AUSTRALIAN FIREFIGHTERS EXPOSURE TO AIR TOXICS IN BUSHFIRE SMOKE.

WHAT DO WE KNOW?

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1 INTRODUCTION

Bushfire firefighting is recognised as one of the most dangerous occupations in the world. The risk of injury and death whether it is directly related to the fire front or as a result of an accident during firefighting tasks can be extremely high. Evident from literature, is the concern regarding the effect of bushfire toxic emissions on firefighter health[1-9]. Bushfire firefighters are likely to be exposed to a multitude of contaminants that result from the combustion of natural forest fuels. Major combustion by-products include carbon monoxide, carbon dioxide, nitrogen oxides, sulphur dioxide, particulate matter of various size distribution, aldehydes, polycyclic aromatic hydrocarbons and several other organic and inorganic compounds[10-13]. To add to this, introduced chemicals such as herbicides or lead deposits may potentially be included in the cocktail of chemicals to which firefighters are exposed. The toxicity of smoke exposure may impair the ability of the firefighter to perform a task both mentally and physically, and could potentially affect their safety on the fire ground. Furthermore extreme or chronic bushfire emissions may cause long-term illnesses such as lung damage, neurologic impairment, heart disease and cancer[3, 5, 14-16].

Although bushfire firefighters share a common exposure with structural firefighters, work practices and environments differ significantly. Typically, bushfire firefighters do not experience extreme acute exposures as do structural firefighters, however bushfire firefighters often persist for long shifts, which may last for days or weeks and have no protection from toxic emissions such as self contained breathing apparatus. Furthermore off shift firefighters during a bushfire campaign are usually camped nearby and thus are further exposed to smoky environments. Multiple chemical exposures and the effects of heat stress and physical fatigue on firefighter health and safety also need to be considered[17-20].

The complexity and unpredictability of a bushfire scenario exacerbates the task of monitoring and assessing firefighters exposures. A wide range of air fuel ratios exist, moisture content varies, fuel source composition changes and wind direction and strength are inconsistent. Another matter to consider when assessing air toxic emissions is sampling and monitoring of firefighters performing different tasks. The numerous roles of a firefighter during the various stages of a fire further complicate the measure of toxic emissions exposure.

This review will present current findings on the constituents and levels of bushfire air toxic emissions, typical for both prescribed and unplanned bushfires. Information will be collated from studies performed in Australia and globally, specifically the United States. It is hoped that the findings along with an understanding of the bushfire scenario, will allow researchers to review accepted exposure indices in light of the bushfire scenario and establish a work code for bushfire firefighting in Australia.

2 BUSHFIRE SMOKE – COMPOSITION & HEALTH EFFECTS

Characterisation of bushfire emissions is extremely complex. Vast arrays of combustible bush fuels exist, with a broad classification including dead woody fuels, live fuels, duff, and litter all with differences in their chemical nature[21]. Fuel composition may also vary from site to site depending on the vegetative nature of the forest. Furthermore a fire consists of different combustion events[21, 22]. Each individual combustion event of a fire will produce different emissions and all the events are likely to occur simultaneously on the fire ground[22].

2.1 Forest fuels

Dead woody fuels may be consumed in a forest fire and include branches, logs, stumps and limbs, either naturally accumulated or due to forest management. Dry, small branches are highly flammable whereas large logs require long periods of dry weather, before becoming highly flammable. Large logs also depend on surrounding fuels to maintain combustion except when very dry[21]. A measure of fuel moisture content and the available mass of dead woody fuel allows for a prediction of the fire risk of unplanned ignition, the possible rate of fire spread and the severity of a bushfire. Prescribed fires are conducted generally to reduce fine and small fuel loadings and hence the likelihood of a severe bushfire.

Live fuels include grasses, low shrubs, ferns, seedlings and other small herbaceous plants. The flammability of live fuels depends on the plant species, moisture content, weather and seasonal variation[21]. In Australia, prescribed burns are conducted annually in low risk conditions.

Duff consists of matted layers of partially decomposed organic matter and soils with high organic content eg humus and peat. Duff is usually moist, compact and supports a slow smouldering combustion process. Duff is often burned when seedlings are planted for regeneration[21].

Litter includes fallen leaves, needles, twigs, bark, and cones that have not decayed. Litter is highly flammable when dry and aerated[21]. Litter poses significant wildfire threat, therefore prescribed burning aims to reduce litter content significantly.

2.2 Combustion

Thermal combustion of the fuels described during a fire involves individual stages, namely, ignition, flaming, and smouldering[21, 22]. All stages generate a large variety of emissions and combustion products that greatly depend on the fuels involved. Ignition is the turning point of endothermic reactions, or energy absorption by the fuels to the initial exothermic reactions of combustion, being flaming. Flaming occurs at initial stages with fine fuels and surface materials supplying the volatile fuel needed to sustain oxidation reactions. During flaming volatile hydrocarbons are vaporised from the fuels. When carbon accumulates on the surface of solid fuel, the gases vaporising from the fuel are no longer sufficient to sustain flaming combustion and the smouldering process of combustion that includes glowing takes over. For combustion to continue oxygen must reach the surface of the fuel, so that oxidation can occur creating heat to accelerate pyrolytic reactions and volatise gases from deep within the woody fuels - this leads to the formation of charcoal, which burns via glowing combustion (surface reaction of oxygen with carbon)[21, 22].

A direct association results between the combustion of fuels and the resulting chemical species emitted. For example, tar (levoglucosan) results from the pyrolysis of cellulose, furan derivatives result from the pyrolysis of pentoses, acetic acid, results from the pyrolysis of acetyl groups in wood, and an assortment of aromatic compounds result from the pyrolysis of lignin[21]. At elevated temperatures, secondary reactions occur and molecules are fragmented as the products of pyrolysis are transported into regions containing sufficient oxygen for combustion. Combustion emissions and pollutants produced from forest fuels are many and may include carbon monoxide (CO), hydrocarbons and incomplete combustion products such as methane, ethylene, alkynes, aldehydes, furans, carboxylic acids, polycyclic organic material (POM), and polynuclear aromatic hydrocarbons (PAHs), particulate matter (mixture of soot, tars and volatile substances) nitrogen oxides (usually form at temperatures greater than most prescribed fires as a N_2 dissociates, but some NO_x form at lower temperatures, the amount of NO_x amount depends on N content of fuels), sulfur oxides (generally negligible as S content of forest fuels are low), ozone and oxidants (found in plumes)[13, 21].

2.3 Air toxics

Experimental burns under controlled simulated conditions in the laboratory provide essential information on combustion products and their variability according to fuel type, fuel conditions and combustion conditions ([23-32] and summarized by Andreae and Merlot[22]). The following section reviews the major air toxics released during combustion of forest fuels and their potential health effects.

2.3.1 Carbon monoxide

Carbon monoxide (CO) is produced during incomplete combustion of vegetation litter and may be present in significant amounts at bushfires. Combustion experiments under controlled conditions have shown that highest ratio of CO production was measured under smouldering conditions immediately after cessation of the flaming phase[13]. Carbon monoxide is a colourless and odourless gas which when inhaled binds to haemoglobin, the red blood pigment that normally carries oxygen to all parts of the body. Carboxyhemoglobin (COHb) is produced inhibiting transport, delivery and utilisation of oxygen. CO has a half life of about 4-5 hours, and COHb levels will return to background levels once CO exposures are eliminated. Exposure to elevated levels of CO can result in cognitive impairment, reduced work capacity, dizziness, nausea, disorientation and behavioural effects. The risk for CO induced symptoms depends on each individual. People at greater risk for CO ill effects include heavy smokers and individuals with cardiovascular disease (possibility of severe health problems if COHb exceeds 5%).

2.3.2 Particulate matter

Particulate matter (PM) or aerosols are produced in large amounts during bushfires with more particles being emitted during the smouldering phase[12, 13]. The majority of particles are those with a mean diameter less than 2.5 μm ($PM_{2.5}$), classed as respirable. Particulate particles specifically respirable, cause extensive respiratory problems, both long and short term for fire fighters annually, as they persist longer in ambient air and can penetrate the alveolar region of the lung. $PM_{2.5}$ particulates also have a large surface area to mass ratio and therefore they may deliver proportionally more harmful adsorbed contaminants deeper into the lung tissue. About 40-70% of the fine particles consist of organic materials, and many of the carcinogenic compounds are contained within this fraction. 2-15% of particulate is graphitic or elemental carbon and the rest is inorganic ash[12, 21].

Polycyclic aromatic hydrocarbons

Polynuclear or polycyclic aromatic hydrocarbons (PAHs) form a portion of the organic compounds contained either within or adsorbed on the fine particulate matter[12, 21]. These compounds form from carbon fragments to large molecules in low oxygen environments (fuel rich region of flame). Numerous PAHs exist and they are produced at different rates depending on the fire conditions, with a strong dependency on the fuels that are burned[28, 33, 34]. One PAH physiologically active carcinogen is Benzo(α)pyrene. The emission factors for Benzo(α)pyrene increase as the density of live vegetation increased in prescribed fire units in Western Washington and Western Oregon USA[12]. There is also a strong dependency on combustion conditions, for example in low intensity backing fires, the ratio of Benzo(α)pyrene to particulate matter ranged from 98 - 274 μg per gram of particulate matter and for heading fires the ratio was 2-3 μg [12]. Many PAHs are recognised as carcinogens and it is hypothesised that PAHs may undergo metabolic activation and can subsequently bind to DNA[16].

Silica

Crystalline silica or silicon dioxide, occurs in the form of mineral quartz eg in sandstone, crystobalite a high temperature form of silica, and tridymite. There is suspicion that exposure can occur during bushfire fighting. Exposure to crystalline silica via inhalation develops a disease known as silicosis. Silicosis can be acute or chronic[35]. Acute silicosis is the most severe case of silicosis, and can occur within months with large exposures to free silica eg quartz. The occurrence of acute silicosis is quite rare, unless poor work practices are adopted. Chronic silicosis is known as the more traditional form of silicosis. At this stage an increase in lung impairment occurs which may eventually lead to respiratory failure and death[36].

2.3.3 Aldehydes

A range of aldehydes are generated during combustion of forest fuels, including formaldehyde, acrolein, acetaldehyde and furaldehyde. Aldehydes are respiratory irritants and some are potential carcinogens. Formaldehyde is the most abundant aldehyde produced during bushfires, and likely to cause irritative effects observed among firefighters. Formaldehyde has also recently been classified by the International Agency for Research on Cancer (IARC) as a known human nasal carcinogen (http://www.iarc.fr/ENG/Press_Releases/archives/pr153a.html). Acrolein is known to cause irritation at levels as low as 100 ppb and is a more potent irritant than formaldehyde[14]. Even though it is likely to be present at lower concentrations, it may contribute significantly to the irritant effects caused by bushfire smoke. 2-Furaldehyde has also been found to be a major product emitted during combustion of forest fuels. 2-Furaldehyde is a suspected carcinogen and may potentially be present at hazardous levels on the fire ground[31].

2.3.4 Organic acids

Organic acids, including formic and acetic acid, are known to be produced during combustion of forest fuels[31, 37], with acetic acid being a major emission product from forest fires. Acetic acid is a respiratory irritant and therefore likely to contribute to eye, nose and throat irritation experienced by firefighters.

2.3.5 Volatile and semi-volatile organic compounds (VOCs and SVOCs))

A range of volatile and semi-volatile organic compounds are released during bushfires[22, 24, 25, 31]. Major VOCs include benzene, toluene, xylenes, as well as phenolic compounds, which are produced from the oxidation of cellulosic fuels. Some of the phenolic compounds are strong irritants.

2.3.6 Ozone

Ozone is formed photochemically near the top of smoke plumes and unlikely to be present at concentrations of concern close to fires. Firefighters working at high altitudes may encounter potentially elevated ozone levels[12, 21].

2.3.7 Free radicals

Free radicals are abundantly produced in bushfire smoke, however little is known about how much of the organic material remains in a free radical state[12, 21]. A recent study by Leonard et al has shown that bushfire smoke particles can generate reactive oxygen species which are important mediators of pulmonary injury, including asthma[38].

2.3.8 Other

Nitrogen oxides and sulphur dioxide (SO_2) are produced from combustion of vegetation containing nitrogen and sulphur. They are produced proportionally to the content of these elements in the vegetation fuel. SO_2 is an irritant of eyes, mucous membranes, respiratory tract and skin.

3 EXPOSURE LEVELS

Personal exposure measurements within the breathing zone of firefighters are essential to assess whether exposure to bushfire smoke air toxics could pose a potential health hazard. The measurements collected during firefighting operations at prescribed burns and accidental wildfires will lead to a better understanding of the extent, frequency and magnitude of firefighters exposure to bushfire smoke, and also enable to determine the key factors that lead to high exposure levels.

The current literature about exposure assessments of bushfire firefighters to air toxics has been limited to the United States with only one available Australian study, done by Brotherhood et al.[39]. The studies reviewed in this paper, and summarized in Table 1 covered primarily the Western States of the US[40-49], except for the study by Kelly[50] conducted in West Virginia and by McMahon & Bush[51] conducted in Georgia. The latter had a primary focus on the presence of herbicide residue in the bushfire smoke.

Between 1988 and 1999, the National Institute for Occupational Safety and Health (NIOSH) conducted six health hazard evaluations on forest firefighting across the USA[4, 40, 43-45, 50]. Four of the studies included personal breathing zone (PBZ) measurements of CO, CO_2, SO_2 and NO_2 using Draeger long-term diffusion tubes as well as measurements of total and respirable particles, VOCs, aldehydes and PAHs[40, 44, 45, 50]. Additionally the same pollutants were measured at base camps[40, 44, 50] and in one instance on the fire ground[44]. Two of the four studies also evaluated effects on lung function, carboxyhemoglobin (COHb) levels from blood samples[44] or from exhaled breath[45] and assessed questionnaires regarding symptoms the firefighters experienced on the fire ground[44, 45]. One of the NIOSH studies investigated cross-season changes in lung function and respiratory symptoms[4], but will not be covered in this review paper. The purpose of the most recent study conducted by NIOSH and the Colorado Department of Public Health and Environment, was to field test a smoke exposure management and monitoring program for CO[43]. The firefighters were provided with CO monitoring equipment and measured their CO exposure levels over one summer firefighting season in 1998.

Extensive exposure assessment studies have also been carried out by the United States Department of Agriculture (USDA) Forest Service[46-49]. They covered both prescribed burns and accidental fires and measured levels of CO, CO_2, benzene, formaldehyde, acrolein and respirable particles. They assessed the inhalation exposure to bushfire smoke among 221 firefighters at 39 prescribed burns in the Pacific Northwest between 1991 and 1994, among 84 firefighters at 8 project wildfires (fires of long duration) and among 45 firefighters during initial attack incidents (forest fires of short duration) in the western states between August 1992 and August 1995.

Additionally to these studies, Materna et al[41] conducted monitoring of firefighters during Northern California fires over 3 fire seasons (1987-1989). They measured CO, total particulate matter, respirable particulate matter, aldehydes, benzene and PAHs.

3.1 Levels of exposures

The data for the PBZ and area measurements are summarized in Table 1. The levels of air toxics are assessed against evaluation criteria for the workplace which included the National Institute of Occupational Safety and Health (NIOSH) recommended exposure limits (RELs), the Occupational Safety and Health Administration (OSHA) permissible exposure limits (PELs) and the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs), displayed in Table 1.

3.1.1 CO exposure

Materna et al[41] reported that the time-weighted average (TWA) exposure for one fire fighter exceeded the 35 ppm 8-hr OSHA permissible limit and that 11% of the fire fighters were exposed to average CO levels greater than 25 ppm. Other studies reported time- weighted averages for CO below the OSHA PEL of 35 ppm[40, 44, 45, 50]. The CO monitoring study done by McCammon and McKenzie[43] has also shown that the time-weighted average exposures never exceeded current occupational exposure limits. The highest average CO exposure level was measured at 22 ppm. The studies carried out at the project wildfires and initial attack incidents by Reinhardt and Ottmar have shown that on average, the OSHA PELs are not exceeded. The maximum averages for CO exposures at the fire line were 39 ppm for the project fires and 28 ppm for the initial attacks, with one measurement above 35 ppm[46]. Issues with exceedances of the recommended guideline of 25 ppm CO were observed for approximately 5% of the shift averages and 10% of the fire line averages during the project wildfires. Only 1 firefighter exceeded this limit during the initial attack wildfires[46]. CO levels at prescribed burns were higher than those measured at wildfires. The TWA exposure for 2 fire fighters exceeded 50 ppm during the burns, but workshift averages remained below this limit. About 1% of the firefighters had workhift averages above 35 ppm, and about 2% and 8% had workshift or fire line averages above 25 ppm[49].

Although CO levels seemed to be within occupational exposure standards, it was suggested that the current standard may not be protective for bushfire firefighters. The CO exposure limit is determined by keeping COHb levels below 5%, and conditions at which the limit has been determined is for a 40-h week work shift and sedentary work at low altitudes. By adjusting for conditions under which the firefighters are likely to work in e.g. correcting for longer work shifts, non-sedentary work and work at elevated altitudes, the adjusted exposure standard would range between 17-21 ppm. If this new adjusted guideline is applied, 30% of the fire fighters sampled during the fire line holding at the Yosemite NP fires[45] and 10% of the firefighters involved in project wildfires[46] exceeded this level. The CO levels taken at the fire ground for the Yellowstone NP fires also exceeded this level[44], indicating that overexposure to CO is a potential hazard even though PBZ measurements did not exceed 8 ppm. Levels of 25 ppm CO are likely to cause headaches, dizziness and inability to properly concentrate on work activities, and Reinhardt and Ottmar[46] suggest that CO should be regularly monitored. This was also highlighted by McMahon & Bush[51], who pointed out that there was not so much a concern of exposures to a lethal dose of CO, but more a concern about CO-induced symptoms of impaired judgement which may lead to inappropriate work behaviour and potential for increased injury risk.

Furthermore the CO ceiling limit of 200 ppm has been found to be exceeded among several wildland firefighters[41-43]. Levels as high as 300 ppm were measured for firefighters operating gasoline engines and doing mop-up work[41, 42]. The highest measured peak concentration for CO in the prescribed burns studied by Reinhardt et al[49] was 179 ppm. The data-logger monitored concentrations over 200 ppm for brief periods of time during the project wildfires, with overall peak exposures ranging from

10-50 ppm[46]. McCammon and McKenzie[43] also reported that 20% of measured CO levels exceeded the NIOSH recommended ceiling exposure limit of 200 ppm and 25% of the CO measurements were above 125 ppm. This indicates that overexposure to CO is a likely hazard during firefighting operations, in particular acute short-term overexposure. McMahon & Bush pointed out that in their study it seemed unlikely to see extremely high CO levels (400-1500 ppm) over a 15-30 min period, but that is was more likely to see periodic exposures to 200 ppm CO[51]. Due to the sampling methods used for CO monitoring, data on peak exposures is quite limited. The use of passive diffusion tubes only provide time-weighted average (TWA) measurements, and peak exposure measurements carried out over short periods of heavy smoke episodes by Reinhardt and Ottmar[46] were limited, in particular during the project wildfires. The use of an electronic data-logger provided much more accurate information on peak exposures

No proper evaluation was achieved for COHb measurements in end exhaled breath. In fact, the samples were taken at the staging areas which were often a 1-2 hr hike through unburned area. Since CO is rapidly metabolized (half-life time of about 4-5 hours), it is likely that the CO was considerably reduced by the time the samples were taken. Furthermore peak exposures experienced on the fire ground cannot be measured. Most of the studies that used biological monitoring for CO measurements reported no to small statistically significant increases in COHb. Brotherhood et al.[39] reported that there was no evidence of hazardous CO levels. Since the samples were not necessarily taken right away when the firefighters returned from the fire ground, they were therefore not able to catch elevated and potentially hazardous exposures while working on the fire ground. The cross-shift changes do not reflect a simple accumulation of additional CO during the shift. Higher levels may have been observed if measurements were taken directly on the fire ground.

Overall, the studies have shown that overexposure to CO is a potential health hazard and therefore would benefit from additional data. It has been shown that TWA levels were in general within occupational guidelines, and that concern about CO-induced symptoms is more likely to arise from short-term elevated CO levels. Therefore, future research on CO monitoring should be carried out using a CO data-logging personal monitor, which would enable to determine acute short-term exposures and relate them to specific conditions or work tasks. This information would be very useful to make firefighters aware of situations where CO levels reach hazardous levels and be included in their training so that they can recognize those situations.

Measurements taken at base camps have shown that they are often located in polluted areas and can not be considered a no-exposure zone. CO levels measured at the base camp by Reh and Deitchman[44] have been as high as the personal breathing zone measurements. This can raise concern, as firefighters may not be able to decrease their COHb levels if they spend most of their time in areas where CO is constantly present. Therefore it is essential to monitor air toxics at base camps, and good practice to measure firefighters COHb levels in exhaled air, before they head back out to the fire ground. It will show whether their rest time in a non-free CO environment was long enough to metabolize excessive levels of CO.

3.1.2 Particles

Personal PM levels measured by NIOSH investigators[40, 44, 50] and McMahon and Bush[51] were low, not exceeding 5 mg/m^3 for respirable particles. Two area samples taken by Reh and Deitchman[44] were exceeding occupational guidelines. Similar one of the area samples taken by McMahon and Bush[51] in dense smoke reached concentrations up to 45 mg/m^3, with an average of 6.3 mg/m^3. Therefore potential overexposure to particles may occur for short-term exposures in dense smoke conditions. The average concentrations for total particulate matter measured during firefighting activities in California exceeded 15 mg/m^3 in 14% of the samples and exceeded 10 mg/m^3 in 32% of the samples. The PEL of 5 mg/m^3 for respirable PM was exceeded for one firefighter. Silica was also detected in one of the personal breathing zone measurements at a level exceeding OSHA PEL of 0.1 mg/m^3[50]. The mean exposures were well below occupational exposure limits, and it could not be explained why one of the samples showed very high levels of respirable particles and silica[50]. The highest level for silica was measured at 0.091 mg/m^3 which approached the OSHA PEL limit of 0.1 mg/m^3[41]. Highest exposure levels to particles were observed during mop-up.

Considering that the composition of respirable bushfire smoke particles is not well known, further studies are necessary to confirm its potential adverse health effects. At this time the use of an inert particles exposure standard may not be adequate to protect firefighters from adverse health effects. In fact smoke particles are likely to contain carcinogens, irritants or other toxics, such as silica, and therefore another guideline may be more appropriate to assess their health effects.

Also all the measurements carried out on particles were done using gravimetric methods. Therefore only the overall particle exposure could be determined. The use of data-logging photometers will enable to provide data on acute short-term exposures, and determine short-term levels that are likely to cause respiratory irritation. As for the CO data loggers, it will help to identify situations where levels of respirable particles are elevated and which may cause potential risk to human health.

3.1.3 Aldehydes

Aldehydes identified in the PBZ measurements included formaldehyde, acetaldehyde, acrolein and furfural, with HCHO being identified as the predominant aldehyde in most studies. Reinhardt et al[49] identified acrolein as the dominant aldehyde during the prescribed burns. Overall levels of aldehydes remained below the OSHA PEL, but there have been some instances where formaldehyde levels reached or exceeded 0.3 ppm, at which concentrations eye or respiratory irritation is likely to occur. Materna et al.[41] reported TWA formaldehyde levels for 2 firefighters at 0.33 and 0.34 ppm. Since formaldehyde is a known nasal carcinogen, it is recommended to keep its exposure levels as low as possible.

NIOSH investigators reported low to very low levels of aldehydes in their area samples and PBZ measurements

3.1.4 VOCs and PAHs

VOCs and PAHs, both gaseous and particle-bound were not detected or below the minimum quantifiable concentration[50]. VOCs identified by Reh et al.[45] included benzene, toluene, xylene and total hydrocarbon compounds, but were present at trace levels. Therefore the NIOSH investigators reported that both VOCs and PAHs are not likely to pose a potential health hazard. Materna et al[41] measured total PAH levels at 1.13 $\mu g/m^3$, which were well below the OSHA PEL of 200 $\mu g/m^3$ and the highest benzene level was measured at 0.5 ppm, with the majority of the benzene levels below 0.08 ppm. Benzene exposure measured during prescribed burns[49] and wildfires [46] remained below the recommended guidelines. Maximum level reached was 0.384 ppm, which was one of the peak exposure measurements to which a firefighter would be exposed to for a maximum of 5% of the time spent on the fire ground. Highest benzene concentrations were observed for engine operators and sawyers.

3.1.5 Other gases

NIOSH investigators monitored crews where smoke conditions during the fires have been considered as light to moderate by the fire fighters. Overall, levels of toxic pollutants are within occupational guideline limits. NO_2 was not detected in any of the PBZ measurements[44, 45] and levels of CO_2 remained below guideline limits[44].

SO_2 levels were exceeding the OSHA limit of 2 ppm in some instances, the highest level being observed at 9 ppm[40, 45, 50]. It was recommended by the authors that administrative controls, eg shortening workshifts, or rotating crews, should be applied to avoid overexposure to SO_2.

3.1.6 Irritant exposure index

Bushfire smoke contains a range of irritants, all of which target the respiratory system. Even though, individual respiratory irritants are below occupation exposure limits, they may have synergistic effects and therefore their combinatory effects need to be taken into account when assessing potential adverse health effects. Reinhardt et al[49] have used a respiratory irritant exposure index to assess exposure of various irritants, eg respirable particles, formaldehyde and acrolein.

The irritant exposure index which measured the additive exposure to respiratory irritants in the bushfire smoke (e.g. formaldehyde, acrolein and respirable particles), was on average 0.4 for work shift exposure and 0.7 for fire line exposure using the recommended TLVs. The highest averages were 4.3 (work shift) and 6.5 (fire line). Based on the enforceable PELs, the irritant exposure index was on average 0.3 for work shift exposure (highest average at 2.6) and 0.4 for fire line exposure (highest average at 3.9). An index greater than 1 indicates that the three irritants exceed the combined exposure limit.

Issues with exceedances of recommended guidelines were observed for CO and respirable irritants for approximately 5-10% of the firefighters, but were compliant with PELs. The irritant exposure index indicated however exposure levels which are likely to cause significant eye, nose and throat irritation for about 30% of the firefighters. Eye, nose and throat irritation were also symptoms reported by 91% of the firefighters at the Yellowstone NP fires[44].

3.2 Factors that influence exposures

Most studies have observed a high degree of variability in exposure levels which is due to firefighters location and assignment, meterological, fuel and combustion conditions.

3.2.1 Work activities

High exposure levels were observed particularly during fire line holding, direct attack operations on spot-fires and supervision of line-holding operations[48]. These work activities are likely to experience exceedances of legal recommended short term exposure limits. Moderate exposure levels were observed during mop-up situations, with elevated levels though observed for respirable particles. Mop-up at smouldering fire has resulted in higher exposure levels than working in proximity to flaming fires[41]. Lowest exposure levels were measured for lighting crews, which in general work upwind of the smoke thereby reducing their smoke exposure. Engine operators were also exposed to high levels of CO[41], and benzene concentrations were more elevated for firefighters lighting burns with drip torches, sawyers and engine operators[41, 48].

3.2.2 Fuel characteristics (type, load, moisture)

A key factor in exposure levels is the development of strong plumes and fuel moisture is a key determinant of fire behaviour and intensity. High moisture content decreases combustion efficiency and thereby increases smoke formation. On the other hand low moisture fuel burns faster, causing oxygen-limiting conditions which lead to incomplete combustion and increased smoke particle formation[52] Reinhardt et al[49] observed a slightly higher smoke exposure for higher fuel loading and high or low fuel moisture. They attributed this to the fact that low fuel moisture (<9%) is likely to create smoky conditions due to more intense fire behaviour and the likelihood of increased spot fire incidences. High fuel moisture (>16%) would similarly result in smoky conditions as the high moisture content would not allow for the development of strong columns to draw the smoke away. Furthermore high moisture fuel is likely to burn more slowly and less completely resulting in an increased pollutant production.

Fuel type is also likely to affect exposure levels due to differences in emission factors for the pollutants and potential different work tactics involved for specific fuels.

Although emission factors have been determined for a range of fuel types, there is not enough data available to evaluate the effect of fuel type on exposure levels.

3.2.3 Meteorology (wind speed, dispersion, humidity, inversion)

Windspeed was the only environmental factor that was correlated to smoke exposure[48]. Downwind smoke exposure increased with ambient windspeed. Increased windspeeds seemed to be an issue if direct fire attack is involved resulting in unhealthy smoke exposure. Materna et al[41] also reported that CO and respirable particle exposures were significantly higher on an evening shift with a temperature inversion compared to a day shift with clear conditions.

3.3 Summary

In summary, the results have shown that exceedances are observed for CO and respiratory irritants and need to be taken into consideration when managing exposure to air toxics. Average shift and fire line smoke exposures as well as peak exposures were higher at prescribed burns than at wildfires. Peak exposures often exceeded ceiling limits. TLVs for CO and Em were exceeded by approximately 5-10% firefighters while on the fire ground. During prescribed burns the TLV for CO was exceeded in 8% of samples and the Em based on the TLVs was exceeded in 30% of the samples (fire line averages). Shift averages were in general below TLVs and PELs as there was some time of no exposure whereas fire line averages exceed TLVs (3-5% during wildfires and 14% during prescribed burns).

Overall CO exposures were within exposure limits, except if adjusted for the work conditions of firefighters. The major concern related to acute short-term exposures which could result in impaired judgment and increase the risk of injury. Even though the TWA for CO are within exposure limits, the firefighter may be exposed to CO levels exceeding current occupational exposure ceiling or excursion limits during as much as 25% of their time on the fire ground. It is also likely to have elevated CO exposures for engine operators, eg sawyers and pump operators. There is clearly a need to better assess peak exposures. For most studies this has not been done as peak exposure assessments were not feasible with the use of diffusion tubes. Some studies used a data-logger which enabled to better assess peak exposures. More data is needed to determine conditions under which high levels of CO are occurring. Other CO monitoring methods are quite useful as they are less expensive, but provide data only for a shift (diffusion tubes) or useful as a post-screening tool (COHb in end-exhaled breath) to determine whether a firefighter could benefit from additional time at the staging area before heading back onto the fire ground. The COHb measurements are not reliable as CO is metabolized quite rapidly and therefore do not indicate high exposures that may have occurred during the shift.

Major respiratory irritants are respirable particles and formaldehyde. Acrolein levels were high during the prescribed burns but remained low in the other studies. Dominant aldehyde was formaldehyde, where it is recommended to keep its exposure levels as low as possible due to the carcinogenic effects of the compound. Levels for HCHO exceeded the proposed limit of 0.3 ppm in some instances, and may be responsible for causing eye and respiratory irritation.

Benzene levels and PAH levels were present, but remained below occupational exposure limits.

4 AUSTRALIA – WHAT DO WE KNOW?

4.1 Current knowledge

In Australia, exposure assessments of bushfire firefighters are very scarce, and the only available study, done by Brotherhood et al.[39], concentrated solely on carbon monoxide (CO) exposures. CO exposures were measured using end exhaled breath analysis (see disadvantage above). Overall sampling time was short (37-187 min) and the likely CO exposure levels were extrapolated to longer workshifts using the Coburn-Foster-Kane (CFK) equation. It is not known whether the sampling time were representative of the firefighters workshift. To date there are no studies available in Australia that evaluate exposure levels of bushfire fighters to air toxics present in the bushfire smoke.

Data can be used from the studies done in the United States but several points need to be taken into account:

- Firefighting operations may not be the same than those in the US, and since work activity is one of the major factors affecting exposure levels, bushfire firefighters exposure to air toxics may be different.
- Due to differences in fuel types, exposure levels for Australian firefighters may be different. Laboratory experiments under controlled conditions have shown

differences in emission factors for various vegetation types. Therefore it is essential to carry out further research on air toxics exposure in Australian bushfire scenarios.

4.2 Future research

Future research should be targeted to:

- assess exposure levels (both average and peak) for Australian bushfire firefighters at prescribed burns and bushfires. The focus should be on short term exposures in dense smoke conditions
- determine exposure levels for various work activities and fuel types which lead to a better understanding under which situations high exposures are likely
- use data-logging monitoring devices which enable to assess short-term exposures of CO and respirable particles. Observations of firefighters are necessary so that high exposures can be linked to specific tasks or situations.
- assess day and night shifts – night shifts are usually more involved in control line strengthening as fire conditions are less intense; furthermore night inversion may trap pollutants and thereby increase concentrations within the breathing zone of firefighters
- monitor off-shift, as base camps may be located in smoky areas in particular during large bushfires and add to the pollutant intake. End exhaled breath measurements for CO exposure may be useful as a post screening tool
- asses correlation between pollutants and possibly allow for a simpler monitoring program
- better characterize particle size distribution and particle composition including hazardous pollutants that may be adsorbed onto the particles. There is a need to develop a more appropriate exposure standard for bushfire smoke particles. It has been shown that the majority of particulate matter is fine particles which consist of 60-70% of organic carbon. PAHs are some of the compounds contained in the organic fraction of fine particulate matter and some of those PAHs adsorbed to the particles may be carcinogenic.
- investigate the synergism between pollutants, in particular for respiratory irritants

- adjust occupational health standards to take into account extended workshifts and heavy workload
- determine ventilation rates so that uptake of pollutants can be assessed and used for further toxicological assessment

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Table 1.

Fire/Burn	Measurements								Ref
	CO [ppm]	SO_2 [ppm]	TPM [mg/m^3]	RPM [mg/m^3]	Formaldehyde [ppm]	Acrolein [ppm]	Benzene [ppm]	Naphthalene [μg/m^3]	
Prescribed burns, Georgia, 1988									[51]
14 prescribed fires monitored									
Firefighters (PBZ)	6-30			0.2-3.7					
	max ~50								
Researchers (PBZ) (high smoke)	18-63			1.1-5.5					
Area samples (high smoke)	21-405			2-45					
Yellowstone NP, Wyoming, 1988									[44]
22 FF monitored; 3 days									
Mop-up (PBZ)	3.6-7.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Fire-line construction (PBZ)	1.9-3.9	ND-1.2	N/A	N/A	N/A	N/A	N/A	N/A	
Base camp (Area)	1.6-6.2	1.0	0.1-0.6	N/A	<0.02	N/A	ND-0.01	ND-3.5	
Fire ground (Area)	3.9-23.3	1.8-1.9	0.2-47.6		< 0.03	N/A	ND-0.03		
Northern California Wildland fires, 1987-1989									[41]
Fire line / mop-up	3-80	N/A	2.7-37.4	0.33-	N/A	N/A	N/A	N/A	
Gasoline engine	20-300	N/A	N/A	5.14	N/A	N/A	N/A	N/A	
Prescribed burning	9.2-17.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Fireline/mop-up & prescribed burning	1.4-38	N/A	N/A	0.24-	0.04-0.34	0.02	< 0.08	0.09-1.13 (total	
				2.71			one at 0.5	PAHs)	
Base camp	4-10	N/A	1.8-4.4	N/A	N/A	N/A	N/A	N/A	
				N/A					
Northern California, 1990									[42]
25 FF monitored; 3 days									
Mop-up peak level exposure	1-16								
	max 339								
Yosemite NP, California, 1990									[45]
3 fire crews; 2 days									
Lighting & fire line holding	6.1-24.2	1.1-2.4	N/A	1.3-1.7	0.06-0.07	0.01	<0.03	20.9-35.9	
Mop-up	1.2-9.4	0.2-2.9	N/A	0.6-1.1	0.02-0.05	ND-0.01	<0.03	11.6-23.9	

Table 1, ctd

Fire/Burn	**Measurements**								**Ref**
	CO [ppm]	SO_2 [ppm]	TPM [mg/m^3]	RPM [mg/m^3]	Formaldehyde [ppm]	Acrolein [ppm]	Benzene [ppm]	Naphthalene [μg/m^3]	
Gallatin NF, Montana, 1991									[40]
2 fire crews; 3 days									
Direct Attack (PBZ)	ND-17	0.6-3	N/A	0.04-4.3 Silica: ND-0.35	ND-0.08	trace	N/A	N/A	
Base camp (Area)	N/A	N/A	0.1	ND	Trace levels		N/A	N/A	
New River Gorge National River, West Virginia, 1991									[50]
20 FF monitored; 2 days									
Direct attack (Fireline construction)	1-9	1-3	N/A	<1.5	Max at 0.1	<0.02	<0.01	<6.1	
Squad or crew boss	2-4	1-3							
Sawyer	2-4	2-9							
Visitor Centre	1	<0.7	0.07	N/A	<0.03	ND	ND	ND	
Prescribed burns, Pacific Northwest, 1991-1994									[49]
221 FF monitored at 39 burns									
Workshift mean	4.1	N/A	N/A	0.63	0.047	0.009	0.016	N/A	
Fireline mean	6.9	N/A	N/A	1.0	0.075	0.015	0.028	N/A	
Workshift maximum	38	N/A	N/A	6.9	0.39	0.06	0.058	N/A	
Fireline maximum	58	N/A	N/A	10.5	0.6	0.098	0.088	N/A	
Peak smoke exposure mean	54	N/A	N/A	7	0.468	0.071	0.064	N/A	
Peak smoke exposure max	179	N/A	N/A	37	1.460	0.129	0.277	N/A	

Table 1, ctd

Fire/Burn	Measurements								Ref
	CO [ppm]	SO_2 [ppm]	TPM [mg/m^3]	RPM [mg/m^3]	Formaldehyde [ppm]	Acrolein [ppm]	Benzene [ppm]	Naphthalene [$\mu g/m^3$]	
Wildfire, Western US, 1992-1995									[46]
Initial attack wildfires (45FF-engine crews; 13 days):									
Workshift mean	1.6	N/A	1.39	0.022	0.006	0.001	0.003	N/A	
Fireline mean	7.4	N/A	5.32	1.11	0.028	0.005	0.014	N/A	
Workshift maximum	13.1	N/A	1.81	1.56	0.058	0.011	0.024	N/A	
Fireline maximum	28.2	N/A	8.64	2.46	0.092	0.037	0.043	N/A	
Peak smoke exposure mean	13	N/A	N/A	2.1	0.087	0.005	0.019	N/A	
Peak smoke exposure max	42	N/A	N/A	6.9	0.339	0.066	0.082	N/A	
Project wildfires (84 FF-hand crews; 17 days):									
Workshift mean	2.8	N/A	1.47	0.5	0.013	0.001	0.004	N/A	
Fireline mean	4.0	N/A	1.72	0.72	0.018	0.002	0.006	N/A	
Workshift maximum	31	N/A	4.17	2.30	0.084	0.015	0.249	N/A	
Fireline maximum	39	N/A	4.38	2.93	0.093	0.016	0.384	N/A	
Wildfire in Colorado, Florida and Idaho, 1998									[43]
3 crews; fire season May-August									
TWA Exposure	0-22								
Peak exposure	0-450								

Occupational exposure standards	CO [ppm]	SO_2 [ppm]	TPM [mg/m^3]	RPM [mg/m^3]	Formaldehyde [ppm]	Acrolein [ppm]	Benzene [ppm]	Naphthalene [µg/m^3]	
TWA (Australia)	30	2			1	0.1	1	52000 ??	
STEL (Australia)	200	5			2	0.3		79000 ??	
NIOSH REL	35[1]	2					0.1		
NIOSH STEL	200								
OSHA PEL	50[2]	2	15[6]	5	0.75	0.1	1	200	
OSHA ceiling limit	200[3]				2[7]				
ACGIH TLV	25[4]	2	10			0.1	10		
ACGIH STEL	400[5]				0.3				

No exposure standard applicable for PM in bushfire smoke. The US studies compared the levels to the ACGIH TLV for particles not otherwise classified and the OSHA PEL for particles not otherwise regulated. This may not be appropriate in assessing exposure to bushfire smoke particles, as they may contain carcinogenic compounds or other toxic elements.

[1] based on risk of cardiovascular effects
[2] formerly at 35 ppm
[3] not to be exceeded at any time over an 8-hr workshift
[4] based on risk of elevated COHb levels
[5] 15 min period, not be repeated more than 4 times per work shift
[6] exposure standard for nuisance dust
[7] 15 min STEL