Arch Environ Contam Toxicol (2009) 56:380–388
DOI 10.1007/s00244-008-9209-3

Respiratory Irritants in Australian Bushfire Smoke: Air Toxics Sampling in a Smoke Chamber and During Prescribed Burns

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Received: 5 December 2007 / Accepted: 21 July 2008 / Published online: 20 August 2008

Abstract Bushfire smoke contains an array of organic and inorganic compounds, including respirable and inspirable particles, aldehydes, and carbon monoxide. These compounds have been found to be a health hazard for firefighters in the United States. Despite the high frequency of bushfires in Australia, analyses of bushfire smoke components are scarce. As part of an occupational health study investigating the respiratory health effects of bushfire smoke in firefighters, air toxics sampling was undertaken in a smoke chamber and during prescribed burns. Levels of formaldehyde and acrolein were demonstrated at respectively 60% and 80% of the Short Term Exposure Limit in the smoke chamber. Carbon monoxide levels exceeded the peak limit of 400 ppm significantly. Although concentrations were lower during the prescribed burns, the study shows that Australian bushfire smoke contains air toxics of concern and provides justification for further research into the levels of air toxics measured at bushfires and the associated health impacts.

Introduction

Bushfire smoke is the evident product of bushfires. It contains a range of organic and inorganic compounds original to the combusted material or formed during the combustion process (Gill et al. 1981; Lees 1995). Combustion is a chemical-physical process in which the fuel properties, the temperature, the moisture, and the ventilation affect the type and amount of the combustion products present in the smoke (Beer and Meyer 1999; Brandt-Rauf et al. 1988; Gill et al. 1981; Terrill et al. 1978). Approximately 200 distinct compounds have been identified in wood smoke, including respirable and inspirable particles, carbon monoxide-, nitrogen-, and sulphur-based compounds, aldehydes, volatile and semivolatile organic compounds, polycyclic aromatic hydrocarbons, dioxins, organic acids, free radicals, and ozone (Dost 1991; Malilay 1999; Reisen and Brown 2006; Ward 1997, 1999). Given that the emissions vary with fuel type and combustion conditions, the chemical basis for acute smoke toxicity is not adequately known. The majority of the findings are based on analyses from United States wildland fire smoke, and it is not clear whether these findings are applicable in the Australian environment, as vegetation types, soils, combustion conditions, and fire-fighting methods differ. Analyses of smoke components pertaining to Australian bushfires are limited. Obtaining the relevant data is complicated by the variation of the vegetation types, changing weather conditions, and often difficult access to the fire ground (Hinwood et al. 2002). Reisen et al. (2006b) conducted a method evaluation for the burning of various forest fuels selected from across Australia. Under controlled conditions, set amounts of these fuels were burned in a burn chamber, and air sampling was undertaken. The main identified toxic compounds were respirable particles, aldehydes (formaldehyde, acetaldehyde, acrolein, 3 furaldehyde), volatile organic compounds (VOCs; benzene, toluene, xylenes, phenol), and carbon monoxide (Table 1). Of these compounds, respirable particles, carbon

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Table 1 Air toxics concentrations generated in burn chamber

Air toxics from 125-g WA coastal scrub	Measured concentrations (mg/m^3)	TWA (mg/m^3)	STEL (mg/m^3)
Respirable particles	35	3.0	–
Carbon monoxide	170 ppm	30 ppm	200 ppm
Formaldehyde	0.26 ppm	0.96 ppm	2.0 ppm
Acetaldehyde	0.67 ppm	100 ppm	150 ppm
Acrolein	0.18 ppm	0.10 ppm	0.3 ppm
Benzene	0.72	1.6	–
Toluene	0.42	100	565
Xylenes	0.15	350	655
Phenol	0.4	4	–

Source: Australian Safety and Compensation Council (1995); Reisen et al. (2006b)

monoxide, and acrolein exceeded the Exposure Standards for Atmospheric Contaminants in the Occupational Environment (Australian Safety and Compensation Council 1995). This was a preliminary evaluation conducted to identify toxics of interest, and concentrations in the burn chamber could not be directly related to exposure levels at real bushfires.

During prescribed and experimental burns across Australia, Reisen et al. (2006a) identified carbon monoxide, respirable particles, formaldehyde, acrolein, benzene, and toluene from firefighter personal air sampling. The carbon monoxide exposure standard of 30 ppm was exceeded for one firefighter (380-min sample), with two additional exposure levels monitored at 26 ppm (35-min and 395-min samples). Respirable particle levels exceeded 10 mg/m^3 at least once over the sampling period for 80% of the samples. It was noted that smoke exposure levels were influenced by a number of factors, including work activities, burn locations, fuel types, and meteorological variables. The findings were consistent with the results of other studies that have identified formaldehyde, acrolein, respirable particles, and carbon monoxide as a smoke hazards for firefighters (Reinhardt and Ottmar 2000; Reisen et al. 2006b; Sharkey 1997).

Formaldehyde is a colorless, strong-smelling, highly flammable gas that occurs naturally in plants and is released through biomass combustion during bushfires (Reinhardt and Ottmar 2000). The human health effects of inhalation of formaldehyde are well documented. There is consistent evidence of respiratory as well as skin and eye irritation after exposure to formaldehyde (Australian Government—Department of Health and Ageing 2005; Hauptmann 2004; International Agency for Research on Cancer 2004b; National Environment Protection Council 2003; World Health Organization 2002b). Epidemiological evidence demonstrates associations between occupational exposure to formaldehyde and nasopharyngeal and sinonasal cancers (McLaughlin 1994; Partanen 1993; Vaughan et al. 2000). Based on these findings, the International Agency for Research on Cancer (IARC) classifies formaldehyde as a Class 1 carcinogen (i.e., carcinogenic for humans) (International Agency for Research on Cancer 2004a, 2004b). The Australian occupational exposure standards for formaldehyde are 1.0 ppm for an 8-h time-weighted average (TWA) and 2.0 ppm for a 15-min short-term exposure limit (STEL). The 8-hTWA is defined as the concentration for a normal 8-h workday and a 40-h workweek to which workers can be exposed, day after day, without adverse effect. The 15-min STEL is defined as the concentration to which workers can be exposed without adverse effect. Exposures should not be longer than 15 min and should not occur more than four times per day, and there should be at least 60 min between successive exposures. The National Industrial Chemicals Notification and Assessment Scheme recommends lowering standards to 0.3 ppm (TWA) and 0.6 ppm (STEL) (Australian Government—Department of Health and Ageing 2005). In the United States, the American Conference of Governmental Industrial Hygienists' Threshold Limit Values for formaldehyde are 1.0 ppm (TWA) and 0.3 ppm (ceiling limit). The National Institute for Occupational Safety and Health recommends lowering occupational standards for formaldehyde from 0.75 to 0.016 ppm (TWA) and from 2.0 to 0.1 ppm (STEL).

Monitoring data during wildfires in the Unites States indicates that firefighters can be exposed to formaldehyde levels up to 0.34 ppm while controlling wildfires. Exposure levels for formaldehyde depend on the work activity being undertaken (Reinhardt and Ottmar 2000). Average formaldehyde levels varied from 0.015 ppm for "holding" compared to 0.098 ppm for "mop-up." These variations in formaldehyde exposure levels were confirmed in a smoke exposure study during prescribed burns by Reinhardt et al. (2000). Similarly, in Australia, Reisen et al. (2006a) measured different personal exposure levels of formaldehyde depending on work activities. Exposure levels for formaldehyde were highest for firefighters who were "patrolling/suppressing with a hose and/or a rake hoe" (up to 0.6 ppm) compared to firefighters who were "lighting" and "supervising" (both up to 0.2 ppm).

Acrolein is a clear, colorless to straw-colored liquid with a pungent, suffocating odor. Forest fires emit acrolein as a product of incomplete combustion of organic matter. Acrolein is an upper-respiratory-tract irritant, causing increased airway resistance and a decreased respiratory rate. Severe respiratory symptoms, including bronchitis or pulmonary edema occur at concentrations of 10–20 ppm (Bolstad-Johnson et al. 2000). Eye irritation can occur at concentrations of 0.01–2.0 ppm and irritation of the nose and throat can occur at 1.0–3.0 ppm (World Health Organization 2002a). Current occupational exposure limits in Australia are 0.1 ppm (TWA) and 0.3 ppm (STEL) (Australian Safety and Compensation Council 1995). Data on the emissions of acrolein from burning vegetation suggest a wide range of possible concentrations in smoke. Reinhardt et al. (2000) found shift averages for acrolein of 0.009 ppm for fire fighters, with the highest exposure averaging 0.06 ppm during the work shift. During the time on the fireline, the firefighters' exposure to acrolein averaged 0.015 ppm, ranging up to 0.098 ppm (Reinhardt et al. 2000). In another study, Reinhardt and Ottmar (2000) found average acrolein exposures of 0.005 ppm during initial attack operation and 0.001 ppm over a work shift. In a study investigating the short-term health effects of exposures to smoke from prescribed burns, Slaughter et al. (2004) found mean levels of acrolein at 0.01 ppm. However, other studies have found acrolein concentrations in smoke as high as 0.1–10 ppm near fires (1997).

Carbon monoxide is a colorless, odorless, tasteless, noncorrosive, highly toxic gas of the same density as air. It is extremely flammable and is present in virtually all fire environments (Lees 1995). It is produced abundantly through the incomplete combustion of biomass fuels, particularly in the smoldering phase, when temperatures are lower. Carbon monoxide has a well-established mechanism of action in humans. It displaces oxygen from hemoglobin in the blood to form carboxyhemoglobin, which leads to a reduction in both oxygen transport and release, resulting in a range of health effects (Bizovi and Leikin 1995; Ellenhorn 1997; Malilay 1999; Townsend and Maynard 2002). Current occupational exposure limits set by the Australian Safety and Compensation Council (1995) are 30 ppm (TWA) for an 8-h workday, 200 ppm (STEL) for 15 min, and a peak limit of 400 ppm, which should not be exceeded at any time. At a concentration of 200 ppm, a healthy individual at rest starts experiencing mild headaches after 2–3 h. At 400 ppm exposure, the individual can experience nausea, headache, and dizziness after 1 or 2 h. With an exposure concentration of 800 ppm and higher, confusion, ataxia, coma, and seizures might develop. At high work levels, these symptoms can be expected to appear at lower exposure levels. Carbon monoxide is present in all fire environments and has been described as the most common and serious acute hazards for firefighters (Treitman et al. 1980). Although firefighters at bushfires infrequently encounter carbon monoxide levels that are capable of causing incapacitation and death within minutes, they are often exposed to levels that can compromise their judgment, psychomotor efficiency, visual vigilance, performance, and safety (Burgess et al. 1979; Hathaway and Proctor 2004; Matticks et al. 1992). Average carbon monoxide concentrations were measured at 14.4 ppm (TWA) (Table 2) and ranged from 1.4 to 38 ppm in 46 samples collected during fireline mop-up and a prescribed burn (Materna et al. 1992). The highest exposures, up to 300 ppm on an instantaneous basis, were associated with operators of gasoline-powered pumping engines. During prescribed burns, TWA levels were measured within occupational exposure limits (i.e., shift average was 38 ppm), and at the fireline, 58 ppm (TWA) was measured (Reinhardt et al. 2000). Smoke exposure measurements among firefighters at wildland fires undertaken between 1992 and 1995 showed that carbon monoxide levels occasionally exceeded full-shift permissible exposure limits (Reinhardt and Ottmar 2000). The average exposures to carbon monoxide at project wildland fires (i.e., eight multiday wildland fires) averaged 2.8 ppm over the work shift, with a maximum TWA exposure to carbon monoxide of 30.5 ppm over the work shift. During initial attack

Table 2 Carbon monoxide levels during fire fighting

	TWA	STEL
Structural fire fighting		
Treitman et al. (1980)	320	>200
Bolstad-Johnson et al. (2000)	26.9	260
Bushfire fighting		
Brotherhood et al. (1990)	17/31[a]	–
Materna et al. (1992)	14.4	300
Beason et al. (1996)	<25	703
Reinhardt et al. (2000)		
Shift average	38	179
At the fireline	58	–
Reinhardt and Ottmar (2000)		
Project wildfires		
Shift average	2.8 (max 30.5)	–
Fireline	4.0 (max 38.8)	–
Initial attack wildfires		
Shift average	1.6 (max 13.1)	–
Fireline	7.4 (max 28.2)	–
Slaughter et al. (2004)	7.19	–

[a] Nonsmokers/smokers

Source: Australian Safety and Compensation Council (1995) wildfires (i.e., fires that were successfully controlled by initial attack forces), carbon monoxide levels averaged 1.6 ppm, with a maximum of 13.1 ppm, during the work shift. Similar levels of carbon monoxide were found in a study investigating the association between lung function and exposure to prescribed burn smoke (Slaughter et al. 2004).

Particulate matter (PM) represents a complex mixture of organic and inorganic substances and consists primarily of condensed hydrocarbon, tar materials, and fragments of vegetation and ash (Ward and Hardy 1991). PM is abundantly produced during bushfires, is highly visible, affects ambient air quality, and has various health effects. The size of PM tends to divide into three groups: coarse particles, 2.5–10 μm; fine particles, 0.1–2.5 μm; and ultrafine particles, smaller than 0.1 μm. The chemical composition and size of the PM in bushfire smoke depends on the combustion conditions and the amount and type of biomass fuels. For example, a low-efficiency fire yields considerably more fine PM (72% of the total PM) than a high-efficiency fire (21% of the total PM), and incomplete combustion, due to a lack of oxygen, produces more toxic PM compared to complete combustion (Beer and Meyer 1999; Sharkey 1997). The fine particles account for up to 90% to nearly 100% of the mass of PM (Ward 1997). Inhalation is the most important route of exposure during bushfires, and when particles are in the ambient air, there is a significant likelihood that firefighters will inhale them. It is extremely complex to determine the health effects of PM in smoke, as the damage-causing properties of particles not only depend on the chemical and toxic characteristics but also on their size, shape, and density (Dost 1991; Naeher et al. 2007; Schwela 2001). Currently, there is no occupational exposure limit available for PM from smoke. In the United States, exposure levels are generally assessed against the occupational exposure levels for nuisance dust (i.e., 5 mg/m^3 for the respirable fraction and 15 mg/m^3 for the total dust fraction). In Australia, the recommended occupational exposure level for inspirable nontoxic dust is 10 mg/m^3 (Australian Safety and Compensation Council 1995). However, this general exposure standard should only be applied where the PM contains no substances that might themselves be toxic or cause physiological impairment at lower concentrations; for example, where a dust contains asbestos, the exposure to these materials should not exceed the appropriate value for these substances. For specific dusts, including coal dust, graphite dust, and hardwood dust, the occupational exposure levels for specific respirable particles vary from 1 to 6 mg/m^3. During bushfire fighting, firefighters are exposed to considerable levels of particles produced by the combustion of biomass. Reinhardt and Ottmar (2000) found maximum PM_3 (PM less than 3 μm in aerodynamic diameter) levels of 2.3 mg/m^3 on the fireline. The complex mixtures of the toxic compounds, which are adhered to the surface of the PM, and associated health effects are largely unknown. Moreover, exposure levels might vary with the specific tasks within a job that are being undertaken. Reinhardt and Ottmar (2000) found that the $PM_{3.5}$ concentration was highest for firefighters during holding and mop-up. These results were expected, as this task involves digging and stirring of ashes and dirt, which causes particles to become airborne. Reisen et al. (2006a) reported similar findings in particulate sampling during prescribed burns in Australia. Although the average work shift concentrations of particles ranged from 0.2 to 9 mg/m^3, the particles reached levels above 20 mg/m^3 during periods of rake hoeing.

This project was carried out to determine and quantify the air toxics in Western Australian bushfire smoke. Static and personal sampling was undertaken as part of an occupational health study investigating the effectiveness of protective filters on firefighter respiratory health during simulated bushfire smoke exposure (De Vos et al. 2006).

Methods

Experimental smoke trials were undertaken in two contexts: in a smoke chamber and during prescribed burns. Personal sampling was undertaken in the breathing zone of the participating firefighters.

Smoke Chamber

The smoke chamber used for the study was a modified sea container (12.2 m × 2.4 m × 2.4 m) that was commonly used by the Fire and Emergency Services Authority of Western Australia (FESA) for education and training purposes. The sea container had two doors, which could be opened to regulate the smoke behavior and density during the trials. A pedestal fan was used inside the smoke chamber to ensure a consistent distribution of the smoke.

A standard drum-type incinerator of 243 L capacity was used to generate the smoke. The incinerator was placed outside the smoke chamber. A ventilation opening on the incinerator was used to manage the combustion process. The incinerator had a flue (diameter: 170 mm) at 1.76 m above floor level, which directed the smoke into the smoke chamber. There was no loss of smoke, as the flue was sealed into the wall of the smoke chamber.

The weight of the fuel used during each 1.5-h trial was ~25 kg. The fuel was a mixture of banksia and coastal heath, which was typical of the material firefighters would encounter in a bushfire situation. Based on workplace reports, these vegetation types were known to create substantial smoke levels during bushfires. The collected vegetation was analyzed for moisture content, which was recorded at 9.4% during the period of the smoke chamber trials (Wilkinson, personal communication, 2004).

A light-smoke situation was produced, defined in the Bush Fire Smoke Exposure Standard Operational Procedures 51 (Fire and Emergency Services Authority Western Australia 2007) as a density of smoke producing a white to light gray color with reasonable visibility of at least 15 m. Visual assessment of the smoke was undertaken by a single observer, using the visual smoke exposure classification as described by Reinhardt and Ottmar (2000). To assist with the assessment of the smoke density, five white circles with a diameter of 30 cm were spray-painted on the rear panel of the smoke chamber as indicators for visibility.

Prescribed Burns

Prescribed burns are low-intensity fires used to reduce the buildup of leaves and twigs on the forest floor. This procedure has proven to be an effective and environmentally sound way of reducing the future risks of destructive, high-intensity bushfires. The frequency of prescribed burns in a given area is variable, with intervals between burns ranging from 5 to 15 years. The preferred seasons are usually during spring and autumn months. The method used to burn is based on the size of the area to be burned, prevailing weather, objectives for each burn, and the availability of resources. Before burns are conducted, firefighters ensure that control lines are established around the area to be burned. Control lines might be natural features, such as streams and existing roads, or can be tracks of vegetation clearedvby hand tools or machinery. The most common method of ignition is to use a hand-held drip torch, which is a canister of flammable liquid fitted with a wand and a burner head. The trials were conducted during four prescribed burns in the Yanchep and Two Rocks area, which is located on the outer fringe of the Perth Metropolitan area in Western Australia. The prescribed burns were undertaken and managed by officers of the Western Australian Department of Environment and Conservation. Table 3 shows the collected field data and predicted conditions for the scheduled days.

Air Sampling

The Chemistry Centre Western Australia, Perth was commissioned to perform the monitoring and analysis of the bushfire smoke compounds of interest, including PM, formaldehyde, acrolein, carbon monoxide, and VOCs.

During the smoke chamber burns, static sampling of PM, formaldehyde, acrolein, VOCs, and carbon monoxide as well as personal sampling of VOCs were undertaken (Table 4). PM was measured by gravimetric sampling. The samples were collected on preweighed 25-mm acrylic filters (pore size: 1 μm; sample rate: 2 L/min). Formaldehyde and acrolein were sampled actively with two sectioned 2,4-dinitrophenylhydrazine SKC® sorbent tubes and analyzed by high-performance liquid chromatography (HPLC), as per National Institute for Occupational Safety and Health (NIOSH) Method No. 2016 (Schlecht and O'Connor 2003). Carbon monoxide and VOC monitoring was performed using the multigas monitor PGM50-5P™. This is a portable monitor with photo-ionization detection, which determines the total level of VOCs. The Hapsite™ field-portable gas chromatograph/mass spectrometer was used to identify and quantify the various VOCs. Personal VOC sampling was conducted on eight firefighters by using 3 M™ organic vapor monitors. This particular sampling was undertaken as part of another study investigating the effectiveness of protective filters on firefighter respiratory health during simulated bushfire smoke exposure (De Vos et al. 2006). The 3 M organic vapor monitors are devices that collect contaminants through the principle of diffusion. The purpose of the use of personal sampling devices was to measure the specific individual exposure, thereby assisting in the determination of the type of respiratory equipment appropriate to the contaminants. Passive personal sampling of organic vapors was conducted as per Australian Standard 2986.2—2003 (Standards Australia 2003). The monitors were attached near the participant's breathing zone (i.e., on the lapel of the jackets). Sampling lasted for 15 min, the minimal required period to obtain sufficient material for analysis (Standards Australia 2003). The organic vapor monitors were desorbed with 1.5 mL carbon disulfide and analyzed by gas chromatography/mass spectrometry with flame ionization detection, as per NIOSH Method No. 1501 (Schlecht and O'Connor 2003).

During the field trials, personal active sampling of formaldehyde was undertaken. The active 2-h sampling was done with 2,4-dinitrophenylhydrazine SKC sorbent tubes (i.e., similar methodology as in the smoke chamber). Analysis was performed by HPLC, as per National Institute for Occupational Safety and Health (NIOSH) Method No. 2016 (Schlecht and O'Connor 2003). No measurements of carbon monoxide, particles, acrolein, and VOCs were conducted during the prescribed burns.

Results

Static sampling was undertaken to characterize and quantify levels of air pollutants in the smoke chamber and in the field during the prescribed burns. Formaldehyde, acrolein, particles, carbon monoxide, and VOC levels were measured for 15 min in the smoke chamber. During the field trial, only formaldehyde was sampled, as a result of logistic limitations due to unstable weather conditions at the time.

Table 3 Prescribed burns environmental and meteorological data

	17 and 20 October 2005	10 and 24 November 2005
Location	Caraban State Forest Block Prescribed Burn (415 057A)—approx. 10 km NE of Two Rocks/Yanchep	Caraban State Forest Block Prescribed Burn (415 055)—approx. 5 km E of Yanchep
Area burned	20–30 hectares per day were burned to provide smoke for the trial	20–30 hectares per day were burned to provide smoke for the trial
	Total burn area: 418 hectares	Total burn area: 210 hectares
Vegetation type	Predominantly Banksia Low Forest A (LAc) with small areas of Dryandra sessilis Dense Heath A	Predominantly Banksia Dense Low Forest A (LAd) with some emergent *Eucalyptus marginate* and *E. gomphocephala*
Associated plant species	*Banksia grandis, Banksia menziesii, Acacia pulchella, Xanthorrhoea preissii, Dryandra sessilis, Scaevola repens, Scaevola canescens, Conostylis aculeate, Dampiera linearis, Hakea prostrata, Hakea lissocarpha, Melaleuca* spp., *Eucalyptus todtiana*	*Eucalyptus marginate, E. gomphocephala, Eucalyptus todtiana, Banksia grandis, B. menziesii, Xanthorrhoea preissii, Allocasurina fraseriana, Carprobrotus sp., Conostylis aculeate, Hakea prostrata, Hakea lissocarpha, Scaevola repens, S. canescens*
Fire behavior	Surface moisture content (SMC) 8–12%	SMC 10–12%
	Rate of Spread ~35 m/h	Rate of Spread ~35 m/hr
	Fire intensity: low to medium	Fire intensity: low to medium
Predicted conditions	*17 October 2005*	*10 November 2005*
	Min SMC for pine 10%	Min SMC for pine 8%
	Fire Danger Index (FDI) 441 m/h and extreme	FDI 181 m/hr and very high
	Winds mostly SW to 35 km/hr	Winds W to 20 km/h
	Temp 21°C and fine	Temp 24°C and fine
	20 October 2005	*24 November 2005*
	Min SMC for pine 7%	Min SMC for pine 6%
	FDI 414 m/h and extreme	FDI 370 m/h and extreme
	Winds mostly W to 25 km/h	Winds mostly SW to 28 km/h
	Temp 21°C and fine	Temp 23°C and fine
		Windy and then showers

Source: L. Sage (personal communication, 2006)

Table 4 Sampling methodology

	Smoke chamber burns	Prescribed burns
Particles	Gravimetric sampling	n/a
Formaldehyde	Sorbent tubes: static sampling	Sorbent tubes: personal sampling
Acrolein	Sorbent tubes: static sampling	Sorbent tubes: personal sampling
Carbon monoxide	Multigas monitor: static sampling	n/a
VOCs	Multigas monitor: static sampling	n/a
	Hapsite Portable GC/MS: static sampling	
	3 M™ organic vapour monitors: personal sampling	

The narrow time window only allowed for an extremely limited preparation period for the researchers involved. Table 5 presents an overview of the results of the static sampling.

Formaldehyde levels ranged from 1.16 to 2.54 mg/m^3 during the three trials in the smoke chamber. Although the STEL level was exceeded slightly in one sample, it must be noted that these are positional or static samples in contrast to personal samples and, thus, personal exposure might have been higher or lower. Formaldehyde levels during the prescribed burns ranged from 0.49 to 0.75 mg/m^3, which is well within the occupational exposure levels of 2.5 mg/m^3 (STEL) and 1.2 mg/m^3 (TWA). The mean formaldehyde level in the smoke chamber was approximately three times

Table 5 Results: Static sampling

Air toxic	15-min sampling						2-h sampling	
	Smoke chamber September 2004		Smoke chamber October 2004		Smoke chamber December 2004		Prescribed burn October 2005	
	n (mg/m^3)	Mean ± SD	*n* (mg/m^3)	Mean ± SD	*n* (mg/m^3)	Mean ± SD	*n* (mg/m^3)	Mean ± SD
Formaldehyde	4	1.53 ± 0.39	4	1.74 ± 0.09	2	2.25 ± 0.41	6	0.62 ± 0.10
TWA 1.2 mg/m^3								
STEL 2.5 mg/m^3								
Acrolein	4	0.08 ± 0.10	4	0.58 ± 0.09	2	0.13 ± 0.04	n.d.[a]	n.d.[a]
TWA 0.23 mg/m^3								
STEL 0.69 mg/m^3								
Particles	n/a		4[c]	10.0 ± 4.10	n/a		n/a	
TWA 10 mg/m^3 [b]								
STEL n/a								
Carbon Monoxide	27 ppm		131 ppm		257 ppm		n/a	
TWA 30 ppm	Range: 2–130 ppm		Range: 5–742 ppm		Range: 1–932 ppm			
STEL 200 ppm								
Total VOCs	2.1 ppm		2.1 ppm		4 ppm		n/a	
	Range: 0–12 ppm		Range: 0–22 ppm		Range: 0–17 ppm			

[a] Not detected

[b] Recommended TWA for inspirable non-toxic particles

[c] Gravimetric sampling

Source: Australian Safety and Compensation Council (1995)

higher compared to the mean level of formaldehyde during the prescribed burns (1.76 vs. 0.62 mg/m^3). This discrepancy might be explained by the confinement and the limited airflow through the smoke chamber.

Acrolein levels were measured in the smoke chamber only and varied from 0 to 0.69 mg/m^3 (mean: 0.58 mg/m^3). The measured concentrations in the second trial reached the STEL of 0.69 mg/m^3 and were significantly higher compared to the levels in the first and third trials. Although the trials were set up in a standard way to ensure consistency of the measurements, the variation in these findings might be explained by uncontrollable factors, including weather conditions, which might have resulted in an increased airflow in the smoke chamber.

Levels of particles in the smoke chamber ranged from 3.9 to 13.1 mg/m^3, with a mean of 10 mg/m^3, and exceeded the TWA of 10 mg/m^3 for nontoxic particles on three occasions. Due to the toxic nature of bushfire smoke, it would be more appropriate to compare these results to occupational standards for toxic particles. However, such standards are not available, and no other existing guideline values capture the unknown synergistic and additive health effects of the individual compounds.

Carbon monoxide levels varied considerably among the three trials in the smoke chamber. The mean values ranged from 27 to 257 ppm. Peak levels were measured at 130 ppm, 742 ppm, and 932 ppm, which exceed the peak limit of 400 ppm on two occasions significantly. Carbon monoxide levels for the field trials were not available.

The mean level of VOCs determined by the multigas monitor was 2.1 ppm (TWA 0.2 ppm; range: 0–11.5 ppm). The major VOCs identified by the Hapsite gas chromatograph/mass spectrometer were benzene, toluene, ethylbenzene, xylenes, styrene, benzaldehyde, benzonitrile, phenol, benzofuran, alkanes, indene, and naphthalene. It was not possible to accurately quantify individual levels because many of the identified compounds were present only in trace amounts and were poorly resolved by the gas chromatograph (Wilkinson, personal communication, 2005).

Personal sampling in the breathing zone of eight participants was undertaken with 3 M organic vapor monitors during one of the smoke chamber trials. These clip-on monitors make it possible to measure personal exposure levels to VOCs. The monitors were analyzed for *N*-hexane, benzene, toluene, ethyl benzene, M & P xylenes, *O*-xylenes, and total C2 benzenes (Table 6). The presence of these organic vapors was demonstrated at extremely low levels compared to the established occupational standards (Australian Safety and Compensation Council 1995) The mean toluene level was measured at 53.91 mg/m^3, with the maximum level of 103.96 mg/m^3, which is ~20% of the STEL (565 mg/m^3).

Table 6 Results: Personal sampling volatile organic compounds

VOC 15-minutes sampling ($n = 8$)	Mean (mg/m^3)	Range (mg/m^3)	STEL (mg/m^3)
N-Hexane	2.11	1.2–4.14	–
Benzene	0.48	0.14–1.91	–
Toluene	53.91	24.17–103.96	565
Ethyl benzene	0.19	0.14–0.25	543
M & P xylenes	0.18	0.13–0.26	655
O-xylenes	0.21	0.10–0.25	655
Total C2 benzenes	0.58	0.41–0.70	–

Source: Australian Safety and Compensation Council (1995)

Discussion

Bushfire smoke is the combustion product of biomass fuels and contains a range of organic and inorganic compounds, including respiratory irritants such as PM, formaldehyde, acrolein, and carbon monoxide. The health effects of PM depend on the size and characteristics of the adsorbed compounds. Consequently, there is no single description available of the health effects of particles of smoke. Formaldehyde is a known human carcinogen and causes direct irritation of both the skin and the respiratory tract. Acrolein is an irritant, and adverse health effects associated with exposure are mostly confined to the tissue of first contact, which is often the respiratory tract, due to inhalation of smoke. Carbon monoxide has acute effects on the body, ranging from slightly diminished work capacity to acute nausea, severe headache, dizziness, and impaired judgment. Death can occur during extreme exposure levels, but these levels are unlikely to exist during bushfire fighting.

The systematic sampling of particulate matter, formaldehyde, acrolein and carbon monoxide has demonstrated the presence of these toxic compounds in Western Australian bushfire smoke. Formaldehyde concentrations in the smoke chamber reached up to 60% of the STEL and exceeded the STEL on one occasion. Formaldehyde levels in the field reached 50% of the TWA. Acrolein concentrations in the smoke chamber reached up to 80% of the STEL and reached the STEL on one occasion. Carbon monoxide monitoring with real-time data loggers in the smoke chamber showed peak levels that exceeded the peak limit significantly. It is assumed that the high levels of particles and carbon monoxide might have been caused by the confinement and the limited ventilation in the smoke chamber.

It is acknowledged that conditions during the trials, in particular in the smoke chamber, do not exactly replicate real bushfire fighting situations due to the nature of the burning process, ventilation, humidity, and variances in meteorological conditions. Therefore, the concentrations of air toxics measured cannot be directly related to concentrations that firefighters will be exposed to during bushfire fighting activities. Nonetheless, exposure studies in the United States and in other Australian states have found similar results from smoke sampling during prescribed burns. Reinhardt et al. (2000) showed that during wildfires, occupational exposure standards were exceeded for up to 14% of firefighters' exposures to respirable particles, formaldehyde, and acrolein, and 8% of exposures to carbon monoxide. In Australia, Reisen et al. (2006a) found during prescribed burns in Victoria, South Australia, and the Northern Territory that respirable particle levels frequently exceeded the STEL of 10 mg/m^3, and carbon monoxide levels exceeded occupational exposure levels in a small (not specified) number of cases related to specific tasks. Furthermore, a strong correlation was found between levels of carbon monoxide and respirable particles and between levels of carbon monoxide and formaldehyde.

The findings of this study demonstrate that Western Australian bushfire smoke contains air toxics of concern and provide a justification for further research into the levels of air toxics measured at bushfires and associated health impacts. Identifying the acute respiratory health effects of occupational exposure to bushfire smoke is relatively straightforward, but quantifying them under actual field conditions is more difficult. Identification and quantification of long-term health effects requires further research.

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