FIREFIGHTING

1. Exposure Data

1.1 Activities and tasks of firefighters

The terms 'firefighting' and 'firefighters' are broad and encompass several types of fire scenarios such as municipal, wildland, industrial, aviation, military, and oil wells. Some municipal firefighters may be permanently assigned to tasks other than fighting fires, including fire scene investigation (i.e. the investigation of suspected criminal fires started by arsonists), hazardous material response, building safety inspections, or technical and administrative support. These individuals may or may not have experience fighting fires, and may or may not be working for municipal fire departments. In addition, municipal firefighters are increasingly being called upon for emergency medical response. Finally, the term "firemen" may refer either to firefighters or to individuals who operate and maintain equipment for power generation (e.g. steam boilers), heating, ventilation, humidity control, refrigeration, and air conditioning. Workers in this latter category are also referred to as "stationary engineers" or "stationary firemen" (Decoufle *et al.*, 1977), and are not considered in this monograph.

There are two more or less distinct phases in municipal structural firefighting: knockdown and overhaul. During knockdown, firefighters control and extinguish the fire. Approximately 90% of municipal structural fires are either extinguished within 5–10 minutes, or abandoned and fought from the outside. This results in an average duration of heavy physical activity at fires of approximately 10 minutes (Gempel & Burgess, 1977; Gilman & Davis, 1993). Knockdown of large fires may last much longer. During overhaul, any remaining small fires are extinguished. The environment during overhaul is not as hot or as smoky as during knockdown, but it still contains products of combustion from small fires or smouldering material. Exposure can differ widely between the two phases of firefighting. The determination of when overhaul begins varies from one fire department to another, and is often left to the judgement of individual firefighters or group leaders (Jankovic *et al.*, 1991; Austin *et al.*, 2001a). Municipal structural fires may be fought in aggressive attack mode during knockdown, or defensively from the outside. In the past, firefighters may have more often attempted to enter a burning structure to fight the fire. For safety reasons, however, modern fire departments are increasingly adopting a defensive approach, unless there are human victims inside the building.

A municipal fire department is composed of 1st line firefighters (pump, ladder, and rescue crews, and operations chiefs) and 2nd line firefighters (drivers and division chiefs). Combat firefighters assigned to pump trucks, ladder trucks, or rescue trucks perform tasks specific to each of those crews. In some municipalities, there is movement of firefighters between different firehalls, while in others, a firefighter is assigned to the same crew at the same firehall for most of his or her career. It is conceivable that there would be differences in exposures between pump truck and ladder truck crews, although no such difference was observed in one older study (Gold *et al*., 1978).

In addition to fighting accidental fires and criminal fires, firefighters and firefighter recruits may be involved in training fires staged in buildings or simulators. Hill *et al*. (1972) describe a permanent structure used for training purposes where approximately 5500 litres of diesel fuel was burned in the lower portion of the building.

Analogous to knockdown and overhaul, wildland firefighting also comprises two phases, referred to as “attack” and “mop-up.” Attack at a wildland fire generally extends over a long period of time, one fire lasting hours, days or weeks. The frequency of aggressive strategies and tactics by firefighters may increase where there is an attempt to save residential developments. Municipal firefighters may also be called upon to fight wildland fires within or adjacent to municipal limits.

Both municipal firefighters and wildland firefighters engage in heavy work activity at fires. In particular, wildland firefighters who use hand tools and carry a considerable amount of equipment with them engage in heavy work activity levels while fighting forest fires (Budd *et al*., 1997; Ruby *et al*., 2002). Typical tasks include hiking, fire-line construction, chainsaw work, and brush removal. As a result, the amount of chemicals inhaled is greater for a firefighter at heavy work levels without respiratory protection than for a worker engaged in regular levels of work (Reh & Deitchman, 1992; Reh *et al.*, 1994). This needs to be taken into consideration when comparing exposure levels to occupational exposure limits that were developed assuming regular work levels.

Also, studies relating to municipal firefighters usually do not distinguish between the different categories of exposed and unexposed firefighters or between the different task assignments.

1.2 Composition of fire smoke

1.2.1 *Fire chemistry*

Smoke from fires comprises suspended liquid and solid particulate matter, gases and vapours that result from the combustion or pyrolysis of material. There is a very large number of toxic components in smoke (for reviews, see Tuve, 1985; Meyer, 1989; DiNenno *et al*., 2002; Côté, 2003). The basic form of the overall combustion reaction of organic (carbon-containing) compounds is illustrated by the burning of methane:

$$CH_4 + 2O_2 + \text{Energy of activation} \rightarrow CO_2 + 2H_2O + \text{Heat of combustion} + \text{Light}$$

Given the appropriate ratio of fuel (wood, solvent, plastic, rubber), oxygen, and combustion temperature, the products of combustion should be only water and carbon dioxide (CO_2).

Complete combustion is approached only under carefully controlled conditions. Uncontrolled or unintentional combustion tends to be "fuel rich" and therefore incomplete. The combustion of methane (CH_4) illustrates the formation of free radicals in an 11-step chain reaction, the first two of which are:

$$CH_4 \rightarrow CH_3^{\bullet} + H^{\bullet}$$
$$H^{\bullet} + O_2 \rightarrow OH^{\bullet} + O^{\bullet}$$

The free radicals formed during combustion are very reactive and side reactions are propagated to yield hundreds of chemical products, and smoke.

Most polymers found in buildings will burn or thermally degrade to simpler monomers. Thermal degradation products include methane, ethane, ethylene, benzene, toluene, and ethylbenzene in addition to the following monomers: ethylene, vinyl chloride, acrylonitrile, tetrafluoroethylene, styrene, methyl methacrylate, ethylene glycol, terephthalic acid, phenol, formaldehyde, hexamethylenediamine, adipic acid, propene, vinyl chloride, vinyl acetate, vinylidene chloride, chloroprene, 1,3-butadiene, ethyl acrylate, ethylene oxide, methylacrylate, urea, phenol, and isoprene.

The burning of plastics typically produces voluminous amounts of soot, together with higher levels of hydrogen cyanide (HCN), hydrochloric acid (HCl) and acrolein (CH_2=CHCHO) than the burning of materials such as wood, and fossil fuels. More smoke evolves from fires involving aromatic polymers, such as polystyrene, compared to aliphatic polymers, such as polyethylene.

In addition to the chemical agents described above, particulate matter is produced under conditions of incomplete combustion. The particulate matter is an aerosol consisting of condensed phase components of the products of combustion and finely divided carbon particulates that have not undergone combustion but remain suspended in the air. Although the particles themselves are microscopic in size (0.3–1.6 μm), they rapidly coalesce and thereby become visible. These particles are also adsorbents (similar to activated charcoal) and are an additional vehicle for the transport and inhalation of toxic combustion products. Smouldering yields a substantially higher conversion of fuel to toxic compounds than does flaming, although it occurs more slowly (Ohlemiller, 2002).

1.2.2 *Modern versus pre-modern fires*

All types of fire release toxic and carcinogenic substances, including benzene, 1,3-butadiene, and formaldehyde. The focus has generally been on substances having short-term acute effects: carbon monoxide (CO), carbon dioxide, hydrogen cyanide, nitrogen oxides (NO_x), sulfur dioxide (SO_2) and hydrogen chloride. With the increasing use of polymers in building construction and furnishings, there is concern that the burning of these new materials might release large quantities of other highly toxic substances (Austin *et al.*, 2001b).

Combustion and pyrolysis products from newer building materials and furnishings were believed to be more toxic than smoke from fires in buildings built before these materials became commonplace, and more toxic than smoke from wildland fires (Betol *et al.*, 1983; Alarie, 1985). However, many of the carcinogenic products of combustion identified are volatile organic compounds and are common to most burning materials. In a more recent study, no new or unusual non-polar volatile organic compounds (VOCs) were observed in current structural fires compared to the combustion of wood (Austin *et al.*, 2001b, 2001c). Adding polyvinyl chloride (PVC) to the fire load at simulated apartment fires was observed to significantly increase levels of polychlorinated phenols (IARC Group 2B), while polycyclic aromatic hydrocarbon (PAH) levels remained essentially unchanged (Ruokojärvi *et al.*, 2000). The increases in levels of polychlorinated biphenyls (PCBs, 0.021 to 0.031 mg/m^3), polychlorinated benzenes (0.002 to 0.010 mg/m^3) and I-TEQs [or PCDD/F] (3.5 to 5.4 ng/m^3) as products of combustion were not significant [possibly due to the small sample size]. In another study, proportionately higher levels of ethyl benzene (IARC Group 2B) were found at an electronics factory fire when compared to levels at residential and mixed occupancy fires (Austin *et al.*, 2001b).

The emission of combustion products (in mg per kg of material burned) for the same material varies greatly depending on combustion conditions such as ventilation (oxygen supply), temperature, and heating rate. Nonetheless, the relative amounts of the various non-polar VOCs found in smoke at municipal structural fires have been found to be remarkably similar from fire to fire, namely with the same 14 of 144 target compounds, dominated by benzene (IARC Group 1), toluene and naphthalene (IARC Group 2B) (Austin *et al.*, 2001b, 2001c).

1.2.3 *Carcinogens found in smoke at fires*

Table 1.1 lists the agents in Groups 1, 2A, and 2B that have been detected at fires in one or more studies, together with corresponding IARC evaluations, human and animal evidence of carcinogenicity, and for the agents in Group 1, the cancer sites in humans.

Table 1.1. IARC evaluations and cancer sites in humans of chemicals measured at fires

Chemicals measured at fires	Overall evaluation	Human evidence	Animal evidence	Volume	Cancer sites in humans (For Group 1 agents only)
Acetaldehyde	2B	Inadequate	Sufficient	36, Suppl. 7, 71	
Arsenic	1	Sufficient	Limited	23, Suppl. 7	Skin, lung, liver (angiosarcoma)
Asbestos	1	Sufficient	Sufficient	14, Suppl. 7	Lung, mesothelioma, larynx, gastrointestinal tract
Benz[*a*]anthracene	2B	Inadequate	Sufficient	32, Suppl. 7, 92	
Benzene	1	Sufficient	Limited	29, Suppl. 7	Leukaemia
Benzo[*b*]fluoranthene	2B	No data	Sufficient	32, Suppl. 7, 92	
Benzo[*k*]fluoranthene	2B	No data	Sufficient	32, Suppl. 7, 92	
Benzofuran (coumarone)	2B	No data	Sufficient	63	
Benzo[*a*]pyrene	1	No data	Sufficient	32, Suppl. 7, 92	Lung, bladder, skin
1,3-Butadiene	1	Sufficient	Sufficient	71, 97	Lymphohaematopoietic system
Cadmium	1	Sufficient	Sufficient	58	Lung
Carbon black (total)	2B	Inadequate	Sufficient	65, 93	
Chrysene	2B	Inadequate	Sufficient	3, 32, Suppl. 7, 92	
Dibenz[*a*,*h*]anthracene	2A	Inadequate	Sufficient	32, Suppl. 7, 92	
Dichloromethane (methylene chloride)	2B	Indadequate	Sufficient	71	
Ethylbenzene	2B	Inadequate	Sufficient	77	
Formaldehyde	1	Sufficient	Sufficient	88	Nasopharynx; (nasal sinuses and leukaemia, suggested)
Furan	2B	Inadequate	Sufficient	63	

Table 1.1 (contd)

Chemicals measured at fires	Overall evaluation	Human evidence	Animal evidence	Volume	Cancer sites in humans (For Group 1 agents only)
Indeno-1,2,3-[*cd*]pyrene	2B	Inadequate	Sufficient	32, Suppl. 7, 92	
Isoprene	2B	Not available	Sufficient	60, 71	
Lead				23, Suppl. 7, 87	
Lead compounds, organic	3	Inadequate	Inadequate	23, Suppl. 7, 87	
Lead compounds, inorganic	2A	Limited	Sufficient	23, Suppl. 7, 87	
Naphthalene	2B	Inadequate	Sufficient	82	
2-Nitroamisole	2B	Inadequate	Sufficient	65	
Polychlorophenols	2B	Limited		41, Suppl. 7, 53, 71,	
Pentachlorophenol			Sufficient		
2,4,6-Trichlorophenol			Limited		
Polychlorinated biphenyls (aroclor; 54%) (chlorodiphenyl)	2A	Limited	Sufficient	18, Suppl. 7	
Polychlorinated dibenzodioxins[a]: see TCDD					
Radioactivity (γ activity)	1	Sufficient	Sufficient	78	All sites combined
Radionuclides (α-particle-emitting)	1	Sufficient	Sufficient	78	All sites combined
Radionuclides (β-particle-emitting)	1	Sufficient	Sufficient	78	All sites combined
Silica (crystalline)	1	Sufficient	-	68	Lung
Silica (amorphous)	3	Inadequate	Inadequate	68	

Table 1.1 (contd)

Chemicals measured at fires	Overall evaluation	Human evidence	Animal evidence	Volume	Cancer sites in humans (For Group 1 agents only)
Styrene	2B	Limited	Limited	60, 82	
Sulfuric acid[b]	1	Sufficient	No data	54	
2,3,7,8-tetrachloro dibenzo-*para*-dioxin	1	Limited	Sufficient	69	All sites combined, lung, non-Hodgkin lymphoma, sarcoma
Tetrachloroethylene (perchloroethylene)	2A	Limited	Sufficient	63	Cervix, oesophagus, non-Hodgkin lymphoma
Toluene diisocyanates	2B	Inadequate	Sufficient	39, Suppl. 7, 71	
Trichloroethylene	2A	Limited	Sufficient	63	Liver and biliary tract, non-Hodgkin lymphoma, renal cell
Trichloromethane (chloroform)	2B	Inadequate	Sufficient	73	
Triphenylene	3	Inadequate	Inadequate	32, Suppl. 7, 92	

[a] Polychlorinated dibenzo-*para*-dioxins as a group are classified in Group 3
[b] Evaluation of occupational exposures to strong inorganic acid mists containing sulfuric acid

1.3 Exposure

1.3.1 *Characterization of firefighter exposures*

The characterization of exposures to fire gases and smoke is challenging due to several factors: work schedules of 10- to 24-hour shifts for 188 days in a year; wide variations between firefighters' time spent at fires; intermittent exposures; exposure to a complex mixture of gases, vapours and particulate matter; unknown effect of heat; gases and free radicals may also be adsorbed onto particulate matter; some semivolatile organic compound (SVOC) vapours measured in the air may be distributed between the solid and vapour phase, this equilibrium shifting in either direction depending on the temperature and on the density of the smoke; and, the difficulty in collecting samples at unpredictable locations in a dangerous and rapidly changing environment.

Given the multitude of chemicals in smoke, some substances may produce metabolites that alone or in combination with other substances or metabolites may become hazardous.

1.3.2 *Time spent at fires*

The number of runs and the time spent at fires varies tremendously between firehalls, depending on the geographic location, the social and economic environment, staffing, and the types of call (number of fires, types of fire, medical calls, hazardous materials [HAZMAT]).

Probably as a result of improved building codes compared to past decades, municipal firefighters today spend surprisingly little time at fires. In a study in Montreal, the time spent at fires was calculated based on an extensive database compiled over a period of 12 months (Austin *et al.*, 2001a). Firefighters from the least busy firehalls responded to approximately eight structural fires per year or 19 fires of all kinds, spending 15.1 hour/yr per firefighter at fires. Firefighters from the busiest firehalls responded to 3.13 times as many structural fires per year (25 structural fires, or 62 fires of all kinds), and spent 3.3 to 3.6 times as long at fires (54 hours). This study did not distinguish between 1st line and 2nd line firefighters. However, based on discussions with the fire department, it was estimated that 2nd line combat firefighter exposures were less than 50% those of 1st line combat firefighters. Overall, firefighters responding to fires spent between 0.75% and 2.7% of their time at fires over the course of a year. More recently, Kales *et al.* (2007) used a similar method to estimate time spent at fires for a municipal fire department in the USA, and national data supplied by the National Fire Protection Association (NFPA) and the International Association of Fire Fighters (IAFF) to produce estimates for smaller fire departments and large metropolitan fire departments, respectively. Firefighters spent 1%, 2%, and 5% of their time at fires in small, municipal, and metropolitan fire departments, respectively. This would represent 20–100 hours per year. Kales *et al.* (2007) estimated that firefighters responded to an average of 1.7 (Standard Deviation (SD), 0.1) to 7.0 (SD, 6.3) fire incidents per year.

Burgess *et al*. (2003) estimated the time spent inside structural fires broken down by tasks for two fire departments in Arizona, USA. The results were: entry/ventilation 5.7 ± 11.7 hour/yr (Phoenix), and 3.5 ± 3.7 hour/yr (Tucson); rescue 5.0 ± 8.0 hour/yr (Phoenix), and 2.1 ± 2.7 hour/yr (Tucson); knockdown (extinction) 5.6 ± 8.9 hour/yr (Phoenix), and 4.5 ± 4.4 hour/yr (Tucson); overhaul 15.0 ± 3.7 hour/yr (Phoenix), and 20.8 ± 76.8 hour/yr (Tucson); and, support/standby 16.3 ± 28.6 hour/yr (Phoenix), and 19.1 ± 76.7 hour/yr (Tucson). Total firefighter activity at fires in Phoenix and Tucson was a mean of 47.6 hour/yr and 50.0 hour/yr, respectively.

In a study among firefighters in Washington, DC, ($n = 43$), at the time of the survey, an average of 9.2 days had elapsed since the last fire. Also, 0.33 fires had been fought in the previous 24 hours, 1.33 in the previous week, 5.91 in the previous month, and 57.1 fires in the previous year (Liou *et al*., 1989).

Little information is available concerning the time that firefighters outside of North America spend at fires. The organization and practices of fire departments might differ, and a greater number of fires may occur at other locations. In one study in Inchon, Republic of Korea, firefighters were questioned about their firefighting activity during the previous 5 days; among these, 33% (24 of 73) had had no fire exposure, 49% (36 of 73) had had less than 8 hours' fire exposure, and 18% (13 of 73) had had more than 8 hours' exposure to fire (Hong *et al*., 2000). Four of 13 volunteer firefighters in Sweden reported that they had not fought any fires within the previous 3 months, while the other nine reported having fought one fire each (Bergström *et al*., 1997). All 13 firefighters had been working as active firefighters for at least 3 years.

Wildland firefighters go to fires more frequently and spend more time at fires during a season than do municipal firefighters during an entire year, and all of their exposure occurs during the wildfire season. A total of 47 California wildland firefighters were surveyed to determine the extent of their firefighting activity (Rothman *et al*., 1993). Early in the wildland fire season, firefighters reported that they had spent a mean of 0.11 hours (Standard Error (SE), 0.89) fighting fires during the previous week, 12.06 hours (SE, 2.77) during the previous 2 weeks, and 16.74 hours (SE, 3.15) during the previous 4 weeks. Firefighting activity increased significantly during the late season, when wildland firefighters reported they had spent a mean of 22.36 hours (SE, 5.03) fighting fires during the previous week, 54.81 hours (SE, 9.29) during the previous 2 weeks, and 97.38 hours (SE, 15.26) fighting fires during the previous 4 weeks (Rothman *et al*., 1993). In the USA, Hot Shot crews [highly-skilled wildland firefighters specially trained in wildland fire suppression tactics] have been estimated to spend 64 days at wildfires and 5 days at prescribed burns, on average, per year, (Booze *et al*., 2004). In Quebec, in 2005, the agency responsible for wildland firefighting reported that wildland firefighters had spent a total of 145 689 hours at fires, or 755 hours per firefighter, on average for that year (Austin, 2008).

1.3.3 *Surrogates of exposure*

As a matter of practicality, epidemiologists have generally used years of employment or, in one case, years of active duty fighting fires (Demers *et al*., 1994), as a surrogate for exposure to smoke. This does not take into account the reduction in exposures when respiratory protection was used, differences between exposure groups, the intermittent nature of exposures, differences in tasks, or the fact that not all firefighters actually combat fires. In a Montreal study, only 66% of fire department personnel were 1st line firefighters (Austin *et al*., 2001a). Years of employment has not been found to correlate with exposure to combustion products or related adverse health effects (decline in pulmonary function or airway responsiveness) (Musk *et al*., 1977; Takehito & Maeda, 1981; Sparrow *et al*., 1982; Sherman *et al*., 1989). The number of fires fought has, however, been correlated with the mean annual reduction in pulmonary function (Peters *et al*., 1974). Among firefighters at the same fire, statistically significant differences in exposure to combustion products have been found between front-line firefighters and both squad leaders and ordinary firefighters (Takehito & Maeda, 1981). The same study found no significant difference between ordinary firefighters and the officers who accompanied them.

Two epidemiological studies used estimated cumulative runs as a surrogate for exposure (Austin *et al*., 2001a; Baris *et al*., 2001). In one study (Austin *et al*., 2001a), a good correlation between the number of runs per firehall and time spent at fires was observed ($r = 0.88$). However, different crews could have similar numbers of runs yet spend significantly different lengths of time at fires. The study by Austin *et al*. (2001a) identified distinct firefighter exposure groups based on job title, fire hall assignment, and time spent at fires.

1.3.4 *Exposure to carcinogens found in smoke at fires*

Table 1.2 presents the results of the studies that have measured the substances listed in Table 1.1, and particulate matter (total, respirable, PM_{10}). Unless otherwise indicated, reported levels do not take into consideration the use of respiratory protection. Table 1.3 provides a summary of the results from Table 1.2 for each substance, according to the type of fire or exposure (i.e. wildland, municipal, training fire, or municipal fire scene (arson) investigation).

The carcinogens found in one or more studies include nine known human carcinogens (Group 1), four probable human carcinogens (Group 2A), and 21 possible human carcinogens (Group 2B) (for a review, see Bendix, 1979; Lees, 1995).

Many of the wildland and municipal firefighter studies result from opportunistic sampling with sometimes wide margins of error, and may not be representative of firefighter exposures.

Two studies reported extremely high levels of benzene, up to 165 and 250 ppm (Burgess *et al*., 1979; Brandt-Rauf *et al*., 1988, respectively) [the former study used an accurate and precise sampling and analytical methodology]. Benzene levels in the remaining studies ranged from not detected to 23 ppm.

Table 1.2. Studies of exposures of firefighters to selected chemicals and agents

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Acetaldehyde									
Jankovic *et al.* (1991), USA	Municipal		22 22 22	21 5 4	ppm ppm ppm		ND ND ND	8.1 1.6 0.9	Knockdown Overhaul Inside face mask
Kelly (1991), USA	Wildland	Shift	1	20	ppm		ND	0.1	Mop-up
NIOSH (1992), USA	Wildland	Shift	1	20	ppm		ND	ND	Mop-up
Reh *et al.* (1994), USA	Wildland		1 1	3 2	ppm ppm		0.01 0.03	0.02 0.04	Low smoke levels Medium smoke levels
Kinnes & Hine (1998), USA	Municipal	TWA	5	8	ppm		ND	0.13	Arson investigation
Bolstad-Johnson *et al.* (2000), USA	Municipal	> 20 min	25	96	ppm	0.34 ± 0.41	0.041	1.75	Overhaul lasting min 20 min
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	–	mg/kg[a]	[607 ± 345]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Burgess *et al*. (2001), USA	Municipal (testing)	Overhaul > 25 min Overhaul < 25 min	7 9	22 19	ppm ppm	0.158 ± 0.037 0.383 ± 0.494			No respiratory protection SCBA used
Reisen *et al*. (2006), Australia	Wildland		6	25	ppm	< 0.08	ND	0.26	4 prescribed and 2 exceptional burns
Arsenic									
Turkington (1984), USA	Municipal	10–15 min	1	1	mg/m^3	0.14			–
Asbestos (chrysotile)									
Bridgman (2001), U.K.	Municipal			2	f/cm^2	[0.0029]	[0.001]	[0.0043]	Factory fire: chrysotile fibres in the weave of the outer fabric of firefighters’ tunics

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments	
Benzene										
Hill *et al*. (1972), U.K.	Training	Grab sample	NR	1	ppm	1.17			Pool fire	
Burgess *et al*. (1979); Treitman *et al* (1980), USA	Municipal		NR	181/197	ppm		ND	165	Inside burning structures during latter stages of structural fires	
Turkington (1984), USA	Municipal	10–15 min	1	1	ppm	1.00				
Lowry *et al*. (1985a), USA	Municipal	At fire	75	NR	ppm	Detected in most fires			Mixed type of exposure	
Brandt-Rauf *et al*. (1988), USA	Municipal	30 min	6	11	ppm	[59.18 ± 83.86]	ND	250	Low smoke levels	Mostly wood structures burning mostly building and contents
		30 min	2	7	ppm	[26.17 ± 30.59]	ND	83.3	Moderate smoke levels	
		30 min	5	6	ppm	[94.87 ± 92.73]	ND	225	High/Intolerable smoke levels	
		30 min	2	2	ppm		23	34	Automobile	

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Jankovic *et al*. (1991), USA	Municipal		22	15	ppm		ND	22	Knockdown
			22	2	ppm		ND	0.3	Overhaul
			22	4	ppm		ND	21	Inside mask
Kinnes & Hine (1998), USA	Municipal	TWA	5	4	ppm	trace			Arson investigation; benzene concentration between LOD and LOQ (0.04–0.12 ppm)
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	95	ppm	0.383 ± 0.425	0.07	1.99	Overhaul
Reinhardt *et al*. (2000), USA	Wildland	Shift TWA			ppm	0.016*		0.058	Prescribed burns (1991–1994)
		Fireline TWA			ppm	0.028*		0.088	

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Reinhardt & Ottmar (2000), USA	Wildland	Shift TWA			ppm	0.004* ± 3.6*		0.25	Project fires (1992–1995)
		Fireline TWA			ppm	0.006* ± 3.6*		0.38	
		Shift TWA			ppm	0.02* ± 0.003*		0.02	Initial attack (1992–1995)
		Fireline TWA			ppm	0.04* ± 0.14*		0.04	
Andreae & Merlet (2001), Germany	Multiple	–	Multiple data sources	NR	mg/kg[a]	[693 ± 663]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm	3.38 ± 3.45	0.12	10.76	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire
Austin *et al*. (2001c), Canada	Municipal (simulated)	Grab sample	15	60	ppm	detected		0.1	In separate burns: wood (spruce), bed mattress, sofa foam, cardboard, plywood, gasoline, varsol, white foam insulation
Burgess *et al*. (2001), USA	Municipal	Overhaul >25 min	7	23		ND			No respiratory protection
		Overhaul >25 min	9	20	ppm	0.557 ± 0.465			SCBA used
Reisen *et al*. (2006), Australia	Wildland		6	8	mg/m^3	0.12	0.002	0.26	4 prescribed and 2 exceptional burns

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Benzofuran (coumarone)									
Andreae & Merlet (2001), Germany	Wildland emissions	Multiple	Multiple data sources	–	mg/kg[a]	[19 ± 12]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm		0.2	2	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire
1,3-Butadiene									
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	NR	mg/kg[a]	[87 ± 79]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm	1.03 ± 1.49	0.03	4.84	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Austin *et al.* (2001c), Canada	Municipal (simulated)	Grab sample	15	60	ppm	detected			In separate burns: wood (spruce), bed mattress, sofa foam, cardboard, plywood, gasoline, varsol, white foam insulation
Cadmium									
Bolstad-Johnson *et al.* (2000), USA	Municipal	>20 min	25	46	–	ND			Overhaul
Carbon black (Total)									
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	–	mg/kg[a]	[747 ± 376]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Dichloromethane (methylene chloride)									
Lowry *et al*. (1985a), USA	Municipal	At fire	75	–	ppm	detected			Mixed types of exposure
Brandt-Rauf *et al*. (1988), USA	Municipal	30min	1	1	ppm	0.280			Mostly wood structures burning mostly building and contents
Ethylbenzene									
Hill *et al*. (1972), U.K.	Training	Grab sample	NR	1	ppm	0.382			Pool fire
Lowry *et al*. (1985a), USA	Municipal	At fire	75	NR	ppm	detected			Mixed type of exposure
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	NR	mg/kg[a]	[54 ± 58]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm	0.86 ± 1.94	0.01	5.97	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Austin *et al*. (2001c), Canada	Municipal (simulated)	Grab sample	15	60	ppm	measured			In separate burns: wood (spruce), bed mattress, sofa foam, cardboard, plywood, gasoline, varsol, white foam insulation
Formaldehyde									
Turkington (1984), USA	Municipal	10–15 min	1	1	ppm	0.71			
Lowry *et al*. (1985a), USA	Municipal	At fire	75	–	ppm	5.0	1	15	Mixed types of exposure
Brandt-Rauf *et al*. (1988), USA	Municipal	30min	6	11	ppm	0.12 ± 0.27	ND	0.8	Mostly wood structures burning with low smoke levels
		30 min	2	7	ppm	0.49 ± 1.24	ND	3.3	Mostly wood structures with moderate smoke levels
		30 min	5	6	ppm	1.74 ± 3.67	ND	8.3	Mostly wood structures with high/intolerable smoke levels
		30 min	2	2		ND			Automobile
Jankovic *et al*. (1991), USA	Municipal	NR	22	16	ppm		ND	8	Knockdown
			22	5	ppm		ND	0.4	Overhaul
			22	5	ppm		ND	0.3	Inside mask

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Kelly (1991), USA	Wildland	Shift	1	20	ppm		ND	0.1	Mop-up
NIOSH (1992), USA	Wildland	Shift	1	20	ppm			0.07	Mop-up
Materna *et al*. (1992), USA	Wildland	Fireline TWA	4 fire seasons	30	ppm	0.16	0.048	0.42	Project fires (1987–1989); mop-up
Reh & Deitchman (1992), USA	Wildland	NR	3	NR	ppm		ND	0.03	Low smoke levels
			1	3	ppm		0.01	0.02	Low smoke levels
			1	2	ppm		0.06	0.07	Medium smoke levels
Kinnes & Hine (1998), USA	Municipal	TWA	5	3	ppm		0.06	0.18	Arson investigation
Bolstad-Johnson *et al.* (2000), USA	Municipal	> 20 min	25	96	ppm	0.25 ± 0.252	0.016	1.18	Overhaul
Reinhardt & Ottmar (2000), USA	Wildland	Fireline TWA	NR		ppm	0.018* ± 2.3*		0.093	Project fires (1992–1995)
					ppm	0.028* ± 3*		0.092	Initial attack (1992–1995)
		Shift TWA			ppm	0.013* ± 2.4*		0.084	Project fires (1992–1995)
					ppm	0.006* ± 3.1*		0.058	Initial attack (1992–1995)

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Reinhardt *et al*. (2000); Slaughter *et al*. (2004), USA	Wildland	Fireline TWA	NR		ppm	0.075*		0.6	Prescribed burns (1991–1994)
		Shift TWA.			ppm	0.047*		0.39	Prescribed burns (1991–1994)
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	NR	mg/kg[a]	[1347 ± 978]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Burgess *et al*. (2001), USA	Municipal	Overhaul > 25 min	7	22	ppm	0.190 ± 0.182			No respiratory protection
		Overhaul > 25 min	9	19	ppm	0.257 ± 0.249			SCBA used
Reisen *et al*. (2006), Australia	Wildland		6	25	ppm	0.230	0.04	0.79	4 prescribed and 2 exceptional burns
Free radicals (short-lived)									
Jankovic *et al*. (1993), USA	Municipal	At fire	7	7	counts/min		ND	127	Knockdown
		At fire	10	10	counts/min		ND	920	Overhaul

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Free radicals (long-lived)									
Lowry *et al*. (1985b), USA	Municipal (simulated)	1 h; 2 room changes	6	6	ppm			1200	"Low energy fire" producing minimal radiant heat; burning 2 kg of paper, cotton and polyester clothing, plastics (including PVC), and wood
		1 h	6	–	ppm			1000	
Jankovic *et al*. (1993), USA	Municipal	At fire	–	–	detected by ESR	detected	–	–	Knockdown
		At fire	–	–	–	detected	–	–	Overhaul
Leonard *et al*. (2000), USA	Wildland	3.5 h	1	6	–	detected			Experimental fire
Leonard *et al*. (2007), USA	Wildland	3.5 h	1	6	–	detected			Mop-up and back-burn operations
Furan									
Lowry *et al*. (1985a), USA	Municipal	At fire	75	–	ppm	detected			Mixed types of exposure

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	–	mg/kg[a]	[508 ± 265]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm		0.2	2	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire
Isoprene									
Hill *et al*. (1972), UK	Training	Grab sample	–	1	ppm	0.167			Pool fire
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	–	mg/kg[a]	[34 ± 36]			Means of published emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Lead									
Turkington (1984), USA	Municipal	10–15 min	1	1	mg/m^3	1.4			

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	46	mg/m^3	0.03	0.03	0.03	Overhaul lasting minimum 20 min
Naphthalene									
Hill *et al*. (1972), U.K.	Training	Grab sample	–	1	ppm	0.418			Pool fire
Kinnes & Hine (1998), USA	Municipal	TWA	5	5	$\mu g/m^3$		200	0.038	Arson investigation
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	88	ppm	0.043 ± 0.019	0.014	0.103	Overhaul lasting minimum 20 min
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm	0.62 ± 0.68	0.01	2.14	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire
Austin *et al*. (2001c), Canada	Municipal (simulated)	Grab sample	15	60	ppm			3	In separate burns: wood (spruce), bed mattress, sofa foam, cardboard, plywood, gasoline, varsol, white foam insulation

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Particulate matter, PM_{10}									
Miranda *et al*. (2005), Portugal	Wildland	15 min average	1	–	mg/m^3	–	–	3.0	Near the fire
Particulate matter, respirable									
Kelly (1991), USA	Wildland	Shift	1	26	mg/m^3		0.040	4.3	Mop-up
NIOSH (1992), USA	Wildland	Shift	1	20	mg/m^3	0.49			Mop-up
Materna *et al*. (1992), USA	Wildland	Fireline TWA	5 fire seasons	22	mg/m^3	1.75	0.327	5.14	Project fires (1987–1989); mop-up
					mg/m^3		0.235	2.71	Prescribed burns
McMahon & Bush (1992), USA	Wildland	2.8 h	14		mg/m^3	1.3**	0.2	3.7	Prescribed burn
Reh & Deitchman (1992), USA	Wildland		1	3	mg/m^3		1.3	1.7	Medium smoke levels
Reh *et al*. (1994), USA	Wildland		1	3	mg/m^3		0.6	1.1	Low smoke levels

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Kinnes & Hines (1998), USA	Municipal	TWA	5	5	mg/m^3		ND	1.2	Arson investigation
Bolstad-Johnson *et al.* (2000), USA	Municipal	> 20 min	25	93	mg/m^3	8.01 ± 8.02	0.71	25.7	Overhaul lasting a minimum of 20 minutes
Reinhardt & Ottmar (2000), USA	Wildland	Shift TWA Fireline TWA Shift TWA Fireline TWA	NR	NR	mg/m^3 mg/m^3 mg/m^3 mg/m^3	0.5* ± 2* 0.7* ± 1.9* 0.022* ± 2.5* 1.11* ± 1.6*		2.3 2.9 1.6 2.5	Project fires (1992–1995) Initial attack (1992–1995)
Reinhardt *et al.* (2000); Slaughter *et al.* (2004), USA	Wildland	Shift TWA Fireline TWA			mg/m^3 mg/m^3	0.6* 1*		6.9 10.5	Prescribed burns (1991–1994)
Andreae & Merlet (2001), Germany	Wildland	NR	Multiple data sources	–	mg/kg[a]	[7933 ± 3206]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Burgess *et al*. (2001), USA	Municipal	Overhaul > 25 min Overhaul > 25 min	7 9	24 19	 mg/m^3	ND 6.180 ± 7.800			No respiratory protection SCBA used
Miranda *et al*. (2005), Portugal	Wildland	15 min average	1	NR	mg/m^3			3.0	Near the fire
Particulate matter, total									
Hill *et al*. (1972), U.K.	Training	Grab sample	NR	NR		–			Pool fire; 80% of particle with diameter < 1 µm
Gold *et al*. (1978), USA	Municipal	~10 min	–	90	mg/m^3	21.5* ± 4.7*	4	650	Knockdown and overhaul
Burgess *et al*. (1979); Treitman *et al*. (1980), USA	Municipal		–	66	mg/m^3		ND	20000	Inside burning structures during latter stages of structural fires (knockdown)
Turkington (1984), USA	Municipal	10-15 min	1	1	mg/m^3	36			–

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Atlas *et al*. (1985), USA	Training	During fire smoke	6	11	mg/m^3	47*	–		200 L of diesel oil floating on a pool of water
								300	Heavy smoke levels
			6	11	mg/m^3		0.15	0.5	
Froines *et al*. (1987), USA	Municipal	Shift	0	7	mg/m^3		0.035	0.48	Diesel emissions in firehalls (4 New York, 2 Boston, 4 Los Angeles)
		Shift	0	9	mg/m^3	0.748			
Brandt-Rauf *et al*. (1988), USA	Municipal	30 min	24	5	mg/m^3	83 ± 131	10.1	344	Mostly wood structures burning mostly building and contents
Duclos *et al*. (1990), USA	Wildland	12 days	1	NR	mg/m^3		0.578	4.158	
Jankovic *et al*. (1991), USA	Municipal		22	4	mg/m^3		ND	560	Knockdown
			22	25	mg/m^3		ND	45	Overhaul
Materna *et al*. (1992), USA	Wildland	Fireline TWA	6 fire seasons	22	mg/m^3	9.46	2.7	37.4	Project fires (1987–1989); mop-up
McMahon & Bush (1992), USA	Wildland	0.3–1.6 h	14		mg/m^3	6.3**	2	44.9	Prescribed burns

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Reh & Deitchman (1992), USA	Training		3	NR	mg/m^3		0.1	47.7	
Kinnes & Hine (1998), USA	Municipal	Peak TWA	5 5	5 5	mg/m^3 mg/m^3		3.5 0.2	31.6 5.3	Arson investigation
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	46	mg/m^3	1.82 ± 8.73	0.364	30.79	Overhaul lasting a minimum of 20 min
Reinhardt *et al*. (2000), USA	Wildland	Shift TWA Fireline TWA Shift TWA Fireline TWA			mg/m^3 mg/m^3 mg/m^3 mg/m^3	1.5* ± 1.7* 1.7* ± 1.8* 1.39* ± 1.2* 5.32* ± 1.4*		4.2 4.4 1.81 8.64	Project fires (1992–1995) Initial attack (1992–1995)
Andreae & Merlet (2001), Germany	Wildland	Multiple	Multiple data sources	NR	mg/kg[a]	[10114 ± 4512]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Reisen *et al*. (2006), Australia	Wildland		6	21	mg/m^3	0.2– > 9		8–20	4 prescribed and 2 exceptional burns; p gravimetric: 2.6–5 mg/m^3 (*n* = 2)
Leonard *et al*. (2007), USA	Wildland	3.5 h	1	6					Mop-up and back burn operations; 20.2% ultrafine particles (0.042–0.24 µm mean diameter); 43.8% fine particles (0.42–2.4 µm mean diameter)
Pentachlorophenol									
Ruokojärvi *et al*. (2000), Finland	Municipal (simulated)	During fire During fire	5 2	5 2	µg/m^3 µg/m^3	53 ± 45 230 ± 99	14 160	104 300	Apartment without PVCs Apartment with PVCs
Polychlorinated biphenyls (Aroclor; 54%)									
Ruokojärvi *et al*. (2000), Finland	Municipal (simulated)	During fire During fire	5 2	5 2	µg/m^3 µg/m^3	21 ± 16 31 ± 35	2.8 6.1	36 56	Apartment without PVCs Apartment with PVCs
Polychlorinated dibenzodioxins									
PCDD									
Ruokojärvi *et al*. (2000), Finland	Municipal (simulated)	During fire During fire	5 2	5 2	ng/m^3 ng/m^3	43 ± 49 69 ± 5.7	12 75	130 83	Apartment without PVCs Apartment with PVCs

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
PCDD/F as I-TEQ									
Ruokojärvi *et al*. (2000), Finland	Municipal (simulated)	During fire During fire	5 2	5 2	ng/m^3 ng/m^3	3.5 ± 2.5 5.4 ± 0.71	1 4.9	7.2 5.9	Apartment without PVCs Apartment with PVCs
PCDF									
Ruokojärvi *et al*. (2000), Finland	Municipal (simulated)	During fire During fire	5 2	5 2	ng/m^3 ng/m^3	96 ± 56 131 ± 24	21 114	160 148	Apartment without PVCs Apartment with PVCs
Polycyclic Aromatic Hydrocarbons									
Feunekes *et al*. (1997), Netherlands	Training	0.5–1.5 h	≥ 1	10	mg/m^3	10.68			Intense firefighting, black smoke
Ruokojärvi *et al*. (2000), Finland	Municipal (simulated)	During the fire During the fire	5 2	5 2	mg/m^3 mg/m^3	121 ± 199 117 ± 33	6.4 94	470 140	Apartment without PVCs Apartment with PVCs
Andreae & Merlet (2001), Germany	Wildland emissions	–	Multiple data sources	–	mg/kg[a]	[21 ± 9]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Benz[*a*]anthracene									
Jankovic *et al*. (1991), USA	Municipal		3	3	mg/m^3	0.015		0.03	Knockdown
			3	3	mg/m^3	0.001		0.003	Overhaul
Kinnes & Hine (1998), USA	Municipal	TWA	5	5	mg/m^3		ND	0.00029	Arson investigation
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0249 ± 0.0049	0.019	0.028	Overhaul lasting a minimum of 20 min
Benzofluoranthenes, unspecified									
Atlas *et al*. (1985), USA	Training	During fire	1	1	mg/m^3	0.0124			200 L of diesel oil floating on a pool of water Heavy smoke levels
			1	1	mg/m^3	0.00014			Very light smoke levels
Benzo[*b*]fluoranthene									
Jankovic *et al*. (1991), USA	Municipal		3	3	mg/m^3	0.006		0.012	Knockdown
			3	3		ND			Overhaul

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Kinnes & Hines (1998), USA	Municipal	TWA	5	5	mg/m^3		ND	0.00021	Arson investigation
Bolstad-Johnson *et al.* (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0223 ± 0.0106	0.01	0.034	Overhaul
Benzo[*k*]fluoranthene									
Jankovic *et al.* (1991), USA	Municipal		3 3	3 3	mg/m^3 mg/m^3	0.003 0.001		0.006 0.004	Knockdown Overhaul
Kinnes & Hine (1998), USA	Municipal	TWA	5	5	mg/m^3		ND	0.00012	Arson investigation
Bolstad-Johnson *et al.* (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0238 ± 0.0017	0.023	0.025	Overhaul
Benzo[*a*]pyrene									
Turkington (1984), USA	Municipal	10–15 min	1	1	mg/m^3	0.007			–

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Atlas *et al*. (1985), USA	Training	During fire	1	1	mg/m^3	0.00855	–		200 L of diesel oil floating on a pool of water.
								–	Very heavy smoke levels
		During fire	1	1	mg/m^3	4.5×10^{-5}			Very light smoke levels
Jankovic *et al*. (1991), USA	Municipal		3	3	mg/m^3	0.01		0.02	Knockdown
			3	3		ND			Overhaul
Feunekes *et al*. (1997), Netherlands	Training	0.5–1.5 h	≥ 1	10	mg/m^3	0.47			Intense firefighting; black smoke
Kinnes & Hine (1998), USA	Municipal	TWA	5	5	mg/m^3		ND	0.00039	Arson investigation
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0332 ± 0.0136	0.019	0.05	Overhaul

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Chrysene									
Jankovic *et al*. (1991), USA	Municipal		3 3	3 3	mg/m^3 mg/m^3	0.01 0.001		0.02 0.003	Knockdown Overhaul
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0129			Overhaul
Chrysene/triphenylene									
Atlas *et al*. (1985), USA	Training	During fire	1	1	mg/m^3	0.0181			200 L of diesel oil floating on a pool of water Very heavy smoke levels
		During fire	1	1	mg/m^3	0.00014			Very light smoke levels
Dibenzo[*a*,*h*]anthracene									
Jankovic *et al*. (1991), USA	Municipal		3 3	3 3	mg/m^3	0.003 ND		0.005	Knockdown Overhaul
Bolstad-Johnson *et al*. (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0455 ± 0.0316	0.023	0.068	Overhaul

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Indeno-1,2,3-[*cd*]pyrene									
Jankovic *et al*. (1991), USA	Municipal		3	3	mg/m^3	0.01		0.02	Knockdown
Kinnes & Hine (1998), USA	Municipal	TWA	5	5	µg/m^3		ND	0.44–1.4	Arson investigation
Bolstad-Johnson *et al.* (2000), USA	Municipal	> 20 min	25	88	mg/m^3	0.0195 ± 0.0084	0.014	0.029	Overhaul
Radioactivity									
Volkerding (2003), USA	Wildland	2 days	1	4	Bq/m^3	–	2×10^{-4}	9×10^{-4}	α Emitters
			1	4	Bq/m^3	–	8×10^{-4}	0.004	β Emitters
			1	4	Bq/filter	–	ND	45.5	Bismuth-212
			1	4	Bq/filter	–	2.4	46.3	Lead-212
			1	4	Bq/filter	–	ND	17	Thallium-208
			1	4	Bq/m^3	–	ND	9.4	Uranium-234
			1	1	Bq/filter	–	–	0.002	Uranium-234

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Silica									
NIOSH (1992), USA	Wildland	Shift	1	10	mg/m^3		0.04	0.35	Mop-up
Styrene									
Hill *et al*. (1972), U.K.	Training	Grab sample	–	1	ppm	0.535			Pool fire
Andreae & Merlet (2001), Germany	Wildland emissions	Multiple	Multiple data sources	–	mg/kg[a]	[102 ± 96]			Means of reported mean emissions factors for savanna and grassland, tropical forest, extratropical forest, biofuel burning, charcoal making, and agricultural fires
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm	0.5 ± 0.68	0.003	2.01	7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire
Austin *et al*. (2001c), Canada	Municipal (simulated)	Grab sample	15	60	ppm	detected		0.4	In separate burns: wood (spruce), bed mattress, sofa foam, cardboard, plywood, gasoline, varsol, white foam insulation

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Sulfuric acid									
Turkington (1984), 1984	Municipal	10–15 min	1	1	mg/m^3	28.5			–
Jankovic *et al*. (1991), USA	Municipal		22 22		mg/m^3 mg/m^3		ND ND	8.5 0.9	Knockdown Overhaul
Kinnes & Hine (1998), USA	Municipal	TWA	5	8	mg/m^3		0.08–0.27	0.29	Arson investigation
Burgess *et al*. (2001), USA	Municipal	Overhaul > 25 min Overhaul > 25 min	7 9	23 19	mg/m^3 mg/m^3	4.9 ± 8.5 13.6 ± 14.6			No respiratory protection SCBA used
Tetrachloroethylene (perchloroethylene)									
Brandt-Rauf *et al*. (1988), USA	Municipal	30 min	2	3	ppm	0.092 ± 0.04	0.064	0.138	Mostly wood structures burning (building and contents)
Trichloroethylene									
Brandt-Rauf *et al*. (1988), USA	Municipal	30 min	2	2	ppm	0.15	0.112	0.181	Mostly wood structures burning (building and contents)

Table 1.2 (contd)

Reference, location	Type of fire	Sampling period and duration	No. of fires	No. of samples	Units	Mean ± SD (*geometric mean, **median)	Min.	Max.	Comments
Trichloromethane (chloroform)									
Lowry *et al*. (1985a), USA	Municipal	At fire	75	–	–	detected			Mixed types of exposure
Brandt-Rauf *et al*. (1988), USA	Municipal	30 min	2	2	ppm	1.44	0.96	1.92	Mostly wood structures burning (building and contents)
Austin *et al*. (2001b), Canada	Municipal	15 min	9	9	ppm	detected			7 mixed occupancy buildings, one electronics industry, one 9-day smouldering fire
Austin *et al*. (2001c), Canada	Municipal (simulated)	Grab sample	15	60	ppm		25	465	In separate burns: wood (spruce), bed mattress, sofa foam, cardboard, plywood, gasoline, varsol, white foam insulation
Trichlorophenol									
Brandt-Rauf *et al*. (1988), USA	Municipal	30 min	1	1	ppm	0.1	0.1	0.1	Mostly wood structures burning (building and contents)

[a] emission factors
ESR, electron spin resonnance; LOD, limit of detection; LOQ, limit of quantitation; ND, Not Detected; SCBA, self-contained breathing apparatus

Thus, firefighters may be exposed to benzene levels exceeding the American Conference of Governmental Industrial Hygienists (ACGIH) 15-minute time-weighted average (15-min TWA) short-term exposure limit (STEL) of 2.5 ppm.

Two studies assessed 1,3-butadiene in smoke at structural and experimental fires (Austin *et al*., 2001b,c). Levels as high as 4.84 ppm were found at moments when at least some firefighters might remove their masks.

Formaldehyde levels measured in smoke at fires ranged from not detected to 15 ppm across studies (see Table 1.2).

One study measured pentachlorophenol at fires in simulated apartments with and without polyvinyl chloride (PVC) (Ruokojärvi *et al*., 2000). Levels of pentachlorophenol ranged from 14–160 μg/m^3 in those without PVC, and from 160–300 μg/m^3 in those with PVC.

Measurement of single specific PAHs at fires ranged from not detected to a maximum of 0.068 mg/m^3 for dibenzo[*a*,*h*]anthracene. In two studies, one of apartment fire simulations and one of training fires, measured total PAHs concentrations ranged from 6.4–470 mg/m^3 (Feunekes *et al*., 1997; Ruokojärvi *et al*., 2000).

Firefighter exposures to respirable particulate matter during overhaul rise to approximately 25 mg/m^3; levels of coarser particles range up to 20 000 mg/m^3 or higher (see Table 1.2). [In the case of wildland firefighters, reported results probably underestimated the actual exposures as these would have been collected during periods of low smoke levels.]

Exposures to VOCs are generally in the low ppm range for all categories of firefighters. [The results probably underestimated the exposures because they did not include the fraction adsorbed onto respirable smoke particles.] Austin *et al*. (2001b,c) found that although levels of total VOCs increased with time in fires burning solids, they decreased in time for fires burning liquids even though the levels of particulate matter increased. This suggests that a significant fraction of VOCs is adsorbed by the particulate matter and escapes detection when only the vapour phase is measured.

Overall, exposures of wildland firefighters to "low" levels of smoke appear to be comparable to those experienced by municipal firefighters during overhaul.

1.3.5 *Exposures to other agents*

(a) Asbestos

Asbestos used in constructions will be released during a fire in the form of fibres; asbestos sheets crack, sometimes disintegrating explosively, and more likely so if the sheet is worn or impregnated with resin (Hoskins & Brown, 1994). Chrysotile breaks down at 450–800 °C, and the amphiboles at 400–600 °C (Hoskins & Brown, 1994; Jeyaratnam & West, 1994). Thus, the denaturing of asbestos during fires may reduce exposure to asbestos fibres.

Table 1.3. Summary of reported concentrations of chemicals during firefighting operations (ranges or means)

Chemical	Units	Wildland	Municipal	Training	Arson investigation
Acetaldehyde	ppm	ND–0.26	ND–8.1	–	0.13[b]
Asbestos	f/cm^2		2.7[a]	0–2.3[d]	
Arsenic	mg/m^3	–	0.14[a]	–	–
Benzene	ppm	0.004[a]–0.38	0.07–250	1.17[a]	< 0.12[b]
Benzofuran	ppm	–	0.2–2	–	–
1,3-Butadiene	ppm	–	0.03–4.84	–	–
Cadmium		–	ND	–	–
Polychlorinated dibenzodioxins	ng/m^3	–	12–148	–	–
I-TEQs	ng/m^3	–	1–7.2	–	–
Dichloromethane	ppm	–	0.28[a]	–	–
Ethyl benzene	ppm	–	0.01–5.97	0.38[a]	–
Formaldehyde	ppm	0.01–0.79	ND–15	–	0.06–0.18
Free radicals					
Furan	ppm	–	0.2–2	–	–
Isoprene	ppm	–	–	0.167[a]	–
Lead	mg/m^3	–	0.03[a]	–	–
Naphthalene	ppm	–	0.01–2.14	0.418[a]	30–200mg/m^3
PM_{10}	mg/m^3	3.0[b]	–	–	–
PM respirable	mg/m^3	0.02[c]–10.5	ND–25.7	–	ND–1.2
PM total	mg/m^3	0.2[a]–44.9	ND–650	0.1–300	0.2–31.6
Knockdown only			ND–20 000		
Overhaul only			ND–45		
Pentachlorophenol	µg/m^3	–	14–300	–	–
Polycyclic aromatic hydrocarbons	mg/m^3	–	6.4–470	10.68[a]	–
Polychlorinated biphenyls	µg/m^3	–	2.8–56	–	–
Silica	mg/m^3		0.04–0.35		
Styrene		–	0.003–2.01	0.535[a]	–
Sulfuric acid		–	ND–28.5	–	0.29[b]
Tetrachloroethylene		–	0.064–0.138	–	–
Trichloroethylene		–	0.112–0.181	–	–
Trichloromethane		–	0.96–465	–	–
Trichlorophenol		–	0.1[a]	–	–

[a] mean; [b] maximum; [c] geometric mean; [d] from helmets and fumes of firefighters; ND, not detected

During a leather factory fire in Merseyside, United Kingdom, in 1994, most of the fallout arose from asbestos bitumen roof paper containing roughly 50% chrysotile (Bridgman, 2001). A low number of asbestos fibres were found on firefighter tunics (0.0029 f/cm^3; range 0.0011–0.0043 f/cm^3), and none was found on the firefighters' raincoats or policemen's uniforms. [A fire hose spray may have washed out airborne asbestos.]

Thermal protective clothing, gloves and helmets that contain asbestos usually contain chrysotile asbestos. In the United Kingdom the helmet covers for navy firefighters, which completely enclose their head and shoulders, used to be made of chrysotile asbestos (Lumley, 1971). Breathing zone samples from users of both new and old helmets with unlined asbestos cloth covers were analysed and had fibre concentrations of 2.30 f/cm^3 and 1.38 f/cm^3, respectively (Lumley, 1971).

(b) Polychlorinated biphenyls, polychlorinated dibenzofurans and polychlorinated dibenzodioxins

Synthetic dielectric (non-conducting) fluids are known as askarels. Firefighters may be exposed to PCBs at fires involving PCB-askarel filled transformers and capacitors (Hutzinger *et al.*, 1985). When askarels burn, copious quantities of oily black soot are produced with very little fire. Where only PCBs are involved, polychlorinated dibenzofurans (PCDFs) are produced as combustion products. In transformers containing a mixture of PCB-askarel and polychlorobenzenes (PCBz), in addition to PCDFs, polychlorinated dibenzodioxins (PCDDs) combustion products are produced from the PCBz (Buser, 1985). PCDFs and PCDDs might also arise from *de novo* synthesis under certain conditions. PCDFs and PCDDs were reported to have been released from a house fire where a 50 lb [23 kg] container of hypochlorite and two gallons [7.6 L] of hydrochloric acid were stored for swimming pool maintenance along with paint thinners and solvents (Rao & Brown, 1990). Other sources of PCBs at fires may include fluorescent light ballasts, PCB-containing mastic, adhesives, duct liners, and fibreglass insulation wrap used in previous decades (Kominsky, 2000). Total 2,3,7,8-tetrachlorodibenzodioxin (TCDD) equivalent (TEQ) levels were 0.24 ppb in a basement soot sample and 0.39–0.75 ng/m^2 in two wipe samples.

PCB concentrations in wipe samples following a fire in a high rise office building were reported to be 7.1–151 μg/m^2 (range, < 1–87610 μg/m^2) (Kominsky, 2000). Debris from a chemical storage vault fire contained 100–750 ppm PCBs, and 2000 ppm PCBs was found in the lubricating grease from the air-handling units (CDC-MMWR, 1987). No PCBs were stored in the storage vault. The source of the PCBs was the paint that coated the surface of the ceiling tiles (15 300–51 000 ppm PCBs).

The use of PCBs in electrical equipment and its effect on some of the numerous fire-related incidents that have occurred in the USA and in Sweden have been reviewed by NIOSH (1986) and Rappe *et al.* (1985a), respectively. A PCB/PCBz-filled transformer fire occurred at the Binghamton State Office Building, New York, USA, in 1981 (O'Keefe *et al.*, 1985). Levels of 2,3,7,8-TCDF and 2,3,7,8-TCDD in a soot sample collected following the fire were 12 ppm and 0.6 ppm, respectively (Buser, 1985). The analysis of soot collected following a capacitor fire at a power station in Finland revealed 3 ppm of 2,3,7,8-TCDF (Buser, 1985). In an earlier study, the replicate concentrations of 2,3,7,8-TCDF and 2,3,7,8-TCDD in a composite soot were 273 and 124 ppm, and 2.8 and 2.9 ppm, respectively (Smith *et al*., 1982).

Firefighter thermal protective clothing can be contaminated with PCBs following fires involving PCBs. In one report, tests revealed 2.7–72 µg PCB/g of clothing following a fire (Kominsky & Melius, 1983). Following the Staten Island fire in the USA, gloves, outer coat sleeves, and outer pants contained peak PCB concentrations of 4 050 000 pg/100 cm^2, 56100 pg/100 cm^2, and 116 000 pg/100 cm^2, respectively (Kelly *et al*., 2002). Overalls and underwear used following the Surahammar fire in Sweden were washed every day (Rappe *et al*., 1985b). After 14 days of use, overalls were analysed and contained 28 ng/m^2 of 2,3,7,8-TCDF, and approximately 100 ng/m^2 all TCDFs combined. Similar levels were found after 1 month of use.

(c) Diesel and gasoline exhaust

Firefighters may be exposed to diesel/gasoline exhaust when vehicles exit and return to the firehall. In a study of diesel emissions in firehalls, shift mean personal measurements of total particulate matter were 0.035–0.48 mg/m^3 (worst-case scenario 0.748 mg/m^3) (Froines *et al*. 1987). [The sampling equipment was removed during the period of highest concentration of diesel exhaust, thereby underestimating actual exposures]. Background ambient particulate matter from ambient aerosol, smoking, and cooking was approximately 0.040 mg/m^3.

Mechanical systems have been available to fire departments since the early 1990s to divert the engine exhaust to the outside of the building (Peters, 1992).

Firefighters are also exposed to diesel emissions from response vehicles that remain running at the fire scene. Firefighters may be positioned near these vehicles during command operations, operation of pumps, when working in defence mode, and during rest breaks.

Firefighters may be exposed to diesel/gasoline exhaust during the operation of vehicles and gasoline-powered hand tools at both structural and wildland fires. No particular methods are used to reduce these exposures. In addition, wildland firefighters are exposed to vapours and combustion products from drip torches used when setting back fires.

(d) Shiftwork

Depending on the jurisdiction, firefighters may work 10-hour dayshifts and 14-hour night shifts, 24-hour or 48-hour shifts. However, given the low frequency of fires over a year, at least in North America, firefighters are often able to sleep at the firehall during the entire night.

(e) Others

Firefighters may be exposed to agents stored, manufactured, or otherwise present at the scene of fire, particularly in factories. Examples are exposure to 2-nitroanisole (Hengstler *et al.*, 1995), and to toluene diisocyanate (Axford *et al.*, 1976) (see Table 1.1).

In many cases, firefighters hold down a second job where they may also be exposed to other agents.

1.4 Biomarkers of exposure

New York City firefighters responded to a Staten Island transformer fire in 1998 in the USA. Exposed firefighters exhibited mean fasting blood serum PCB levels of 2.92 ± 1.96 ppb (range 1.9–11.0 ppb; $n = 58$) 2–3 weeks following exposure (Kelly *et al.*, 2002). Mean levels of serum 2,3,7,8-TCDF, 2,3,7,8-TCDD, and TEQ were 0.20 pg/g (SD 0.69; range ND–2.78; $n = 60$), 3.77 (SD 4.16; range ND–13.4; $n = 60$), and 39.0 pg/g (SD 21.53; range 8.77–120.63; $n = 60$).

In a study of firefighters in Toronto, Canada, firefighters were exposed to low levels of smoke. Self-contained breathing apparatus was consistently used during knockdown, less consistently during overhaul, and intermittently during external firefighting activities. All urine produced during the 20 hours following the end of exposure was collected. Only two of 43 subjects were smokers. Ranges of urinary *trans*,*trans*-muconic acid levels in firefighters who were present at fires during knockdown only, during overhaul only, and during both knockdown and overhaul ranged from not detected to 2.82 mmol/mol creatinine ($n = 5$), to 1.12 mmol/mol creatinine ($n = 8$), and to 1.06 mmol/mol creatinine ($n = 24$), respectively (Caux *et al.*, 2002). The only two firefighters who wore their masks at all times had no measurable urinary *trans*,*trans*-muconic. Levels of urinary 1-hydroxypyrene were 0.12 µmol/mol creatinine (range 0.05–0.19; $n = 5$), 0.23 µmol/mol creatinine (range 0.11–0.34; $n = 8$), and 0.38 and µmol/mol creatinine (range 0.08–3.63; $n = 24$), for the three groups respectively. There was no relationship between measured levels of urinary *trans*,*trans*-muconic acid and 1-hydroxypyrene.

One study was conducted following the September 11th, 2001, attack of the World Trade Center in New York City, USA (Edelman *et al.*, 2003). Blood and urine samples were collected from firefighters 20 days following the attack. Table 1.4 presents adjusted geometric means of concentrations of the chemicals detected in blood and/or urine. The maximum levels of blood mercury found in firefighters following the attack were < 1.7 µg/L blood. Elevated total mercury levels > 20 µg/L blood in one control and 3 exposed firefighters represented organic mercury contributions from dietary sources (e.g. fish).

Table 1.4. Blood and urinary levels in firefighters 20 days following the World Trade Center attack in 2001

Agent	Matrix	Unit	Controls (n = 318)	Special command (n = 95)	Other (n = 195)
1,4-Dichlorobenzene	Blood	µg/L	0.165	0.343*	0.231
m-/*p*-Xylene	Blood	µg/L	0.051	0.081*	0.057
Cadmium	Urine	µg/L	0.377	0.351	0.303
Lead	Blood	µg/L	1.93	3.77*	2.43*
	Urine	µg/L	1.01	1.77*	0.96
Uranium	Urine	µg/L	0.00752	0.00610	0.00607
HCDBD	Lipid	pg/g	19.2	30.6*	25.9*
1-Hydroxypyrene	Urine	ng/L	62.5	159*	77.9

*Significantly elevated compared to the controls, $P < 0.01$
HCDBD, heptachlorodibenzodioxin

1.5 Respiratory protection

1.5.1 *Evolution of respiratory protection and protection factors*

In prior decades, firefighters were known as “smoke eaters.” However, respiratory protection devices for firefighters have existed for over a century. Early US patented devices included air purifying respirators using charcoal to remove toxic gases and vapours (e.g. Guillemard, 1920), and carbon monoxide (e.g. Loeb, 1893), and self-contained breathing apparatus that supplied air to the user (e.g. Hurd, 1889). Air purifying respirators and self-contained breathing apparatus in use today have improved designs, but the basic principles are the same. Modern positive-pressure type self-contained breathing apparatus with a protection factor of 50 to more than 100 came into more widespread use during the 1960s and 1970s (Hyatt, 1976). These were replaced shortly thereafter with pressure-demand type self-contained breathing apparatus with a protection factor of 10 000 (Hyatt, 1976). Pressure-demand self-contained breathing apparatus are commonly used today by municipal firefighters.

1.5.2 *Efficacy of respiratory protection*

Pressure-demand self-contained breathing apparatus have been determined to be adequate in a firefighter risk assessment given the levels of fire atmosphere contaminants reported in the literature (Burgess & Crutchfield, 1995a,b). In these studies, 50 of

51 firefighters (98%) achieved a protection factor exceeding 10 000; estimates of worst case scenarios yielded a protection factor of 4600.

In 1978, firefighters in Scotland, United Kingdom, reportedly used self-contained breathing apparatus routinely at residential fires (Symington *et al.*, 1978). There were no significant differences found in cyanide or thiocyanate levels between these firefighters ($n = 94$) and controls, suggesting that the breathing apparatus used offered adequate protection against hydrogen cyanide.

There is currently no respiratory protection standard for wildland firefighters. One bottle of compressed air used with a self-contained breathing apparatus lasts approximately 15–30 minutes, so self-contained breathing apparatus are not an option for wildland firefighters who work extended shifts at fires for consecutive days or weeks. The only other options are administrative controls to reduce exposure, or the use of air purifying respirators. Air purifying respirators have recently been evaluated for use by firefighters (De Vos *et al.*, 2006; Anthony *et al.*, 2007). In some jurisdictions, such as Australia, wildland firefighters use negative-pressure air purifying respirators (De Vos *et al.*, 2006). In many others, such as in Canada and the USA, wildland firefighters generally do not use any form of respiratory protection (Austin & Goyer, 2007).

1.5.3 *Prevalence of use of self-contained breathing apparatus*

Firefighters tend to use their masks “when they see smoke.” In the past, there was some avoidance of the use of respiratory protection (Guidotti, 1992); over the years, firefighters have become much more health and safety conscious.

There are several other reasons why firefighters might be reluctant to use respiratory protection. These include the added physiological demands and heat stress placed upon the user, the difficulty in communicating while wearing a mask, and the desire to conserve air. However, several studies have demonstrated that firefighters are not able to visually assess the level of contamination. A study in Boston, USA, found no clear patterns or trends that would allow firefighters to predict the levels of smoke contaminants to which they were exposed (Burgess *et al.*, 1979). In one study, a firefighter who was working without a respirator because he believed that his exposure was insignificant was actually exposed to 27 000 ppm of carbon monoxide (Burgess *et al.*, 1977), 680 times the current ACGIH Treshold Limit Value (TLV, 25 ppm). Results of other studies also suggest that structural firefighters cannot estimate levels of smoke contaminants (Brandt-Rauf *et al.*, 1988, 1989).

A “Mandatory Mask Rule” was fully implemented in 1977 at the Boston fire department requiring all firefighters to wear respiratory protective equipment before entering a building for firefighting operations. The mask is not to be removed until after knockdown and after the building has been thoroughly ventilated (Paul, 1977).

Since the introduction of modern self-contained breathing apparatus in the fire service, the lack of standard operating procedures (SOPs) mandating the use of respiratory protection equipment or the failure to enforce existing SOPs have resulted in them not being used appropriately. Even where masks are consistently used during knockdown, they are usually not used or used inconsistently during overhaul.

In a study in West-Haven, CT, USA, half of the firefighters (eight of 16) involved in structural fires did not use breathing apparatus (Loke *et al.*, 1976). In Washington DC, USA, the frequency of wearing masks during knockdown was: always (36%); very often (36%); never or seldom (5%). During overhaul, 62% never or seldom wore masks (Liou *et al.*, 1989). A NIOSH study of different fire departments in the USA (Pennsylvania Fire Training Academy, Pittsburgh Bureau of Fire, New York City, Phoenix, Boston, and Cincinnati) found that 70% of municipal firefighters wore their self-contained breathing apparatus masks less than 100% of the time, and one third used them less than 50% of the time during knockdown (Jankovic *et al.*, 1991). In Sweden, only four of nine volunteer firefighters surveyed reported having used protective equipment while fighting fires within the previous 3 months (Bergström *et al.*, 1997). In a 1993–1994 study of Montreal firefighters, the storage and distribution of all compressed breathing air was tracked and records kept of the time and place of all cylinders, including initial and final pressures along with records of firefighter assignments and alarms. The authors concluded that respiratory protection was used for approximately 50% of the time at structural fires, but for only 6% of the time at all types of fires combined (Austin *et al.*, 2001a). In Toronto, Canada, firefighters "reported consistent usage of self-contained breathing apparatus during knockdown activities inside structures, less consistent usage throughout internal overhaul activities, and intermittent usage during external fire fighting activities" (Caux *et al.*, 2002). In a study in Phoenix and Tucson, AZ, respiratory protection was used during entry/ventilation for 86–95.4% and 74–91.7% of the time, respectively. During overhaul, Phoenix and Tucson firefighters used respiratory protection for 38% and 46.2% of the time, respectively (Burgess *et al.*, 2003).

1.6 Regulations and guidelines

Table 1.5 presents occupational exposure limits for selected chemicals to which firefighters are exposed. Occupational exposure limits have been developed for workers generally exposed to single substances and engaged in light levels of work. Firefighters are exposed to a complex mixture of toxic combustion and pyrolysis products while engaged in very high workloads. Also, given the intermittent nature of the exposures, determination of TWAs will result in calculated exposures far below the established TLVs for different substances. In addition, this does not take into account peak exposures and possible synergistic effects of multiple, potential toxicants. Biomonitoring overcomes some of these difficulties and takes into account the use of respiratory protection.

Table 1.5. Regulations and guidelines for the chemicals measured in smoke at fires presented in Table 1.2 (ACGIH, 2007)

Chemicals measured at fires	Units	BEI		TLV/TWA		STEL		Ceiling	Permitted excursion	Maximum excursion
		ACGIH	EU	ACGIH	EU	ACGIH	EU	ACGIH	ACGIH	ACGIH
Arsenic	mg/m^3	Yes		0.01		–		–	0.03	0.05
Asbestos	f/cm^3	–		0.1	0.1	–		–	0.3	0.5
Acetaldehyde	ppm	–		–		–		25	–	25
Benz[*a*]anthracene	mg/m^3			–		–		–		
Benzene	ppm	Yes	Yes	0.5	1	2.5		–	–	–
Benzo[*a*]pyrene	mg/m^3									
1,3-Butadiene	ppm	Yes		2		–		–	6	10
Cadmium	mg/m^3	Yes		0.01		–		–	0.03	0.05
Carbon black (total)	mg/m^3	–	Under discussion	3.5	Under discussion	–	Under discussion	–	10.5	17.5
Dichloromethane (methylene chloride)	ppm	Yes		50	Under discussion	–		–	150	250
Ethylbenzene	ppm	Yes		100	100	125	200	–	–	–
Formaldehyde	ppm	–			Under discussion	–		0.3	–	–
Furan/tetrahydrofuran	ppm	–		–	50	–	100	–	–	–
Isoprene	ppm	–		–		–		–	–	–
Lead	mg/m^3	Yes		0.15	0.15	–		–	0.45	0.75
Naphthalene	ppm	–		10	10	15		–	–	–
Particulate matter (respirable)	mg/m^3	–		3		–		–	9	15
Particulate matter (total)	mg/m^3	–		10		–		–	30	50
Pentachlorophenol	µg/m^3	Yes		0.5						
Polychlorinated biphenyls (Aroclor; 54%) (Chlorodiphenyl)	µg/m^3	–		0.5		–		–	1.5	2.5
Polycyclic Aromatic Hydrocarbons	mg/m^3	Yes		0.2		–		–	0.6	1.0

Table 1.5 (contd)

Chemicals measured at fires	Units	BEI		TLV/TWA		STEL		Ceiling	Permitted excursion	Maximum excursion
		ACGIH	EU	ACGIH	EU	ACGIH	EU	ACGIH	ACGIH	ACGIH
Styrene	ppm	Yes		20		40		–	–	–
Sulfuric acid	mg/m^3	–		0.2	Under discussion	–		–	–	–
Tetrachloroethylene (Perchloroethylene)	ppm	Yes		25	Under discussion	100.0			–	–
Trichloroethylene	ppm	Yes		10	Under discussion	25.0		–	–	–
Trichloromethane (chloroform)	ppm	–		10	2	–		–	30	50
Trichlorophenol	ppm	–		–		–		–	–	–

ACGIH, American Conference of Governmental Industrial Hygienists; BEI, Biological Exposure Index; EU, European Union; STEL, short-term exposure limit; TLV, Threshold Limit Value.

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