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A Screening-Level Assessment of the Health Risks of Chronic Smoke Exposure for Wildland Firefighters

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A screening health risk assessment was performed to assess the upper-bound risks of cancer and noncancer adverse health effects among wildland firefighters performing wildfire suppression and prescribed burn management. Of the hundreds of chemicals in wildland fire smoke, we identified 15 substances of potential concern from the standpoints of concentration and toxicology; these included aldehydes, polycyclic aromatic hydrocarbons, carbon monoxide, benzene, and respirable particulate matter. Data defining daily exposures to smoke at prescribed burns and wildfires, potential days of exposure in a year, and career lengths were used to estimate average and reasonable maximum career inhalation exposures to these substances. Of the 15 substances in smoke that were evaluated, only benzene and formaldehyde posed a cancer risk greater than 1 per million, while only acrolein and respirable particulate matter exposures resulted in hazard indices greater than 1.0. The estimated upper-bound cancer risks ranged from 1.4 to 220 excess cancers per million, and noncancer hazard indices ranged from 9 to 360, depending on the exposure group. These values only indicate the likelihood of adverse health effects, not whether they will or will not occur. The risk assessment process narrows the field of substances that deserve further assessment, and the hazards identified by risk assessment generally agree with those identified as a concern in occupational exposure assessments.

Keywords cancer, firefighters, health, risk assessment, smoke exposure

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INTRODUCTION

Every year in the United States thousands of wildland firefighters suppress wildfires and conduct prescribed burns. Wildland firefighters work at vegetation fires of forests, rangeland, and other natural fuels, as opposed to structural firefighters who are mainly concerned with the built environment. In contrast to wildfires that are suppressed, prescribed burns are preplanned fires in natural fuels that are allowed to burn to achieve resource management goals. Although measurements have documented the exposure to smoke among wildland firefighters,(1) we are unaware of a risk assessment of potential adverse health effects from long-term exposure to wildland fire smoke.

To fill this void the Health Hazards of Smoke Technical Committee of the National Wildfire Coordinating Group, Safety and Health Working Team commissioned our screening health risk assessment (HRA) to identify whether smoke exposure could pose a significant health risk to hand crew firefighters at either wildfires or prescribed burns. Human HRA guidance was developed by the U.S. Environmental Protection Agency (EPA) as part of the national Superfund program.(2) The procedures used here followed guidelines developed by the State of California and EPA for a risk assessment.(3,4) Though not developed by an agency charged with regulating occupational health, these risk assessment procedures are widely accepted and are the best method, short of epidemiological data, to estimate risk from occupational exposures. The exposure algorithms are appropriate for estimating both general population and worker exposures, providing estimates of the exposure and risk to a human receptor regardless of whether it is for occupational or non-occupational exposure. The difference is defined by the exposure assumption factors, not the algorithms.

The Superfund guidance, and subsequent updates, describes the steps required to conduct an in-depth risk assessment and this methodology was generally followed for this project. However, the purpose of this study was not to complete an in-depth assessment looking at all possible chemicals and exposure pathways that might be applicable to firefighters. Rather, this is a screening-level risk assessment in that a number of simplifying assumptions were made to indicate whether there might or might not be a health risk and to attempt to identify areas that could be worthy of further study. Specifically, chemicals previously identified in the literature as potential concerns to firefighters were evaluated only for the inhalation pathway using simplified assumptions of exposure. These chemicals and the inhalation route would be expected to be by far the most important contributors to any potential health risks. An in-depth risk assessment would evaluate more chemicals and more exposure pathways than this screening-level assessment. As appropriate for a screening HRA, we made assumptions where suitably detailed specific data were unavailable. These assumptions were conservative estimates designed to be protective of health—resulting in risk estimates that were likely to be greater than those actually present.

Smoke exposures of all firefighters were calculated using two sets of exposure assumptions: (1) the reasonable maximum exposure (RME) assumptions were used to estimate exposures in the upper range of potential exposure and represent the highest exposure reasonably expected to occur; and (2) the average (mean) exposure, which uses average exposure assumptions intended to represent a more likely human exposure.

HAZARD IDENTIFICATION

The hazard assessment is where we selected the chemicals and physical agents in smoke that are most likely to pose a health risk based on a review of the relevant literature. The chemicals of potential concern (COPC) in smoke that we evaluated included:

- acrolein
- anthracene
- benzene
- benzo(a)anthracene
- benzo(a)pyrene
- benzo(b)fluoranthene
- benzo(k)fluoranthene
- carbon monoxide (CO)
- chrysene
- fluoranthene
- formaldehyde
- indeno(1,2,3-cd)pyrene
- respirable particulate matter—fine particles smaller than 10 μm, with a median diameter of 3.5 μm (PM3.5), following the definition of respirable provided by the U.S. Occupational Safety and Health Administration (OSHA) in Table Z-3 of 29 CFR 1910.1000[5]
- phenanthrene
- pyrene

These agents were chosen as representative COPCs for exposure to smoke based on fire emissions research and the exposure data in the literature.[1]

TOXICITY ASSESSMENT

For this HRA we evaluated only those effects for which EPA reference doses (RfD) or cancer slope factors were readily available or could be easily developed. These toxicity values are often based on the most sensitive adverse effect found (i.e., the effect occurring at the lowest dose or concentration). Although the most sensitive endpoint may not be related to what firefighters might experience, its use is in keeping with the health conservative nature inherent in a screening HRA. The toxicity values were obtained primarily from the Integrated Risk Information System (IRIS), maintained by EPA.[6] These values are found in Table I.

Noncarcinogen Toxicity Values

To evaluate the potential for adverse effects of noncarcinogens the estimated exposure to a COPC is compared to the safe level of exposure for that COPC. This comparison, which produces a hazard quotient (HQ), can be made for noncarcinogens because they are believed to have a threshold of toxicity, below which toxicity is unlikely. When hazard quotients are summed they are referred to as hazard indices (HI).

The inhalation RfD, in units of milligram of chemical/dust per kilogram of body weight per day (mg/kg/day), is the toxicity value used to evaluate noncarcinogenic health effects in this HRA. RfDs are the EPA's standard estimates of the daily exposure to the human population (including sensitive subgroups) that are likely to be without an appreciable risk of adverse effects. We used chronic RfDs developed for long-term exposures to evaluate exposure for this HRA. When the dose of a particular chemical equals the RfD, then the hazard of the chemical is equal to one. Target health goals for noncarcinogens are thus hazard quotients or indices of one or less.

Carcinogen Toxicity Values

Carcinogens are assumed to have no toxicity thresholds and to pose a potential risk of causing cancer regardless of the level of exposure—the greater the exposure, the greater the potential risk. They are therefore evaluated by assessing the level of cancer risk posed by the exposure. This risk was compared to "acceptable risks" established by regulatory agencies in order to determine whether the risk should be considered significant. The target risk range considered acceptable by EPA is 10^{-4} to 10^{-6}.[7] Some agencies and individuals may consider higher risks acceptable for workers.

Toxicity information used in evaluating carcinogenic effects for this screening risk assessment includes the EPA weight of evidence (A through E) classification, and inhalation slope factors (SFs) in units of mg/kg/day.

Toxicity Values Used in this Screening Risk Assessment

The EPA hierarchy establishing the order of preference for toxicity values was followed:

- IRIS.[6] The online database maintained by the EPA containing EPA-verified, up-to-date toxicity information and regulatory values for a number of chemicals.

TABLE I. Toxicity Values for Contaminants of Potential Concern

Chemical	EPA Cancer Classification[A]	Chronic Inhalation RfD (mg/kg/day)	Inhalation Slope Factor (mg/kg/day)
Acrolein	—	5.7×10^{-6}	—
Anthracene	—	3.0×10^{-1B}	—
Benzene	A	—	2.9×10^{-2}
Benz(a)anthracene	B2	—	3.1×10^{-1C}
Benzo(a)pyrene	B2	—	$3.1 \times 10^{+0C}$
Benzo(b)fluoranthene	B2	—	3.1×10^{-1C}
Benzo(k)fluoranthene	B2	—	3.1×10^{-2C}
Carbon monoxide	—	$8.3 \times 10^{+0D}$	—
Chrysene	B2	—	3.1×10^{-3C}
Fluoranthene	—	4.0×10^{-2B}	—
Formaldehyde	B1	—	4.6×10^{-2}
Indeno(1,2,3-cd)pyrene	B2	—	3.1×10^{-1C}
Respirable particulate matter (PM3.5)	—	1.4×10^{-2E}	—
Phenanthrene	—	3.0×10^{-2F}	—
Pyrene	—	3.0×10^{-2B}	—

Note: RfD = Reference dose; all values from Reference 6 with the following exceptions.
[A] U.S. EPA carcinogen classifications: A = human carcinogen; B1 = probable human carcinogen (limited evidence in humans); B2 = probable human carcinogen (sufficient evidence in animals, little or no evidence in humans).
[B] Toxicity value extrapolated from oral exposure route.
[C] U.S. EPA Superfund Technical Support Center.
[D] Derived from the ACGIH® TLV.®
[E] Toxicity value developed from the literature.
[F] Pyrene toxicity value used as surrogate.

- Health Effects Assessment Tables.[8] Also produced by the EPA, this document provides values that may not be found in IRIS.
- The U.S. EPA Superfund Technical Support Center at the National Center for Environmental Assessment in Cincinnati, Ohio.

Acrolein was the only COPC with an EPA-derived RfD for noncarcinogenic effects via the inhalation route of exposure. Surrogate inhalation RfDs were derived for the noncarcinogens anthracene, CO, fluoranthene, phenanthrene, pyrene, and PM3.5. Although they have noncarcinogenic effects, the carcinogenic COPCs were evaluated only as carcinogens because cancer was the most significant end point.

For CO we used the American Conference of Governmental Industrial Hygienists' (ACGIH®) Threshold Limit Value (TLV®) of 25 ppm to derive a surrogate inhalation RfD. Because TLVs are for occupational exposures we did not use uncertainty factors in our conversion from the TLV to the RfD. We simply multiplied the TLV (in units of mg/m^3), by the daily intake of air for a worker (20 m^3), and divided by a worker's bodyweight (70 kg) to give an acceptable daily intake in units of mg/kg/day. The EPA's recent publication of defaults for construction workers noted that 20 m^3 per day is scientifically valid for relatively young healthy workers involved in the construction industry.[9] Available inhalation studies indicate that 20 m^3 in an 8-hr day is a reasonable average for outdoor workers engaged in heavy activities.[10] Therefore, for those engaged in physically demanding work such as firefighting, 20 m^3/day is more representative of the amount of air that would be inhaled over the shorter duration of a firefighting season than the OSHA generic worker default of 10 m^3/day.

The noncancer inhalation toxicity value of 0.014 mg/kg/day for PM3.5 was based on a study of long-term respiratory effects in healthy nonsmoking adults.[11] The study found a statistically significant association between decreased forced expiratory air volume and frequency of days where PM10 was >100 μg/m^3 for males whose parents had respiratory problems (i.e., asthma, bronchitis, emphysema, or hay fever). There were no significant effects for the other adult groups studied. Although the particulate measured in this study was PM10 rather than PM3.5 or 2.5, the study was conducted in urban areas of southern California where the majority of the PM was likely combustion products less than 3.5 μm in diameter. The mean concentration of PM10 during this study was approximately 50 μg/m^3. The value of 50 μg/m^3 was converted to a reference dose of 0.014 mg/kg/day by assuming a daily air intake of 20 m^3 and a body weight of 70 kg. The value of 50 μg/m^3 is higher than that proposed for the general public of 15 μg/m^3 by EPA (annual PM2.5 standard proposed in 1997) and 12 μg/m^3 recently passed by the California legislation as an annual PM2.5 standard. Generally allowed occupational exposures are higher than those that are acceptable for the general population because the general population includes sensitive subgroups such as children and the elderly that are not part of the workforce.

Although the particle size distribution curve differs slightly from the PM3.5 we measured, the TLV for respirable particles (PM4) of 3 mg/m^3 was considered as a reference dose, but it is several orders of magnitude larger than the 50 $\mu g/m^3$ selected for this screening-level study. The TLV is based on the ability of clearance mechanisms in the lungs to successfully clear particles that are not otherwise associated with toxicity;[12] however, ACGIH is proposing to remove this value as a TLV and refer to it instead as a guideline because "it is not possible to meet the standard level of evidence used to assign a TLV."[13] The EPA, which has reviewed hundreds of studies in their recent review of the PM literature, questioned whether lung overload was a relevant endpoint in humans[14] with the possible exception of occupational exposures with very high dust exposures.[15] Lung overload is likely not the most sensitive toxicological endpoint. Respiratory effects based on epidemiological findings rather than lung clearance mechanisms were selected as the most applicable endpoints for the firefighting population for this screening level assessment that was designed to over- rather than underestimate health risks.

While the actual mechanisms causing the toxicity of particulate matter are still unknown, the latest epidemiological and mechanistic evidence is focusing on two adverse health outcomes that are the most applicable to particulate exposures: cardiovascular effects and respiratory effects.[12] Of these two, respiratory effects, particularly those associated with decreased lung function and increased respiratory symptoms (e.g., cough, phlegm, difficulty breathing), are likely more relevant to firefighters. Because firefighters are relatively young and physically fit due to the physical requirements of the work, those individuals with cardiovascular problems and/or those at increased risk of cardiovascular problems would not be expected to be firefighters. In addition, studies with cardiovascular endpoints where the studied population was comprised of healthy adults could not be located. How the cardiovascular endpoint for occupational dust exposures relates to the working population may be worthy of future study.

A route-to-route extrapolation using the oral RfDs was used to develop surrogate inhalation RfDs for anthracene, fluoranthene, phenanthrene, and pyrene. The RfD for pyrene was used as a surrogate for phenanthrene that had no oral or inhalation RfD. Table I lists the inhalation toxicity values for COPCs that were evaluated in this screening HRA.

EXPOSURE ASSESSMENT

The cumulative exposure to COPCs over a firefighting career required assumptions about the severity and frequency of daily exposures, the rate of uptake of the COPCs from smoke, and the number of years in a career that a firefighter is exposed to smoke. Although a comprehensive exposure assessment would include the quantity ingested as well as inhaled and include dermal exposures for some chemicals (i.e., the polycyclic aromatic hydrocarbons (PAHs)), these were omitted in this screening HRA because we considered them negligible in comparison to the inhalation exposure. We also assumed that 100% of the available exposure via inhalation was absorbed because there were no readily available absorption data for each COPC.

This screening HRA was limited to firefighters who are members of hand crews. Wildland fire agencies in the U.S. have two basic classifications for hand crews: Type I and Type II crews. Type I crews are more highly-trained than Type II crews and are therefore often assigned to more hazardous areas of a wildfire. Type I crew examples include smokejumpers and hotshot crews. Type II crews include local district fire management personnel, crews formed primarily to conduct prescribed burning, and crews comprised of personnel for which firefighting is only a collateral duty. Engine-based (ground tanker) crews were omitted from the HRA because there were not sufficient data to estimate their exposures. However, some occupational exposure data from engine crews were used to estimate hand crew exposure to PAHs, because hand crew-specific PAH exposure data were not available.

Most of the elite Type I crews spend proportionately more days performing wildfire suppression than working at prescribed burns and many Type II crews do more prescribed burning. We therefore estimated the number of days at prescribed burns and wildfires separately for each type of crew. However, the daily exposure to COPCs at a prescribed burn or wildfire was assumed to be independent of crew type because personnel from both types of crew often perform the same job tasks at wildfires and prescribed burns.

Smoke Exposure During Wildfire Suppression

Smoke exposure during wildfire suppression was estimated after reviewing data from several different studies. These include those by the U.S. Department of Agriculture (USDA) Forest Service,[16] and the National Institute for Occupational Safety and Health (NIOSH).[17] The Forest Service study measured smoke exposure among 84 firefighters (both Type I and II hand crews) during 17 days of work at 8 large project wildfires in the western United States between 1992 and 1995. The NIOSH study measured smoke exposure among 16 firefighters from 2 Type I hand crews during 2 days of firefighting at a large wildfire in Yosemite National Park, California, during 1990.

In the Forest Service study, wildfires were selected for sampling in the western United States based on logistical constraints and the greatest potential for smoke exposure. Up to six firefighters were monitored per day out of a group of volunteers that included both smokers and nonsmokers (smokers refrained from smoking during sampling). Monitored firefighters wore a 4-kg sampling apparatus containing 3 battery-powered personal sampling pumps. Each pump was optimized for the following samples and media:

- An inert gas sampling bag (Calibrated Instruments, Inc.) with a glass fiber filter on the sampler inlet, for fixed-rate (20 to 200 L/min) whole air sample collection and later analysis of CO by nondispersive infrared spectroscopy via Intersociety Committee Method (ICM) 128.[18]

- Sorbent tubes collected at 0.15 L/min for analysis of benzene by gas chromatography/flame ionization detection using NIOSH Method 1501, and at 0.2 L/min for analysis of formaldehyde and acrolein on 2,4-dinitrophenylhydrazine-coated C-18 coated silica gel Sep-Paks using high-performance liquid chromatography methods in EPA Method TO-11.[19,20]
- A 2.0-μm Teflon 37-mm filter in a polystyrene 3-piece cassette with a Dorr-Oliver-design 10-mm nylon cyclone assembly for sample collection and later analysis of PM3.5 at 1.7 L/min according to NIOSH Method 0600.[21]

For the 1995 fire season the ICM 128 method for CO analysis was replaced by electronic data-logging dosimeters measuring CO according to OSHA method ID-209.[22] Samples were analyzed at the Pacific Northwest Research Station, Seattle Forestry Sciences Laboratory. Standard operating procedures, improvements, and modifications to the above methods to enhance accuracy and precision are detailed in the referenced project reports. Data collection took place under an extensive quality assurance project plan. Method detection limits were periodically evaluated for each analytical method according to EPA procedures.[23]

Table II summarizes estimated exposures for firefighters at wildfires based on the data from the Forest Service study because it comprised the largest and most diverse data set. Data are included for acrolein, benzene, CO, formaldehyde, and PM3.5. All data have been converted as needed to the equivalent concentration in mg/m^3 at 25°C, 760 mmHg. The exposure hours are the daily number of work hours with exposure potential that were observed among the studied firefighters (i.e., time on the fireline not including travel to and from fires).

The (geometric) mean exposures and durations were the actual results for 84 time-weighted average (TWA) exposures over 17 days of wildfire suppression at large "project" wildfires, obtained by Reinhardt and Ottmar.[16]

For estimating RME exposures from the original data we used the procedure for estimating the upper 95% confidence interval (UCL) of the arithmetic mean of lognormally distributed data, as outlined by the EPA.[24] As a clarification of terminology the term RME in risk assessment convention refers to the entire constellation of exposure factors that are utilized in calculating an RME risk or hazard. The concentration of the chemical of concern is just one of those exposure factors. By convention, the concentration term used to calculate the RME scenario is always the upper 95% confidence limit of the arithmetic mean of the applicable data (e.g., the UCL—the average plus the Z-value multiplied by the standard deviation). For the central tendency scenario the average of the applicable data is used as the concentration term.

Several reports of smoke exposure during prescribed burns were reviewed to derive the prescribed burning smoke exposure data in Table II. These included two studies by the USDA Forest Service,[25,26] and one by the State of California Department of Health Services.[27] One of the Forest Service studies measured smoke exposure among 221 firefighters at 39 prescribed fires in the Pacific Northwest during 1991–1993.[25] The other Forest Service study examined exposure to CO, total particulate matter, and herbicides among firefighters conducting 14 days of prescribed burning in southern pine plantations treated with herbicides during 1988.[26]

Data from Reinhardt et al.[25] were used as the basis of the Table II exposure estimates for prescribed burns because of the larger data set and the consistency of the findings with the work of McMahon and Bush,[26] and the results of Materna et al.[27] Reinhardt et al.[25]obtained 2886 measurements from breathing zone samples at 39 prescribed burns in Washington and Oregon between 1991 and 1994. They collected 1937 validated measurements of firefighters' exposure to benzene, acrolein, formaldehyde, CO, carbon dioxide, and PM3.5 during prescribed burns, using the methods described above for wildfires. Hours per day were again obtained from actual measurements of hours per day at prescribed burns among the studied firefighters.

Polycyclic Aromatic Hydrocarbon Exposure Estimation

Combustion of woody fuels in wildland fire emits PAHs, including the COPCs anthracene, benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene,

TABLE II. Estimated Wildland Firefighter Exposures to COPCs

		Estimated Pollutant Concentration (mg/m^3)				
		Acrolein	Benzene	CO	Formaldehyde	PM3.5
Geometric mean	Prescribed burns	0.034	0.089	7.90	0.092	1.00
	Wildfire suppression	0.005	0.019	4.58	0.022	0.72
95% UCL	Prescribed burns	0.041	0.118	13.90	0.139	1.59
	Wildfire suppression	0.014	0.078	10.43	0.042	1.10
Exposure hours/day	Prescribed burns	Arithmetic mean: 7.0 (range 0–13)				
	Wildfire suppression	Arithmetic mean: 10.4 (range 0–24)				

TABLE III. Polycyclic Aromatic Hydrocarbon Exposure Estimates for Wildfires and Prescribed Burns

PAH	Geometric Mean (and Range) of PAH Exposure (μg/m^3)	95% UCL (μg/m^3)
Anthracene	0.061 (0.005–0.152)	0.136
Benz(a)anthracene	0.015 (ND–0.034)	0.025
Benzo(a)pyrene	0.012 (ND–0.034)	0.025
Benzo(b)fluoranthene	0.018 (ND–0.120)	0.053
Benzo(k)fluoranthene	0.004 (ND–0.014)	0.013
Benzo(ghi)perylene	0.022 (ND–0.032)	0.027
Chrysene	0.025 (ND–0.080)	0.048
Fluoranthene	0.048 (ND–0.101)	0.256
Indeno-1,2,3-(cd)pyrene	0.016 (ND–0.042)	0.051
Phenanthrene	0.257 (0.013–0.869)	1.013
Pyrene	0.075 (ND–0.110)	0.162

Notes: ND = not detected; all PAH exposure data are from Materna et al.(27)

chrysene, fluoranthene, indeno(1,2,3-cd)pyrene, phenanthrene, and pyrene. Few measurements of PAH exposure have been made among firefighters at wildfires, and no measurements from prescribed burns have been published. Three references include data about PAH exposure: two by NIOSH(28,29) and one by the State of California Department of Health Services.(27) The latter reports the results of 22 PAH samples obtained from the breathing zone of firefighters at wildfires in Northern California,(27) and provides the PAH exposure estimates for this screening HRA. Arithmetic means were presented in that paper, but after obtaining the raw data from the authors, geometric means and UCLs were calculated via EPA methods. Table III summarizes these breathing-zone data.

Annual Exposure

Fire frequency and severity varies substantially from year to year, as do crew assignments for wildfires and prescribed burns. These data vary regionally as well; thus, the number of exposed days is a tenuous estimate. Several studies of smoke exposure and health effects among firefighters were reviewed for estimates of the annual number of days that firefighters worked on the fireline, but some aspect of each study limited the usefulness of the data as an estimator of annual days of firefighting. These included Letts et al.(29) and Betchley et al.(30) To provide a better estimate of annual days of smoke exposure, two key data sets were obtained:

- A database of personnel participation at wildfires and prescribed burns obtained from the Okanogan National Forest in Washington State.(31) Data for two Forest Service ranger districts (Winthrop and Twisp, since consolidated into one) over 5 years (1990–1994) were used to compute the results for prescribed burning. The data for prescribed burning were limited to Type II personnel stationed at the two districts (often, neighboring districts supply personnel for prescribed burning) and Type I crewpersons from an adjacent Forest Service smokejumper base (North Cascades Smokejumper Base). The data for the annual number of days that Type II personnel worked at wildfires were also based on these two districts.
- Types I and II crew data for 1990–1994 wildfire mobilizations were obtained from the Northwest Regional Coordinating Center.(32) These data were used to estimate the annual days at wildfires for Type I crews. The Type II crew data were not used because the Type II crews were unlikely to consist of the same personnel on every dispatch, in contrast to Type I crews.

Mean annual days at fires were calculated and the RMEs were obtained as the 95th percentile value of each frequency distribution. Type I crews averaged 64 days at wildfires and 5 days of prescribed burning per year, with 95th percentile values of 97 and 17 days for wildfires and prescribed burns, respectively. The estimates of annual days at wildfires may be slightly high because days spent mobilizing to or from the fires were not specified in the data. Also, the distribution of annual prescribed burns and wildfires for smokejumpers may differ from Type I hotshot crews. Type II crews averaged 10 days at wildfires and 3 days of prescribed burning per year, with 95th percentile values of 46 days for wildfires and 22 days for prescribed burns. The data indicated that many Type II personnel were infrequently assigned to fire duties, thus the data likely underestimate the average exposure of Type II crews mainly assigned to fire management. Finally, the distribution of annual days at fires may differ in other regions for both the Type I and Type II personnel.

Career Duration

This final term in the exposure assessment is the number of years during which a firefighter is exposed to smoke at wildfires or prescribed burns. After fruitless review of the literature for potential data sources, we solicited a senior fire manager from the Forest Service to provide career estimates based on expert opinion.(33) He estimated the mean and reasonable maximum career durations to be 8 and 25 years, respectively, for Type I crewpersons, but could not estimate these factors for Type II personnel. We developed an estimate for the latter based on the distribution of crewpersons' years of experience data from the exposure study of Reh, Letts, and Deitchman, who recorded a mean of 4 years of experience for 10 Type I crewpersons and 7 years for 11 Type II crewpersons, respectively.(17) We used the value of 7 years for the Type II crewperson mean, with an RME value of 25 years calculated from the median plus 3 standard deviations of their years of experience data.

Exposure Calculations

Daily, annual, and career estimates of exposure were derived as explained above. Doses were calculated using a standard exposure algorithm for inhalation, shown below. Ventilation rates of 2.4 m^3/hr and 3.6 m^3/hr were used for the mean and

TABLE IV. Summary of Potential Cancer Risks

Crew Type	COPC	Wildfires Mean (and RME)	Prescribed Burns Mean (and RME)
Type I	Total	1.2×10^{-5} (2.2×10^{-4})	2.6×10^{-6} (6.0×10^{-5})
	Benzene	3.9×10^{-6} (1.2×10^{-4})	9.7×10^{-7} (2.1×10^{-5})
	Formaldehyde	9.2×10^{-6} (9.8×10^{-5})	1.6×10^{-6} (3.8×10^{-5})
	Benzo(a)anthracene	3.3×10^{-8} (3.9×10^{-7})	1.8×10^{-9} (4.6×10^{-8})
	Benzo(a)pyrene	2.7×10^{-7} (3.9×10^{-6})	1.4×10^{-8} (4.6×10^{-7})
	Benzo(b)fluoranthene	4.0×10^{-8} (8.3×10^{-7})	2.1×10^{-9} (9.8×10^{-8})
	Benzo(k)fluoranthene	8.9×10^{-10} (2.0×10^{-8})	4.7×10^{-11} (2.4×10^{-9})
	Chrysene	5.5×10^{-10} (7.6×10^{-9})	2.9×10^{-11} (8.9×10^{-10})
	Indeno(123cd)pyrene	3.5×10^{-8} (8.0×10^{-7})	1.9×10^{-9} (9.5×10^{-8})
Type II	Total	1.6×10^{-6} (1.0×10^{-4})	1.4×10^{-6} (7.7×10^{-5})
	Benzene	5.4×10^{-7} (5.4×10^{-5})	5.1×10^{-7} (2.7×10^{-5})
	Formaldehyde	9.9×10^{-7} (4.6×10^{-5})	8.4×10^{-7} (5.0×10^{-5})
	Benzo(a)anthracene	4.4×10^{-9} (1.9×10^{-7})	9.2×10^{-10} (6.0×10^{-8})
	Benzo(a)pyrene	3.6×10^{-8} (1.9×10^{-6})	7.3×10^{-9} (6.0×10^{-7})
	Benzo(b)fluoranthene	5.4×10^{-9} (4.0×10^{-7})	1.1×10^{-9} (1.3×10^{-7})
	Benzo(k)fluoranthene	1.2×10^{-10} (9.7×10^{-9})	2.4×10^{-11} (3.1×10^{-9})
	Chrysene	7.6×10^{-11} (3.6×10^{-9})	1.5×10^{-11} (1.2×10^{-9})
	Indeno(123cd)pyrene	4.8×10^{-9} (3.8×10^{-7})	9.8×10^{-10} (1.2×10^{-7})

RME, respectively.[34]

$$\text{Intake(mg/kg/day)} = \frac{\text{CA} \times \text{IR} \times \text{EF} \times \text{ET} \times \text{ED}}{\text{BW} \times \text{AT}}$$

where CA = contaminant concentration in air (mg/m^3), IR = inhalation rate (m^3 per 7- or 10.4-hr workday), EF = exposure frequency (days/year), ET = exposure time (hrs/day), ED = exposure duration (years), BW = body weight (kg) and, AT = averaging time (days).

RISK CHARACTERIZATION

The estimated exposure concentrations were compared to chemical-specific toxicity concentrations to determine if COPC concentrations warrant concern for human health. The following subsections summarize the methodology used to characterize the cancer risk and noncancer hazard indices.

Risk Characterization for Carcinogens

The carcinogenic risk estimate is an upper-bound estimate of the probability of developing cancer over a lifetime of exposure. We consider potentially acceptable cancer risks calculated for a given exposure to range from 10^{-6} to 10^{-4}. Within this range cancer risks below 10^{-6} are generally always considered acceptable and are not to be evaluated further, while cancer risks above 10^{-4} are generally considered unacceptable and warrant some type of action.[7] Cancer risks in the middle of the range may or may not be acceptable.[7] Estimated cancer risks for each COPC were calculated for each firefighter by multiplying the calculated exposures by the appropriate cancer SF. The estimated COPC-specific cancer risks were added to determine the firefighters' total estimated cancer risk from all COPCs. Table IV presents these estimated total cancer risks. The cancer risks presented are the number of additional cancer cases (i.e., above the normal background cancer incidence) per a given population, e.g., 1×10^{-6} refers to one excess case per one million.

Total cancer risks were calculated to range from 1.4×10^{-6} (Type II mean, prescribed burns) to 2.2×10^{-4} (Type I RME,wildfires) with benzene and formaldehyde being the most significant contributors to these risks. With the assumptions used in this risk assessment, exposure at wildfires posed a greater risk than exposure at prescribed burns for all crew types. This is because the duration and frequency of exposure at wildfires was greater than at prescribed burns, even though the exposure to COPCs was lower at wildfires. Many Type I and Type II firefighters participate at both wildfires and prescribed burns in a given year, thus their combined risk from both exposure scenarios may be as great as the sum of the totals for wildfires and prescribed burns for each of the exposure groups (e.g., Type I, RME) in Table IV.

Risk Characterization for Noncarcinogens

The individual HQs for developing noncarcinogenic adverse health effects from chronic exposure are presented in Table V. Each HQ is the estimated exposure divided by the RfD. If exposure results in an HQ exceed 1, a potential for an adverse effect may exist.[2] The HQ for each route of exposure would be summed in a comprehensive risk assessment to arrive at the HI for each COPC; because we only considered inhalation

TABLE V. Summary of Noncancer Hazard Indices

Crew Type	Primary Contributors[A]	Wildfires Mean (and RME)	Prescribed Burns Mean (and RME)
Type I	Total	58 (360)	20 (123)
	Acrolein	55 (349)	20 (121)
	PM3.5	3.2 (11.2)	<1 (1.9)
Type II	Total	8.8 (171)	11.8 (159)
	Acrolein	8.6 (166)	11.8 (156)
	PM3.5	<1 (5.3)	<1 (2.5)

[A]All other noncancer COPCs (anthracene, carbon monoxide, fluoranthene, formaldehyde, phenanthrene, and pyrene) have an HI less than 1.0.

exposures, each COPC's HI is equal to the inhalation HQ. The magnitude of the HI should not be used as a quantitative indication of the likelihood of an adverse effect. Instead, it indicates that a potential for adverse health effects exists and that this potential should be examined further. Summing individual chemical HQs or HIs with other chemicals assumes the toxic endpoints are the same (a conservative assumption for this screening risk assessment).

The total hazard indices range from 9 (Type II mean, wildfires) to 360 (Type I RME, wildfires) with acrolein dominating the HIs. The only other COPC with an HQ greater than 1.0 was PM3.5, with HQs ranging from <1 to 11.2. Generally, the HIs due to exposure at wildfires were greater than those due to exposure at prescribed burns for all populations except the Type II mean. The acrolein concentrations were found to be higher at prescribed burns than at wildfires; although this is also true for the Type I mean, the difference between annual days at wildfires versus annual days at prescribed burns is greater for the Type I crews than for the Type II crews. Further examination of the total HI shows that even if the COPC-specific HIs are segregated by target organ, each population's HI still exceeds 1.0 because of the acrolein HI alone. Like the cancer risks, the total HI for Type I or Type II firefighters who work at both wildfires and prescribed burns may be as great as the sum of the two HI columns for their respective exposure groups.

DISCUSSION

In this screening HRA we evaluated the potential for the occurrence of adverse health effects resulting from long-term exposure to smoke. The results indicate a potential total cancer risk ranging from 1.4×10^{-6} to 2.2×10^{-4}, and total hazard indices ranging from 9 to 360 depending on the exposure group. The two carcinogenic COPCs contributing the most to cancer risk were benzene and formaldehyde. The COPC contributing the majority of the overall hazard index was acrolein, secondarily particulates. Most of the other COPCs had risks and hazards below levels considered significant by regulatory agencies.[7]

The actual total risks and hazard indices are not likely to be greater and may, in fact, be significantly less. The values obtained in this screening HRA are based on the conservative assumptions we made and should be considered upper-bound estimates. If actual exposures are less, then the risks and hazard indices will also be less. It should be noted that the total estimated cancer risks are the results of a mathematical tool. They do not mean that 1.4 out of 1,000,000 or 2.2 out of 10,000 firefighters exposed under the assumptions used in this report will develop cancer. Instead, they are values used to help in risk management decisions. Similarly, hazard indices or hazard quotients greater than 1.0 do not indicate that an adverse effect will occur, only that the exposure exceeds what is considered a safe level.

One of the COPCs with an HQ greater than 1.0 is acrolein. The exposures to acrolein ranged from 0.005 to 0.041 mg/m^3 resulting in HIs ranging from 8.6 to 349. The RfD for acrolein is based on microscopic changes in the cells lining the nasal passage and occurs as a response to irritation.

The other COPC with an HQ greater than 1.0 is PM3.5. Although the highest HQ is relatively low (11.2) there is much uncertainty surrounding both the composition of this particulate matter and the relationship between the dose and the onset of toxicity. Even if the particulate matter is inert and does not cause toxicity by direct chemical action there is still a significant lack of quantitative data concerning the effects of PM3.5 and its potential to decrease lung functions, increase the risk of cardiovascular problems, or enhance the toxicity of other chemicals by impairing the lungs' self-cleansing capacity. Without such data there is much uncertainty regarding the potential for toxicity. All other COPCs examined for noncarcinogenic effects (i.e., anthracene, CO, fluoranthene, formaldehyde, phenanthrene, and pyrene) had HQs less than 1.0.

UNCERTAINTY ASSESSMENT

As in all risk assessments there are several areas of uncertainty. The most significant uncertainty issues include the following:

(1) The hazard identification process may not have included all of the significant COPCs. Particulate matter, which we have assumed to be relatively inert as a COPC, can be included in this category. Although we believe that the majority of the potential toxicity of fire-derived PM3.5 has been captured in the evaluation of the other COPCs associated with particulate matter, we may be underestimating the total risks associated with PM3.5.

(2) In the toxicity assessment, the lack of inhalation toxicity values required us to develop values based on other routes of exposure, surrogate chemicals, or with other significant data gaps. This in turn may cause either an over- or underestimation of risk (or hazard index) depending on the toxicological endpoint. Overestimation of risk can result from the use of toxicity values based on the most sensitive toxicological endpoint, because it may not be relevant to firefighter exposure. The use of toxicity values based on noninhalation routes of exposure may either under- or overestimate risk. Underestimation of risk can result from using a toxicity value with significant uncertainty to evaluate a COPC (e.g., PM3.5).

(3) The RfD selected for respirable particulate matter (PM3.5) was derived from a study that measured inhalable particulate matter (PM10). Consequently, using a mean of 50 μg/m^3 PM10 as a reference concentration may have overestimated the "safe" amount if the toxic effects were due primarily to the respirable fraction and that fraction was less than 50 μg/m^3. Studies measuring PM2.5 have shown statistically significant respiratory and lung function effects at concentrations less than 50 μg/m^3. However, those studies were generally not conducted on a healthy adult population. For the eight studies reviewed by EPA in their *Criteria* document on short-term increases in PM2.5 associated with decreased lung function and increased respiratory symptoms, mean PM2.5 levels range from 18 μg/m^3 to 24.5 μg/m^3 (excluding lowest concentration study). For all but one of these studies healthy adults were not the subject population, rather potential subpopulations at increased risk from particulate exposures were selected, such as children with asthma or the elderly. The levels necessary to elicit an adverse effect in sensitive subpopulations would be lower than those that would adversely affect healthy adults.

Conversely, the RfD used to evaluate particulates may have overestimated potential health effects if the appropriate safe level of exposure is the TLV of 3 mg/m^3 for PM3.5. While lung overloading may not be an appropriate endpoint for human health, there is currently insufficient information to evaluate what a reasonable estimate for occupational exposures might be for another endpoint, such as lung function decreases or cardiovascular diseases.

(4) The exposure assessment also contains significant uncertainty. The estimates made here about exposure frequency, duration, concentration of chemical, and so on, can result in risk estimates either greater or less than what is actually occurring.

Although several areas of uncertainty have been mentioned, this HRA addresses them by using conservative assumptions to compensate for the lack of more specific data. These include using uncertainty factors in toxicity values, assuming toxicity is additive, and providing a range of results using mean and RME values. The end result is a set of risk estimates that, if not representing the true risk, will err on the side of health protectiveness. The risk estimates might be improved through a sensitivity analysis to determine how much of an effect is exerted on the total risk by each component of the risk assessment. Based on such an analysis, a hierarchy of data needs can be constructed to prioritize resource expenditures to acquire more representative data.

CONCLUSION

The results of this screening-level risk assessment indicate a relatively low risk for several of the COPCs evaluated. These results can be used to make a case that further risk assessment efforts and respiratory protection priorities should be focused on just those few COPCs that resulted in potentially significant risks (i.e., benzene, formaldehyde, acrolein, and PM3.5), since adverse health effects appear to be unlikely for the other COPCs. In spite of our tendency toward health-conservative assumptions we note that the two Forest Service research papers that provided the bulk of the occupational exposure data concluded that about 5–10% of exposures to the respiratory irritants formaldehyde, acrolein, and PM3.5 exceeded the respective respiratory irritant mixture TLV and a similar percentage of CO exposures that exceeded the CO TLV.[16,25] Further, many of those CO exposures would have exceeded the daily CO permissible exposure limits had the individual exposures been adjusted downward to account for the extended workshifts. Therefore, this screening risk assessment identified many of the same potential inhalation hazards as the actual exposure measurements, lending validation to the risk assessment process.

Finally, although the risks of smoke exposure were found to be relatively low, perhaps even lower than one might have expected, we must caution that risk assessments based on research under different conditions such as in different wildland fuel types or among firefighters with different exposure patterns (such as those in the southeastern United States) may indicate risks higher than those found in our study. We recommend that before significant risk management decisions are made, the underlying exposure data be replicated among a wider population to validate their extension to the entire population of wildland firefighters.

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