Health impact of smoke exposure in wildland-urban interface fires: 
a literature review

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Introduction

Fires in the wildland-urban interface (WUI) have become more common because of climate change and increased residential development in the WUI (Flannigan et al. 2005, Canadian Council of Forest Ministers 2006). In a WUI fire both forest fuels and structural fuels burn, creating a noxious mixture of chemicals in a firefighter’s breathing space. WUI fires vary considerably in size and complexity, and each will generate a different level of smoke hazard. On large WUI fires, numerous firefighters, emergency responders and equipment operators are deployed to support suppression efforts. Often, many responders possess limited or no knowledge of the unique smoke hazard that exists. As the frequency and extent of WUI fires increase, so does the firefighter’s exposure to a dangerous smoke environment.

Of particular concern are wildland firefighters exposed to smoke from burning buildings while working in WUI fire events. Unlike a structural firefighter, a wildland firefighter is not equipped with a self-contained breathing apparatus (SCBA) to protect him/her from inhaling structural smoke. Although provincial agencies train wildland firefighters to recognize the hazard and avoid it when possible, many firefighters nevertheless find themselves working in these hazardous smoke conditions.

I reviewed the existing literature relating to the smoke hazard associated with forest and structural fires and the resulting health impact from exposure. This review is the second conducted by our group (Gibos 2005) and is part of our on-going mandate to monitor advances in wildfire safety.

Objectives

1. Collect and summarize existing literature on:
   - the smoke hazard present in structural and wildland fires
   - the health impact of exposure

2. Determine the smoke hazard from fires in the WUI and the health impact on wildland firefighters, equipment operators, emergency responders and the public.

3. Identify the measures used by firefighting agencies to mitigate the health risk of smoke exposure.

4. Identify the gaps in our knowledge of the WUI fire smoke hazard and of the resulting health impact on exposed individuals.

Methods

I searched for literature using Google Scholar with the keywords ‘wildland firefighting smoke hazards health impacts’ and ‘urban structural firefighting smoke hazards health impacts’. I identified additional documents and reports by referring to the References Cited section of each paper I obtained. I categorized the documents based on the smoke source (wildland or structural); the personnel affected (wildland firefighter, structural firefighter, general public); and whether the report evaluated the hazard, health impact, or other.
Findings

Smoke Characterization

Wildland Smoke

A study by Reinhardt et al. (2000) found that the most hazardous chemicals generated in the combustion of wildland fuels was carbon monoxide, aldehydes (formaldehyde and acrolein), benzene and respirable particulates less than 3.5 microns. A smoke sampling study conducted in Australia on prescribed burns and wildfires (Reisen and Meyer 2011) identified the toxic chemicals present in the firefighter’s breathing space and found that only carbon monoxide, formaldehyde and respirable particulates exceeded the occupational exposure limit.

Carbon monoxide is produced during conditions of incomplete combustion. The colorless, odorless gas attaches to hemoglobin and reduces the oxygen-carrying capacity of blood. Formaldehyde is a strong irritant and potential carcinogen. Acrolein burns eyes and irritates the airways (Sharkey 1997b). Respirable particulates are airborne soot particles which irritate airways and create the potential for the deposit of carcinogens in the lung tissue.

Structural Smoke

Several chemical substances generated by smoke in structural fires are of concern because of their potential toxic effects on the respiratory system. These substances include:

- asphyxiates (carbon monoxide, carbon dioxide and hydrogen sulfide)
- irritants (ammonia, hydrogen chloride, particulates, nitrogen oxides, phenol and sulfur dioxide),
- allergens
- carcinogens (asbestos, benzene, styrene, polycyclic aromatic hydrocarbons and certain heavy metals)

Other potentially toxic components of structural smoke include ultrafine respirable particles (less than 0.1 micron) and gaseous effluents which may condense on protective equipment and exposed skin (Fabian et al. 2010).

While the composition of wildland vegetative fuels is relatively consistent, the fuel composition in a structural fire is less predictable. Widely used synthetic materials such as styrene and vinyl polymers produce a greater volume of smoke particles and gases than natural products. The combustion of synthetic materials generates 12.5 times more particles per mass unit than natural materials (Fabian et al. 2010). Given the greater complexity, unpredictability and volume of harmful chemicals generated by the combustion of synthetic materials, smoke from structural fires is of greater concern for wildland firefighters and other emergency responders during WUI fire events.

Factors Influencing Exposure

Ventilation Conditions

In their study, Fabian et al. (2010) found that ventilation had an inverse relationship with smoke and gas production in a structural fire: considerably higher levels of smoke particulates and gases were observed
in contained fires than in uncontained fires, and the smoke and gas levels were greater inside of contained structures than outside.

In wildland fires, a convective draw (high intensity fires) can help buoy toxic gases, draw them up into the atmosphere and away from the firefighters’ breathing space. Conversely, strong winds can force a smoke plume downwards resulting in increased smoke exposure to firefighters downwind (Reinhardt and Ottmar 2004). Fire camps, especially in mountainous terrain, often experience heavy smoke conditions due to inversions. In this situation, firefighters do not have a clean air environment in which to recover from smoke exposure experienced throughout the work day.

**Mop-Up and Overhaul Operations**

Firefighters generally conduct mop-up (wildland) and overhaul operations (structural) during low-intensity burning conditions (smouldering phase). This phase produces higher levels of particulate matter, carbon monoxide, nitrogen oxide, sulphur oxide, polynuclear aromatic hydrocarbons, aldehydes, and free radicals (Fowler 2003, Ward 1999) which linger close to the ground. During structural overhaul operations, exposure limits for several chemical substances are often exceeded (Bolstad-Johnson et al. 2000). Because of the low fire intensity of this stage, firefighters (and others) may be inclined to move closer to the smouldering materials without the protection of a breathing apparatus (Brandt-Rauf et al. 1988).

Bolstad-Johnson et al. (2000) also determined that CO levels in this phase did not reliably predict concentrations of other products of combustion and should not be used as an indicator for the presence other contaminants. Due to the variety of structure materials and contents, the concentrations of chemical substances encountered in the overhaul phase vary considerably from one fire to another.

**Firefighter Behaviour**

Although not yet validated, many believe that because firefighters work at higher levels of exertion they breathe in larger amounts of smoke more frequently than non-firefighters (Austin 2008, Naeher et al. 2007). In addition, anecdotal observations suggest that both structural and wildland firefighters often ignore heavy and changing smoke conditions because of the urgent and demanding nature of their work.

**Health Impact of Smoke Exposure**

Both structural and wildland firefighters suffer short-term and long-term impacts from smoke in their associated fire environment (Booze et al. 2004, Haas et al. 2003, Swiston et al. 2008). This research has identified several factors that can influence the probability and severity of health impacts: type of smoke, intensity of combustion, duration of exposure, frequency of exposure, career length and fitness level.

**Impact on Wildland Firefighters in the Wildland Environment**

Short-term exposure to wildland smoke typically results in eye irritation and coughing, with small daily and seasonal declines in pulmonary function. These declines usually reverse after a period of time in a smoke-free environment. Exposure to smoke for several days, or weeks, can reduce the firefighter’s ability to remove particulate from his airway (by coughing, spitting or swallowing) and this could increase the risk of bronchitis. Short-term exposure to smoke can also compromise the immune system (Sharkey 1997b).
**Impact on Structural Firefighters in the Structural Environment**

The suppression and overhaul phases of a structural fire generate high levels of ultrafine particles. These ultrafine particles deposit deep into the lung tissue and can cause the release of inflammatory mediators into the circulation system, causing toxic effects on internal tissues. Airborne toxins attached to particulate matter can also be transmitted into the lung tissue and potentially to other body tissues (Fabian et al. 2010). Smoke from synthetic materials found in structural fires can result in residual chemical deposits on skin, clothing or other personal effects (Fabian et al. 2010).

**Impact on the General Public**

Moore et al. (2006) reviewed physician’s records in two British Columbia communities following the catastrophic 2003 fire season. This study suggested that the concentration of particulate matter produced by nearby wildfires was a key factor in the incidence of respiratory ailments. In another study on the immediate health effects of smoke from a wildland fire, Shusterman et al. (1993) found that more than half the cases treated at a hospital emergency department were smoke related disorders. Fabian et al. (2010) found a positive correlation between exposure to particulate matter and increases in cardiovascular morbidity and mortality for the general population. Asthmatics, young children, the elderly and smokers suffer the greatest from exposure to wildfire smoke (Fowler 2003).

A study by Lispett et al. (1994) also compiled data from hospital and emergency treatment records during urban fire events, and for an extended period following the events. This study found an increased number of visits for lower respiratory conditions. Similar to other studies on smoke impacts from wildfires, patients with a previous history of asthma made up a large proportion of the lower respiratory diagnoses.

**Smoke Sources Specific to the WUI**

In addition to the numerous sources of smoke generated by the combustion of synthetic building materials and furnishings, there are other smoke sources in the WUI that may be encountered by wildland firefighters.

**Diesel Exhaust Emissions**

Diesel exhaust contains hundreds of chemical substances in both the gas and particle phase (NIOSH 1988). The gaseous products include carbon dioxide, oxygen, nitrogen, water vapor, carbon monoxide, nitrogen compounds, sulfur compounds, and low molecular-weight hydrocarbons and their derivatives. Particulate matter includes carbon, adsorbed organic compounds and small amounts of sulfate, nitrate, metals and trace elements.

Diesel particulate matter poses a health risk to exposed firefighters because of its small size and large surface area. Small particulate matter is more readily deposited in the lower portions of the respiratory tract and deep lung (80%-95% of the diesel particulate matter is less than 2.5 micrometers). The large surface area of diesel particulate matter increases the possibility for gaseous compounds to be adsorbed by the particulate matter and deposited in the lungs (United States Environmental Protection Agency 2002).

**Fire in Waste Dumps and Waste Transfer Sites**

Wildland firefighters are often dispatched to investigate and, in some cases, suppress fires in waste dumps and transfer sites. Municipal waste transfer sites have rigid standards to isolate toxic chemicals
and to prevent fire. However, unauthorized dump sites exist and it is difficult to evaluate the smoke hazard posed by the potential waste products at such sites. The toxic compounds generated by waste fires are variable and unpredictable. Smoke toxicity in these environments is also dependent on other factors such as combustion phase, available oxygen, and combustion efficiency (Kinnes and Deitchman 1995).

**Vehicle Fires**

Burning synthetic materials in automobiles release hundreds of organic and inorganic compounds in both gaseous and particulate form. Fent et al. (2010) attempted to characterize and measure the toxic chemicals and particle hazard resulting from a vehicle fire during vehicle fire suppression training exercises. Researchers found it impossible to test for all suspect chemicals because of the bulk and weight of the air sampling equipment; however, their study indicated that firefighters may be exposed to levels of formaldehyde, carbon monoxide and isocyanates beyond short-term exposure limits.

**Mitigation Measures**

Wildfire management agencies are challenged with implementing broad rules for firefighter safety and mitigating smoke exposure. The dynamic nature of wildfire, the number of firefighters working at any time, and the variety of tasks conducted by firefighters make hazard assessment and risk management difficult. This becomes even more challenging in the WUI where firefighters face additional smoke hazards.

During the 1987 fires of northern California and the 1988 Yellowstone fires, thousands of firefighters experienced respiratory problems. In 1989, the National Wildfire Coordinating Group (NWCG) responded by convening wildfire management agencies, employee groups and occupational health experts to develop a comprehensive study plan that would determine the short and long-term effects of exposure to forest fire smoke. Following years of study and analysis, a conference was held in 1997 to review findings from each area of the study plan (Sharkey 1997a). The conference developed a consensus on the elements of a risk management plan that could be implemented by wildfire management agencies. These elements included training and tactics, smoke monitoring, health maintenance, respiratory protection, medical surveillance and research, and risk communication. This project was a landmark study in firefighter safety and while few wildfire management agencies implemented the entire recommended risk management plan for smoke mitigation, they do address many of these elements through various programs and standard operating procedures.

**Training**

Training is a low cost/high benefit administrative control that can mitigate the impact of smoke exposure during firefighting activities. Training occurs at several levels: formal training courses, information board notices, and daily briefings. Wildland firefighters are trained to recognize potential sources of toxic smoke and modify tactics to avoid smoke hazards in the WUI.

**Occupational Health and Safety Programs**

Occupational Health and Safety (OHS) legislation sets out the employer’s responsibilities for employee safety and well-being. The legislation also outlines occupational exposure limits (OELs) to chemical and biological hazards and other harmful substances. These OELs are established by the American Conference of Government Industrial Hygienists (ACGIH) and the National Institute of Occupational Health and Safety (NIOSH).
The Alberta OHS Code (Alberta Queen’s Printer 2009) outlines requirements regarding the exposure to multiple substances; exposure during shifts longer than 8 hours; reviews of exposure limits; potential worker exposure; and the measurement of concentrations of airborne substances. The Alberta OHS code also specifies OELs to some of the chemicals and particulates found in smoke (e.g., acrolein, benzene).

**Smoke Exposure Monitoring Programs**

A smoke monitoring program could help evaluate smoke hazards and determine the risk of exposure during different suppression activities and fire conditions. A smoke exposure monitoring program was developed by Reinhardt et al. (1999) and field tested during wildland fire suppression operations by McCammon and McKenzie (2000). Firefighters were equipped with personal breathing zone carbon monoxide monitors (dosimeters) which recorded carbon monoxide levels every minute and sounded an alarm when levels exceeded pre-set threshold exposure levels. The program successfully collected information from four wildland firefighting crews over one fire season which was used to estimate concentrations of acrolein, formaldehyde and respirable particulate matter.

**Discussion**

**Knowledge Gaps**

Wildland firefighters and other support workers are not expected to operate in the same proximity to burning buildings as structural firefighters and should not, therefore, be exposed to the same concentrations of chemicals and particulates. Nevertheless, the composition and amount of structural smoke to which wildland firefighters may be exposed should be further evaluated (Reinhardt and Ottmar 1997, Grant 2007). Understanding and categorizing the risk of smoke exposure is critical to establishing safe procedures for working in a WUI fire.

My review of existing literature has revealed that, although there is substantive research on the smoke hazard in each specific fire environment (structural vs. forest), there are some significant gaps in our knowledge concerning the smoke hazard from a WUI fire to wildland firefighters:

- Health impact from short-term exposure to structural smoke.
- Combined health effect of simultaneous exposure to both wildland and structural smoke.
- Potential structural smoke exposure levels for various suppression activities and fire conditions.
- Level of firefighters’ understanding of WUI smoke hazard and avoidance options.
- Effectiveness of administrative controls, such as hazard assessment and risk control processes and firefighter training.
- Potential health hazard of residual chemical deposits on skin, clothing or other personal effects.
- Cumulative effect of the factors that affect the probability and severity of health impact: intensity of combustion, duration of exposure, frequency of exposure, career length, and fitness level.
On-going Research

Despite the minimal amount of literature found that applies directly to the smoke hazard encountered in WUI fires, there are some current studies and initiatives making advances in this area.

Riesen (2011) has completed the first phase of research which has inventoried combustible materials in the rural urban interface (RUI) and identified combustion products and yields of these materials. The next phase of this project will evaluate emission levels and assess the firefighter’s exposures to air toxins and exposure risk.

Recommendations by Grant (2007) provided an impetus to firefighting research agencies to conduct research on respiratory health related topics and the National Fire Protection Association (NFPA) Fire Protection Research Foundation continues research in firefighter safety and best practices in fire suppression.

In 2008, the NWCG established a smoke committee that continues to work to resolve issues concerning fire emissions and air quality impacts on firefighter and public safety and health. The NWCG Smoke Committee works with the NWCG Safety and Health Committee on projects such as the Firefighter and Base Camp Worker Smoke Exposure Project.

Recommendations

Firefighter Behaviour

- Extinguishment of smouldering structures is not a responsibility of wildland firefighters; however, they should always be aware of lingering smoke in the vicinity of overhaul activities and avoid working downwind from smouldering structures.

- Diesel exhaust should be regarded as a potential occupational carcinogen and direct exposure should be limited (NIOSH 1988). Firefighters can avoid direct exposure by standing upwind from the source.

- Researchers (Fent et al. 2010) recommend that firefighters use SCBA while suppressing a vehicle fire. Wildland firefighters, equipment operators and the general public should not approach burning vehicles and should stay upwind. Wildland firefighters should limit their suppression efforts to preventing the fire from spreading from the vehicle to adjacent fuels.

- Wildland firefighters use physical responses to smoke (such as eye irritation, coughing and nausea) as triggers to reassess the smoke environment and consider smoke avoidance. In a more toxic WUI smoke environment it is critical to heed these triggers and exercise tactical mitigation.

Training

- Training program evaluations and a needs analysis could help to identify knowledge and operational gaps. Communicating smoke hazards on WUI fire incidents through safety briefings, information boards, and safety messages is critical to firefighter awareness and risk mitigation.
Smoke Monitoring Programs

- Although a smoke monitoring program can assist in WUI hazard assessment, contributing factors are extremely variable. In the absence of smoke monitoring instruments, firefighters need to evaluate factors such as their proximity to the smoke source, type of materials consumed, exposure to the smoke source (direct or indirect), fire intensity, smoke characteristics (color and quantity), and weather (wind driven or plume dominated smoke).

Research Opportunities

- Because of the low fire intensity, the mop-up or overhaul phase can provide good opportunities for researchers to quantify by-products of smouldering materials.

- Documenting firefighter smoke exposure during WUI fires could be useful in developing correlations between respiratory ailments and factors such as exposure time, proximity to a smoke source, materials combusting, and fire intensity.
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