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Chemical Substances and Biological Agents

Studies and Research Projects

REPORT **R-572**

Wildland firefighter health risks and respiratory protection

Claire Austin

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The visual aspects of this report have been much enhanced by the contributions of photographs courtesy of la SOPFEU, MSA, 3M, and the U.S. Forest Service. I thank them all.

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ABSTRACT

Wildland firefighters are exposed to a complex mixture of combustion products including carbon monoxide, irritant gases and vapours, carcinogens, respirable particles, and nanoparticles. They engage in heavy exercise levels while fighting fires and their work shifts extend to 16 hours or more.

Wildland firefighter studies have been conducted in the United States and in Australia, but no such studies have been conducted in Quebec. Wildland firefighters frequently report respiratory and neurological symptoms. Cross-shift and cross-seasonal decrements in lung function have also been observed. Because of the difficulty in getting sampling equipment to the fire line at the beginning of a fire, most studies have collected personal samples when smoke intensity is “low” or “low to medium”. While some of these studies have been interpreted to show that exposure levels, when averaged over a firefighter’s work week or career, are below 8-hr time weighted average occupational exposure limits, others have demonstrated that exposures to some toxic combustion products far exceed occupational short term exposure limits at least some of the time. Peak carbon monoxide personal exposures up to 1200 ppm have been observed while fighting wildland fires. Peak exposures to combustion products have been found to exceed short-term exposure limits in approximately 50% of cases, up to 3-10 times the STEL.

The substances of greatest concern are carbon monoxide, formaldehyde, acrolein, and respirable and inhalable particles. A second group of concern, but present at proportionally lower concentrations, includes benzene, carbon dioxide (CO_2), nitrogen oxides, PAH, ammonia, and furfural. A third group of concern, but present at proportionally lower concentrations again, includes acetaldehyde, 1,3-butadiene, methane, methanol, styrene, acetonitrile, propionaldehyde, toluene, methyl bromide, methylethylketone, acetone, methyl chloride, xylenes, phenol, tetrahydrofuran, methyl iodide, and mercury. Data suggests that if wildland firefighters are exposed to 25 ppm of carbon monoxide (below the permissible exposure value), they may be overexposed to formaldehyde, acrolein, PAH (benzo[a]pyrene), and respirable particles.

The U.S. National Fire Protection Association has recently announced that it is proceeding with the development of a new wildland firefighting respiratory protection Standard, but it will be some time still before respirators certified for wildland firefighting will become available.

If administrative controls are unsuccessful in reducing exposures to acceptable levels, wildland firefighters should be provided with air purifying respirators for formaldehyde, respirable particulate matter, organic vapours and acids, acrolein, and PAH. However, wildland firefighters should be cautioned that at high work levels the effectiveness and duration of air purifying cartridges is unknown. There is also a concern that firefighters using air purifying respirators may unknowingly expose themselves to higher levels of contaminants not removed by their respirator than they would otherwise. Until a respirator is developed for wildland firefighting that effectively removes carbon monoxide, air purifying respirators should be used in conjunction with a carbon monoxide alarm.

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1. OBJECTIVES

This report is in response to a request received by the IRSST from the *Association de santé et sécurité des industries de la forêt du Québec* (ASSIFQ) (Forest industry health and safety association) and the *Société de protection des forêts contre le feu* (SOPFEU) (Forest fire protection company) for information concerning the need for respiratory protection for wildland firefighters. The IRSST is a non governmental organization whose Board of Directors is made up of equal numbers of representatives from employers and unions. The objective of this study were two-fold: (a) summarize the relevant literature concerning exposure to potentially toxic substances present in smoke from wildland fires and the resulting health risks to firefighters; and, (b) make an independent, health-based recommendation concerning the need for respiratory protection.

2. METHODS

2.1 Literature search

Medline and Current Contents were searched for relevant articles using the search term ((fire*) and (wildland)) or (bushfire*) or (firefight*) or ((emission*) and (fire*)) until September 2007. The U.S. Department of Agriculture Forest Service was searched for relevant reports. The reference lists of the identified publications were reviewed for additional pertinent studies.

2.2 Human resources, working conditions, and accidents

The joint employer/union health and safety committee of SOPFEU was solicited for relevant information and documentation. SOPFEU also provided information concerning workplace accident and workmen's compensation claims. The author, however, had no direct access to or control over this data. Information for other jurisdictions was extracted from the literature.

2.3 Field observations

The author observed wildland firefighter activities for two consecutive days during mop-up at the large 2005 Chibougamau fire on Quebec, Canada. However, no sampling or task analysis was conducted as this was not part of the mandate of this study.

2.4 Smoke components

The components of smoke at wildland fires were identified from exposure studies of wildland firefighters and from emissions studies of burning extratropical forests.

2.5 Hazard ratios

Emissions factors were extracted from the literature. Hazard ratios were calculated for each smoke component by dividing its emission factor by the 8-hour time weighted average threshold limit value (TLV_{TWA}). In the case of formaldehyde and acrolein, ceiling values were used instead of TWAs, and the TWA for nitrogen dioxide was used in the case of nitrogen oxides. Since the result is not based on actual exposure measurements, these hazard ratios were then normalized to the result obtained for carbon monoxide.

2.6 Exposure data

Shift mean time-weighted exposures and peak exposure levels were extracted from the wildland firefighter literature.

3. WILDLAND FIRE MANAGEMENT

3.1 Management agencies

In Quebec, SOPFEU is responsible for the prevention, detection and suppression of forest fires in the province. IPIQ, the Quebec Institute for Fire Protection (Institut de protection contre les incendies du Québec) and EFP, the Quebec Firefighter Training School (École de formation des pompiers) are limited to training municipal firefighters for whom the working conditions, equipment, exposure time, and strategies and tactics used are very different than those affecting wildland firefighters. In Quebec, as in the rest of Canada and in the U.S., wildland firefighter training occurs largely on-the-job.

In Canada, the Canadian Interagency Forest Fire Centre (CIFFC) provides operational fire-control services, as well as management and information services to its member agencies which fall under provincial jurisdiction. CIFFC coordinates services for all of the provinces and territories as well as the sharing of resources with the United States and other countries.

In the United States, the National Wildfire Coordinating Group (NWCG) is made up of the U.S. Department of Agriculture (USDA) Forest Service; the Federal Emergency Management Agency (FEMA); the U.S. Fire Administration; four Department of the Interior agencies: Bureau of Land Management (BLM), National Park Service (NPS), Bureau of Indian Affairs (BIA), and the Fish and Wildlife Service (FWS); the Intertribal Timber Council; and, State forestry agencies through the National Association of State Foresters. The NWCG provides a formalized system to agree upon standards of training, equipment, qualifications, and other operational functions.

3.2 Operational objectives in Québec

Quebec is divided into two zones that receive either intensive or limited wildfire protection. Intensive wildfire protection is provided for 130 million acres (52 665 832 hectares) in Zone 1 covering all regions extending from the Eastern Townships (bordering the United States) to Matagami, Chibougamau and Manic-5 north of the St. Lawrence River. There are five principal wildfire protection stations located in Val d'Or, Maniwaki, Roberval, and Baie-Comeau. In Zone 2, north of this area, there is only limited wildfire protection and wildfires are generally allowed to burn themselves out without any intervention. The wildfire season usually begins in April with approximately 50 wildfires in the Province. The number of wildfires generally rise to approximately 200 per month from May to August, inclusive, then decrease to about 50 fires/month during September and October. On average, 810 wildfires per year burn 0,2 million acres (81 000 hectares) in Zone 1 in spite of the intensive wildfire protection that this area receives (SOPFEU 2003). Large downed wood is not consumed during the passage of the fire front. It is consumed after the fire front has passed during the "ongoing" or smouldering stage.

SOPFEU's operational objectives for all wildland fires in Zone 1 are to "*detect the wildfire before it becomes larger than 1.2 acres (0.5 hectares); attack the fire in full force within one hour of its discovery; control the fire on all fronts before 10:00 a.m. the following day; and, contain and extinguish the fire within a maximum of 7.4 acres (3 hectares).*" In 2003, these objectives were met in 88%-89% of cases. Fire suppression of the remaining 11%-12% of wildfires in Zone 1 may last a number of weeks during which wildland firefighters may be continuously exposed to smoke in varying degrees.

3.3 Human resources

In Quebec, seasonal wildland fire employees are covered by six different collective agreements (SOPFEU 2003). In 2005, there were approximately 450 wildland firefighters potentially exposed to smoke. Of these, 193 permanent wildland firefighters (186 men and 7 women) had 17 years experience, on average. Their mean age was 42 years. Permanent Quebec wildland firefighters are also called upon to fight fires in other provinces when mutual aid is implemented. In 2003, for example, 113 Quebec wildland firefighters were sent to other provinces, particularly to British Columbia.

In the United States, approximately 80,000 wildland firefighters fight approximately 70,000 forest fires that burn approximately 2 million acres (0.81 million hectares) of forest (USDA Forest Service 1989). In addition, more than 5000 municipal firefighters fight more than 2000 wildfires burning 0.5 million acres (0.2 million ha) of wildland and urban interface areas (Hill 2000).

The profile of U.S. wildland firefighters is quite different from those in Quebec. Seasonal workers comprised 95% of participants in a Yosemite National Park study, California (Reh et al. 1994). The mean age of participants was 28 years (n=21, SD=8); 71% of participants were male and 29% were female; 48% of participants were Caucasian, 38% were Native American, and 14% were Hispanic. Smoking status of participants in the Yosemite National Park study was: never smoker (76%), former smoker (10%), and current smoker (14%). Participants reported asthma (10%) and allergy (10%). Study participants had worked five fire seasons, on average (n=21; SD=5). The mean career duration of Type II crew members has been estimated to be 7 years (Reh et al. 1994; Booze et al. 2004), while that of Type I firefighters have been estimated to be 8 years, on average, or a maximum of 25 years (Aldrich 1995).

4. WORKING CONDITIONS

4.1 Transportation, lodging and work shifts

In Quebec, wildland firefighters have much better working conditions than in the other Canadian provinces or the U.S. Unlike their counterparts in western Canada and in the U.S., Quebec wildland firefighters are transported to the fire by land vehicle or helicopter each morning from a motel or hunting lodge located in a relatively smoke free area (Figure 1 and Figure 2). In 2005, they spent a total of 145,689 hours at fires, or 755 hours per firefighter, on average (Drouin 2006).

In the U.S., wildland firefighters experience work shifts of up to 24 hours, sleep deprivation, high altitude, poor diet, heat stress, and exposure to smoke (Ruby et al. 2002). Twelve to 24 hour shifts for 6 days, followed by one day off is typical. Wildland firefighters may work at one fire for two weeks or more. They may hike in each day from temporary base camps or sleep near the fire line because the hike is too long or because there is less smoke than at the base camp. Type I Hot Shot crews from two districts in the State of Washington have been estimated to spend 64 days at wildfires and 5 days at prescribed burns, on average, per year (1990-1994), with the 95th percentile values being 97 days and 17 days, respectively (Booze et al. 2004).

Figure 1 Temporary base camp at a hunting lodge for wildland firefighters battling the 2005 Chibougamau fire (shown in Figure 2).

Courtesy C. Austin

Figure 2. A large forest fire in northern Quebec (Chibougamau, 2005).

In addition to wildfires, there are two types of prescribed fires: (a) low intensity underburn, beneath the canopy which preserves the trees; and, (b) broadcast, or complete burn, which may be high intensity. Type II crews from two districts in the State of Washington have been estimated to spend 10 days at wildfires and 3 days at prescribed burns, on average, per year (1990-1994), with the 95th percentile values being 46 days and 22 days, respectively (Booze et al. 2004). In one study, crew members worked at an altitude of 6100 feet and spent 9 hours on the fire line (Reh et al. 1994). Smoke levels are generally greater at prescribed burns than at wildfires even though the former are generally associated with lower concentrations of fuels. Firefighters must keep the fire within pre-defined limits at prescribed burns causing them to be closer to the fire and resulting in higher personal exposures to smoke than at wildfires. In the case of wildfires, if the fire jumps the fire line, firefighters would likely move further away from the fire and start a new fire line rather than attempt to extinguish the fire and maintain the compromised fire line.

4.2 Physiological work levels

Given the differences in tactics and work methods, it is not known if the total energy expenditure of Quebec wildland firefighters is comparable to that of their counterparts in the United States. However, field observations suggest that wildland firefighting in Quebec is a physically demanding occupation conducted under adverse conditions while at the fire line and during mop-up activities.

Observations of firefighters suggest that they engage in heavy work activity levels while fighting forest fires (Reh et al. 1994). The U.S. Environmental Protection Agency (EPA) estimate for the volume of air inhaled by outdoor workers engaged in heavy work is 20 m^3/day (EPA 1997; EPA 2001). Ventilation rates of 2.4 m^3/hr and 3.6 m^3/hr have been used for wildland firefighter mean and reasonable maximum exposure (RME) level calculations, respectively (Booze et al. 2004). The maximum total energy expenditure for humans is approximately 29-37 MJ/day (Westerterp et al. 1986). Tasks such as hiking, fire-line construction, chainsaw work, and brush removal requires approximately 7.5 kcal/min (Budd et al. 1997; Ruby et al. 2002). Total energy expenditure (TEE) of hot shot crew members engaged in fire suppression activities over five days was approximately 20 MJ/day for men, comparable to 21 MJ/day for simulated military combat training (Hoyt et al. 1991; Ruby et al. 2002). Physical activity (EEA) is approximately 4-12 MJ/day for hot shot crew members and is affected by work assignment, self-selected work intensity and fire location (Ruby et al. 2002; Ruby et al. 2003a; Ruby et al. 2003b, Eglin 2008). Wildland firefighters in the U.S. make heavy use of hand tools and carry a considerable amount of equipment with them (Figure 3). Tactics used in Quebec differ markedly from those used in the U.S. and Western Canada. Figure 4 shows gear typically carried by U.S. Forest Service wildland firefighters. Quebec wildland firefighters make much less extensive use of hand tools, for example, use much more water for suppression, and carry less equipment on their backs

Figure **5**). Being transported by land vehicle or helicopter, Quebec wildland firefighters also hike much shorter distances to the fire.

4.3 Heat stress

Wildland firefighters are routinely exposed to air temperatures of 25-60 °C and a radiant heat flux of 1-8 kW/m^2 (ISO 2006). Heat stress arises primarily from physical exertion in the case of wildland firefighters (approximately 500 Watts) rather than by the fire itself (approximately 200 Watts) (Budd et al. 1996). Wildland firefighters typically lose 1-2 litres of water per hour through perspiration.

During hazardous conditions of short duration, firefighters may be exposed to air temperatures of 60-300 °C and a radiant heat flux of 8-20 kw/m^2. Nasal breathing becomes difficult at 125 °C and mouth breathing becomes difficult at 150 °C, while irreversible injury to dry skin occurs in 30 seconds at 180 °C (ISO 2006).

Firefighters would not be expected to escape from fire over-run or entrapment conditions without serious life-threatening injuries. Under these emergency conditions they could be exposed to air temperatures of 300-1200 °C and radiant heat fluxes of 20-100 kW/m^2 that occur during extreme fire activity.

Courtesy U.S. Forest Service

Figure 3. Wildland firefighters in the U.S. using hand tools (U.S. Department of Agriculture Forest Service 1999).

A

B

Courtesy U.S. Forest Service

Figure 4. Gear carried by U.S. Forest Service wildland firefighters. Photograph A shows equipment typically carried during initial attack. The vertical pouch on the rear is a hydration reservoir ("*camel bac*"). The large pouch in the rear is a fire shelter. The left side pouch holds basic water handling equipment (nozzle, thread adapters, etc). A hose clamp (out of view) is carried on the right side. If assigned to an engine, the firefighter would also carry a 30 pound hose pack. Photograph B shows the additional personal gear pack (water and Gatorade, lunch, extra clothing, etc.) carried on the fire line during extended period assignments (eg. hand crews).

Courtesy SOPFEU

Figure 5. Quebec wildland firefighter using a fire hose. Water, an abundant ressource in Quebec, is pumped from a nearby lake or river.

5. TOXICITY AND EXPOSURE LIMITS OF SMOKE COMPONENTS

5.1 Composition of smoke

The composition of smoke from fires burning various materials is surprisingly similar (Austin 1997; Austin 2001b; Austin et al. 2001b; Austin et al. 2001c; Austin and Wang 2002). Smoke from wildland fires is comprised of a mixture of gases, organic compounds and particles, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), benzene, aldehydes (eg. formaldehyde, acetaldehyde), free radicals and respirable particulate matter (RPM). The major classes of organic compounds identified from biomass burning are homologous series of n-alkanes, n-alkenes, n-alkanoic acids, and n-alkanols; methoxyphenolics from lignin, monosaccharide derivatives from cellulose; steroid and terpenoid biomarkers, and PAHs (Simoneit 2002; Naeher et al. 2007).

The major PAHs found in total extract and some separated fractions from smoke of burning twigs, needles, and cones of conifers, for example, include phenanthrene, fluoranthene, and pyrene, with minor contributions of anthracene, C_1- and C_2-phenanthrenes/anthracenes, benzo[a]pyrene, benz[a]anthracene, m-chrysene, cyclopenta[c,d]pyrene (XXI), and benzo[ghi]perylene (Simoneit 2002). Particulate matter collected from aircraft flying through "thick" smoke at a prescribed burn were less than 1.0 µm, with the majority being 0.1 µm (Vines 1976). However, agglomerates were found having a diameter of 50 µm. A plume of "thick" smoke at a prescribed burn was found to contain up to 10^5-10^6 particles/cm^3 (Vines 1976). The mean composition of the particulate matter was: tar (55%), carbon (25%), and ash (20%) (Vines 1976). A U.S. Forest study sampling wildland fire smoke plumes found similar distribution of particle size and number, the number concentration increasing with decreasing aerodynamic diameter (Radke et al. 1990).

5.2 Smoke toxicity

5.2.1 Acute effects

Smoke from wildland fires is toxic, although it may be less toxic than smoke from municipal fires (Naeher et al. 2007). Population epidemiological studies have demonstrated an association between exposure to ambient particles and increased respiratory symptoms (including reduced pulmonary function), increased hospital admissions, increased emergency department visits, and increased mortality. A few community studies have failed to find increased asthma presentations to hospital emergency departments in association with wildland fires (Cooper et al. 1994; Smith et al. 1996). However, other studies have found an association (Duclos et al. 1990; Emmanuel 2000; Johnson et al. 2002; Chen et al. 2006). Reisen and Brown have discussed the implications for community health from exposure to smoke from wildland fires (Reisen and Brown 2006).

Wildland firefighters are exposed to a large number of substances for which the individual hazard ratios are low relative to carbon monoxide (see sections 6.2.1 and 6.2.2) but for which the irritant effects are additive: acetaldehyde, acetone, acid gases, acrolein, ammonia, formaldehyde, furfural, methyl bromide, methylethylketone (MEK), methyl iodide, nitrogen oxides, propionaldehyde, respirable particles, styrene, tetrahydrofuran, and xylenes. The particulate matter present in smoke likely has irritant properties also as a result of adsorbed gases and vapours. The following smoke components have central nervous system effects which may be additive also: carbon monoxide, nitrogen oxides, methane, methanol, toluene, methylethylketone (MEK), methyl chloride, phenol, tetrahydrofuran, methyl iodide, mercury, and ethylbenzene. Possible synergistic effects resulting from exposure to the mixture of toxic substances present in smoke from wildland fires is unknown. A recent NIOSH study of smoke particles ranging from 0.042-24 μm at wildland fires during mop-up and backburn operations found that ultra-fine particles (0.042-0.24 μm) generated the highest amount of reactive oxygen species (ROS) damage (Leonard et al. 2007). Both ultra-fine and fine particles (0.42-2.4 μm) induced lipid peroxidation. All particle sizes measured generated hydroxide radicals ($^{\bullet}OH$) in the presence of H_2O_2 and caused DNA damage in the presence of H_2O_2, also.

5.2.2 Immunotoxicity

Gas-phase radical precursors contained in wood smoke have sufficiently long lifetimes to be deposited deep in the long where they decompose to free radicals which can cause lung damage (Pryor 1992). Exposure to wood smoke has been shown to result in increased serum amyloid A and plasma factors in humans and changes in general indicators of toxicity in rodents: increased blood platelet number, circulating white blood cells and spleen weight, and decreased blood urea nitrogen, serum alanine, aminotransferase and liver weight (Barregard et al. 2006; Reed et al. 2006). Aldehydes and acids reduce ciliary activity, reducing the ability of the respiratory tract to remove particles and micro-organisms (Dost 1991). It has been demonstrated that immunotoxicity results from exposure to low doses of wood smoke (Fick et al. 1984; Thomas and Zelikoff 1999; Zelikoff et al. 2002a; Zelikoff et al. 2002b; Reed et al. 2006). This may explain, at least in part, an NWCG/U.S. Forest Service observation that 30-50% of visits to field first aid stations were for upper respiratory problems (cold, cough, sore throat) (NWCG 1997). It is unknown to what extent other factors may result in reduced immune function.

5.2.3 Carcinogenicity

Adverse health effects of smoke from biomass fuel have not been well studied. However, IARC has found sufficient scientific evidence to classify smoke from biomass fuel as “probably carcinogenic to humans” (Group 2A) (Straif et al. 2006; IARC In Press). This evaluation was based on limited evidence of carcinogenicity of biomass combustion emissions (mainly from wood) in humans and experimental animals, sufficient evidence of carcinogenicity of wood-smoke extracts in experimental animals, and strong evidence of mutagenicity (Straif et al. 2006; IARC In Press).

Firefighters are exposed to a complex mixture of products of combustion including many carcinogens. However, exposure patterns to intermittently high levels of smoke of variable composition are difficult to quantify in studies of cancer in firefighters. This limits the ability of traditionally designed studies, such as those that have been conducted so far, to properly identify cancer rates in firefighters. Thus, on the basis of “limited evidence of carcinogenicity in humans", IARC has classified firefighting as possibly carcinogenic to humans (Group 2B) (Straif et al. 2007; IARC et al. (In Press)).

The carcinogenic properties of tar from smoke collected at prescribed burns appeared to be much less than coal tar and benzopyrene used as controls, although these tests were inconclusive (Vines 1976). However, a number of known human carcinogens are found in smoke from wildland fires (eg. benzene, benzo[a]pyrene, 1,3-butadiene, formaldehyde, and soot) (NTP 2005; IARC 2006). Many others substances found in smoke from wildland fires can be reasonably anticipated to be human carcinogens (eg. acetaldehyde, ethylbenzene, furan, isoprene, and naphthalene) (IARC 2000; NTP 2005). Others are confirmed animal carcinogens with unknown relevance to humans (eg. tetrahydrofuran) (ACGIH 2007b).

5.2.4 Toxicological models

Much of the work done on the toxicity of smoke has focused on the life threatening aspects of brief, acute exposures to high levels of toxic gases that result in a level of incapacitation that prevents escape or that result in death following escape. Considerable effort has been devoted to the development of models that predict incapacitation based on the combined effects of a mixture of toxic gases from fires (Speitel 1995; Levin 1996; Levin 1997; Purser 2002; ISO 2005; Stuhmiller et al. 2006). All of the models completely ignore aerosols, and although they represent the standard fire gases (CO, HCN, NO_2, SO_2, HCl, HF, HBr, CO_2, acrolein, low O_2) and heat release rate, there are many other toxic compounds present in smoke that are not taken into consideration. Current models of toxic effects of smoke also ignore a number of other important parameters (Stuhmiller et al. 2006): the effect of internal interactions on breathing control mechanisms; the effects on predisposed or hyper susceptible populations; interaction of irritant gases in the upper respiratory tract that may alter uptake; the distinction between low concentrations of irritant gases causing damage resulting in later effects and high concentrations causing immediate effects. In addition, the ventilation response is quite different across species, complicating the extrapolation of test results to humans. Finally, current models ignore internal biochemical and physiological toxic interactions or potentiation effects that are known to occur. These include the interaction of CO_2 and low O_2 (Duffin et al. 2000), competition for hemoglobin among O_2, CO, and NO_2 (Weibel 1984). There are likely many other unknown toxic interactions. Most importantly, these models do not predict either acute or chronic health effects resulting from occupational exposure to smoke.

5.3 Occupational exposure limits

5.3.1 Guidelines vs. legally enforceable limits

This report refers to both health-based recommendations and legally enforceable occupational exposure limits. Occupational exposure limit guidelines are published by the National Institute of Occupational Safety and Health (IDLHs) and by the American Conference of Government Industrial Hygienists (TLVs, BEIs and STELs and ceiling levels). The National Institute of Occupational Safety and Health (NIOSH) is a branch of the U.S. government Department of Health and Human Services, Centers for Disease Control and Prevention (CDC). The ACGIH is a private, non-profit, nongovernment organization. ACGIH occupational exposure limits, published annually, are based on a review of the peer reviewed scientific literature (industrial hygiene, toxicology, occupational medicine, and epidemiology) by committees of experts in public health and related sciences. Unlike consensus standards, the ACGIH does not seek to set limits that are acceptable to all stakeholders. Also, unlike government bodies, the ACGIH does not consider economic and technical feasibility, or the availability of acceptable methods to determine compliance. ACGIH exposure limits are an expression of scientific opinion and are intended for the use of industrial hygienists as guidelines or recommendations to assist in the evaluation and control of potential workplace health hazards. They are only one of multiple factors to be considered in evaluating specific workplace situations and conditions (ACGIH 2007b). In the United States, legally enforceable exposure limits are referred to as "*permissible exposure limits (PELs)*" and are published by the U.S. Occupational Safety and Health Administration (OSHA). In Quebec, legally enforceable "*permissible exposure values (PEVs)*" are published in French and in English in the Occupational Health and Safety Regulations (Province of Quebec 2007).

5.3.2 Various types of occupational exposure limits

TLV. A threshold limit value is the concentration to which it is believed that nearly all workers may be repeatedly exposed, day after day, over a working lifetime, without adverse health effects (ACGIH 2007b). TLVs must be used in conjunction with the most recent edition of the Documentation (ACGIH 2007a). TLVs are listed based on 8-hour time-weighted-averages (TLV_{TWA}), 15-minute time-weighted-average short term exposure limit (TLV_{STEL}), and ceiling values (TLV_C). TLVs are recommended exposure limits.

TLV_{TWA}. Time-weighted-averages are for a conventional 8-hour workday and a 40-hour work week.

TLV_C. Ceiling values are concentrations of substances that must not be exceeded at any time during the day, even briefly (ACGIH 2007b).

STEL. Short term exposure limits are 15-minute time-weighted-average exposures not to be exceeded at any time during a workday even if the time-weighted-average for the entire shift is below the published TLV_{TWA} (ACGIH 2007b). STELs are levels to which it is believed that workers can be exposed without suffering from irritation, chronic or irreversible tissue damage, dose-rate-dependent toxic effects, or narcosis of sufficient degree to cause to increase the likelihood of accidental injury, impaired self-rescue, or materially reduced work efficiency (ACGIH 2007b). Exposures to the STEL should not occur more than 4 times per day, and there should be at least 60 minutes between successive exposures in this range (ACGIH 2007b).

Excursion limit. These may be applied to substances for which there is no STEL or ceiling value. Excursions in exposure levels may exceed 3 times the TLV_{TWA} for no more than a total of 30 minutes during a work day, and under no circumstances should they exceed 5 times the TLV_{TWA}, provided that the TLV_{TWA} is not exceeded (ACGIH 2007b).

IDLH. Immediately dangerous to life and health levels are based on threats of death or immediate or delayed permanent adverse health effects that might occur as a consequence of a 30-minute exposure. This is NOT meant to imply that workers may be exposed to these levels for 30 minutes! (NIOSH 2004a).

PEL. Permissible exposure limits established by the U.S. Occupational Safety and Health Administration (OSHA). These are legally enforceable in the United States.

PEV. Permissible exposure values established by the government of Quebec. These are legally enforceable by the CSST (Commission de santé et sécurité au travail, or workmen's compensation board) in the province of Quebec. The TWAEV is the permissible 8-hour time-weighted average exposure value corresponding to the ACGIH TLV_{TWA}. The STEV is the 15-minute TWA short-term exposure value corresponding to the ACGIH STEL.

5.3.3 Occupational exposure measurement units

Aerosols include suspensions of liquid droplets and particulate matter. The concentration of aerosols in air is expressed as mg/m^3. The concentration of gases and vapours in air may be expressed as either mg/m^3 or parts-per-million (ppm). To convert from mg/m^3 to ppm at NTP (25 ºC and 760 Torr) use Equation 1 (ACGIH 2007b):

Equation 1. Conversion formula (mg/m^3 to ppm)

$$ppm = \frac{\frac{mg}{m^3} \times 24.45}{MW}$$

MW = Molecular weight (molar mass) of the gas or vapour

To convert from ppm to mg/m^3 at NTP (25 ºC and 760 Torr) use Equation 2:

Equation 2. Conversion formula (ppm to mg/m^3)

$$\frac{mg}{m^3} = \frac{ppm \times MW}{24.45}$$

5.3.4 Adjustment of occupational exposure limits

Occupational exposure limits were developed for 8-hour/day, 5-days/week work schedules. Consequently, some exposure limits cited in this report may need to be adjusted in the case of wildland firefighters working longer shifts. The IRSST uses the Haber method to do this. The reader should consult the IRSST Technical Report T-22 (Brodeur et al. 2001; ACGIH 2007b; Drolet 2008). Occupational exposure limits may also need to be adjusted downward to account for the high work levels engaged in by wildland firefighters. Such adjustments exceed the scope of the present report.

5.4 Selected components of smoke

Odour thresholds of selected smoke components and American Conference of Government Industrial Hygienists (ACGIH) threshold limit values (TLV), biological exposure indices (BEI), short term exposure limits (STEL), and levels immediately dangerous to life and health levels (IDLH) are given in Table 1. Occupational exposure limits do not exist for all smoke components having adverse health effects (eg. free radicals).

5.4.1 Particulate matter

There are no occupational exposure limits specifically applicable to smoke particles. However, it is believed that even particulate matter (PM) having low toxicity may still have adverse health effects (ACGIH 2007b). Smoke particulate matter includes a significant fraction of respirable particles (median aerodynamic diameter ≤ 4 µm), including ultrafine or nanoparticles. More than two decades ago, Morrow et al. provided a rational for limiting exposure to respirable particulate matter not otherwise classified (PNOC) to an 8-hour time-weighted-average concentration of 1 mg/m^3 (Morrow et al. 1991). It is unknown what exposure limit would be protective in the case of ultrafine particles that escape alveolar macrophage engulfment and penetrate the alveolar interstitium or translocate to extrapulmonary organs such as the liver and brain (Morrow 1992; Oberdörster 2004). At this time, the ACGIH recommends that exposures to respirable particulate matter not otherwise classified be kept below 3 mg/m^3 (ACGIH 2007b). The 4 µm median cut point is equivalent to $PM_{3.5}$ in older literature. Exposure to respirable smoke particles certainly should not exceed 3 mg/m^3 since they also serve as a vehicle to carry adsorbed toxic gases and vapours into the gas-exchange region of the lung. In the case of inhalable particulate matter (i.e. particles having a median aerodynamic diameter equal to 100 µm) not otherwise classified, the ACGIH recommends that exposures be kept below 10 mg/m^3 (ACGIH 2007b). Historically, environmental regulators have focused on respirable particles having an aerodynamic diameter of 2.5 µm ($PM_{2.5}$) and thoracic particulate matter having an aerodynamic diameter of 10 µm (PM_{10}). There are no exposure limits for particle number. In Quebec, there are no permissible exposure values for either respirable or thoracic particulate matter. The permissible exposure value in Quebec for total particulate matter not otherwise classified is 10 mg/m^3.

Table 1. Occupational exposure limits of selected substances present in smoke

Compound	Units	TLV[a]			IDLH[e]	Odour threshold	BEI[f]					Basis of exposure limit	Remarks
		TWA[b]	STEL[c]	CEILING[d]									
Acrolein (Quebec)[g]	ppm	- (0.1)	- (0.3)	0.1 (-)	2	0.16[h]	-	-	-	-	-	Eye and upper respiratory tract irritation. Pulmonary edema. Pulmonary emphysema.	Skin irritant. Burns easily and is easily volatilized. Intense irritation at 5.5 ppm (Henderson and Haggard 1943). In a short time, 10 ppm or more is lethal.
Benzene (Quebec)	ppm	0.5 (1)	2.5 (5)	- (-)	500	34-119[i]	End-of-shift End-of-shift	Urine Urine	S-Phenyl-mercapturic acid t,t-Muconic acid	25 500	µg/g creatinine µg/g creatinine	Cancer (leukemia). Confirmed human carcinogen.	Skin absorption.
Carbon monoxide (Quebec)	ppm	25 (35)	 (200)	200[j] (-)	1200	odourless[j]	End-of-shift End-of-shift	Blood End-exhaled breath	Carboxy-hemoglobin (COHb) Carbon monoxide (CO)	3.5 20	%COHb ppm	To prevent adverse neurobehavioral changes and maintain cardiovascular exercise capacity for workers at rest or light activity.	-
Formalde-hyde (Quebec)	ppm	- (-)	- (-)	0.3 (2)	20	0.5-1.0[k]	-	-	-	-	-	Upper respiratory tract and eye irritation.	Sensitizer (allergen). Suspected human carcinogen. Most humans experience irritation of the eyes, nose, and throat at 1 to 3 ppm; many subjects cannot tolerate prolonged exposures to 4 to 5 ppm
Benzo[a]-pyrene (Quebec)	mg/m^3	- (0.005)	- (-)	- (-)	-							Cancer	

[a]American Conference of Industrial Hygienists (ACGIH) threshold limit value (TLV). [b]Time-weighted-average over 8 hours. [c]Short term exposure limit averaged over 15 minutes. [d]Ceiling value. The concentration of a substance that should not be exceeded during any part of the working exposure. [e]Immediatley dangerous to life and health. National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit to ensure that a worker can escape from an exposure condition that is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from the environment. [f]ACGIH biological exposure index. The levels of determinants that are most likely to be observed in specimens collected from healthy workers who have been exposed to chemicals to the same extent as workers with inhalation exposure at the TLV. See also the Quebec Guide of biological monitoring (IRSST 2004). [g]Quebec legal exposure limit (Province of Quebec 2007). [h](Amoore and Hautala 1983; ATSDR 2000). [i](AIHA 1989; ATSDR 2007). [j](NIOSH 2005b). [k](ATSDR 1999; Costa 2001).

5.4.1 Polyaromatic compounds (PAHs)

One of most extensively studies polyaromatic compounds is the semi-volatile organic compound (SVOC) and known human carcinogen, benzo[a]pyrene. It is found in coal tar pitch volatiles, coke oven emissions, diesel exhaust, cigarette smoke, and charcoal-grilled food. The OSHA PEL for coal tar pitch volatiles is 0.2 mg/m^3 and for coke oven emissions is 0.15 mg/m^3), but there is no PEL specifically for benzo[a]pyrene. The ACGIH has not established a TLV for benzo[a]pyrene but, given its carcinogenicity, it recommends that exposure by all routes be carefully controlled to levels as low as possible. In Quebec, the permissible exposure value (PEV) for coal tar pitch volatiles is 0.2 mg/m^3 and the ceiling value for benzo[a]pyrene is 0.005 mg/m^3 (Province of Quebec 2007).

5.4.2 Formaldehyde

Exposure to 10 to 20 ppm has been reported to produce almost immediate eye irritation and a sharp burning sensation of the nose and throat which may be associated with sneezing, difficulty in taking a deep breath, and coughing (Eastman Kodak Company 1963). It has been estimated that exposure for 5 to 10 minutes to 50 to 100 ppm might cause serious injury to the lower respiratory passages (Eastman Kodak Company 1963). Most humans experience irritation of the eyes, nose, and throat at 1 to 3 ppm, while many individuals cannot tolerate prolonged exposures to 4 to 5 ppm, and difficulty in breathing is experienced at 10 to 20 ppm (IARC 1982). Upper airway irritation and increased nasal airway resistance has been reported at 0.1 to 25 ppm and lower airway and chronic pulmonary obstruction at 5 to 30 ppm (NRC 1981). It has been estimated that exposure for 5 to 10 minutes to 50 to 100 ppm might cause serious injury to the lower respiratory passages in man (Eastman Kodak Company 1963). In addition to its irritant effects, formaldehyde is a known human carcinogen. There is sufficient evidence that occupational exposure causes nasopharyngeal cancer and strong evidence that occupational exposure causes leukemia in humans (IARC 1985; IARC 1987; IARC 1995; IARC 2004). In Quebec, the ceiling value for formaldehyde is 2 ppm (Province of Quebec 2007).

5.4.3 Carbon monoxide (CO)

Headache may be caused by exposure to 10-20 ppm carbon monoxide at rest or light work levels (Table 2). Other contaminants present in smoke may also cause headache. In addition, poor diet, dehydration, and/or heat stress (all of which have been reported in wildland firefighters in the U.S.) may lead to headache.

Studies of humans at rest exposed to carbon monoxide have found increases in cardiac output above 5% COHb (Ayres et al. 1969; Stewart et al. 1973). Kizakevich et al. (2000) studied 21 healthy, young men exposed to different levels of COHb (5%, 10%, 15% and 20% COHb). At each exposure level subjects exercised with progressively increasing intensity for a total of 15 minutes. There were rest and recovery periods between each exposure. Consistent with previous studies, cardiac output increased in subjects above 5% COHb at rest. It was also found that brief moderate exercise at higher COHb levels may adversely affect cardiac contractility, although it was unlikely to induce irritability of the myocardium or any significant pathological changes in ECG rhythm or wave shape during these very brief exercise periods (Kizakevich et al. 2000).

The ACGIH TLV_{TWA} of 25 ppm corresponds to a BEI of 3.5% carboxyhemoglobin which is intended to prevent adverse neurobehavioral changes and maintain cardiovascular exercise capacity for workers at rest or light activity. Individuals absorb more CO with increasing exercise, so the exposure limit will have to be adjusted downward in the case of wildland firefighters to prevent COHb levels from rising above 3.5% at maximum work levels (Austin 2001a, Scarino and Tardif 2005). In addition, signs and symptoms may be more severe at high exercise levels compared to those reported in Table 2 for any given level of COHb due to the higher oxygen demand of the body during exercise.

In Quebec, the permissible exposure value for carbon monoxide is 35 ppm (Province of Quebec 2007).

Table 2. Carboxyhemoglobin (COHb) and related signs and symptoms

%COHb[a]	Signs and symptoms[b] at rest[c]
< 3	No symptoms.
3-6	Slightly decreased exercise capacity (by 5-7%).
4-17	Slightly decreased exercise time in young healthy men during strenuous exercise. Confusion. Diminution of visual perception, manual dexterity, ability to learn, or performance in tasks such as driving.
10–20	Tightness in forehead, possible slight headache, and dilation of cutaneous blood vessels.
16-20	Headache; Visual-evoked response abnormal.
20–30	Headache and throbbing in temples, easily fatigued, and possibly dizziness.
30–40	Severe headache, weakness, dizziness, confusion, vision dimness, nausea, vomiting, collapse, syncope.
40–50	Same as above, but severity is higher; increased pulse and respiratory rate.
50–60	Increased respiratory and pulse rate, coma, intermittent convulsions, and Cheyne-Stokes respiration, possible death.
60–70	Coma, intermittent convulsions, depressed heart action & respiratory rate, lethal if not treated.
70–80	Weak pulse, slow respiration, respiratory failure, and death within a few hours.
80–90	Death in less than an hour.
> 90	Death in a few minutes.

[a]Percent carboxyhemoglobin for subjects at rest unless otherwise specified.
[b]Stewart (1973, 1975a,b), Horvath (1975), Shephard (1983), NRC (1985).
[c]Signs and symptoms may appear at lower levels of COHb during exercise when the body has a greater demand for oxygen.

5.4.4 Acrolein

Exposure to 5.5 ppm has been reported to produce intense irritation and marked lacrimation, after 60 seconds (Henderson and Haggard 1943). Exposures to 1.8 ppm result in slight eye irritation after 1 minute and profuse lacrimation after 4 minutes (NRC 1981). In volunteers exposed for 5 minutes, concentrations of 2 to 2.3 ppm produced severe irritation (Darley et al. 1960). A 10-minute exposure at 8 ppm and a 5-minute exposure at 1.2 ppm elicit extreme irritation described as "only just tolerable" (Sim and Pattle 1957). In Quebec, the ceiling value for acrolein is 0.3 ppm (Province of Quebec 2007).

6. EPIDEMIOLOGY AND HEALTH SURVEILLANCE

6.1 Epidemiology

There are no epidemiological studies of wildland firefighters, neither in Quebec nor elsewhere.

From 1910-2004, there were 918 wildland firefighter work-related fatalities recorded in the United States (NIFC 2003). From 1990-1998, heart attack was the third leading causing of fatalities (28.21%) in wildland firefighters, following burnovers (29%) and aircraft accidents (30.23%) (MTDC 1999a; NIFC 2003). Volunteer firefighters were more likely than any other group to die at wildland fires: volunteer (31%), federal (26%), contractor (21%), state (14%), city/county (5%), private (2%), and military (1%). Heart attack accounted for 42% of volunteer wildland firefighter fatalities, 15% of federal agency fatalities, and 11% of state organization fatalities. In addition, heat stress accounted for another 11% of State organization fatalities. Figure 6 shows total wildland work-related fatalities and heart attacks in the United States for 1910-2004, while Figure 7 shows the number of work-related heart attacks for the different categories of wildland firefighters: volunteer, Federal, State, County/City, private, contractor, other (NIFC 2003). It can be hypothesized that the apparently higher number of heart attack amongst volunteer wildland firefighters can be explained by a lower level of physical fitness and other personal factors compared to career wildland firefighters. However, more information is needed before attempting to interpret the above data (eg. total number of firefighters in each group and their total number of hours of task related activities).

Structural firefighters working at wildland fires may have a somewhat greater risk of death due to stress and/or heart attack than wildland firefighters. Of 147 firefighter deaths during the period 1978-1987, 111 occurred during fire suppression and 64 of these were municipal firefighters (NWCG 1990). More than half of these municipal firefighter deaths were caused by stress and physical exertion (NWCG 1990). However, epidemiological evidence of increased cardiovascular disease amongst structural firefighters has been inconclusive (Guidotti 1992; Guidotti and Clough 1992; Guidotti 1993; IDSP 1994; Guidotti 1995; Steenland 1996; Haas et al. 2003). In a recent study of Massachusetts municipal firefighters, approximately 75% of retirements were attributed to coronary heart disease (CHD) (Holder et al. 2006). It was found that fire suppression accounted for 43% of on duty events leading to retirement and a 6.4-fold increase in the relative risk of a cardiovascular event during an alarm response. This is a noteworthy observation given that municipal firefighters spend 1-5% of their time at fires (Austin et al. 2001a; Kales et al. 2007). A high prevalence of personal cardiovascular risk factors (46% obesity, for example) was also found amongst municipal firefighters (Holder et al. 2006). A recent case-control study of U.S. firefighters found that increased risk of death from coronary artery disease was associated with fire suppression (OR 12-136), alarm response (OR 3-14), physical training (OR 3-7), and alarm return (OR 2-10) (Kales et al. 2007). These studies suggest that certain firefighting activities increase the risk of a cardiovascular event in susceptible firefighters. However, the relative importance of high physical activity and exposure to smoke (particularly carbon monoxide) in increasing the risk of heart attack in susceptible individuals during firefighting is unknown.

Surprisingly, animal studies have not found wood smoke to be a strong lung carcinogen (Liang et al. 1988; Reed et al. 2006), consistent with epidemiological studies of municipal firefighters that have failed to show a strong association between occupational exposure to smoke and lung cancer. The occupational risk of brain, kidney, and bladder tumours in firefighters has been reviewed by the IRSST (McGregor 2005a; McGregor 2005b; McGregor 2005c).

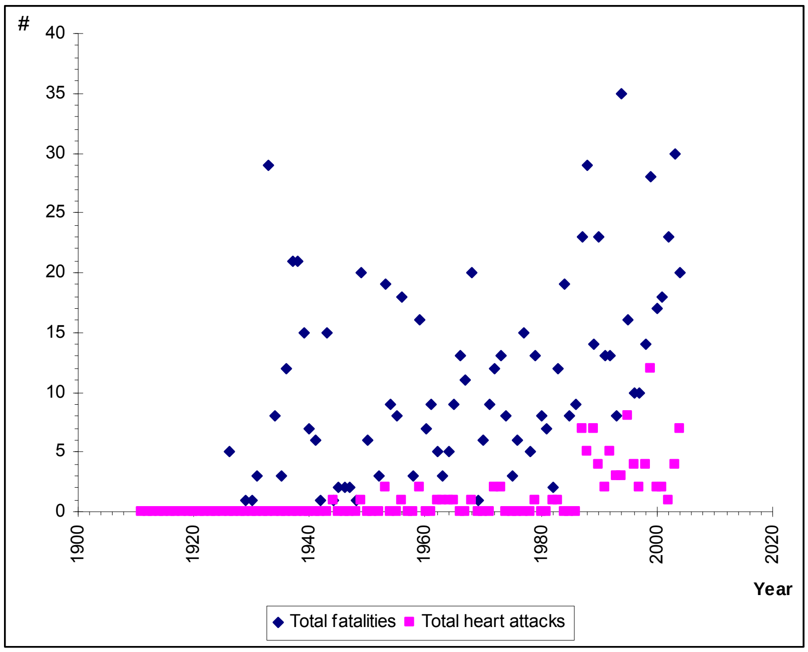


Figure 6. Wildland firefighter work-related total fatalities and heart attacks for the 1910-2004. Adapted from (NIFC 2003) data.

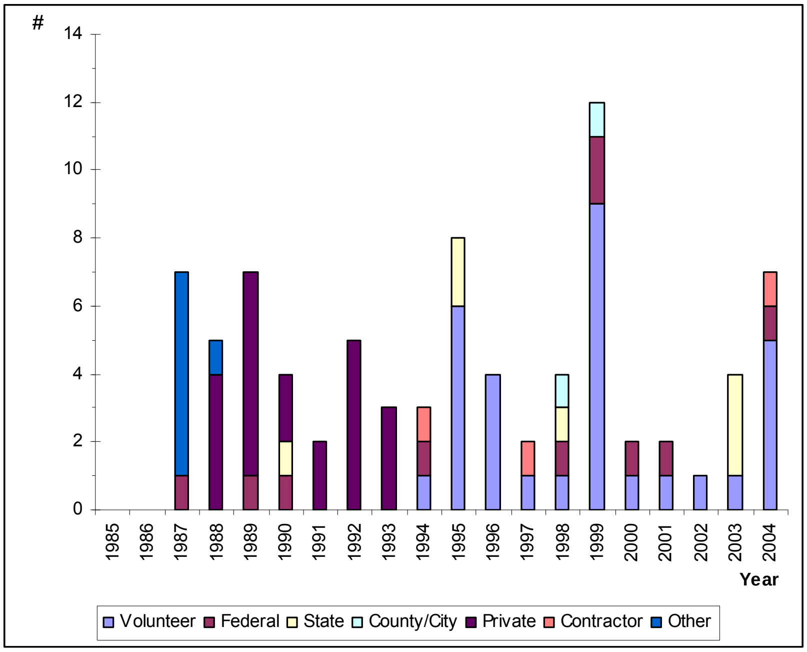


Figure 7. Work-related heart attacks for different categories of wildland firefighters for the years 1910-2004. Adapted from (National Interagency Fire Center 2003) data.

Although municipal firefighter epidemiological studies have found statistically significant associations between firefighting and various forms of cancer: bladder, brain and nervous system, colon, esophageal, genitourinary (aggregate), kidney, liver, lymphatic/hematopoietic, melanoma, multiple myeloma, non-Hodgkin's lymphoma, prostate, rectal, testicular, and ureter cancers (Decoufle 1977; Milham 1983; Eliopoulos 1984; Vena and Fielder 1987; Howe and Burch 1990; Sama et al. 1990; Beaumont et al. 1991; Grimes et al. 1991; Demers et al. 1992; Guidotti and Clough 1992; Guidotti 1993; Aronson et al. 1994; Demers et al. 1994; Tornling et al. 1994; Guidotti 1995; LeMasters et al. 2006; Bates 2007), the findings are not consistent across studies. However, a recent review of the epidemiological literature by the World Health Organization (WHO) International Agency for Research on Cancer (IARC) found that the relative risk compared to the general population was consistently increased for testicular cancer, prostate cancer, and non-Hodgkin lymphoma (Straif et al. 2007).

The observation that municipal firefighters spend only 1-5% of their time (or 18-90 hours per year) at fires (Austin et al. 2001a; Kales et al. 2007) and that exposure levels to many of the potential carcinogens may be relatively low suggests that smoke may be an unusually potent carcinogenic mixture. The suggestion should be considered with caution, however, since the estimate of time spent at fires is based on data collected since the mid 1990's, while the epidemiological data was collected from earlier decades when firefighters may have spent more time at fires and worn little or no respiratory protection. Although a recent study of California firefighters found little evidence of changing trends with time for the periods 1988-1995 and 1996-2003, respiratory protection was in use during both of these time periods (Bates 2007). Benzene is found in virtually all smoke from fires and, at exposure levels typical of firefighting, it is a plausible causative agent for firefighter increased leukemic risk (Austin 2002). Further study is required to clarify the question of carcinogenic potency of smoke from both municipal structural and wildland fires.

Wildland firefighter exposures are intermittent, but they may spend up to 755 hours at fires per season, 8-42 times longer than municipal firefighters. Although smoke intensity inside burning buildings may be higher than that encountered by wildland firefighters, the latter's actual peak exposures may be higher than their municipal counterparts since they do not wear respiratory protection. In view of the above, it would be reasonable to hypothesise that there is an association between wildland firefighting and cancer. It is imperative that epidemiological studies be conducted on wildland firefighters to explore this possibility.

6.2 Medical surveillance

There are no medical surveillance studies of Quebec wildland firefighters. The only data available, culled from SOPFEU records, reveal that during a period of six years (from 2000 to 2005), there were a total of six work-related accidents involving smoke inhalation: two in 2202, two in 2003, and two in 2005 (Drouin 2006). Two of these were asthma cases exacerbated by smoke. In one case, occurring in British Columbia during mutual aid, the subject had difficulty breathing and was vomiting. Amongst the six cases, two occurred during travel on land, one in a helicopter, one during manual work using a shovel, and two during fire suppression using a fire hose. A seventh case, bronchitis, occurred in 2003 during fire suppression using a fire hose, but the treating physician determined that this was not work-related. It is important to note that the numbers of reported work-related accidents provide no information concerning the prevalence of symptoms related to smoke exposure, and that SOPFEU does not collect this type of information.

The most frequently reported symptoms in a NIOSH study of wildland firefighters at the Arch Rock Fire in Yosemite National Park were nose irritation and headache (Reh et al. 1994). In a study of 94 firefighters at the Klamath National Forest fires, 76% reported respiratory symptoms (cough, wheezing, or shortness of breath) and 70% reported at least one neurological symptom (dizziness, light-headedness, headache, loss of consciousness, diminished concentration, confusion, or visual disturbances) (CDHS 1990). The most frequent cross-shift symptoms reported by Type II crews (n=10) were nose irritation and headache but these did not correlate with self-reported exposure levels (Reh et al. 1994). In a study of all California fire fighters, smoke inhalation accounted for 38% of all reported injuries and illnesses (USDA Forest Service 1989). During the 1988 Yellowstone fires, forest firefighters made 30,000 medical visits of which 40% were for respiratory problems (USDA Forest Service 1989). Forest firefighters have been reported to experience cross-seasonal increases in the prevalence of eye and nose irritation, cough, phlegm production, and wheezing (Rothman et al. 1991).

A number of studies of wildland firefighters have found cross-shift and cross-seasonal decrements in pulmonary function (CDHS 1990; Rosado et al. 1990; Letts et al. 1991; NIOSH 1991; Rothman et al. 1991; Liu et al. 1992; Reh et al. 1994; Betchley et al. 1997; Slaughter et al. 2004). The medical significance of the observed cross-shift declines is uncertain, however, since they are generally less than 8% (Ghio et al. 1991). Data suggest that wildland firefighting is associated with decreases in lung function and increases in airway responsiveness and that these associations are independent of a history of cigarette smoking, asthma or allergies, years as a firefighter, age, gender, or crew (Liu et al. 1992; Reh et al. 1994). Changes tend to be small, however, and have not been found to correlate with self-reported smoke exposure levels (Reh et al. 1994). It is not clear whether or not cross-shift declines in lung function are related to diurnal changes (Reh et al. 1994). Cross-shift spirometric measurements were conducted on 65 wildland firefighters while exposures to $PM_{3.5}$ (0.2-1.3 mg/m^3), acrolein (0.002-0.018 ppm), formaldehyde (0.008-0.085 ppm), and carbon monoxide (2.1-10.5 ppm) were measured over the entire shift at prescribed burns (Slaughter et al. 2004). While cross-shift FEV_1 changed by -0.125 L ($p<0.001$), this could not be significantly associated with exposure to any of the measured smoke components. The failure to detect an association with smoke exposure may be due to the fact that peak exposure levels were not measured.

Potential confounders (eg. smoking, colds during the previous four weeks, lung conditions, allergies) have been found to have little effect on cross-shift declines in pulmonary function (Betchley et al. 1997). Similarly, cross-season co-variates (eg. smoke exposure prior to pre-season testing, smoking, colds during the previous four weeks, allergies, and medications) have been found to have little or no effect on cross-season declines in pulmonary function, except for the use of wood for home heating (Betchley et al. 1997). These authors found improvements in lung function from season to season, but noted that longitudinal studies are needed to determine whether or not there are long-term chronic effects.

Charcoal production workers have exposure patterns to wood smoke similar to wildland firefighters. The work involves cutting wood, piling it up and covering it with soil to make kilns of 15-90 m^3, and letting the kilns burn. In a study of charcoal workers exposed to wood smoke for 9-19 h/d for 2-4 weeks, workers experienced increased respiratory symptoms, decreased pulmonary function, and daily headache. Observed mean pulmonary function decrements (FEV_1 -0.196 L (-7%), FVC -1.57 L (-5%), FEF -4 L/s (-15%)) were comparable to those of wildland firefighters in the exposure groups having the heaviest and most prolonged exposures (Tzanakis et al. 2001). Mean peak expiratory flow (PEF) decrements of 16-26 L/min were observed. These decrements were greater in the evening than at midday and greater at midday than in the morning. Given the study design, it was not possible to determine if this diurnal pattern was due to increased exposure time during the day or to cessation of exposure during the night. During exposure, the workers had significantly elevated levels of cough, sputum production (phlegm), wheezing, dyspnoea, and haemoptysis compared to controls, and these symptoms were also significantly increased compared to their pre-exposure assessment. All workers reported daily acute eye, nose, and throat irritation and headache during the exposure period.

In March of 2005, NIOSH invited a small number of researchers and wildland firefighting personnel to a symposium to share unpublished results of ongoing studies and to discuss the direction of future research related to wildland firefighter occupational exposures and health (NIOSH 2005a). Participants heard presentations by Jean-Cox Ganser, Dave Niemi, Denise Gaughan, Sandra Anderson, David Weissman, Brit Rosso, Kevin Jensen, Paul Enright, Steve Leonard, Mark Hoover, Randy Boylstein, and Claire Austin. An ongoing NIOSH medical surveillance study, has found cross-shift and cross-season declines in lung function, post-fire increases in acute respiratory symptoms. These preliminary results have lead the authors to conclude that, "*wildland firefighters are at risk for acute respiratory effects, apparently associated with fighting wildfires*" (Gaughan et al. 2005). In a cross-sectional comparison of municipal firefighters and police, it has been found that firefighters have lower serum pneumoproteins (SP-A) than do police in the absence of differences in FVC, FEV_1, and diffusing capacity between the two groups (Burgess et al. 2003). The clinical significance of this observation is unknown, but the authors hypothesize that SP-A decreases with chronic occupational exposure due to loss of cells in the distal airways and alveoli and that spirometry is too insensitive to measure this effect.

The issue of asthmatic firefighters was discussed at the NIOSH 2005 symposium. Most crew members in the ongoing NIOSH study were non-smokers. Ten participants reported a history of diagnosed asthma – five with active disease. They have replaced flammable inhalers with water soluble inhalers. Legislation prohibits identifying a blanket group, such as asthmatics, and disallowing them for a job. However, the employer does not allow asthmatics at the fire unless the disease is stable and under control. It was pointed out that wildland firefighters work in an environment that is allergen rich (not only smoke and dust) due to the presence of pollens. It is unknown if fire conditions lead to exposure to sensitizers found in some woods (California redwood, eastern white cedar, pine, western red cedar, ash, aspen/poplar/cottonwood, beech, and oak) (ACGIH 2007a). It is not thought that wildland firefighting leads to a pattern of restrictive disease, but there is a question as to whether or not there is an occupational association with asthma or chronic obstructive disease (COPD). There is 10-20% asthma and COPD in the general population, so 4-5 asthmatic individuals in a crew is concerning. There may be a subset of firefighters who are experiencing cumulative damage with successive fire seasons. Forest firefighters are remaining in this occupation for more years than they used to and, as a group, are older than they used to be. There is a question as to whether or not increased asthma or COPD is a result of firefighting or of aging.

Crew leaders have expressed the desire to know which crew members are asthmatic. It was pointed out that the identification of asthmatics is a medical clearance process, not a disqualification process and that it is important to remove the fear in peoples' minds of disclosure by making them realize that very few people are negatively impacted by their employer. The questions are: How to you accommodate individuals who have already been hired and have COPD detected after perhaps 10 years? What should be done when an asthmatic is identified in a pre-hire test? Is it necessary to place asthmatics in low exposure positions? The two key questions are: (1) Can an individual do their job safely and efficiently; and, (2) Can a place be found within the crew or the camp for an asthmatic individual to do a job without placing undue hardship on the employer? The conclusion was that, "There is a lot that can be done. You don't just throw people out, especially when they have accumulated skills and knowledge over a number of years."

Although medical surveillance of wildland firefighters has thus far focused almost exclusively on respiratory effects, it must be emphasized that smoke is a complex mixture of toxic substances having both acute and chronic effects on multiple organ systems. Respiratory health hazards are not the only health risks to which wildland firefighters are exposed.

A recent study has linked biological measurements of wood-smoke derived chemicals with personal measurements of woodsmoke exposure in wildland firefighters (Neitzel et al. 2008). Shift changes in individual and summed creatinine-adjusted guaiacol urinary methoxyphenols were highly associated with CO and, to a lesser degree, levoglucosan. The shift mean CO exposure was 3 ppm. The mean levoglucosan concentration was 0.075 mg/m^3, approximately 8% of the $PM_{2.5}$ mass.

6.3 Periodic medical evaluation

In Quebec, all career wildland firefighters undergo a pre-hiring medical evaluation that includes a medical exam, questionnaire, urine test, audiometry, spirometry, and a lumbo-sacral X-ray. They also undergo annual medical evaluations that include a medical exam and questionnaire.

NFPA Standard 1582 contains descriptive requirements for a comprehensive occupational medical program for fire Departments (NFPA 2007b) and is applicable to fire department candidates and members whose job descriptions are outlined in NFPA 1051, Standard for Wildland Fire Fighter Professional Qualifications (NFPA 2007c), that identifies the minimum job performance requirements for wildland fire duties and responsibilities. The minimum requirements for the development, implementation, and management of a health-related fitness program (HRFP) are described in NFPA 1583 (NFPA 2000). Firefighters must receive medical clearance prior to participating in the fitness assessment described in NFPA 1583. The International Association of Firefighters (IAFF) and the International Association of Fire Chiefs (IAFC) are both committed to firefighter medical and fitness programs as evidenced by the Fire Service Joint Labor Management Wellness Fitness Initiative, developed by the Fire Service Joint Labor Management Wellness-Fitness Task Force (IAFF). The U.S. Forest Service also has a firefighter fitness program.

7. SMOKE EXPOSURE ASSESSMENT

There are no smoke exposure studies of wildland firefighters in Quebec or in the rest of Canada. During the 1987 wildland fires in northern California and the 1989 Yellowstone National Park forest fire, thousands of firefighters experienced respiratory problems. During the 1989 Yellowstone National Park fire, over 12,000 firefighters made medical visits for respiratory problems and 600 required subsequent medical care. During the 1988 Clover Mist fire in Yellowstone National Park, 26 firefighters reported to a medical clinic with the following symptoms: nausea/vomiting (69%), headache (38%), eye irritation (27%), cough (23%), shortness of breath (19%), and chest pain (19%) (Reh and Deitchman 1988). NIOSH investigators believe that firefighter exposure to chemical by-products generated when sulphur-rich soil and rock burns, such as that found in the geothermal areas at Yellowstone National Park, was responsible for the reported symptoms. A literature review conducted by the U.S. Bureau of Land Management in 1991 concluded that there was a critical need for exposure assessment of wildland firefighters (Dost 1991). The 1987-1989 fires prompted the NWCG, the U.S. Forest Service and other related agencies to conduct studies of wildland firefighter exposures to smoke between 1989 and 1997. The results of those studies were reviewed at an NWCG/U.S. Forest Service Consensus Conference in 1997 where participants voted on a list of recommendations (NWCG 1997; MTDC 1999b). The results of these studies have also been published in various reports and journal articles (Driessen et al. 1992; Materna et al. 1992; Materna and Koshland 1993; Betchley et al. 1997; Reinhardt and Ottmar 1997; Reinhardt et al. 1999; Reinhardt and Ottmar 2000; Reinhardt et al. 2000; Booze et al. 2004; Reinhardt and Ottmar 2004; Slaughter et al. 2004). The NWCG/U.S. Forest Service 1997 Consensus Conference report noted that, "*exposure studies show that firefighters are sometimes exposed to levels of smoke that exceed OSHA (U.S. Occupational Safety and Health Administration) permissible exposure limits*" (NWCG 1997). A review and discussion of the literature by the U.S. Forest Service in 1997 noted that, "*Smoke exposure data are limited in geographic scope and representativeness and focus mostly on large Western U.S. wildfires or prescribed fires in the Pacific Northwest. Data collection efforts have been ill-prepared for the mobility and responsiveness needed to capture smoke exposure during initial attack. As a result, most studies have obtained many duplicative measurements of smoke exposure during the latter stages of fire suppression when smoke exposure is considered low. Exceptions to this have identified a limited but significant problem. Smoke exposure is likely to be the highest during initial attack, during direct attack of fires in high winds, and in large-fire situations that suffer from poor atmospheric dispersion*" (Reinhardt and Ottmar 1997).

7.1 Visual assessment of smoke

Forest firefighters rely on personal judgment based on a visual evaluation of smoke intensity and the degree of eye and respiratory irritation to make field decisions for acceptable smoke exposure. Photographs can illustrate the types of exposure experiences by firefighters, but they must be interpreted with caution. Figure 2 and Figures 8-9 show the situation at a large forest fire in Chibougamau in 2005 where a series of photographs taken by the author illustrate how photographs taken seconds apart or at a slightly different angle can give a different impression of reality (Austin 2005). With that caveat, Figure 10 shows different smoke exposure situations faced by Quebec firefighters.

7.1.1 "Low", "medium", "heavy" smoke levels

Visual estimates of smoke exposure have been made (low, medium, heavy smoke) based on how far firefighters thought that they could see through the smoke (Reh et al. 1994). Medium intensity was defined as "thick enough to make it difficult to see beyond 100 yards". Discussions with two SOPFEU wildland firefighters, members of the respiratory protection committee, and comparison of photos shown in Figures 8-13 suggest that U.S. and Quebec wildland firefighters would be in agreement in their assessment of what constitutes low, medium, heavy, and very heavy smoke levels. As part of U.S. Forest Service study conducted in the western U.S. from 1992 to 1995, an attempt was made to correlate measurement of smoke components with visual assessments of smoke intensity (Figures 11-13). Ten observers were asked to categorize their exposures as 1 none, 2 light, 3 medium, 4 heavy, or 5 very heavy. Statistically significant, but highly variable, linear correlations were found between observers' categorization of smoke intensity and measured exposures to $PM_{3.5}$ (r=0.77, n=41), carbon monoxide (r=0.60, n=58), and formaldehyde (r=0.62, n=56), sampling periods lasting a maximum of 20 minutes (Reinhardt and Ottmar 2000). The best correlation was found with particulate matter (Figure 14). Variability appeared to increase with increasing smoke intensity for levels greater than light smoke, more so in the case of carbon monoxide and formaldehyde than in the case of respirable particulate matter. Nonetheless, the authors of this U.S. Forest Service study found that observers could visually estimate smoke exposure sufficiently accurately to determine whether or not administrative controls should be implemented or respiratory protection used.

One firefighter who had been working in very heavy smoke suffered from extreme nausea (Figure 13). It was estimated from extrapolated regression curves (described further in the text) that he had been exposed to 58 ppm carbon monoxide, 0.3 ppm formaldehyde, and 6 mg/m^3 respirable particles (Reinhardt and Ottmar 2000). However, actual measured levels were 3-5 times higher than predicted from the regression equations. Smoke conditions for firefighters holding a fire line at a prescribed fire were found to be uncomfortably high in Figure 15 (Reinhardt et al. 2000).

A. B.

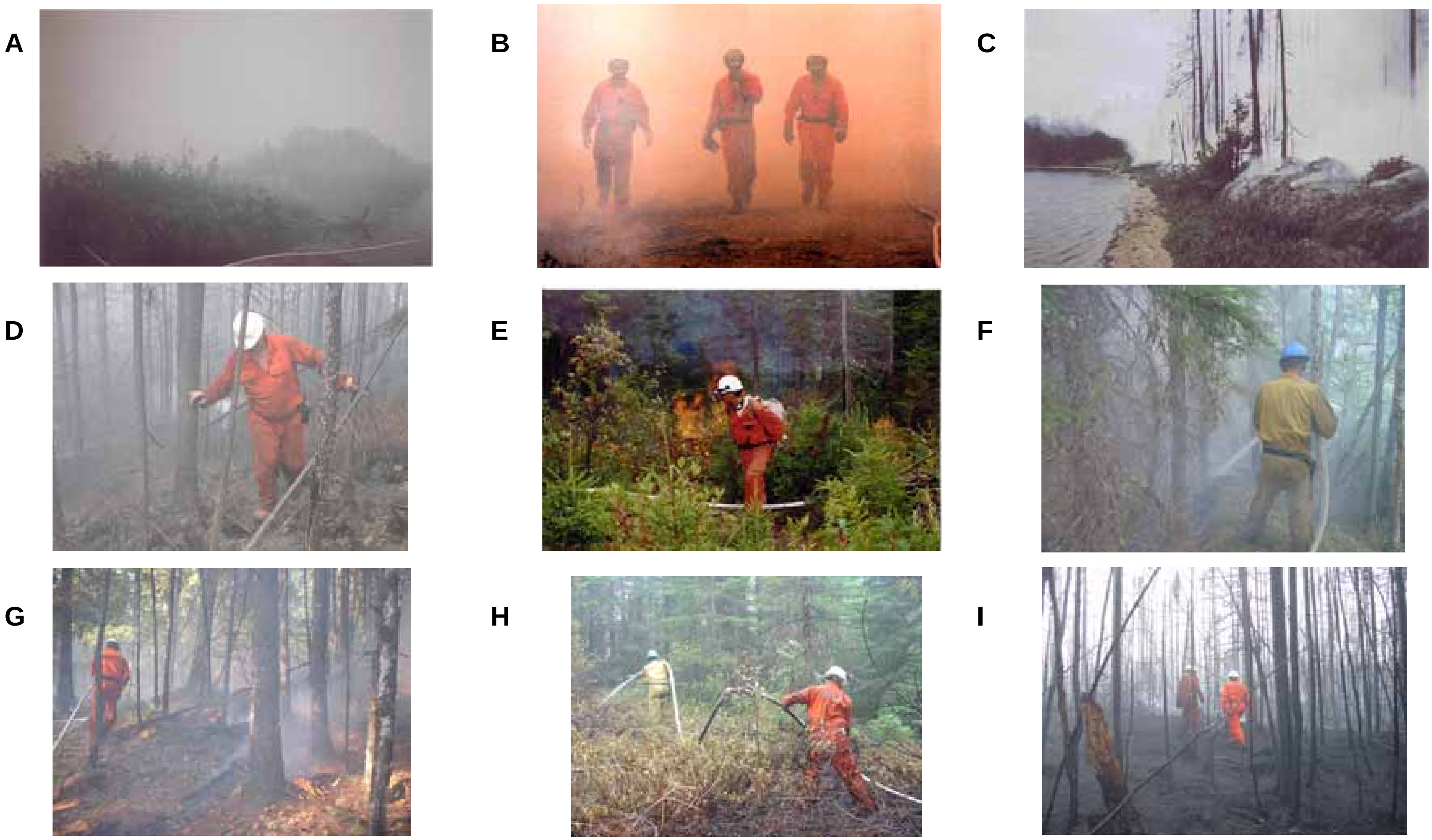
Courtesy C. Austin

Figure 8. Mop-up at a large forest fire in Quebec; no respirator worn (Austin 2005). Photographs A and B were taken within a minute of each other, illustrating the rapidly changing exposure levels in a fixed location.

A. B.

Courtesy C. Austin

Figure 9. Mop-up at a large forest fire in Quebec; no respirator worn (Austin 2005). Photographs A and B were taken within a second of each other but from a slightly different angle, illustrating how two photographs of the same scene can convey different impressions of smoke intensity.



Courtesy C. Austin & SOPFEU

Figure 10. Examples of smoke exposure situations encountered by Quebec forest firefighters.

MEDIUM

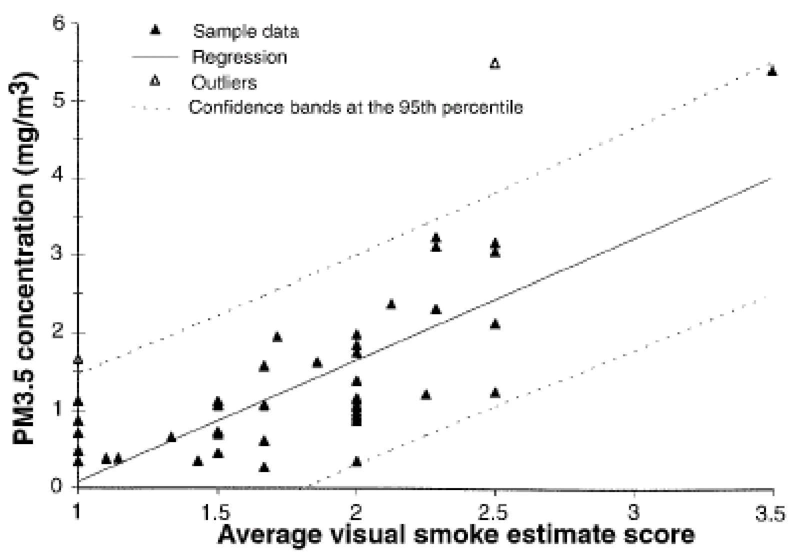
Figure 11. Mop-up at a large forest fire; no respirator worn (Ottmar, R.D. 1994). "Medium" smoke exposure (classified by field observers). No air samples were collected. Levels of contaminants predicted from regression curves (Reinhardt et al. 2000) were: carbon monoxide = 30 ppm, formaldehyde = 0.15 ppm, particles (respirable) = 3 mg/m^3.

HEAVY

Figure 12. Holding a fire line at a prescribed burn; no respirator worn (Ottmar, R.D. 1994). "Heavy" smoke exposure (classified by field observers). No air samples were collected. Levels of contaminants predicted from extrapolated regression curves (Reinhardt et al. 2000) were: carbon monoxide = 44 ppm, formaldehyde = 0.20 ppm, particles (respirable) = 5 mg/m^3. Actual measured levels were 3-5 times higher than predicted (Reinhardt 2007) (Reinhardt, personal communication).

VERY HEAVY

Figure 13. Holding a fire line at a prescribed burn; no respirator worn (Ottmar, R.D. 1994). "Very heavy" smoke exposure (classified by field observers). The firefighter (center of the photograph) suffered extreme nausea. No air samples were collected. Levels of contaminants predicted from extrapolated regression curves (Reinhardt et al. 2000) were: carbon monoxide = 58 ppm, formaldehyde = 0.30 ppm, particles (respirable) = 6 mg/m^3. Actual measured levels were 3-5 times higher than predicted (Reinhardt, personal communication). Figures 11 and 12 were taken minutes apart.



Courtesy U.S. Forest Service

Figure 14. Visual assessment of smoke intensity. Ten observers made visual assessments during project fires and initial attack fires in the Western United States from 1992-1995 (Reinhardt and Ottmar 2000). Sampling periods were less than 20 minutes duration. $r^2 = 0.60$. Smoke intensity categories were: 1 none, 2 light, 3 medium, 4 heavy, 5 very heavy.

Courtesy U.S. Forest Service

Figure 15. Smoke levels were uncomfortably high for firefighters holding a fire line during smoky episodes at a prescribed fire where carbon monoxide and irritant concentrations exceeded occupational exposure limits (Reinhardt and Ottmar 2000).

7.1.2 Confounding factors in visual assessment of smoke

Apart from the type of smoke itself (colour, flaming vs. smouldering conditions, type of combustible), other factors complicate any evaluation of smoke exposure based on a visual assessment. These include light conditions (eg. day vs. night; sun vs. cloud; shade vs. sunlight; sunny day vs. cloudy day), and the moisture content of the smoke (eg. moisture boiled from smouldering fuels, fog, spray from fire hoses). Superfog, for example, is dense white smoke rising several meters off the ground (

Figure **16**). It typically has a visibility of less than a meter and generally dissipates shortly after sunrise (Achtemeier 2003). The five hypotheses explaining Superfog go beyond the parameters of this report. Suffice it to say that the smoke content of Superfog varies greatly from one hypothesis to another. For example, the dense smoke hypothesis is that Superfog is not fog but very dense smoke. The excess moisture hypothesis holds that moisture is released from smouldering logs and stumps and condenses into fog as it cools (Achtemeier 2003). Future correlation studies between visual assessment of smoke intensity and exposure level should take confounding factors into consideration.

Figure 16. Superfog

7.2 Smoke measurement

Smoke from wildland fires comprises a complex mixture of gases, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and particulate matter (see also Section 5.1).

7.2.1 Emission factors

The amount of carbon in biomass material is approximately 45% and, regardless of the combustion phase, most of the carbon released during biomass burning is in the form of CO_2 (85-90%) and CO (Delmas et al. 1995). Emission ratios for the other combustion products can be calculated using the regression line between the species of interest and either CO_2 or CO (Delmas et al. 1995). For compounds emitted during the smouldering phase, correlation is generally better with CO than with CO_2 (Delmas et al. 1995). Emission factors (mg/kg burned), predicting the amount of compound emitted per kilogram of biomass burned, can then be calculated from emission ratios using the carbon mass balance method.

Emission factors for products of combustion from open burning have been extensively reviewed and considerable data is available for prescribed burns and forest fires, agricultural burning, backyard trash burning, and the burning of liquid fuels (Lemieux et al. 2004). The U.S. Forest Service has also studied smoke emissions from wildland fires (Barney and Berglund 1974; Radke et al. 1990; Hardy et al. 1996).

Although VOCs, SVOCs, ketones, and aldehydes are emitted in large quantities from the thermal decomposition of cellulose, the amount of carbon monoxide and particulate matter (PM) emitted from prescribed burns and forest fires is several orders of magnitude greater. Typical emission factors for CO and PM at such fires are 114,700 mg/kg and 17,600 mg/kg, respectively. Other substances of interest include formaldehyde, methanol, 2,3-butanedione, acetone, acetaldehyde, benzene, 2-methyl furan, furfural, methylethylketone (MEK), toluene, acrolein, xylenes, acetonitrile, styrene), 1,3-butadiene, benzaldehyde, PAH, phenol, and TEQ (toxic equivalents of dioxin) (Andreae and Merlet 2001; Gullett et al. 2003).

There may be considerable uncertainty associated with the data used to calculated emission factors. Sources of error include: differences in combustion conditions, particularly flaming vs. smouldering; differences in sampling and analytical methods used to acquire data upon which the calculation of emission ratios is based; and, the substrate material. Emission factors for fire types other than biomass burning (eg. municipal fires; burning of tires, automobiles, fibreglass or liquids) can be quite different. Combustion of biomass produces smaller quantities of VOCs, SVOCs and PAHs than combustion of man-made products such as fibreglass and automobiles, but larger quantities of carbonyls (eg. formaldehyde). The larger quantities of formaldehyde from burning biomass are likely due to the high levels of elemental oxygen bound within cellulose (Lemieux et al. 2004). Tire fires, burning fibreglass, and to a lesser extent burning liquid fuels, emit the greatest quantities of PAHs. The emission factor for PAHs from tire fires, for example, is 4,363.6 mg/kg, while that for benzene at tire fires and burning liquids is 2,180.55 mg/kg and 1,022 mg/kg, respectively (Lemieux and Ryan 1993).

7.2.2 Normalized hazard ratios

Emission factors cannot be used to estimate exposure levels of wildland firefighters to the various components of smoke. However, in the absence of comprehensive exposure data, emissions factors can be used for a first approximation of the types and relative amounts of substances to which wildland firefighters might be exposed, enabling identification of substances of concern. Table 3 shows available emission factors for smoke components from wildland fires in extra-tropical forests (Andreae and Merlet 2001; Lemieux et al. 2004). See also (Simoneit 2002). Carbon dioxide (CO_2) and carbon monoxide (CO) account for 90.2% and 6.60%, respectively, of the burned mass. It should be noted that the available data does not include naphthalene, a prominent smoke component and possible human carcinogen.

Hazard ratios were calculated for each of the smoke components and normalized to the concentration of CO (see Section 2.5 – Methods). Normalized hazard ratios suggest that the substances of greatest concern from an exposure and health standpoint are: formaldehyde, with a normalized hazard ratio of 1.5 times that of carbon monoxide, carbon monoxide (1.0), $PM_{2.5}$ (1.08), acrolein (0.30), and nitrogen oxides (0.134). A second group of substances that may also be of concern, but for which normalized hazard ratios are an order of magnitude less than that of carbon monoxide include: benzene, carbon dioxide (CO_2), PAH, ammonia, and furfural. Finally, a third group includes those substances for which normalized hazard ratios are at least two orders of magnitude less

Table 3. Wildland fire emission factors and normalized hazard ratios for extra-tropical forests

Contaminant	Emission factor studies	% of mass burned [a]	EF [b] (mg/kg)	TLV [c] (mg/m^3)	Hazard Ratio EF/TLV	Hazard Ratio Normalized to CO	Critical effects (ACGIH) [d]
formaldehyde [e]	(Lemieux et al. 2004)	0.13	2,200	0.36 **C** [f]	6111	1.5	irritation, sensitization, cancer A2
carbon monoxide	idem	6.6	114,700	28.6	4005	1.0	anoxia, CVS, CNS, reproductive
$PM_{2.5}$	(Andreae and Merlet 2001)	0.76	13,000	3	4333	1.08	
PM (total)	idem	1.01	17,600	10	1760	0.4	
acrolein	(Lemieux et al. 2004)	0.014	240	0.2 **C**	1200	0.30	irritation, pulmonary edema
benzene [e]	idem	0.028	490	2	307	0.077	cancer A1
carbon dioxide	(Andreae and Merlet 2001)	90.2	1,569,000	9000	174	0.044	asphyxiation
NO_x (as NO)	idem	0.17	3,000	5.6	536	0.134	irritation, pulmonary edema, reproductive, blood, CNS
N_2O	idem	0.015	260	50	3	0.001	CNS, hematologic, embryo/fetus
PAH (benzo[a]pyrene) [e]	idem	0.0014	25	0.2 [g]	125	0.031	cancer A1
ammonia	idem	0.081	1,400	17	80	0.020	irritation
furfural	(Lemieux et al. 2004)	0.027	460	8	59	0.015	irritation
acetaldehyde [e]	idem	0.029	500	45 **C**	11	0.0034	irritation, cancer A3
1,3-butadiene [e]	idem	0.0035	60	4	14	0.0034	cancer A2
methane	(Andreae and Merlet 2001)	0.27	4,700	654	7	0.0018	CNS depression, cardiac sensitization
methanol	(Lemieux et al. 2004)	0.12	2,000	262	8	0.0019	neuropathy, vision, CNS
styrene	idem	0.0075	130	85	2	0.0004	neurotoxicity, irritation, CNS
acetonitrile	idem	0.011	190	34	6	0.0014	skin, lung
propionaldehyde		0.008	140	48	3	0.00074	irritation, nasal
toluene	idem	0.023	400	188	2	0.00053	CNS
methyl bromide	idem	0.00018	3.2	4	1	0.00021	skin, irritation
methylethylketone	idem	0.026	455	590	1	0.00019	irritation, CNS
acetone	idem	0.032	555	1187	0.5	0.00012	irritation
methyl chloride	idem	0.0029	50	102	0.5	0.00012	kidney, CNS, reproductive
xylenes	idem	0.012	200	434	0.5	0.00012	irritation
phenol	idem	0.00029	5	19	0.3	$6.5x10^{-5}$	skin, irritation, CNS, blood
tetrahydrofuran	idem	0.0012	20	147	0.14	$3.4x10^{-5}$	respiratory tract irritation, CNS, hepatic, renal, cancer A3
methyliodide	idem	0.000035	0.6	12	0.1	$1.3x10^{-5}$	CNS, irritation
mercury	(Andreae and Merlet 2001)	$5.8x10^{-6}$	0.1	0.025	0.0045	$1.1x10^{-6}$	CNS, kidney, reproductive

[a]Percent mass burned = EF÷total mg/kg × 100. [b]Emission factor (mg emitted per kg burned). [c]Threshold Limit Value (ACGIH). [d]American Conference of Government Industrial Hygienists. [e]Known, probably or possible human carcinogen (IARC). [f]Ceiling value (concentration not to be exceeded during any part of the exposure). [g]Coal tar pitch volatiles as benzene soluble aerosol.

than that of carbon monoxide: acetaldehyde, 1,3-butadiene, methane, methanol, styrene, acetonitrile, propionaldehyde, toluene, methyl bromide, methylethylketone, acetone, methyl chloride, xylenes, phenol, tetrahydrofuran, methyl iodide, and mercury. Substances for which no TLVs exist accounted for less than 0.12% of the burned mass and do not appear in Table 3 (2,3-butanedione, 2-methylfuran, furan, butanals, pentanones, 3-methylfuran, 2,5-dimethylfuran, ethylbenzene, benzaldehyde, benzofuran, hexanals, octanones, 2,4-dimethylfuran, 2,3-dihydrofuran, 2-ethylfuran, heptanones, and heptanals in decreasing order of importance from 0.044-0.00019 % of burned mass). However, some of these substances are possible human or known animal carcinogens (benzofuran, ethylbenzene, furan, isoprene, and tetrahydrofuran) and should be included in any assessment of smoke carcinogenicity together with the other carcinogens present in smoke at higher concentrations (benzene, benzo[a]pyrene, 1,3-butadiene, and formaldehyde).

The normalized hazard ratios calculated in Table 3 suggest that if wildland firefighters are exposed to 25 ppm of carbon monoxide, they will be overexposed to formaldehyde and possibly also to respirable particulate matter.

Use of Quebec permissible exposure values (PEVs) instead of threshold limit values (TLVs) in the calculation of hazard ratios also yields three groups of substances similar to those identified above. There are two notable exceptions resulting from differences in the exposure limits for carbon monoxide, formaldehyde, and benzo[a]pyrene. Table 4 compares the normalized hazard ratios for the substances of potential concern identified from the available emissions factors. In this case, the results suggest that if wildland firefighters are exposed to 35 ppm of carbon monoxide, they will be overexposed to PAH (benzo[a]pyrene).

The general conclusion arising from this discussion is that limiting exposures to the occupational exposure limit of carbon monoxide may not protect wildland firefighters from overexposure to other substances of concern, in particular respirable particles, formaldehyde, benzo[a]pyrene, and acrolein. The likelihood that this is true is much greater when one considers that an 8-hour time-weighted-average measurement of exposure to carbon monoxide masks peak exposures and that the occupational exposure limits for formaldehyde, benzo[a]pyrene, and acrolein are expressed as ceiling levels that apply specifically to peak exposures.

It should be emphasized that these calculations are based on imperfect data and that they do not represent the concentration of smoke in air. The purpose of this exercise is to identify the most important substances for field sampling and potential candidates that could be used as surrogate measures of smoke exposure. Task related breathing zone measurements are necessary in order to determine actual wildland firefighter exposures to compounds of potential concern. Also, relative amounts of these substances may differ from the emission factors cited above, depending on combustion conditions, temperature (flaming versus smouldering), oxygen transport, local fuel moisture, fuel and soil composition, and wind. Ferlay and Picard, for example, found levels of benzene, phenol and furfural at wildland fires in excess of occupational exposure limits (Ferlay and Picard 1997). In addition to compounds typically emitted at prescribed burns and forest fires, wildland firefighters may be exposed to higher levels of some of these same substances from other sources, including drip torches, burning tires, particulate matter arising from soil and ash kicked up while working, and exhaust from chain saws, pumps, generators, vehicles, and aircraft. Finally, this discussion does not take into consideration

Table 4. Comparison of hazard ratios based on ACGIH TLVs and Quebec PEVs

Contaminant	Emission Factor (EF) (mg/kg burned)	ACGIH TLV [a] mg/m³	Quebec PEV [b] mg/m³	Hazard Ratio based on ACGIH TLV (EF/TLV)	Hazard Ratio based on ACGIH TLV Normalized to CO	Hazard Ratio based on Quebec PEV (EF/TLV)	Hazard Ratio based on Quebec PEV Normalized to CO
PAH (benzo[a]pyrene)	25	0.2 [c]	.005 **C** [d]	125	0.031	5,000	1.7
carbon monoxide	114,700	28.6	40	4,005	1.0	2,861	1.0
formaldehyde	2200	0.36 C	3 **C**	6,111	1.5	733	0.3
acrolein	240	0.2 C	0.7 **C**	1,200	0.3	348	0.1
nitrogen oxides	3,000	5.6	6	536	0.134	536	0.2
carbon dioxide	1,569,000	9,000	9,000	174	0.044	174	0.061
benzene	490	2	3	307	0.077	153	0.05
ammonia	1,400	17	17	80	0.020	80	0.02
furfural	460	8	8	59	0.01	59	0.02
1,3-butadiene	60	4	4	14	0.003	14	0.005
acetaldehyde	500	45	45 C	11	0.003	11	0.004

[a]Threshold Limit Value (American Conference of Government Industrial Hygienists.
[b]Permissible Exposure Value (Quebec regulation).
[c]Coal tar pitch volatiles as benzene soluble aerosol.
[d]Ceiling value (concentration not to be exceeded during any part of the exposure).

potential additive and synergistic effects which certainly exist and which would increase the toxic hazard of smoke exposure.

7.3 Personal exposure measurements

7.3.1 Shift mean time-weighted-average exposures

Because of the difficulty in getting sampling equipment to the fire line at the beginning of a fire, most studies have collected personal samples when smoke exposures are low. NIOSH has conducted five such measurement campaigns at wildland fires in the United States (Table 5). Sampling using a polytetrafluorethylene filter and sorbent tube found low levels of the particulate-bound PAHs: acenaphthene (ND-1.7 µg/m³), anthracene (ND-1.2 µg/m³, n=5), benzo(b)fluoranthene (ND-1.7 µg/m³, n=5), fluoroanthene (ND-9.3 µg/m³, n=5) ((Reh et al. 1994). Levels of gaseous PAHs found were: acenaphthene (ND-1.0 µg/m³), anthracene (ND-26.5 µg/m³, n=5), and naphthalene (ND-35.9 µg/m³, n=5) (Reh et al. 1994). The results of the NIOSH studies are comparable to measurements collect at experimental burns on shrub land in Portugal where the dominant species were *Erica umbellate*, *Erica australis*, and *Chamaespartium tridentatum*. Immediately following a 19 minute experimental burn of a 7650 m² plot of land with a fuel load of 9.9 kg/m² consisting mainly of shrubs with some isolated trees, smoke measurements conducted 75 m from the edge of the plot found the following (Miranda et al. 2005): PM_{10} (3.0 mg/m³), CO (0.055 mg/m³), NO_x (0.45 mg/m³), respectively. Following a 7 minute burn of a similar 5151 m²

Table 5. Firefighter shift mean time-weighted-average exposure levels measured in NIOSH wildland fire studies

Place	Fire	Study	Smoke level	Carbon monoxide		Carbon dioxide		Sulfur dioxide		Nitrogen dioxide		Formaldehyde		Acetaldehyde		Acrolein		Furfural		Respirable particles		Total particles	
				ppm	n[a]	ppm	n	ppm	n	ppm	n	ppm	n	ppm	n	ppm	n	ppm	n	mg/m^3	n	mg/m^3	n
Yellowstone National Park	Shoshone, Clover mist, and North Fork fires	(Reh and Deitchman 1992)	low	1.9-7.8		1000		ND-1.2		-	-	ND-0.03		-	-	-	-	-	-	-	-	0.1-47.7	
Galatin National Forest	Thompson Creek fire	(Kelly 1992b)	low	0-17	20	-	-	0.6-3.0	20	-	-	ND-0.1	20	ND-0.1	20	trace	20	ND-0.04	20	0.04-4.3	26	-	-
New River Gorge National River, West Virginia	Gauley Mountain fire	(Kelly 1992a)	low	1-9	20	-	-	1-3	20	-	-	0.07	20	ND	20	ND	20	high of 0.03	20	0.49	20	-	-
Yosemite National Park, California	Arch Rock fire	(Reh et al. 1994)	low	1.2-9.4	9	-	-	0.2-2.8	5	ND	5	0.01-0.02	3	0.01-0.02	3	ND-0.01	3	0.002-0.004	3	0.6-1.1	3	-	-
Yosemite National Park, California	Arch Rock fire	(Reh et al. 1994)	medium	6.1-24.2	10	-	-	1.1-2.4	6	ND	5	0.06-0.07	2	0.03-0.04	2	0.01	2	0.005-0.008	2	1.3-1.7	3	-	-
Colorado, Florida, Idaho	40 fires	(McCammon and McKenzie 2000)	-	0-22[l]	40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Occupational exposure limit	ACGIH TLV			25		5000		.25 **C**[b]		3		0.3		25 **C**		0.1 C		2		3			
	Quebec PEV			35		5000		2		3		2 **C**		25 **C**		0.3 STEV[c]		2		-			

[a]Number of samples. [b]Ceiling limit. [c]Short term exposure value

plot, peak concentrations of $PM_{2.5}$ measured were 3.0 mg/m^3 at a distance of 110 m from the edge of the plot.

A more recent NIOSH study collected area samples of particulate matter using MOUDI cascade impactors placed in proximity to firefighters at mop-up and back-burn operations over five days and operated without grease substrate (Leonard et al. 2007). The total mass concentration found ranged from 0.75-1.3 mg/m^3. Particle sizes ranged from 0.042-24 µm with approximately 78% of the mass being respirable (Figure 17). Ultra-fine particles (0.042-0.24 µm) accounted for 20% of the mass, approximately half of this mass fraction being in the nanoparticle size range (≤ 0.100 µm).

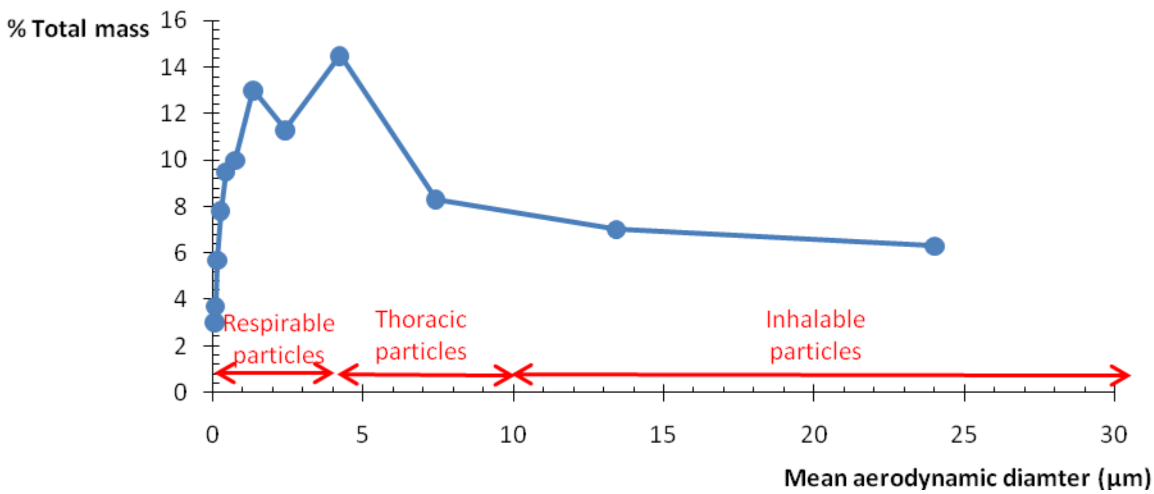


Figure 17. Smoke particle mass distribution. The percent total mass of smoke particles was measured at a wildland fire during mop-up and backburn operations. Adapted from (Leonard et al. 2007).

The U.S. Forest Service conducted a study of 200 firefighters at prescribed burns in the Pacific Northwest from 1991-1994 (Reinhardt et al. 2000), and 84 wildland firefighters at 8 project fires in remote areas for a total of 17 days, and 45 firefighters during initial attack in or adjacent to urban areas for a total of 13 days from 1992 to 1995 (Reinhardt and Ottmar 2000). Smoke intensity was generally "light" or between light and "medium." The fuel species, in order of importance, were: northern and southern California chapparral and oak; western annual grasses and fescues; lodgepole pine; mixed conifers, grand fir, and western larch; oak; and, ponderosa pine. Smoke intensity ranged from none to medium-heavy (see Figures 11-13). Shift and fire-line geometric means and standard deviations for carbon monoxide, respirable particulates, total particulates, formaldehyde, acrolein, benzene, and an irritant index calculated by the authors are summarized in Table 6. The authors found that peak exposures to carbon monoxide likely exceed short term exposure limits during direct attack, initial attack, and while holding the fire-line (Reinhardt and Ottmar 2000). It was thought that exposures would increase, also, during temperature inversion conditions and when firefighters are located on the flanks or downwind of a

Table 6. Firefighter mean time-weighted-average exposure levels measured in U.S. Forest Service wildland fire studies

Type of fire	TWA[a]	Study	Carbon monoxide ppm			Carbon dioxide ppm			Formaldehyde ppm			Acrolein ppm			Benzene ppm			Respirable particles mg/m³			Total particles mg/m³			Irritant index[b,c]	
			max	mean	SD	max	mean	SD	max	mean	SD	max	mean	SD	max	mean	SD	max	mean	SD	max	mean	SD	max	mean
Project fires (1987-1989)	Fireline	Materna 1992	80	-	-	-	-	-	0.42	0.16	-	0.052	-	-	-	-	-	5.14	1.75	-	2.71	1.15	-	-	-
Prescribed burns (1991-1994)	Shift	Reinhardt 2000a	38	4.1	-	-	450	-	0.39	0.047	-	0.060	0.009	-	0.058	0.016	-	6.9	0.6	-	-	-	-	4.3	0.4
	Fireline	Reinhardt 2000a	58	6.9	-	-	519	-	0.60	0.075	-	0.098	0.015	-	0.088	0.028	-	10.5	1.0	-	-	-	-	6.5	0.7
Project fires (1992-1995)	Shift	Reinhardt 2000b	30.5	4.0	2.6	588	465	1.1	0.084	0.013	2.4	0.015	0.001	4.0	0.25	0.004	3.6	2.3	0.5	2.0	4.2	1.5	1.7	1.1	0.2
	Fireline	Reinhardt 2000b	38.8	2.8	2.5	668	493	1.2	0.093	0.018	2.3	0.016	0.020	3.6	0.38	0.006	3.6	2.9	0.7	1.9	4.4	1.7	1.8	1.4	0.3
Initial attack (1992-1995)	Shift	Reinhardt 2000b	13.1	1.6	3.0	706	391	1.2	0.058	0.006	3.1	0.011	0.001	4.0	0.02	0.003	3.3	1.6	0.022	2.50	1.81	1.39	1.2	0.8	0.1
	Fireline	Reinhardt 2000b	28.2	7.4	2.2	742	488	1.2	0.092	0.028	3.0	0.037	0.005	4.0	0.04	0.140	3.2	2.5	1.110	1.60	8.64	5.32	1.4	1.4	0.6
Occupational exposure limit		ACGIH TLV		25			5000			0.3			0.1 **C**			0.5			3			10			1
		Quebec PEV		35			5000			2 **C**			0.3 STEV			1			-			10			1

[a]Time-weighted-average. [b]An irritant index calculated for the combination of formaldehyde, acrolein and respirable particles. It is important to note that this irritant index likely underestimates the irritant effect of the smoke because these authors did not include all of the irritants present in smoke. [c]The occupational exposure limit is exceeded when the irritant index exceeds 1.0.

wildland fire on windy days. An irritant index is calculated assuming simple additive effects of all irritants present in the smoke using Equation 3. Its purpose is to reduce the combined TLV of the individual components:

Equation 3. Additive mixture formula

$$\frac{C_1}{TLV_1} + \frac{C_2}{TLV_2} + \ldots + \frac{C_n}{TLV_n}$$

C = concentrations of components having similar health effects on the same target organ or system.

TLV = applicable TWA, STEL, ceiling, or excursion limits.

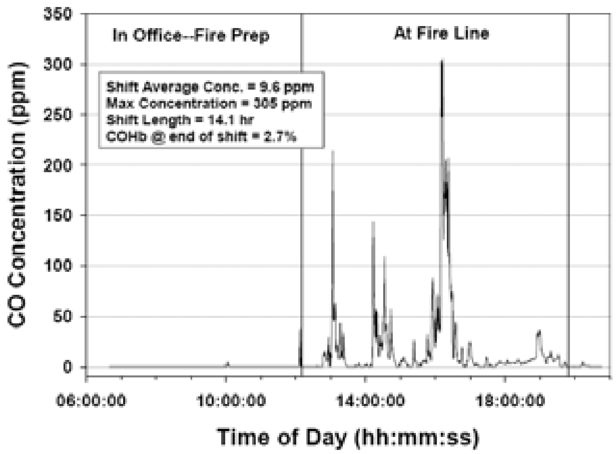
The irritant index calculated by the authors in Table 6 considers only three smoke components: formaldehyde, acrolein, and respirable particles. The result may underestimate the actual irritant index since other smoke components having irritant properties were not included in the calculation (eg. acetaldehyde, acetone, acid gases, ammonia, benzene, furfural, methyl bromide, methylethylketone (MEK), methyl iodide, nitrogen oxides, phenol, propionaldehyde, styrene, tetrahydrofuran, and xylenes). Also, increased irritancy of the smoke particles due to the presence of adsorbed components was not considered. Nonetheless, the authors of this U.S. Forest Service study found that peak exposures to respiratory irritants likely exceed short term exposure limits during direct attack, initial attack, and while holding the fire-line (Reinhardt and Ottmar 2000). Exposure monitoring of 40 firefighters and 10 researchers at more than 20 fires in Australia revealed that the irritant index (considering respirable particles, formaldehyde and acrolein) was exceeded for 30% of the samples collected (Reisen et al. 2007).

Earlier results from prescribed burns show that holding personal are among the more highly exposed groups. However, there is little published data of task related exposures. Although the authors believe that data were collected during average wildland firefighting conditions, most of the sampling at project fires was conducted in the mid to latter phases of the fire. The data are not, therefore, representative of higher smoke levels that may occur earlier during fire suppression efforts. The authors note that the distribution of these shift mean time-weighted-average smoke exposure measurements is biased low, also, because wildland firefighters experience many more low-exposure than high-exposure hours during the season. Discussions with SOPFEU wildland firefighters suggest that that is the case in Quebec also. The authors further note that this data may not be representative of wildland firefighting in the western United States because the individuals sampled were mostly from the same crew at any given fire and data was collected on sequential days at only eight separate fires. In the case of initial attack measurements, the reported shift mean time-weighted-average is biased low, also, because these firefighters spent an average of only 3.3 hours on the fire-line compared to 10.3 hours at project fires. In view of these limitations, the risk assessment (Booze et al. 2004) published by the U.S. Forest Service needs to be re-evaluated.

If measured concentrations of toxic substances to which wildland firefighters are exposed are averaged over a shift, a season or an entire career, and compared to time-weighted-average threshold limit value (TLV_{TWA}), the exposures do appear to be quite low. However, given typical intermittently high exposure patterns, that type of data manipulation is not the most appropriate risk assessment technique for wildland firefighter exposures resulting in both acute and chronic effects. It is also necessary to measure short term exposures and compare the results to threshold limit value (TLV) 15-minute short term exposure limit (TLV_{STEL}) or ceiling values, when available, or to excursion limits (three times the TLV_{TWA}). Where task specific monitoring has been undertaken for a group of wildland firefighters, it is likely that the data is log normally distributed and summary results are properly expressed as the geometric mean ± geometric standard deviation. However, when evaluating the chronic health risks the arithmetic mean, which is always greater than the geometric mean, should be compared to the TLV (Mulhausen and Damiano 1998; Ignacio and Bullock 2006). For compounds having acute effects, the appropriate summary measurement to use is the upper limit of the 95% confidence interval. Exposure data should, therefore, report the arithmetic mean, standard deviation (SD), and the number of samples (n). The data in Table 6, therefore, underestimate exposures when compared to the relevant occupational exposure limits.

7.3.2 Peak smoke exposure levels

Results of another NIOSH study illustrate the importance of measuring short term exposures and not only shift mean exposures (McCammon and McKenzie 2000). A datalogging instrument was used to record shift mean and peak carbon monoxide personal exposures during firefighting activities at 41 fires in Colorado, Florida, and Idaho. While mean shift exposures to carbon monoxide were 3.3 ppm (0-22 ppm, SD 5.2, n=40), mean peak exposures were 88 ppm (1-392 ppm, SD 116, n=40). An additional sample worn by a driver/pump operator recorded a mean of 6 ppm CO with a peak of 450 ppm. A U.S. Forest Service 5-week exposure study at prescribed burns used real-time datalogging instruments to measure peak levels of carbon monoxide and particulate matter. The intermittent nature of peak exposures is illustrated in Figure 18 and in Figure 19 (Edwards et al. 2005; Naeher 2006; Naeher et al. 2006). An example is shown where a maximum peak of 305 ppm CO was found, although the mean shift carbon monoxide concentration was 9.6 ppm (Figure 18) (Naeher et al. 2006).



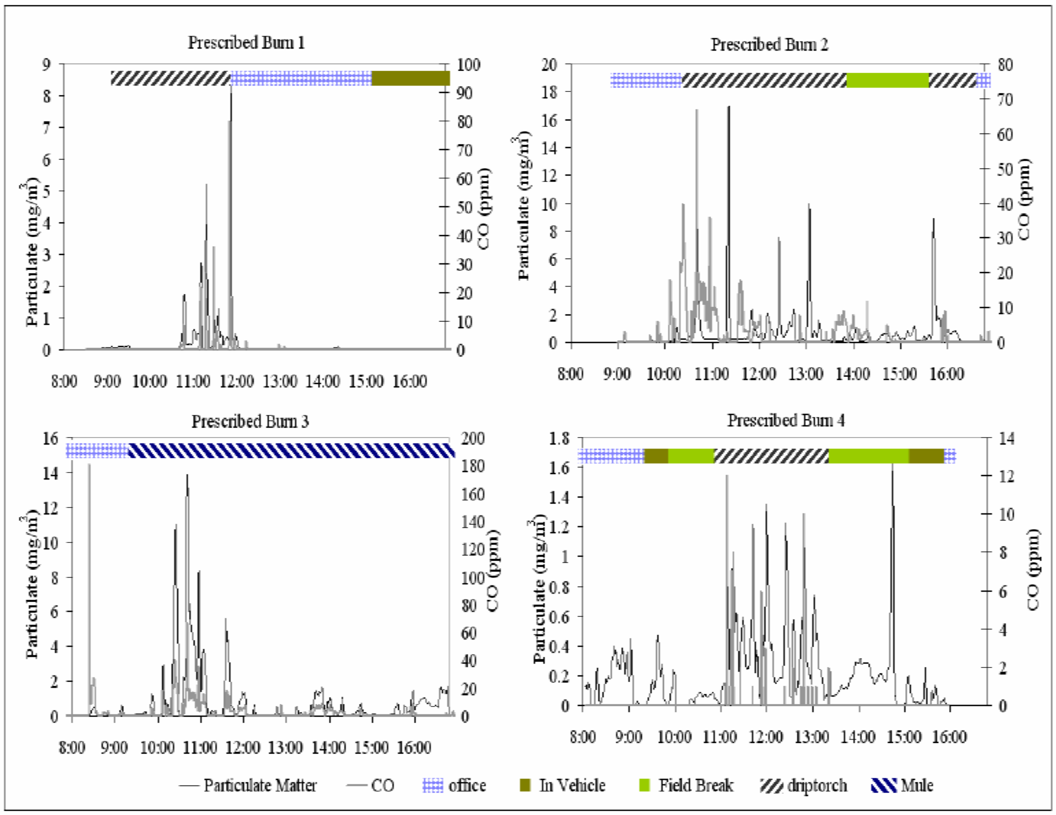
Courtesy R. Edwards

Figure 18. Wildland firefighter intermittent exposures to carbon monoxide at the fire line (Naeher et al. 2006).

Figure 19 illustrates the high variability in carbon monoxide and particulate matter in wildland firefighter exposures (Edwards et al. 2005). Whereas peak $PM_{2.5}$ and carbon monoxide concentrations ranged up to 17 mg/m^3 and 68 ppm, respectively, shift means were 0.16-0.67 mg/m^3 and 0.05-4.4 ppm. Rise and fall of particulate matter and carbon monoxide levels coincided sometimes, but not always. It is possible that this inconsistency is due to changes in the nature of the smoke. Higher particle levels may also have arisen from soil and ash when walking or using hand tools, and higher carbon monoxide levels may be due to the use of drip torches, in this example. Drip torches are very rarely used in Quebec (Figure 20).

The authors of a large U.S. Forest Service study found that exposures exceeded short-term exposure limits in approximately 50% of cases (Reinhardt and Ottmar 2000). They found exposures for firefighters holding fire lines could easily be three times short-term occupational exposures limits. An Australian study found that 8% of samples collected at more than 23 wildland fires exceeded 400 ppm for CO (Reisen et al. 2006; Reisen et al. 2007). NIOSH recommends a ceiling level of 200 ppn for CO. Measured peak exposures reached as high as 1200 ppm – the immediately dangerous to life and health (IDLH) value for CO (NIOSH 1995). In this study, 2% of time-weighted-samples samples exceeded 30 ppm.

The NWCG/U.S. Forest Service study found that some firefighters were exposed to components of smoke far exceeding threshold limit values (TLV) or ceiling limits (C) for selected substances sampled at prescribed burns for 20-32 minutes (Table 7) (Reinhardt and Ottmar 2004). These exposures were 3 to 6 times higher than the levels estimated by extrapolation of visual smoke estimate curves while holding a fire line at a large project fire where a firefighter suffered from nausea as a result of his exposure to “very heavy” smoke conditions (Figure 13). The NWCG/U.S. Forest Service study also found that at least one third of peak exposures during initial attack, project wildfires and prescribed burns were above short-term exposure limits (STEL), exceeding 10 times the ACGIH STELs in some cases. Typically, such exposures would be expected to be intermittent, as illustrated in Figure 18 and in Figure 19.



Courtesy Archives of Environmental and Occupational Health

Figure 19. PM2.5 particulate matter and carbon monoxide exposures of wildland firefighters at a prescribed burn with associated tasks (Edwards et al. 2005). Drip torches (flaming liquid fuel) are used to set backfires, burnouts, and prescribed burns (see Figure 20). A mule is a 4-wheel all terrain vehicle.

Courtesy L. Naeher

Figure 20. Wildland firefighter using a drip torch to set a backfire. A flaming mixture of gasoline and diesel fuel drips from the device. Drip torches are rarely used in Quebec.

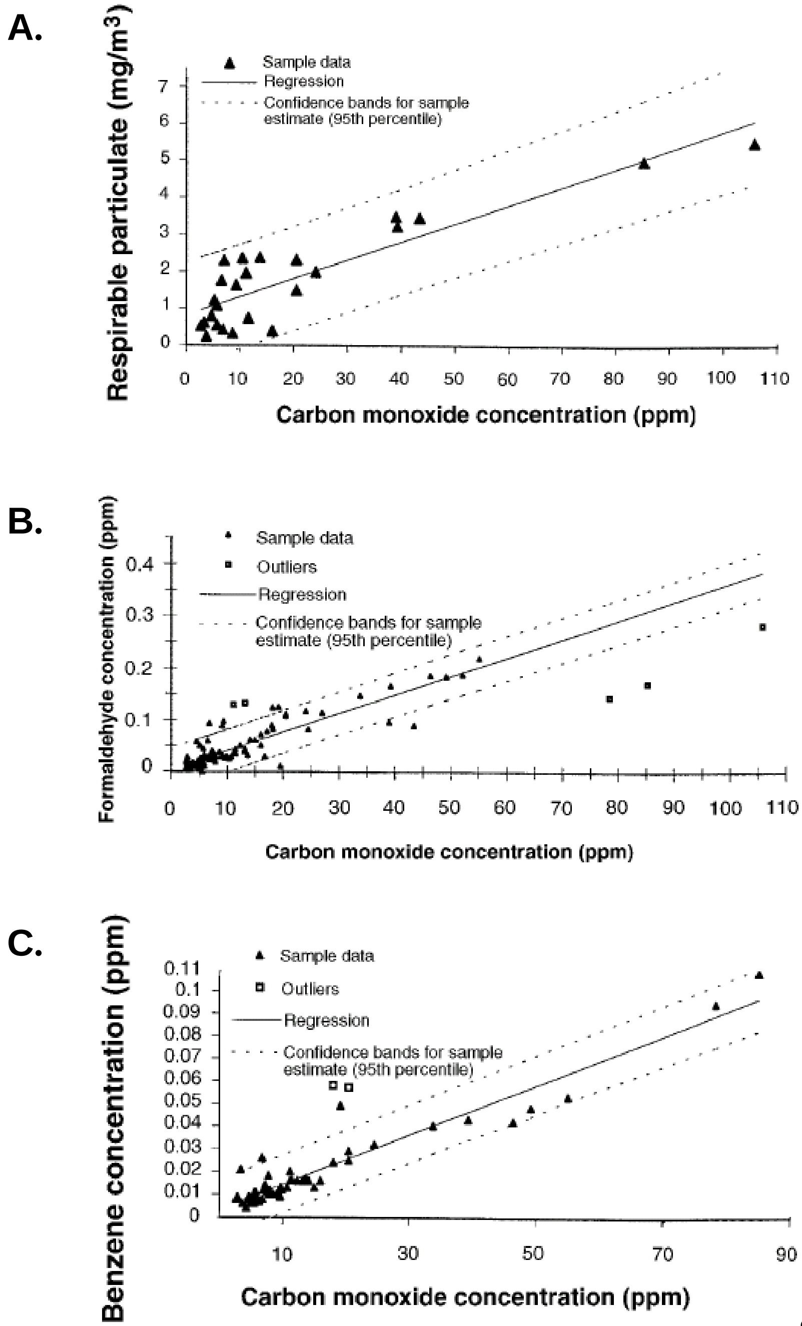
Table 7. 30-Minute exposures at prescribed burns[a]

Smoke Components	Units	Exposure level	TLV[b]	
Respirable particles	mg/m^3	37	3	(TWA[c])
Carbon monoxide	ppm	179	25	(TWA)
Formaldehyde	ppm	1.46	0.3	(C[d])
Acrolein	ppm	0.129	0.1	(C)
Benzene	ppm	0.277	0.5	(TWA)

[a]See (Reinhardt and Ottmar 2004).
[b]American Conference of Government Industrial Hygienists Threshold Limit Values.
[c]8-hour time-weighted-average.
[d]Ceiling.

7.4 Carbon monoxide as a surrogate of smoke exposure

It would be extremely useful if reliable correlations could be found between one easily measurable component of smoke, such as carbon monoxide, that could be used as a surrogate measure for exposure to the other components of concern. In an Australian study of wildland firefighter exposures, good correlation was observed between CO and respirable particles and aldehydes (Reisen et al. 2007). The 1992-1995 U.S. Forest Study also found statistically significant correlations between carbon monoxide and the following smoke components for time weighted average personal exposure measurements at project wildfires (Reinhardt and Ottmar 2000): benzene, excluding use of fuel powered vehicles and equipment (r=0.95, n=54), $PM_{3.5}$ (r=0.89, n=25), formaldehyde (r=0.89, n=103), and acrolein (r=0.82, n=41). Total particulate matter did not correlate well. This is likely due to the contribution of larger particles from disturbed ash and soil dust. Unfortunately, the correlation between carbon monoxide and $PM_{3.5}$ was very poor when carbon monoxide levels were below the ACGIH threshold limit value of 25 ppm. However, observed levels of respirable particulate matter were all below the ACGIH TLV of 3 mg/m^3 when carbon monoxide was less than 25 ppm (n=20) in this study (Figure 21A), as were levels of formaldehyde (ACGIH ceiling value = 0.3 ppm) and benzene (ACGIH TLV=0.5 ppm) (Figures 21B and 21C, respectively). When carbon monoxide levels were below its TLV, the highest observed level of formaldehyde was 0.15 ppm (CO 10-25 ppm), and the highest observed level of benzene was 0.03 (CO 10-25 ppm. Although statistically significant, correlations between the different wildfire smoke components were poorer at initial attack fires occurring in or near urban areas, presumably as a result of the confounding influence of urban pollution. Comparison of these results with those represented in Figure 14 suggests that these samples were collected under mostly “light smoke” conditions to a maximum intensity of “medium” smoke (see Figure 11, also). These regression curves underestimated exposure levels in heavy and very heavy smoke conditions where actual concentrations of contaminants were 3-5 times the predicted levels.



Courtesy U.S. Forest Service

Figure 21. Relationship between carbon monoxide and levels of other smoke components. Statistically significant correlations were observed with respirable particulates (r=0.89), formaldehyde (r=0.89), and benzene (r=0.91). Data points represent time weighted average personal exposure measurements at project wildfires under mostly *"light smoke"* conditions.

8. RESPIRATORY PROTECTION

8.1 Current practices

The wildland firefighting community has voiced its concerns since the 1980's about the short-term and long-term health risks of exposure to smoke. The Western Forestry Conservation Association (WFCA) includes approximately 500 members and 40 companies and organizations from private and public forestry and conservation interests in the western United States and Canada. At their December 4th, 1990, annual meeting in Cour d'Alene, Idaho, the WCFA adopted a resolution urging, "*continuation and completion of studies that will scientifically quantify wildland smoke exposure risks and identify appropriate and acceptable protective measures*" (MTDC 1991). A survey of 300 Federal and State agency employees revealed that 82.2% of respondents thought that the hazards of smoke warranted respiratory protection, especially during direct attack (70.4%), line holding (79.8%) and mop-up (64.8%) (Driessen et al. 1992).

Self-contained-breathing-apparatus (SCBA) where a bottle of air may last 15-30 minutes is not an option for wildland firefighters who work 12-16 hr/day or more in rugged terrain and remote areas for days or weeks at a time. Unlike their municipal counterparts, there currently exists no respiratory protection Standard for wildland firefighting and no respirator certified for use by wildland firefighters. In the absence of a wildland firefighter respirator Standard, a number of uncertified and unapproved devices are currently being marketed to and used by some wildland firefighters. In other cases, NIOSH-certified respirators are being used inappropriately by wildland firefighters.

A survey of 63 Florida fire chiefs found that 46% of the fire departments did not provide wildland personal protective clothing and equipment to firefighters (Hill 2000). The primary reason for not providing wildland personal protective equipment to municipal firefighters was cost and frequency of wildland fires (Hill 2000). In many cases, municipal firefighters engaged in suppression of wildland fires wear personal protective equipment designed for structural fire suppression (Hill 2000). This increases the potential for physiological stress and heat related injuries.

The NWCG/U.S. Forest Service 1997 Consensus Conference report recommended that performance criteria and tests be established for air-purifying respirators for use on prescribed and wildland fires. It refrained from concluding that respiratory protection is or is not required, preferring instead to state that, "*the need for respiratory protection will require further study and development*." However, recognizing the need to reduce wildland firefighter exposures to smoke, the NWCG/U.S. Forest Service 1997 Consensus Report also recommended that there be "*changes in training and tactics to further minimize exposure,*" and that a model respiratory protection program be developed where 95N/multi-gas respirators would be used at field study sites at prescribed fires. A follow-up NIOSH study of the firefighter exposure management program found that wildland firefighters were exposed to CO levels in excess of ceiling or excursion limits during as much as 25% of their time fighting fires (McCammon and McKenzie 2000). In 1999, the U.S. Forest Service wildland firefighter health and safety conference recommended that smoke exposure data be collected using dosimeters (MTDC 1999b). U.S. Forest Service reports published in the year 2000 concluded that, "*Our data also suggest that current respirators for organic vapors and particulates should be worn in conjunction with CO* *alarm dosimeters to warn of concomitant CO exposure,*" and that these need to be used in "*medium to heavy smoke situations which are readily apparent to most firefighters*" (Reinhardt and Ottmar 2000; Reinhardt et al. 2000). Again, in an article published in the scientific literature, authors from the U.S. Forest Service stated, "*We recommend using electrochemical CO dosimeters when wearing an air-purifying respirator to provide instant warnings about the CO levels in smoky situations*" (Reinhardt and Ottmar 2004). To date, the U.S. Forest Service has still not implemented these recommendations.

At this time, the various agencies responsible for wildland firefighting in North America, generally do not issue respirators or recommend that they be used. Nonetheless, forest firefighters are known to cover their face with a bandanna in a futile attempt to reduce smoke exposure (Reh et al. 1994). This practice may be more prevalent amongst those new to the job; more experienced firefighters don't bother. Alberta Forest Service (AFS) entrapment procedures specify that one should avoid inhaling dense smoke and that "a *dry handkerchief held over the nose will help* (AFS 1999). Even more astonishingly, the same advice is proffered in the case of exposure to burning paints and plastics: "*A strong acid smell usually results from burning paint and plastic materials. Hydrogen chloride is readily water soluble and discomfort can be relieved by breathing through a dry cloth*" (AFS 1999).

In California, the Lawrence Livermore Laboratory has, for a number of years, issued negative pressure full-face air purifying respirators with HEPA/P100 filters and acid gas/organic vapour cartridges and a pre-filter to its wildland firefighters (Johnson, 2007). During the past year, firefighters have been given a choice between a full-face and a half-face respirator. In Western Australia, FESA has issued negative pressure half-face masks with particulate air purifying cartridges to its career firefighters for a number of years, adding a formaldehyde cartridge in 2006 (FESA 2003; De Vos et al. 2006; Parlour 2007). Use of these respirators is voluntary, and while a minority of the firefighters do not use them because they find them uncomfortable, most of the career firefighters do choose to use them mainly for high intensity short duration urban interface wildland fires and they are satisfied with the result (Parlour 2007). FESA is currently considering whether or not to make the use of respirators mandatory for all career firefighters and is to develop criteria to enable distribution for volunteer firefighters working in similar conditions.

8.2 Current Standards

Standards pertaining wildland firefighting are silent concerning the use of respiratory protection (NFPA 1995; AFS 1997; ONGC 1997b; ONGC 1997a; ONGC 1998; AFS 1999). The one exception in this regard is the current edition of the ISO/CD 16073-2002 Standard on wildland firefighting personal protective equipment that states that wildland firefighters *may* use a disposable dust mask certified to EN149 with a minimum rating of FFP2 (corresponding to an N-95 NIOSH certified respirator) (International Standards Organization, 2002) (ISO 2002). This section is not expected to be included in the next edition of the ISO Standard since the responsibility for respiratory protection for wildland firefighters will likely be transferred to another committee (TC94/SC14/WG to TC94/SC15/WG2) (Poulin 2007). Various other publications also make no recommendations concerning the use of respirators by wildland firefighters (Bollinger and Schutz 1987; Lara and Vennes 1998; Lara 2002; NIOSH 2004b).

On February 27, 2007, the U.S. National Institute for Occupational Safety and Health (NIOSH) submitted a Comment Letter to the NFPA Standards Council supporting the development of a respiratory protection standard for wildland firefighters. The author pointed out that there have been numerous studies in the past and that there are other ongoing studies investigating expected inhalation hazards and health consequences associated with wildland firefighting. He concluded that, "*There seems to be little debate the hazards are present and can for some period of time and under certain situations exceed limits requiring respiratory protection for the time that they are encountered*" (Boord 2007).

On March 20, 2007, the NFPA Standards Council announced that it has decided to proceed with the development of a new respiratory Standard for wildland firefighting (NFPA 2007d; NFPA 2007a). « It expected that that an NFPA APR/PAPR Standard for Wildland Firefighting will be issued early in 2011. It is also expected that this Standard will mandate that the removal of carbon monoxide (CO) in addition to particulate matter and other gases and vapours found in smoke."

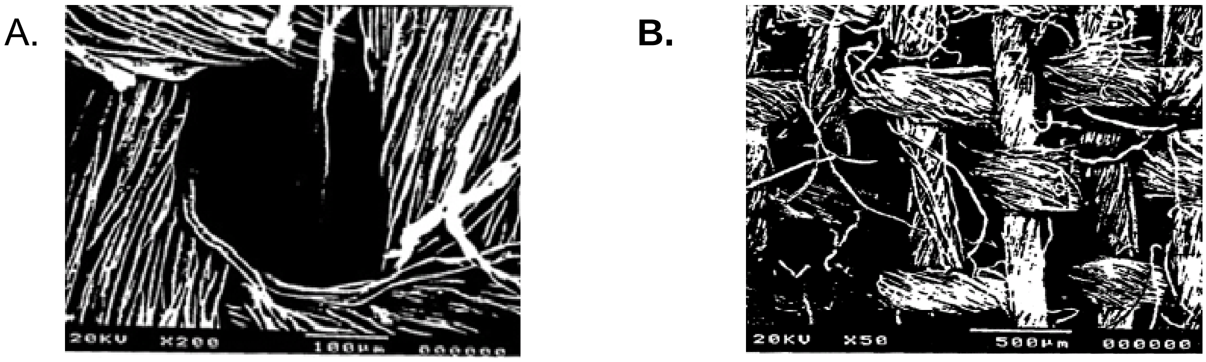
It is important to make the distinction between the need for a respirator performance Standard and the need for wildland firefighter respiratory protection (Austin and Goyer 2007). An NFPA respirator performance Standard would not mandate the use of a respirator by wildland firefighters nor would it provide guidelines for its use. However, in the event that a wildland firefighter or the authority having jurisdiction were to determine that respiratory protection was necessary in any particular circumstance, then the respirator selected would need to meet the minimum specifications established by a future NFPA performance Standard and it would need to be NIOSH (National Institute for Occupational Safety and Health) certified.

8.3 Available options

A NIOSH study of old bandana samples demonstrated that the pore size of the bandana was approximately 200 μm x 200 μm, roughly 500 to 2000 times larger than smoke particles (0.100-0.400 μm) (Reh et al. 1994). Gases, vapours, and respirable and inhalable particulate matter would pass through the fabric as readily as a mosquito through an open door (Figure 22). There was no indication that frequent washing and hot air drying significantly reduced the pore size of the fabric. The use of bandanas for respiratory protection should be prohibited (Reh and Deitchman 1992; Reh et al. 1994).

The only NIOSH-approved respirators currently available that can be considered for use by wildland firefighters are air purifying respirators (APR) or powered air purifying (PAPR) respirators (Table 8). However, none of these will remove carbon monoxide (CO) and none is approved for use under firefighting conditions. Under controlled conditions, it has been found that half-face air purifying respirators with particulate (P) filter cartridges do not protect firefighters from cough, wheezing and shortness of breath following 15-minute exposures under "light" smoke conditions (De Vos et al. 2006). While particulate/organic vapour (POV) cartridges were more protective, particulate/organic vapour/ formaldehyde cartridges provided better protection. Anthony et al. also found that formaldehyde present in smoke from fires penetrated multi-gas and CBRN air purifying respirators (Anthony et al. 2007).

Recent studies have demonstrated large differences in the effectiveness of various respirators certified for industrial use in removing the toxic components of smoke. The multi-gas



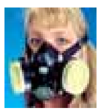
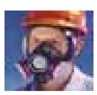
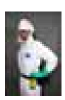
Courtesy U.S. National Institute of Safety and Health

Figure 22. Scanning electron microscope (SEM) images of a new unwashed bandanna at (A) x200 magnification, and (B) x50 magnification (Reh et al. 1994). Pore size is approximately 200 x 200 µm, roughly 500 to 2000 times larger than the majority of the particles (0.100 to 0.400 µm) found in smoke. Respirable smoke particles, gases and vapours would pass through a bandana as readily as a mosquito through an open door.

air purifying respirators are not effective against all of the toxic vapours, especially the aldehydes. None of the filtering respirators remove carbon monoxide (CO). All of the currently available respirators have serious shortcomings for use in a wildland fire situation. Even if they were effective, some wildland firefighters are understandably reluctant to accept negative pressure air purifying face masks for use at high work levels for long periods of time. A full face mask is generally more comfortable than a half-face mask and it provides full eye protection. Full eye protection is necessary the case of contaminants exceeding the threshold limit value where the threshold limit value is based on irritant effects. Since the contaminants having warning properties such as odour or irritant effects are removed by air purifying respirators, there is a legitimate concern that firefighters wearing such respirators might unknowingly expose themselves to higher levels of toxic contaminants not removed by the respirator than they would otherwise. This could easily result in over exposure to carbon monoxide and lead to serious, perhaps deadly, consequences. To avoid this, a carbon monoxide monitor with alarm should be used in conjunction with air purifying respirators used when fighting wildland fires.

The ISO technical committee has concluded that wildland firefighting personal protective equipment (PPE) needs to achieve an acceptable compromise between increasing the protection from flames and elevated temperatures, and reducing the build-up of metabolic heat and heat stress (ISO 2006). In addition to providing PPE that enables wildland firefighters to work for extended durations it must also be sufficiently rugged for use under extreme conditions. Work levels and heat stress are high in the case of wildland firefighting. A respiratory protection program and realistic respirator performance criteria need to be developed that strike a balance between the need for respiratory protection from intermittently high levels of smoke, the need for a reasonable degree of comfort while working in a hot environment for extended periods in remote areas performing physically demanding tasks, and the need to control and extinguish wildland fires. One interesting option might be the development of a loose-fitting PAPR respirator for wildland firefighting (Johnson et al. 2008).

Table 8. Types of respirators currently available

Respirators		NIOSH certified	APF[c]	Type		Comments		
Bandana[a,b]	 	NO	0	*This is **not** a respirator*		*Bandanas offer **no** protection from respirable particles, gases or vapours.*		None of these respirators protect against carbon monoxide (CO) poisoning.
Disposable	 © 3M	yes	10	APR[d]	Tight fitting	Fit test required.	Offers no protection from gases or vapours; only from particles.	
Half-face	 © MSA	yes	10 50	APR PAPR[e]	Tight fitting	Fit test required. Various cartridges available[f].	No facial hair allowed.	
Full-face	 © MSA		50 1000	APR PAPR			No glasses allowed.	
Helmet	  © 3M	yes	25	PAPR	Loose fitting	No fit test required. Various cartridges available[f].	Facial hair permitted. Glasses permitted.	
Hood	 © 3M		1000	PAPR				

[a]Pores are 500-2000 times larger than most smoke particles (0.1-0.4 μm).
[b]See (Reh et al. 1994).
[c]Assigned protection factor.
[d]Air purifying respirator (negative pressure).
[e]Powered air purifying respirator (positive pressure).
[f]Various cartridges are available to remove different contaminants. More than one cartridge can be fitted to the mask.

9. CONCLUSIONS

Personal exposure assessments have not been conducted for all toxic substances of concern that are known to be emitted at wildland fires, comprehensive health evaluations of wildland firefighters have not been done, and there are no epidemiological studies that have evaluated the long term health effects of occupational exposures to smoke at wildland fires. Most of the exposure studies to date have been conducted at “low” smoke levels, with a few reporting results from “medium” smoke levels. It is not clear if the results from available exposure studies are representative of wildland firefighter exposures. Likewise, it is not clear if reported peak exposures are representative of actual wildland firefighter exposures.

Nonetheless, sampling has demonstrated that, even for “low” or “low to medium” smoke exposures, some wildland firefighters are at times excessively exposed to smoke that includes acutely toxic carbon monoxide, irritant gases and vapours such as acrolein, carcinogens such as formaldehyde and benzene, and ultra fine respirable particles (<1 μm), and that occupational exposure to smoke causes decrements in pulmonary function. Wildland firefighter smoke exposures are highly variable and depend on the strategies and tactics employed, the work methods used, the threat level to populated areas and economic interests, and other factors including the type of soil and vegetation, fuel moisture, fire intensity, and wind. Unexpected exposures may also occur as a result of unpredictable events.

Outstanding issues concerning respiratory protection for wildland firefighters include: the quality and completeness of the wildland firefighter exposure assessment databases; methods used to summarize exposure data; possible synergistic effects between toxic substances present in smoke; higher work levels and pulmonary ventilation rates and longer work shifts that result in higher internal doses than assumed when establishing occupational exposure limits; toxicological significance of intermittent exposures to high concentrations; exposure to soil and ash particles kicked up while working; difficulties in monitoring the exposure and the health of a transient and seasonal workforce; identification of tasks and situations where respirators are and are not needed; shortcomings of respirators that are currently available; management of a respiratory protection program for a diverse and mobile workforce operating in a rapidly changing and sometimes unpredictable environment in remote areas for extended periods of time; identification of changes in tactics, work methods, and administrative controls that will reduce exposure to smoke without the use of respirators; and, cost. Current regulations ignore particle number, ultrafine particles (<0.1 μm), and chemical speciation of particulate matter which are likely important factors impacting human health. The most important research question with respect to wildland fire particle emissions is the relationship between emission, acute and chronic exposure, and health effects. Fundamental to this question is chemical speciation of the smoke particles.

Respiratory protection for wildland firefighters is a complex issue and the subject of heated debate, diverging opinions, and the dissemination of a considerable amount of misinformation. Sampling has shown that wildland firefighters are exposed to a complex mixture of combustion products including carbon monoxide, irritant gases and vapours, carcinogens and ultra fine respirable particles. While some studies have been interpreted to show that exposure levels, when averaged over a firefighter’s work week or career, are below 8-hr time weighted average (TWA) occupational exposure limits, others have demonstrated that exposures to some toxic combustion products exceed occupational short term exposure limits (STEL) limits or ceiling limits some of the time.

There have been no exposure studies of wildland firefighters in Quebec. If exposure levels of Quebec wildland firefighters are similar to those measured in studies conducted in the United States, it is probable that these exposures exceed short term occupational exposure limits at least some of the time. However, given the many differences in actual working conditions, especially differences in tactics, unless field studies are conducted one cannot predict what the exposure levels would be for wildland firefighters working in different jurisdictions.

Wildland firefighters working in Quebec are exposed to smoke and, therefore, to ultrafine respirable smoke particles (<1 μm), organic vapours and acids, acrolein, formaldehyde, and carbon monoxide. There have been no field studies conducted in Quebec to measure the levels of these exposures. Although some exposure studies have been conducted in other jurisdictions it is difficult to generalize the results of those studies to the Quebec situation given that the vegetation, the soils, and especially the tactics and methods used to fight wildland fires are different in Quebec than elsewhere. Field observations together with discussions with representatives of the U.S. Forest Service and SOPFEU suggest that wildland firefighters in Quebec are, in general, less exposed to smoke than their counterparts in the United States. However, it appears that they are also sometimes exposed to smoke levels similar to those measured in studies of U.S. wildland firefighters. Therefore, it is likely that Quebec wildland firefighters are exposed to components of smoke at levels exceeding occupational exposure limits.

10. RECOMMENDATIONS FOR RESPIRATORY PROTECTION

The primary method of protection of wildland firefighters from smoke exposure should be through management controls, engineering controls, and modification of work practices. The use of respirators should be considered a secondary means of protection. If administrative controls and other primary methods are unsuccessful in reducing exposures to acceptable levels, wildland firefighters in Quebec should be provided with a NIOSH certified respirator to be used during the times that they are excessively exposed to smoke. In such cases, it is recommended that a certified air purifying respirator (APR) or powered air purifying respirator (PAPR) be used for respirable particles, organic vapours and acids, acrolein, formaldehyde, and PAH. However, since none of the currently available air purifying respirators effectively remove carbon monoxide, firefighters using these devices might unknowingly expose themselves to higher levels of carbon monoxide than they would otherwise. Carbon monoxide is a colorless, tasteless, odourless, highly toxic gas. Until a respirator is developed for wildland firefighting that effectively removes carbon monoxide (CO), certified air purifying respirators should always be used in conjunction with a carbon monoxide monitor that sounds an audible vibrating alarm at a predetermined set-point to warn when the occupational exposure limit for CO is exceeded. Wildland firefighters wearing air purifying respirators that do not remove CO should retreat from areas where CO levels exceed occupational exposure limits. Wildland firefighters should not use uncertified masks or mouthpiece devices for respiratory protection from smoke.

CO monitors should also be used by wildland firefighters who work in smoky areas without a respirator. Since CO levels correlate with levels of other toxic smoke components, the set-point should be fixed at a CO concentration where it would be expected that levels of CO, formaldehyde, acrolein, PAH, respirable particulate matter and total particulate matter would all be below their respective occupational exposure limits and where the irritant index would be expected to be <1.0. More research is needed to determine what this set-point should be and what procedures should be followed in the event of an alarm.

At this time, there are too many unknown factors to make a definitive recommendation concerning the type of respirator that wildland firefighters should use. A negative pressure half-face mask APR offers an assigned protection factor (APF) of 10, while the full-face mask offers an APF of 50 and also protects the eyes. Eye protection may be a requirement since wildland firefighters have been found to be overexposed to irritants, including formaldehyde. All APRs reduce a wildland firefighter’s work capacity. Powered air purifying respirators (PAPR) are positive pressure devices offering increased protection factors (an APF of 50 for half-face, and an APF of 1000 for full-face respirators), and reduced breathing resistance which is especially important at high work levels. When selecting a PAPR from various models on the market, consideration should be given to weight, noise, field ruggedness, and battery life.

Use of half-face and full-face APR or PAPR respirators requires implementation of a formal respiratory protection program, including fit testing, and beards would be prohibited. The use of a PAPR-helmet-faceshield system (a loose fitting respirator) would provide an APF of 25. The principle advantages of this type of system are comfort, the fact that fit testing would not be required, and beards would be permitted. Some models employing a hood can be demonstrated to have an APF up to 1000.

Regardless of the type of respiratory protection used, wildland firefighters should also be warned that none of the currently available respirators protect against all of the toxic components present in smoke. They should also be cautioned that, given the complex mixture of smoke components and the high work levels typical of wildland firefighting, the effectiveness and duration of air purifying cartridges is unknown. Finally, APRs and PAPRs may not be used in IDLH atmospheres. In such cases, (eg. in the wildland urban interface where firefighters may be exposed to IDLH atmospheres in burning buildings), a self-contained-breathing-apparatus (SCBA) would be required.

11. FUTURE RESEARCH

Action is required on the part of management responsible for wildland firefighters in Quebec to ensure that exposures do not exceed legally enforceable occupational exposure limits with respect to the substances of greatest concern (carbon monoxide, respirable and total particulate matter, formaldehyde, acrolein, benzo[a]pyrene, benzene, furfural, and acid gases). This is an impossible task without a better understanding of actual wildland firefighter exposures and exposure variability. It is no more intelligent to invest heavily in respiratory protection where it is not needed than to fail to provide it where it is needed. In order to be able to manage wildland firefighter smoke exposures, either by administrative controls or by the use of respiratory protection, it is strongly recommended that a comprehensive task-specific personal exposure study of wildland firefighters be conducted in Quebec.

Since most sampling reported in the literature has been conducted during the latter stages of wildland fires when exposures have been considered to be relatively low, it is important that the Quebec study be organized for rapid mobility and responsiveness in order to permit representative sampling during the different types of conditions encountered by wildland firefighters, including initial attack. It is important, also, that sampling not be limited to the measurement of time-weighted-average values over a work shift, but that peak levels and short-term 15-minute time-weighted-average exposures be measured. Exposure variability must be determined using datalogging instruments.

Chemical characterization of smoke particles should also be conducted. In addition to evaluating wildland firefighter exposures to the substances of greatest concern, it is recommended that the correlation between these substances be determined to identify a reliable, surrogate measure of smoke (eg. carbon monoxide). Exposure conditions need to be clearly documented during all sampling to distinguish tasks, to identify fire and meteorological conditions, to identify soils and fuels including fuel moisture, and to distinguish between exposure to smoke and other sources of contamination such as vehicle exhaust, aircraft exhaust, equipment exhaust, gasoline fumes, etc. Since wildland firefighters are also exposed to dust and ash kicked up while travelling through burned out areas where there is little or no smoke, exposures to total and respirable particles and crystalline silica should be evaluated at these times also, including chemical characterization of the particulate matter.

Personal sampling should be conducted in relation with visual assessment of smoke intensity documented with photographs. It is therefore necessary to conduct a preliminary field study with experienced wildland firefighters to develop a well-defined, photo-documented scale for the visual assessment of smoke intensity and quality, for example low, medium, heavy, and very heavy.

It is recommended that a medical surveillance study be conducted (eg. cross-shift and cross-season pulmonary function tests, prevalence of respiratory and neurological symptoms) in conjunction with exposure measurements. When assessing symptoms such as headache, consideration should be given to the possibility of exposure to carbon monoxide, poor diet, and heat stress. The study should also include a physiological evaluation of wildland firefighter work levels and energy expenditure. It is recommended that a study of respirator performance be conducted at wildfires.

The design of an epidemiological study to determine the health effects of wildland firefighting would present many challenges: seasonal workers, intermittent and variable exposures, varied and variable tasks, confounding factors, and population size. It is recommended that an epidemiologist be consulted to determine the feasibility of such a study.

The need for more data does not imply that action is not required now based on the data that we do have. Exposure studies conducted to date clearly show that at least some wildland firefighters are exposed to smoke components at levels exceeding regulatory limits. It is not necessary, indeed it would be inappropriate, to wait until all possible studies are conducted before reducing these exposures to acceptable levels either by administrative controls or by the use of respiratory protection.

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