6]		
Casting of other plastics	29	< 0.1 [< 0.1]	< 0.1–0.2 [< 0.1–0.3]		
Plastics manufacturing (Canada)					Tikuisis *et al.* (1995)
Polyethylene extrusion	9	NR	max., [< 0.12]	NR	

GSD, geometric standard deviation; NR, not reported; TWA, time-weighted average

[a] Arithmetic mean unless otherwise specified

[b] Geometric mean

[c] Some of the results were affected by the simultaneous occurrence in the samples of particulates that contained formaldehyde (leading to high values).

occasionally in factories close to cupola ovens and hardening chambers (Heikkilä *et al.,* 1991). Other exposures in man-made vitreous fibre production have been described in a previous monograph (IARC, 2002).

Personal measurements of maintenance and production workers were taken in a fibreglass insulation manufacturing plant. The average level of exposure to formaldehyde for all fixed location workers (basement workers, forehearth operators and curing oven operators; 17 samples) was 0.07 mg/m^3. The mean of the measurements for all mobile workers (packaging crew, washwater tender, mechanical repairer, electrician, sheet metal workers, welder and pipefitter; 20 samples) was 0.03 mg/m^3. No measurement was below the limit of detection (Milton *et al*., 1996).

(*i*) *Plastics production*

Formaldehyde-based plastics are used in the production of electrical parts, dishware and various other plastic products (Table 10).

The concentrations of formaldehyde measured in such industries have usually been < 1 ppm [1.2 mg/m^3], but much higher exposures may occur. Plastic dust and fumes may be present in the atmospheres of moulded plastic product plants, and exposures in these facilities are usually considerably higher than those in facilities where the products are used. The mean concentration of formaldehyde was > 1 ppm in many plants in the USA where moulding compounds were used. Some workers may have been exposed to pigments, lubricants and fillers (e.g. historically, asbestos and wood flour) that were used as constituents of moulding compounds (Stewart *et al*., 1987).

An experimental scenario was created in Canada to evaluate thermal decomposition products that are emitted from the extrusion of polyethylene into a variety of products. Eight-hour area samples, collected at worst-case locations at typical operator locations, and 8-h personal samples were collected. All levels of formaldehyde were below 0.12 mg/m^3 (Tikuisis *et al*., 1995).

(*j*) *Firefighters*

Measurements of the exposure of firefighters to formaldehyde are given in Table 11. One study measured personal exposures to formaldehyde outside a self-contained breathing apparatus (if worn) while fighting fires in two cities in the USA. Formaldehyde was detected in six of 24 samples. Concentrations ranged from 0.1 to 8.3 ppm [0.12–10.2 mg/m^3], with a second highest concentration of 3.3 ppm [4.1 mg/m^3] (Brandt-Rauf *et al*., 1988). In another study in the USA, levels of formaldehyde ranged from the limit of detection (0.13 mg/m^3) to 9.8 mg/m^3 during knockdown (when the main body of the fire is brought under control), and formaldehyde was detected in 73% of the samples, from the limit of detection to 0.5 mg/m^3, during overhaul (searching for and extinguishing hidden fires) for 22 fires (Jankovic *et al*., 1991). Exposure levels inside the self-contained breathing masks ranged from the limit of detection to 0.4 mg/m^3. Two of the measurements during knockdown exceeded the 15-min short-term exposure limit (STEL) of 2.5 mg/m^3.

Table 11. Concentrations of formaldehyde during firefighting and exposure to engine exhausts

Industry and operation (location) Type of sample	No. of measurements	Mean[a] (ppm [mg/m^3])	Range (ppm [mg/m^3])	Year	Reference
Firefighting					
City fire (USA)	24	0.55 [0.68][b]	0.1–8.3 [0.1–10.2][b]	1986	Brandt-Rauf *et al*. (1988)
City fire (USA)	22 fires			NR	Jankovic *et al*. (1991)
Knockdown[c]		NR	ND–8 [ND–9.8]		
Overhaul[c]		NR	ND–0.4 [ND–0.5]		
Inside mask		NR	ND–0.3 [ND–0.4]		
Wildland fire (USA)	5	0.05 [0.06]	0.02–0.07 [0.02–0.09]	1990	Reh *et al.* (1994)
Wildland fire (USA)	30	0.13 [0.16]	0.04–0.3 [0.05–0.4]	1989	Materna *et al*. (1992)
City fire (USA)	96	0.25 [0.31]	0.02–1.2 [0.02–1.5]	1998	Bolstad-Johnson *et al*. (2000)
Engine exhaust					
Chain-sawing (Sweden)	NR	0.05 [0.06]	0.02–0.11 [0.03–0.13]	NR	Hagberg *et al*. (1985)
Chain-sawing (Finland) 8-h TWA	NR	< 0.1 [< 0.1]	< 0.1–0.5 [< 0.1–0.6]	NR	Heikkilä *et al*. (1991)
Automobile garage Personal samples	53	0.03 [0.04]	NR	NR	Zhang *et al.* (2003)

ND, not detected; NR, not reported; TWA, time-weighted average

[a] Arithmetic mean

[b] Excluding 18 values noted as 0

[c] See text for definitions

A comprehensive study that monitored air was conducted to characterize exposures of firefighters during 25 structure fires. Exposures of firefighters during overhaul, when they look for hidden fire inside attics, ceilings and walls often without respiratory protection, were measured. Ceiling values for formaldehyde (National Institute for Occupational Safety and Health [NIOSH]; 0.1 ppm [0.12 mg/m^3]) were exceeded at 22 fires (Bolstad-Johnson *et al.*, 2000).

Limited studies of exposure to aldehydes that is related to forest and wildland fires indicate lower exposures. Formaldehyde was detected in all 30 samples collected during a study of wildland fires. Concentrations ranged from 0.048 to 0.42 mg/m^3; the mean was 0.16 mg/m^3 (Materna *et al.*, 1992). A smaller study by NIOSH also detected formaldehyde in each of five samples collected during wildfire. Concentrations ranged from 0.02 to 0.07 ppm [0.02–0.09 mg/m^3] and the mean was 0.05 ppm [0.06 mg/m^3] (Reh *et al.*, 1994).

(*k*) *Automobile and engine exhausts*

Engine exhausts are a source of exposure to formaldehyde (see Section 1.3.3; Table 11).

Maître *et al.* (2002) evaluated individual airborne exposures to gaseous and particulate pollutants of a group of policemen who worked close to traffic in the centre of Grenoble, France. Personal active air samples were collected during the workshifts of eight policemen in summer and winter during the occurrence of a thermal inversion phenomenon for 4 days at each period. Stationary air samples were taken in the policemen's work area during the same period. The median concentration of the personal samples for formaldehyde was 14 µg/m^3 in the summer and 21 µg/m^3 in the winter.

Zhang *et al.* (2003) examined whether work in an automobile garage and tobacco smoke can significantly affect personal exposure to a number of important carbonyl compounds, including formaldehyde. The study was carried out on 22 garage workers (nine smokers and 13 nonsmokers) and 15 non-garage workers (four smokers and 11 nonsmokers). Daily exposure was estimated using 48-h integrated measurements of breathing zone concentrations. The mean formaldehyde concentrations were: 40.6 µg/m^3 for smoking garage workers, 41.1 µg/m^3 for nonsmoking garage workers, 34.6 µg/m^3 for smoking non-garage workers and 30.2 µg/m^3 for nonsmoking non-garage workers (total range, 14.1–80.1 µg/m^3).

(*l*) *Offices and public buildings*

Concentrations of formaldehyde in offices and public buildings (museums, geriatric homes) are given in Table 12.

In Australia, measurements of formaldehyde over 3–4 days were found to average 0.03 mg/m^3 in conventional offices and 1.4 mg/m^3 in portable office buildings (Dingle *et al.*, 2000).

Exposure measurements were taken for an epidemiological study of nasal symptoms in a Swedish office building that had recently been painted with low-emitting products [the

Table 12. Concentrations of formaldehyde in offices and miscellaneous other workplaces

Industry and operation (location) Type of sample	No. of measurements	Mean (ppm [mg/m^3])[a]	Range (ppm [mg/m^3])[a]	Year	Reference
Offices					
Offices (USA)	25	80.0[b] μg/m^3	NR	1981–84	Shah & Singh (1988)
Non-industrial office workplaces and restaurants (Brazil)	12	20.4 μg/m^3	4.7–60.7 μg/m^3	1993	Miguel *et al.* (1995)
Four offices on several floors of an office building (Brazil)	11	40 μg/m^3	12.2–99.7 μg/m^3	1995	Brickus *et al.* (1998)
Offices (Sweden)				1995–96	Wieslander *et al.* (1999a)
Recently painted with low-emitting paint	NR	18 μg/m^3	16–20 μg/m^3		
Three months later	NR	8 μg/m^3	7–10 μg/m^3		
Control (at the time and 3 months later)	NR	8 μg/m^3	8–9 μg/m^3		
Offices (Australia)				NR	Dingle *et al.* (2000)
Conventional offices (18 sites)	NR	27 μg/m^3	12–96 μg/m^3		
Portable office buildings (20 sites)	40	1400 μg/m^3	516–2595 μg/m^3		
Six office buildings (USA)	[72]	1.7–13.3 μg/m^3 [c]	NR	1996–97	Reynolds *et al.* (2001)
Five office buildings (Taiwan, China) 8-h average during working time from measurements conducted continuously ≥ 24 h	54	140–1190 μg/m^3 [d]	NR	NR	Wu *et al.* (2003)
Miscellaneous					
Coal coking plant (former Czechoslovakia)	NR	0.05[e] [0.06]	< 0.01–0.25 [< 0.01–0.3]	NR	Mašek (1972)
Pitch coking plant (former Czechoslovakia)	NR	0.4[e] [0.5]	0.05–1.6 [0.07–2.0]	NR	Mašek (1972)
Electrical machinery manufacture (Finland)				1977–79	Niemelä & Vainio (1981)
Soldering	47	< 0.1 [< 0.1]	NR		
Lacquering and treatment of melamine plastics	8	0.35 [0.4]	NR		
Rubber processing (USA)	NR	NR	0.4–0.8 [0.5–0.98]	1975	IARC (1982)
Painting with bake-drying paints (Sweden)	13	< 0.1 [< 0.1]	NR	1980s	Rosén *et al.* (1984)
Abrasive production (Sweden)	20	0.2 [0.3]	NR	1980s	Rosén *et al.* (1984)

Table 12 (contd)

Industry and operation (location) Type of sample	No. of measurements	Mean (ppm [mg/m^3])[a]	Range (ppm [mg/m^3])[a]	Year	Reference
Sugar mill (Sweden)				1980s	Rosén *et al.* (1984)
Preservation of sugar beets	26	0.4 [0.5]	NR		
Fur processing 8-h TWA	16	NR	0.8–1.6 [1.0–2.0]	1980s	Rosén *et al.* (1984)
Photographic film manufacture (USA)				1983–84	Stewart *et al.* (1987)
Plants no. 4 and 5, summer	49	0.1[e] [0.1]	< 0.01–0.4 [< 0.01–0.5]		
Plants no. 4 and 5, winter	29	0.3[e] [0.4]	0.02–0.9 [0.03–1.1]		
Agriculture (Finland)					Heikkilä *et al.* (1991)
Handling of fodder	NR	NR	0.02–0.4 [0.03–0.5]	1982	
Disinfection of eggs	11	2.6 [3.2]	0.2–7.8 [0.3–9.6]	1981–86	
Metalware plant, bake painting (Finland)	18	0.3 [0.4]	0.03–0.7 [0.04–0.9]	1981–86	Heikkilä *et al.* (1991)
Print (Finland)				1981–86	Heikkilä *et al.* (1991)
Development of photographs	11	0.04 [0.05]	0.02–0.1 [0.03–0.13]		
Malt barley production (Finland)				1981	Heikkilä *et al.* (1991)
Preservation of malt barley	6	0.7 [0.9]	0.4–1.5 [0.5–1.8]		
Photographic laboratories (Finland)	10	0.07 [0.09]	0.02–0.3 [0.03–0.40]	1981–86	Heikkilä *et al.* (1991)
Fish hatchery (USA)				NR	Lee & Radtke (1998)
Treating fish eggs (6 sites) 8-h TWA	6	0.02 [0.02]	0.006–0.038 [0.007–0.05]		

NR, not reported; TWA, time-weighted average

[a] Arithmetic mean unless otherwise specified; values in ppm [mg/m^3], unless stated otherwise

[b] Median

[c] Range of geometric means

[d] Range of arithmetic means

[e] Mean of arithmetic means

recency was not identified but appeared to be within a few months]. The measurements taken at that time showed average levels of formaldehyde of 18 μg/m^3 (range, 16–20 μg/m^3); those taken 3 months later averaged 8 μg/m^3 (range, 7–10 μg/m^3) (Wieslander *et al.*, 1999a). The latter were equivalent to the levels found in the same office complex in an area that had not been redecorated (mean, 8–9 μg/m^3).

Laser-jet printers have been found to be a source of formaldehyde, as a result of the ozonolysis reactions of volatile organic compounds emitted from the toner powder (Wolkoff *et al.*, 1992; Tuomi *et al.*, 2000). In a study in an office environment in Finland (Tuomi *et al.*, 2000), the emission rate of formaldehyde of three printers that used traditional corona-discharge technology (dating from approximately 1990) ranged from 9 to 46 μg/m^3, whereas a newer technology printer did not produce detectable levels of formaldehyde.

In another study in Sweden, average levels of formaldehyde in four geriatric homes ranged from 2 to 7 μg/m^3 (Wieslander *et al.*, 1999b).

(*m*) *Miscellaneous*

Formaldehyde is used in agriculture as a preservative for fodder and as a disinfectant (Table 12). For example, fodder was preserved with a 2% formalin solution several times per year from the late 1960s until the early 1980s on farms in Finland. As the air concentration during preservation was < 0.5 ppm [0.6 mg/m^3], the annual mean exposure was probably very low. Formaldehyde gas is also used 5–10 times a year to disinfect eggs in brooding houses. The concentration of formaldehyde in front of the disinfection chamber immediately after disinfection was as high as 7–8 ppm [8.6–9.8 mg/m^3], but annual exposure from this source probably remains very low (Heikkilä *et al.*, 1991).

One worker in each of six different fish hatcheries in the USA was monitored once over the 15–90-min period it took to treat fish eggs with a formalin solution to control infection. Concentrations ranged from not quantifiable to 1 mg/m^3. Area measurements during treatment were < 0.062–0.84 mg/m^3, and 8-h TWAs were reported to be < 0.01–0.05 mg/m^3 (mean, 0.02 mg/m^3) (Lee & Radtke, 1998).

Formaldehyde is also used or formed during many other industrial operations, such as treatment of fur and leather, preservation of barley and sugar beets, coal and pitch coking, rubber processing and production of abrasives (Table 12). Some of these activities may entail heavy exposure. For example, treatment of furs with formaldehyde resulted in the highest exposure to formaldehyde of all jobs and industries studied in a large Swedish survey in the early 1980s. The 8-h TWA concentration of formaldehyde was assessed to be 0.8–1.6 ppm [1.0–2.0 mg/m^3] and high peak exposures occurred many times per day (Rosén *et al.*, 1984).

Heating of bake-drying paints and soldering may release some formaldehyde in plants where metalware and electrical equipment are produced, but the measured concentrations are usually well below 1 ppm [1.2 mg/m^3] (Rosén *et al.*, 1984).

The mean concentrations of formaldehyde measured during the coating of photographic films and during development of photographs are usually well below 1 ppm [1.2 mg/m^3]

(Table 12). Methanol, ethanol, acetone and ammonia are other volatile agents that may occur in film manufacturing facilities (Stewart *et al.*, 1987).

Formaldehyde has been found consistently in spacecraft atmospheres at concentrations that exceed the 180-day spacecraft maximum allowable concentration of 0.05 mg/m^3. The source is thought to be hardware off-gassing and possibly leakage from experiments that involve fixatives. Small amounts could also be present from human metabolism and exhalation (James, 1997).

1.3.3 *Ambient (outdoor) air*

Measurements of indoor and outdoor levels of formaldehyde have been generated in many countries for several decades. Standard sampling and analytical methodologies are sufficiently sensitive to detect formaldehyde in most samples of ambient (outdoor) air. Concentrations of formaldehyde in urban, suburban and rural areas are presented in Table 13.

Although formaldehyde is a natural component of ambient air, anthropogenic sources usually contribute most to the levels of formaldehyde in populated regions, since ambient levels are generally < 1 μg/m^3 in remote areas. For example, in the unpopulated Eniwetok Atoll in the Pacific Ocean, a mean of 0.5 μg/m^3 and a maximum of 1.0 μg/m^3 formaldehyde were measured in outdoor air (Preuss *et al.*, 1985). Other authors have reported similar levels in remote, unpopulated areas (De Serves, 1994; IARC, 1995; Environment Canada/ Health Canada, 2001).

Outdoor air concentrations of formaldehyde in urban environments are more variable and depend on local conditions. They are usually in the range of 1–20 μg/m^3 (Preuss *et al.*, 1985; IARC, 1995; Jurvelin, 2001). Urban air concentrations in heavy traffic or during severe inversions can range up to 100 μg/m^3 (Báez *et al.*, 1995; IARC, 1995; Williams *et al.*, 1996; de Andrade *et al.*, 1998).

A major source of formaldehyde in urban air is incomplete combustion of hydrocarbon fuels, especially from vehicle emissions (Vaught, 1991; Pohanish, 2002). Combustion processes account directly or indirectly for most of the formaldehyde that enters the atmosphere, particularly from engines that are not equipped with catalytic converters (WHO, 1989; Pohanish, 2002). In the USA, emissions of formaldehyde from automobiles were estimated to be about 277 million kg each year just prior to the introduction of the catalytic converter in 1975 (Environmental Protection Agency, 1976) and to have decreased since (Zweidinger *et al.*, 1988). In Mexico, a comparison of exhaust emissions from light-duty vehicles in the early 1990s showed a 10–30-fold decrease in emissions of formaldehyde from vehicles that were equipped with a catalytic converter compared with those with no catalyst (Schifter *et al.*, 2001). In contrast, emissions of formaldehyde from automobile exhaust have been reported to have risen again with the introduction of oxygenated fuels (Kirchstetter *et al.*, 1996). Gaffney *et al.* (1997) found that, in Albuquerque (NM, USA), the introduction of oxygenated fuels was associated with higher ambient air levels of formaldehyde during the winter, the season during which these fuels were used. Levels of

Table 13. Occurrence of formaldehyde in outdoor (ambient) air

Country	Location/region	Settings	Sampling period	No. of samples	Mean concentration or range of means (μg/m^3)[a]	Range (μg/m^3)[a]	Comments	Reference
Algeria	Algiers	Urban	2000–01	10	12.7	5.2–27.1		Cecinato *et al.* (2002)
	Ouargla	Urban		4	4.0	2.6–5.2		
	Algiers	Suburban		14	11.9	6.0–21.2		
Austria	Exelberg	Semi-rural	1986–87	21	6.4–13.4 ppb	NR	Measured in July and August	Puxbaum *et al.* (1988)
	Raasdorf	Semi-rural		18	6.6–11.1 ppb	NR	Measured in July and August	
	Schoeneben	Rural		20	4.0–8.9 ppb	NR	Measured in September	
Brazil	São Paulo and Rio de Janeiro	Urban	1993	12	10.7	4.0–27.7	Measured outside non-industrial office workplaces and restaurants	Miguel *et al.* (1995)
	Salvador, Bahia	Urban	NR	68	2.9–80 ppb	1.3–88 ppb	Collected at six sites around the city	de Andrade *et al.* (1998)
	Rio de Janeiro	Rural	1995	37	1.2–1.5 ppb	0.2–4.6 ppb	Collected at two sites in rural area	Brickus *et al.* (1998)
		Urban		11	14.5 ppb	7.1–21.0 ppb	Measured outside of an office building	
	São Paulo	Urban	1999	37			Collected in winter at two sites:	Montero *et al.* (2001)
					16.4–18.0 ppb	1.1–46.3 ppb	Morning	
					10.7–13.1 ppb	1.2–28.3 ppb	Midday	
					9.8–10.7 ppb	2.7–38.1 ppb	Evening	
	São Paulo	Urban	1997	11	5.0 ppb	1.4–9.7 ppb	Measured in February during use of alcohol fuel	Nguyen *et al.* (2001)
	Theobroma	Rural	1995	15	12.8 ppb daytime, 16.5 ppb nighttime, 8.6 ppb	5–25 ppb	Measured during 1 week of an open agricultural and silvicultural biomass burning period	Reinhardt *et al.* (2001)
	Rio de Janeiro	Urban	2000	13	10.8	NR	Collected from May to November during morning commute	Grosjean *et al.* (2002)
	Rio de Janeiro	Urban	1998–2001	28	13.7 ppb	1.5–54.3 ppb	Measured on a high traffic street in the downtown area	Corrêa *et al.* (2003)

Table 13 (contd)

Country	Location/region	Settings	Sampling period	No. of samples	Mean concentration or range of means (μg/m^3)[a]	Range (μg/m^3)[a]	Comments	Reference
Canada	Ontario	Rural	1988	49	1.6 ppb	0.6–4.4 ppb	Dorset site	Shepson *et al.* (1991)
				47	1.8 ppb	0.7–4.2 ppb	Egbert site	
	Alert, Nunavut	Remote	1992	NR	0.48	0.04–0.74	Polar night	De Serves (1994)
					NR	0.12–0.86	Sunlit period	
	Nova Scotia	Remote	1993	108	NR	< 0.6–4.2	Summer measurements	Tanner *et al*. (1994), cited in Environment Canada/Health Canada (2001)
	Six provinces	Various	1989–98	NR	NR	ND–27.5	Measured at eight urban sites	Environment Canada (1999), cited in Environment Canada/Health Canada (2001)
				NR	NR	ND–12.0	Measured at two suburban sites	
				NR	NR	ND–9.9	Measured at six rural sites	
		Rural	1995–96	NR	NR		Near a forest product plant	Environment Canada (1997), cited in Environment Canada/Health Canada (2001)
			Spring			max., 3.0		
			Summer			max., 1.7		
			Winter			max., 4.4		
	Prince Rupert, BC	Urban, residential, and industrial areas	1994–95	96	0.7–3.9	0.08–14.7	Collected from the roofs at four sites	Environment Canada/Health Canada (2001)
	Various	Urban and suburban	1990–98	2819	3.3 (2.8)[b]		Four urban and four suburban sites from the National Air Pollution Survey programme	Liteplo & Meek (2003)

Table 13 (contd)

Country	Location/region	Settings	Sampling period	No. of samples	Mean concentration or range of means (µg/m³)[a]	Range (µg/m³)[a]	Comments	Reference
China	Hong Kong	Urban	1997–2000	182	3.6–4.2	0.6–10	Residential and commercial	Sin *et al*. (2001)
					4.8–5.1	1.9–11	Residential, commercial and light industrial	
	Hong Kong	Urban	1999–2000	41	4.1	1.0–11.3	Overall average (12 months)	Ho *et al*. (2002)
					5.9	NR	Summer average (May–August)	
					2.6	NR	Winter average (November–February)	
	Guangzhou	Urban	2002	25	12.4	6.4–29.0	Measured outside a hotel in the evening on 7 consecutive days	Feng *et al.* (2004)
Denmark	Copenhagen	Urban	1994	37	2.6 ppb	0.2–6.4 ppb	Winter measurements (February)	Granby *et al*. (1997)
	Lille Valby	Semi-rural		18	0.9 ppb	0.1–2.8 ppb	Winter measurements (February)	
				28	0.8 ppb	0.3–1.8 ppb	Spring measurements (April)	
	Lille Valby	Semi-rural	1995	244	1.2 ppb	0.1–4.7 ppb	Measured in May–July	Christensen *et al.* (2000)
Egypt	Cairo	Urban	1999	98	33 ppb	SD, 8.6	Residential area	Khoder *et al.* (2000)
				49	29 ppb	SD, 7.1	Spring	
				49	37 ppb	SD, 9.5	Summer	
France	Grenoble	Urban	1995	NR	NR	2–18 ppb	Measured during 1 week in May	Ferrari *et al.* (1998)
	Paris	Urban and semi-urban	1985	NR	2–32 ppb	NR	Measured at one urban site and three rural sites with some urban influence	Kalabokas *et al.* (1988)

Table 13 (contd)

Country	Location/region	Settings	Sampling period	No. of samples	Mean concentration or range of means (µg/m^3)[a]	Range (µg/m^3)[a]	Comments	Reference
Germany	Mainz-Finthen	Semi-rural	1979	14	1.9 ppb	0.7–5.1 ppb	Measured during July–October	Neitzert & Seiler (1981)
	Deuselbach	Rural		14	1.7 ppb	0.4–3.8 ppb	Measured during November	
	The Alps	Rural	1991	NR	1.3 ppb	0.4–3.3 ppb	Measurement at summit of Wank mountain in October	Slemr & Junkermann (1992)
	Schauinsland	Rural	1992	22	1.0 ppb	0.4–2.3 ppb	Measured continuously over 11 days	Slemr *et al.* (1996)
Hungary	Budapest	Urban	1987–89	185	14.9 ppb 34.6 ppb	ND–58 ppb 7–176 ppb	Measured at downtown site Measured at the border of downtown with a possible local emission source	Haszpra *et al.* (1991)
Italy	Rome	Urban	1994–95	56 57	17.0 ppb 11.2 ppb	8.8–27.7 ppb 8.2–17.0 ppb	Measured in summer 1994 Measured in winter 1995	Possanzini *et al.* (1996)
	Milan	Urban	1998–99	NR	NR 5.9 8.0–15.7	4.1–53.4 NR NR	Winter measurements (six sites) Rural-industrial (one site) Urban (five sites)	Andreini *et al.* (2000)
Japan	Takasaki	Urban	1984	38	NR	2.5–11.4 ppb	Measured during July and August	Satsumabayashi *et al.* (1995)
	Osaka	Urban	1997	NR	1.9 ppb	0.1–4.3 ppb	Measured in October–December	Nguyen *et al.* (2001)
	Nagoya	NR	1998	37	5.8[c]	GSD, 1.5	Measured in February	Sakai *et al.* (2004)
Lithuania	Kaunas	NR	1998	NR	3.1	1.4–5.3	Measured at 12 municipal monitoring sites	Maroziene & Grazuleviciene (2002)
Mexico	Mexico City	Urban	1993	48	35.5 ppb	5.9–110 ppb	Measured at the University of Mexico campus	Báez *et al.* (1995)
	Mexico City and Xalapa	Urban	1996–98	145[d]	4–32	2–63	Measured outside two houses, three museums and two offices	Báez *et al.* (2003)

Table 13 (contd)

Country	Location/region	Settings	Sampling period	No. of samples	Mean concentration or range of means (µg/m^3)[a]	Range (µg/m^3)[a]	Comments	Reference
Norway	Drammen	Urban	1994–97 1998–2000	974 973	8.9 2.9	NR NR	Reduction of mean levels attributed to increase in vehicles with catalysts	Hagen *et al.* (2000); Oftedal *et al.* (2003)
South Africa	Cape Point	Semi-rural	1979	5	0.5 ppb	0.2–1.0 ppb	Measured during December	Neitzert & Seiler (1981)
Spain	Madrid	Urban	1996	NR	9.0	4.7–20	Air sampling in September–October from 8 h to 16 h	García-Alonso & Pérez-Pastor (1998)
Sweden	Uppsala	Urban	1998	27	1.3[c]	GSD, 1.8	Measured in February–May near 22 houses and five apartments	Sakai *et al.* (2004)
Taiwan, China	Taipei	Urban	1999	NR	7.2–9.8 ppb	range of max., 20.6–34.8 ppb	Measured from February–June at five locations	Mathew *et al.* (2001)
United Kingdom	London	Urban	1991–92	9 7	19.2 ppb 7.4 ppb	ND–98 ppb 0.8–13.5 ppb	West London, residential area North London, residential area	Williams *et al.* (1996)
USA	Country-wide	Various Urban Suburban Rural	1975–85	629 332 281 12	8.3 ppb (4.1 ppb)[b] 6.5 ppb[b] 2.7 ppb[b] 2.7 ppbv[b]	NR NR NR NR	All sites combined[e]	Shah & Singh (1988)[f]
	Atlanta, GA	Urban	1992	217	2.7–3.0 ppb	max., 8.3 ppb	Measured at four locations during July and August	Grosjean *et al.* (1993)
	Albany, NY	Semi-urban	1991	NR	NR	0.6–3.7 ppb	Measured during October	Khwaja (1995)
	Boston, MA	Residential	1993	8	3.1 ppb	0–3.1 ppb	Winter measurements, outside four residences	Reiss *et al.* (1995)
				18	2.6 ppb	1.2–5.9 ppb	Summer measurements, outside nine residences	

Table 13 (contd)

Country	Location/region	Settings	Sampling period	No. of samples	Mean concentration or range of means (µg/m^3)[a]	Range (µg/m^3)[a]	Comments	Reference
USA (contd)	Denver, CO	Urban	1987–91	NR	3.9 ppb	NR	Measured in winter	Anderson *et al.* (1996)
					2.3 ppb	NR	Measured in spring	
					2.7 ppb	NR	Measured in summer	
	Los Angeles, CA	Urban	1993	32	5.3 ppb	1.4–10.6 ppb	Measured during the smog season (September)	Grosjean *et al.* (1996)
		Rural			0.8 ppb	0.7–1.0 ppb	Background location	
	Eniwetok Atoll	Remote	1980	7	0.4 ppb	max., 0.8 ppb	South Pacific	Preuss *et al.* (1985)
	Minnesota	Mixed	1991–99	2494	1.7 (1.37)[b]	< 0.05–21	Collected at 25 sites throughout the state for varying periods of time	Pratt *et al.* (2000)
	New York City, NY	Urban	1999	36	2.1		Winter measurements	Kinney *et al.* (2002)
				36	5.3		Summer measurements	
	Los Angeles County, CA	Semi-urban	1999–2000	69	7.2 ppb	4.3–14.0 ppb		Delfino *et al.* (2003)
	California	Urban	1990–2002	NR	2.0–4.3	NR	Range of annual averages	California Air Resources Board (2004)

GSD, geometric standard deviation; NR, not reported; SD, standard deviation

[a] Unless otherwise specified

[b] Median

[c] Geometric mean

[d] Number of indoor and outdoor measurements combined (see Table 14)

[e] Includes urban, suburban, rural, remote and source-dominated sources.

[f] Data collected from literature searches, direct contacts with individuals and organisations, reports, computer tapes and direct electronic transfers

formaldehyde in vehicle emissions in 1994 were found to increase by 13% within 2 months after the average oxygen content of fuels sold in the San Francisco Bay (CA, USA) area increased from 0.3 to 2.0% by weight (Kirchstetter *et al.*, 1996). In the Denver (CO, USA) area, use of oxygenated fuels was associated with a 20–75% increase in ambient air levels of formaldehyde, although nearly all ambient air measurements remained below 6 μg/m^3 (Spitzer, 1997). Local air concentrations as high as 35.4, 41.8 and 44.2 μg/m^3 have been reported inside vehicles, in parking garages and at service stations, respectively (Spitzer, 1997).

Formaldehyde was detected (detection limit, 0.05 μg/m^3) in 3810 of 3842 24-h samples from rural, suburban and urban areas in Canada that were collected at 16 sites in six provinces surveyed from August 1989 to August 1998 (Environment Canada, 1999, cited in Environment Canada/Health Canada, 2001). Concentrations ranged from below the detection limit to a maximum of 27.5 μg/m^3 for eight urban sites, a maximum of 12.03 μg/m^3 for two suburban sites and a maximum of 9.88 μg/m^3 for six rural sites. Long-term (1 month–1 year) mean concentrations for the rural sites ranged from 0.78 to 8.76 μg/m^3. Monthly mean concentrations were highest during the summer, but there was no apparent long-term trend in concentrations of formaldehyde at these sites over this 9-year period (Environment Canada/Health Canada, 2001).

In addition to primary emissions of formaldehyde in vehicle exhaust, secondary formation of formaldehyde by oxidation of alkenes in the atmosphere is also an important source (Altshuller, 1993; Seila *et al.*, 2001). Patterns of diurnal and seasonal variation in levels of formaldehyde and formaldehyde:acetaldehyde ratios have led to the suggestion that natural sources of alkenes add significantly to anthropogenic emissions, particularly during the summer months (Gaffney *et al.*, 1997; Viskari *et al.*, 2000). Photo-oxidation is also a primary degradation pathway for formaldehyde in the atmosphere, with an estimated half-life in the range of a few hours (ATSDR, 1999).

1.3.4 *Residential indoor air*

The occurrence of formaldehyde in indoor air in private housing and public settings is summarized in Table 14.

Levels of formaldehyde in indoor air are often higher by one order of magnitude or more than those outdoors. The concentrations in dwellings depend on the sources of formaldehyde that are present, the age of the source materials, ventilation, temperature and humidity. Indoor sources include pressed wood products (e.g. plywood, particle-board), some insulation materials, carpets, paints and varnishes, clothing and fabrics, cooking, tobacco smoke and the use of formaldehyde as a disinfectant (Gammage & Gupta, 1984; IARC, 1995; Dingle *et al.*, 2000; Hodgson *et al.*, 2000, 2002; Jurvelin, 2003). Off-gassing of urea–formaldehyde foam insulation and particle-board has been reported historically to be a major source of formaldehyde in some dwellings.

In a study on indoor emissions of formaldehyde, quasi steady-state emission rates of formaldehyde from new carpets were measured in a large-scale environmental chamber

Table 14. Occurrence of formaldehyde in indoor air in residential and public settings

Country	Location/ region	Sampling period	No. of samples	Mean concentration or range of means (µg/m^3)[a]	Range (µg/m^3)[a]	Comments	Reference
Residential							
Australia	Victoria	1994–95	NR	12.6 ppb[b]		Eighty households	Garrett *et al*. (1997, 1999)
				13.8 ppb[b]	< 0.3–105	Bedroom	
				11.3 ppb[b]	< 0.3–108	Living-room	
				11.4 ppb[b]	< 0.3–108	Kitchen	
Austria	Burgenland, Carinthia and Styria	1988–89	234 apartments	< 30–100 ppb		Measured in 33% of the apartments	Koeck *et al*. (1997)
				100–500 ppb		Measured in 48% of the apartments	
				> 500 ppb		Measured in 19% of the apartments	
Canada	Quebec City, QC	NR	28	7.3	max., 20.2	Basement, with combustion appliance	Lévesque *et al*. (2001)
			3	9.2	max., 19.7	Basement, without combustion appliance	
			34	8.2	max., 23.4	Ground floor, with combustion appliance	
			6	9.9	max., 19.5	Ground floor, without combustion appliance	
	Various	1989–95	151	35.9 (29.8[b])	NR	Pooled data from five studies at various locations	Liteplo & Meek (2003)
Egypt	Cairo	1999	294			Seven apartments	Khoder *et al*. (2000)
				89 ppb	35–192 ppb	Kitchen	
				100 ppb	30–213 ppb	Bedroom	
				100 ppb	28–225 ppb	Living room	
			147	87.6 ppb	NR	Measured in spring	
			147	105.6 ppb	NR	Measured in summer	
France	Paris	2001				Sixty-one dwellings in Paris and suburbs	Clarisse *et al*. (2003)
			61	21.7[c]	NR	Kitchen	
			61	24.2[c]	NR	Living room	
			61	24.5[c]	NR	Bedroom	
Hungary		1998	123	17.5	0.6–56.7	Homes in six medium-sized cities	Erdei *et al*. (2003)

Table 14 (contd)

Country	Location/ region	Sampling period	No. of samples	Mean concentration or range of means ($\mu g/m^3$)[a]	Range ($\mu g/m^3$)[a]	Comments	Reference
Japan	Country-wide	1998–2001	1642	120 (95.7[b])	max., 979	From 1422 homes distributed throughout the country	Park & Ikeda (2003)
	NR	2000	171			Rooms from 81 houses	Azuma *et al.* (2003)
				110 ppb	20–872 ppb	Active DNPH method	
				120 ppb	11–840 ppb	Detector tube method	
	Niigata Prefecture	1999	104	NR	0–740	Data from figure; 29% greater than 100 $\mu g/m^3$	Sakaguchi & Akabayashi (2003)
	Nagoya	1998	37	17.6[c]	max., 73	Dwelling factors and airborne concentrations were also compared	Sakai *et al.* (2004)
Mexico	Mexico City and Xalapa	1996–98	50[d]	37–47	12–81	Measured in two houses	Báez *et al.* (2003)
Sweden	Uppsala	1998	27	8.3[c]	max., 19	Dwelling factors and airborne concentrations were also compared	Sakai *et al.* (2004)
United Kingdom	London	1991–92	17	15.0 ppb	ND–93.1 ppb	West London, residential area	Williams *et al.* (1996)
			40	3.4 ppb	ND–10.3 ppb	North London, residential area	
USA	San Francisco Bay Area, CA	1984	48	41 ppb	NR	Kitchen	Sexton *et al.* (1986)
			45	36 ppb	NR	Main bedroom	
	Various	1981–84	273	44.0[b]	NR	Mixed locations	Shah & Singh (1988)[e]
	Colorado	1992–93	9	26[d]	8–66	Prior to occupancy	Lindstrom *et al.* (1995)
				49[d]	33–81	After 5 months of occupancy	
	Boston, MA	1993	14	11.1 ppb	6.0–16.1 ppb	Winter measurements, four residences	Reiss *et al.* (1995)
			26	16.1 ppb	5.9–53.8 ppb	Summer measurements, nine residences	
	Louisiana	NR	419	460	ND–6600	Measured in 53 houses (75% urban, 25% rural); also measured seasonal differences	Lemus *et al.* (1998)

Table 14 (contd)

Country	Location/ region	Sampling period	No. of samples	Mean concentration or range of means (µg/m³)[a]	Range (µg/m³)[a]	Comments	Reference
USA (contd)	East and South-East	1997–98	4 7	34 ppb[d] 36 ppb[d]	21–47 ppb 14–58 ppb	Manufactured houses Site–built houses	Hodgson *et al.* (2000)
	Florida	2000	NR	94.9	NR	New manufactured house	Hodgson *et al.* (2002)
	New York City, NY	1999	38 41	12.1 20.9	NR NR	Winter measurements Summer measurements	Kinney *et al.* (2002)
Public settings							
China	Hotel ballroom	2002	28	29.7	26.3–63.0	Measured in four hotel ballrooms in the evening on 7 consecutive days	Feng *et al.* (2004)
Italy	Library	1995–96	16	32.7	1.7–67.8	Sixteen libraries at the University of Modena; 10 samples with detectable levels	Fantuzzi *et al.* (1996)
Mexico	Museum	1996–98	60[d]	11–34	4–59	Three museums	Báez *et al.* (2003)
Sweden	Hospital	1997	4	5	2–7	Geriatric hospitals built in 1925, 1985, 1993 and 1994	Wieslander *et al.* (1999b)
	Primary school	1993, 1995	48	9.5	3–16	Twelve randomly selected primary schools	Norbäck *et al.* (2000)

ND, not detected; NR, not reported

[a] Unless stated otherwise

[b] Median

[c] Geometric mean

[d] Number of indoor and outdoor measurements combined (see Table 13)

[e] Data collected from literature searches, direct contacts with individuals and organisations, reports, computer tapes and direct electronic transfers

(Hodgson *et al*., 1993). The emission rates in single samples were 57.2 and 18.2 µg/m^2/h at 24 and 168 h, respectively, after the start of each experiment. Similar results were observed in a Swedish study in which indoor levels of formaldehyde were found to be higher in homes that had wall-to-wall carpeting (Norbäck *et al*., 1995).

The release of formaldehyde and volatile organic compounds from newly painted indoor surfaces was investigated in a sample of 62 dwellings in Uppsala, Sweden, in 1991–92. Concentrations of formaldehyde were significantly increased in dwellings where wood paint had been used, but were not related to other types of painting. Wall-to-wall carpeting and wood painting made approximately equal contributions of 13 µg/m^3 and 16 µg/m^3 formaldehyde, respectively (Wieslander *et al*., 1997). The adsorption of formaldehyde to dust particles on wipe samples from homes and offices was investigated to evaluate the extent to which such particles could act as carriers for volatile pollutants and contribute to exposure to formaldehyde. A person exposed to an ambient concentration of 1 ppm [1.2 mg/m^3] formaldehyde would inhale about 1 mg/h formaldehyde vapour when breathing normally (15 L/min). In the presence of 1 mg/m^3 dust (that contains 10 ng/mg formaldehyde based on analysis of the dust samples), the amount of particle-associated formaldehyde inhaled would be approximately 10 ng/h, i.e. five orders of magnitude lower (Rothenberg *et al*., 1989). The dose of particle-associated formaldehyde to the lower respiratory tract is predicted to be at least four orders of magnitude smaller than the vapour-phase dose to the upper respiratory tract. [The Working Group noted that the conditions of this investigation are also relevant to industrial environments.]

Data on concentrations of formaldehyde in residential indoor air from five studies conducted in Canada between 1989 and 1995 were examined (Health Canada, 2000). Despite differences in sampling mode and duration (i.e. active sampling for 24 h or passive sampling for 7 days), the distribution of concentrations was similar in the five studies. The median, arithmetic mean, 95th percentile and 99th percentile concentrations of the pooled data (151 samples) were 29.8, 35.9, 84.6 and 116 µg/m^3, respectively (Health Canada, 2000). Similar concentrations have been measured in non-workplace indoor air in other countries.

Personal 48-h exposures of 15 randomly selected participants as well as microenvironment concentrations in each participant's residence and workplace were measured for 16 carbonyl compounds, including formaldehyde, during the summer and autumn of 1997 as part of the Air Pollution Exposure of Adult Urban Populations in Europe (EXPOLIS) study in Helsinki, Finland. The mean personal exposure concentration of formaldehyde was 21.4 ppb [26.3 µg/m^3]; the mean indoor residential concentration was 33.3 ppb [41.0 µg/m^3]; the mean outdoor residential concentration was 2.6 ppb [3.2 µg/m^3]; and the mean workplace concentration was 12.0 ppb [14.8 µg/m^3] (Jurvelin *et al*., 2003).

In earlier studies summarized by Preuss *et al*. (1985), the mean concentrations in conventional homes with no urea–formaldehyde foam insulation were 25–60 µg/m^3. Since the late 1970s, many studies have reported formaldehyde levels in 'mobile homes' (caravans) (see, for example, the review of Gammage & Travis, 1989). The levels appear to decrease as the mobile home ages, with a half-life of 4–5 years (Preuss *et al*., 1985). In the early 1980s, mean concentrations of 0.4 ppm [0.5 mg/m^3] and individual values as high as several parts per million were measured in new mobile homes. As a result of new standards and regulations established in the mid-1980s for building materials and voluntary reductions by the manufacturers, concentrations of formaldehyde in mobile homes have decreased to approximately 0.1 ppm [0.12 mg/m^3] or less (Gammage & Travis, 1989; Sexton *et al*., 1989; Gylseth & Digernes, 1992; Lehmann & Roffael, 1992).

Formaldehyde may also occur in indoor air through the degradation of other organic compounds. Naturally occurring unsaturated hydrocarbons, such as limonene and pinene (which may also be released from consumer products), anthropogenic compounds, such as 4-vinylcyclohexene (an emission from carpet padding), and other alkenes that are commonly found in indoor air have been found to produce formaldehyde via their initial reaction with ozone (Zhang *et al*., 1994; Weschler & Shields, 1996). Reiss *et al*. (1995) estimated that the effective average rate of emissions of formaldehyde from this process in four residences in Boston (MA, USA) was about three times higher in the summer than in the winter.

In a study conducted at the Inhalation Toxicology Research Institute, release rates of formaldehyde were measured for six types of consumer product (Pickrell *et al*., 1983, 1984). Release rates calculated per unit surface area (μg/m^2 per day) were used to rank the products in the following order: pressed wood products >> clothes ~ insulation products ~ paper products > fabric > carpet. Release rates from pressed wood products ranged from below the limit of detection for an exterior plywood to 36 000 μg/m^2 per day for some panelling. Other release rates were 15–550 μg/m^2 per day for articles of new clothing that had not previously been washed, 52–620 μg/m^2 per day for insulation products, 75–1000 μg/m^2 per day for paper plates and cups, from below the limit of detection to 350 μg/m^2 per day for fabrics and from below the limit of detection to 65 μg/m^2 per day for carpets.

In a follow-up study that was performed as a result of changes in product manufacturing processes, many of these release rates were re-investigated (Kelly *et al*., 1999). Release rates of formaldehyde were reported to range typically from 9 to 1578 μg/m^2/h for a variety of bare urea–formaldehyde wood products, from 1 to 461 μg/m^2/h for coated urea–formaldehyde wood products, from 42 to 214 μg/m^2/h for permanent press fabrics, from 4 to 50 μg/m^2/h for decorative laminates, from 16 to 32 μg/m^2/h for fibreglass products and from 4 to 9 μg/m^2/h for bare phenol–formaldehyde wood products (Kelly *et al*., 1999). Paper grocery bags and towels had emission rates of < 0.5 and < 0.6 μg/m^2/h, respectively. For wet products, the emission rates were: latex paint, 326–854 μg/m^2/h; fingernail hardener, 178 000–354 000 μg/m^2/h; nail polish, 20 700 μg/m^2/h; and commercially applied urea–formaldehyde floor finish, 1 050 000 and 421 000 μg/m^2/h for base and topcoats, respectively (Kelly *et al*., 1999).

1.3.5 *Other exposures*

According to the Environmental Protection Agency Toxics Release Inventory (TRI), in 2001, approximately 9500 tonnes of formaldehyde were released into the environment from 800 domestic manufacturing and processing facilities in the USA. This number represents the sum of all releases of formaldehyde to air (4800 tonnes), water (160 tonnes), soil (70 tonnes) and underground injection wells (4500 tonnes). The TRI data should be used with caution because not all facilities are required to report releases of formaldehyde into the environment (National Library of Medicine, 2004).

Cigarette smoke has been reported to contain levels of a few to over 100 µg formaldehyde per cigarette (IARC, 2004). A 'pack-a-day' smoker may inhale as much as 0.4–2.0 mg formaldehyde (IARC, 1995; ACGIH® Worldwide, 2003).

Cosmetic products that contain formaldehyde, formalin and/or paraformaldehyde may come into contact with hair (e.g. shampoos and hair preparations), skin (deodorants, bath products, skin preparations and lotions), eyes (mascara and eye make-up), oral mucosa (mouthwashes and breath fresheners), vaginal mucosa (vaginal deodorants) and nails (cuticle softeners, nail creams and lotions). Use of aerosol products (e.g. shaving creams) may result in potential inhalation of formaldehyde (Cosmetic Ingredient Review Expert Panel, 1984). A Swedish study on indoor emissions reported that oil-based skin care products that are known to contain formaldehyde precursors (donors) still release formaldehyde into the air after storage for 1 year (Karlberg *et al.*, 1998).

Formaldehyde occurs naturally in foods, and foods may be contaminated as a result of fumigation (e.g. grain), cooking (as a combustion product) and release from formaldehyde resin-based tableware (WHO, 1989). It has been used as a bacteriostatic agent in some foods, such as cheese (Restani *et al.*, 1992). Fruit and vegetables typically contain 3–60 mg/kg, milk and milk products contain about 1 mg/kg, meat and fish contain 6–20 mg/kg and shellfish contain 1–100 mg/kg. Drinking-water generally contains < 0.1 mg/L (WHO, 1989).

Formaldehyde can also be emitted into indoor air during the cooking of fish. Amounts of formaldehyde that formed in a headspace when various kinds of fish flesh were heated to 200 °C ranged from 0.48 µg/g for mackerel to 5.31 µg/g for sardine (Yasuhara & Shibamoto, 1995). Free formaldehyde was found in fish at levels ranging from 1.4 to 40.3 ppm [1.7 to 49.6 mg/m^3]; the high levels were attributed to the processes used to freeze the fish products (Nielsen, 2002). When cooking oils are heated to high temperatures (240–280 °C) that are typical of Chinese wok cooking, several volatile mutagenic organic compounds are released, including formaldehyde. Emissions of formaldehyde from several cooking oils (rapeseed, canola, soya bean, peanut) ranged from 23 to 71 µg/L (Shields *et al.*, 1995).

Composting of household waste was also found to generate formaldehyde (Eitzer *et al.*, 1997). [Composting may also be of concern for occupational exposures.]

In some regions, mosquito coils are burned in residences for mosquito control. In a study of the combustion products from two common brands of mosquito coil, formaldehyde was generated at a level of approximately 2–4 mg/g of mosquito coil, which would result in air concentrations in the range of 0.16–0.40 ppm [0.19–0.49 mg/m^3] (Chang & Lin, 1998).

Formaldehyde has been used as a chemical germicide to control bacterial contamination in water distribution systems and in the dialysis fluid pathways of artificial kidney machines. In addition, formaldehyde has been used to disinfect hollow fibre dialysers (artificial kidneys) that are reprocessed and re-used only by the same patient (Centers for Disease Control, 1986).

When formalin-sterilized dialysers were rinsed by the technique used in many dialysis centres in the 1970s, undesirable concentrations of formaldehyde were found in the apparatuses at the start of dialysis. When the technique was modified by passing part of the saline through the blood compartment immediately before connection and discarding the saline left in the dialyser at the time of connection, the concentration of formaldehyde infused into the patient fell to below 2 μg/mL. However, the dialysers still contained up to 13 mg formaldehyde which leached slowly during simulated dialysis. Some residual formaldehyde was found in several components of the dialyser, but the majority was contained in the cellulose membrane (Lewis *et al*., 1981).

Stragier *et al*. (1995) studied the influence of the type of disinfecting agent used on the necessary rinsing time and rebound release after rinsing re-used dialysers. The rinsing time required to reach undetectable levels of disinfecting agent was longest for formaldehyde and the rebound release 30 min after completion of rinsing was the highest for formaldehyde.

In the USA, the proportion of dialysis centres that use formaldehyde to reprocess dialysers decreased from 94 to 31% during 1983–2000 (Tokars *et al*., 2000).

1.4 Regulations and guidelines

Occupational exposure limits and guidelines for formaldehyde are presented in Table 15. International regulations and guidelines related to emissions of and exposures to formaldehyde in occupational settings, indoor air and building materials have been reviewed (IARC, 1995; Paustenbach *et al*., 1997; ATSDR, 1999).

The European Union has adopted a Directive that imposes concentration limits for formaldehyde and paraformaldehyde in cosmetics. These substances are permitted at a maximal concentration of 0.2% by weight or volume (expressed as free formaldehyde) in all cosmetic formulations except nail hardeners, oral hygiene products and aerosol dispensers. Nail hardeners and oral hygiene products may contain maximal concentrations of 5 and 0.1%, respectively, whereas formaldehyde and paraformaldehyde are prohibited for use in aerosol dispensers (except for foams). Labels of cosmetic products are required to list formaldehyde and paraformaldehyde as ingredients when the concentration of either exceeds 0.05% (Cosmetic Ingredient Review Expert Panel, 1984; European Commission, 1990).

The Food and Drug Administration (2003) in the USA identifies formaldehyde: as a secondary direct food additive that is permitted in food for human consumption; for use as a preservative in defoaming agents; as an indirect food additive for use only as a component of adhesives; as an indirect food additive for use only as paper and paperboard

Table 15. Occupational exposure standards and guidelines for formaldehyde

Country or region	Concentration (mg/m^3) [ppm]	Interpretation	Carcinogen classification
Australia	1.2 [1]	TWA	2; Sen
	2.5 [2]	STEL	
Belgium	0.37 [0.3]	Ceiling	
Brazil	2 [1.6]	Ceiling	
China	0.5	Ceiling	
Canada			
Alberta	2.5 [2]	Ceiling	
Ontario	0.37 [0.3]	Ceiling	
Quebec	2.5 [2]	Ceiling	A2[a]
Denmark	0.4 [0.3]	STEL	L, K
Finland	0.37 [0.3]	TWA	
	1.2 [1]	Ceiling	
France	0.6 [0.5]	TWA	
	1.2 [1]	STEL	
Germany	0.37 [0.3]	TWA (MAK)	4; Sh; I
		STEL	
	0.7 [0.6]	Ceiling	
	1.2 [1]		
Hong Kong	0.37 [0.3]	Ceiling	A2[b]
Ireland	2.5 [2]	TWA	
	2.5 [2]	STEL	
Japan	0.6 [0.5]	TWA	2A
Malaysia	0.37 [0.3]	Ceiling	
Mexico	2.5 [2]	Ceiling	A2[b]
Netherlands	1.2 [1]	TWA	
	2.5 [2]	STEL	
New Zealand	1.2 [1]	Ceiling	A2[b]
Norway	0.6 [0.5]	TWA	Ca[c]; Sen
	1.2 [1]	Ceiling	
Poland	0.5	TWA	
	1	STEL	
South Africa	2.5 [2]	TWA	
	2.5 [2]	STEL	
Spain	0.37 [0.3]	STEL	
Sweden	0.6 [0.5]	TWA	Ca[d]; Sen
	1.2 [1]	Ceiling	
Switzerland	0.37 [0.3]	TWA	Sen
	0.74 [0.6]	STEL	
United Kingdom (MEL)	2.5 [2]	TWA	
	2.5 [2]	STEL	

Table 15 (contd)

Country or region	Concentration (mg/m^3) [ppm]	Interpretation	Carcinogen classification
USA			
ACGIH (TLV)	0.37 [0.3]	Ceiling	A2[b]; Sen
NIOSH (REL)	0.02 [0.016]	TWA	Ca[d]
	0.12 [0.1]	Ceiling	
OSHA (PEL)	0.9 [0.75]	TWA	Ca[d]
	2.5 [2]	STEL	

From Arbejdstilsynet (2002); Health & Safety Executive (2002); Työsuojelusäädöksiä (2002); ACGIH® Worldwide (2003); Deutsche Forschungsgemeinschaft (2003); Suva (2003); INRS (2005)

I, local irritant; K, carcinogenic; L, substance with ceiling value; MEL, maximum exposure limit; PEL, permissible exposure limit; REL, recommended exposure limit; Sen, sensitizer; Sh, skin sensitizer; STEL, short-term exposure limit; TLV, threshold limit value; TWA, time-weighted average; 2, probable human carcinogen; 2A, probably carcinogenic to humans (IARC classification); 4, carcinogenic potential with no or little genotoxicity

[a] A2: carcinogenic effects suspected in humans

[b] A2: suspected human carcinogen

[c] Ca: potential cancer-causing agent

[d] Ca: Substance is carcinogenic.

components; as an indirect food additive for use as a preservative in textile and textile fibre polymers; as an indirect food additive for use as an adjuvant in animal glue; and, under specified conditions, as an animal drug and in the manufacture of animal feeds.

Guidelines for levels of formaldehyde in ambient air in living spaces have been set in several countries and range from 0.05 to 0.4 ppm [0.06–0.5 mg/m^3], with a preference for 0.1 ppm [0.12 mg/m^3] (Lehmann & Roffael, 1992).

Some European countries have established maximum limits for emissions of formaldehyde from particle-boards, other wood products, furniture and insulation foam: for instance, Denmark, Finland and Sweden have set a maximum of 0.15 mg/m^3, measured in a test room of 225 L under standard conditions; in France, the content of formaldehyde that arises from walls insulated with urea–formaldehyde foam should not exceed 0.2 ppm (European Union, 1989).

In the USA, all plywood and particle-board materials that are bonded with a resin system or coated with a surface finish that contains formaldehyde cannot exceed the following formaldehyde emission levels when installed in manufactured homes, as expressed as air concentrations using standard conditions: plywood materials and particle-board flooring products (including urea–formaldehyde-bonded particle-board), 0.25 mg/m^3; particle-board materials and medium-density fibre-board, 0.37 mg/m^3 (Composite Panel Association, 1999, 2002; Department of Housing and Urban Development, 2003).