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Baseline Measurements of Smoke Exposure Among Wildland Firefighters

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Extensive measurements of smoke exposure among wildland firefighters are summarized, showing that firefighters can be exposed to significant levels of carbon monoxide and respiratory irritants, including formaldehyde, acrolein, and respirable particulate matter. Benzene was also measured and found to be well below permissible exposure limits, with the highest concentrations occurring among firefighters working with engines and torches burning petroleum-based fuel. Exposures to all pollutants were higher among firefighters at prescribed burns than at wildfires, while shift-average smoke exposures were lowest among firefighters who performed initial attack of wildfires in the early stages of the fires. Smoke exposure reaches its highest levels among firefighters maintaining fire within designated firelines and performing direct attack of spot fires that cross firelines. These events and the associated smoke exposures were positively correlated with increasing ambient wind speeds, which hamper fire management and carry the convective plume of the fire into firefighters' breathing zone. The pollutants measured in smoke were reasonably well-correlated with each other, enabling estimation of exposure to multiple pollutants in smoke from measurements of a single pollutant such as carbon monoxide.

Keywords carbon monoxide, firefighter, hazard, health, smoke, wildfire

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This article communicates what we have learned about smoke exposure among wildland firefighters during several long-term projects in the early 1990s. We provide an overview of the work force, the respiratory hazards we have identified, and our methods to measure them. We summarize the results of 5 years of breathing-zone exposure monitoring, providing a baseline data set that the National Wildfire Coordinating Group (NWCG) has used in developing smoke exposure management recommendations.(1) As land management organizations adopt specific measures to reduce overexposures to smoke, their success can be evaluated by comparing future measurements of smoke exposure among wildland firefighters against these baseline data.

Wildland firefighters have the primary responsibility to suppress fires in wildland fuels such as forests, grasslands, and brush (such as chaparral). Most wildland firefighters are employed by government land management agencies such as the U.S. Forest Service, the U.S. Department of Interior's Bureau of Land Management (BLM), and National Park Service (NPS), and state agencies such as the Florida Division of Forestry and the California Department of Forestry and Fire Protection (CDF). In contrast to structural firefighters, who are experts at fire suppression and rescue operations in the built environment, wildland firefighters are the experts on fire management in natural fuels. Wildland fire refers to wildfires *and* prescribed burns; "firefighters" will mean *wildland* firefighters for the remainder of the article.

In wildland vegetation fuels, fire management objectives are not limited to fire suppression because fire is a natural phenomenon with important functions in fire-adapted ecosystems. In prescribed burning, wildland firefighters apply fire within the boundaries of specific land areas, or "units," maintaining it within those unit boundaries until it burns out in a day or so; they thereby implement regional-scale plans for a certain level of prescribed fire in such ecosystems.

Wildfire suppression begins once the fire is reported and resources are dispatched to the scene to put it out. The "initial attack" is the fire suppression effort that occurs on the first day of a wildfire. It is fast-paced and successfully controls over 95% of all wildfires in the United States. When it fails, a wildfire becomes a "project" fire, often requiring multiple weeks and hundreds of personnel to put it out. Unlike the initial attack fire suppression, which has similar strategies to a structural fire, project fires involve a more measured approach and tactics sustainable for a longer campaign. Among their other differences from structural firefighters, wildland firefighters do not presently wear respiratory protection. For most wildland firefighters, a cotton bandanna remains the state of the art in respiratory protection, and the protection afforded is imaginary.

Firefighters are organized into particular crew types. The main division is between highly trained and experienced Type I crews (such as "hotshot," "smokejumper," or "helitack" crews) and Type II crews (those with less training and often less experience). Most Type I and Type II crews are made up of "handcrew" firefighters, who are organized into 20-person crews. Engine crews assigned to wildland fire trucks include 3–5 firefighters per crew.

Respiratory Hazards to Firefighters

Several studies of occupational exposure to smoke among firefighters have been reported in the literature.[2,3] These studies have evaluated occupational exposure to various pollutants found in smoke, and some have demonstrated transient adverse health effects among the exposed firefighters. Our most extensive measurements of smoke exposure among firefighters occurred between 1991 and 1995. These form the basis for this article, and they are available on the web (http://www.fs.fed.us/pnw/publications) as complete research reports from the USDA Forest Service, Pacific Northwest Research Station.[4,5]

Smoke is mostly carbon dioxide (CO_2) and water vapor, but the remainder is a complex mixture of hundreds of gas-, liquid-, and solid-phase chemicals. The toxicity of CO_2 is relatively low despite its dominance in smoke. There is general agreement in the reported literature that the potential hazards to firefighters include carbon monoxide (CO), total (suspended) particulate matter, and respirable particulate matter. Following the convention in ambient air pollution measurements of referring to thoracic particulate matter (sampled with a 50% efficiency at 10 μm) as PM10, and fine particulate matter (sampled with a 50% efficiency at 2.5 μm) as PM2.5, henceforth we will refer to respirable particulate matter as PM3.5 since we used the standard Dorr-Oliver design nylon cyclone, which samples with 50% efficiency at 3.5 μm.

Based on earlier measurements, we believed that formaldehyde and acrolein also belong on the list of significant hazards in smoke.[6] Benzene is present in smoke but is also found in the gas and diesel fuels used to power chainsaws, brush cutters, portable pumps, and generators used at wildland fires. Polycyclic aromatic hydrocarbons, sulfur dioxide, and oxides of nitrogen either have been measured by others or should be measurable in smoke. We omitted these latter chemicals from our studies based on the low concentrations reported by others.[2,7]

METHODS

We measured carbon monoxide, carbon dioxide (easily coanalyzed in the carbon monoxide samples), benzene, formaldehyde, acrolein, and respirable particulate matter (PM3.5). In 1995, we added total particulate matter and dropped CO_2. Data were collected at prescribed burns in Washington and Oregon during initial attack of wildfires in the Redding, California, area; in southern California; and at extended duration project wildfires in Washington, Idaho, Montana, and California. We analyzed data from these three milieus separately due to key differences among them: (1) the work pace was generally faster during initial attack than at project fires, but the work was also of a much shorter duration; and (2) most shift time at project wildfires was spent at the fire, while most of the shift at initial attacks was spent waiting for a fire to occur. Our methods were essentially the same at all fires.

Sampling and Analytical

Firefighters selected for monitoring wore a 4-kilogram sampling apparatus that contained three battery-powered personal sampling pumps, optimized for the following:

- An inert gas sampling bag, 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 and CO_2 by nondispersive infrared spectroscopy via Intersociety Committee Method (ICM) 128.[8]
- Sorbent tubes for collection of two types of volatile emissions: (1) benzene (on charcoal at 0.15 L/min) with analysis by gas chromatography/flame ionization detection via National Institute for Occupational Safety and Health (NIOSH) method 1501; and (2) formaldehyde and acrolein (on 2,4-dinitrophenylhydrazine-coated C-18 coated silica gel Sep-Paks at 0.2 L/min) using high-performance liquid chromatography according to EPA method TO-11.[9,10] We used enhanced chromatographic conditions and summation of three "x-acrolein" degradation products to achieve quantitative acrolein recovery from Method TO-11.[11] The likely identity of these products has recently been evaluated by Liu et al.,[12] providing the basis for a major improvement in the sampling of aldehydes.
- A 2.0 μm pore size Teflon® 37-mm filter/cassette and nylon cyclone assembly for sample collection and later analysis of PM3.5 at 1.7 L/min according to NIOSH method 0600.[13]

For the 1995 fire season, the ICM 128 method for CO and CO_2 analysis was replaced by electronic datalogging dosimeters measuring CO via Occupational Safety and Health Administration (OSHA) method ID-209.[14] To assess exposure to dusts generated by soil disturbance while crews are hiking and digging firelines, we also added sampling for total suspended particulate matter exposure according to NIOSH method 0500.[15] All 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 that included the use of second-source check standards to supplement routine calibration standards, evaluation of field and lab blanks, and replicates (precision was measured as relative standard deviation among 3–6 field replicates per day), and method and matrix spikes to evaluate accuracy (accuracy was measured as percent recovery of theoretical). Method detection limits were periodically evaluated for each analytical method according to EPA procedures.[16]

Data Analysis

Correlations between pollutants were evaluated using linear regression where pairs of pollutants were successfully measured concurrently with a given sampling pack; these data included exposure samples from firefighters as well as field replicates, which were obtained daily as side-by-side samples of near-field ambient smoke at the fires. Regression residuals were examined as a function of possible confounding variables to ensure that the models were unbiased.[17]

Time-weighted average (TWA) smoke exposures were calculated for each firefighter to assess shift-average and fireline-average exposure. The shift TWA included the paid hours during the shift. The fireline-average TWA included only time at the fire scene. Because the CDF engine crews performing initial attack of wildfires worked a 96-hour on-call shift, their work shift was defined for each day of sampling as the net time from morning wake-up until the end of fire-related duties in the evening, including meals.

Individual sample periods were classified by observed work activity; some samples were not amenable to single activity classifications because more than one activity occurred. Geometric mean concentrations by job task were calculated for each pollutant. Data were treated separately for initial attack wildfires, project wildfires, and prescribed burns. The log-transformed pollutant concentration data for each job task were tested for normality by the Shapiro-Wilk's procedure.[18]

Site variable data obtained at prescribed burns were those known to affect fire behavior, including preburn fuel moisture (fuel refers to the woody biomass on site), fuel loading (in tons per acre), duff (partially decomposed forest floor material) loading, and ambient windspeed adjacent to the burn (measured with a cup anemometer 5 feet above ground level). Fuel moisture data were obtained either by the cooperating agencies or by our direct measurements of fuel moisture via a conductivity-based moisture probe. These site-specific environmental data were not available at most project wildfires and the initial attack fires in southern California, though we did make wind speed observations with hand-held anemometers at wildfires in 1994–1995. We obtained wind speed, fuel moisture, and National Fire Danger Rating System (NFDRS)[19] predictions of fire behavior from CDF for the initial attack wildfires in Redding, California. All environmental data were paired by time with our smoke exposure data to assess relations among smoke exposure and windspeed, relative humidity, fuel moisture, and (for Redding initial attack fires only) key NFDRS fire behavior variables. Wind speed data for Redding initial attack fires were obtained from an anemometer 20 feet above ground level at the Redding airport.

RESULTS

We monitored smoke exposure during 30 days of wildfire suppression between August 1992 and August 1995 in Washington, Oregon, Idaho, California, and Montana. At these wildfires, 84 firefighters were selected for exposure monitoring during 17 days at 8 separate project wildfires, and 45 firefighters were monitored during 13 days of initial attack incidents. To assess smoke exposure at prescribed burns, we measured smoke exposure among 221 firefighters at 39 prescribed burns in Washington and Oregon between 1991 and 1994. The method detection limits and overall accuracy and precision of the combined data from the wildfire and prescribed burn smoke exposure measurements are summarized in Table I.

TABLE I. Method Detection Limits, Accuracy, and Precision of Smoke Exposure Measurements

		Method Detection Limits			
Pollutant	Method	2-Hour Sample	15-Minute Sample	Overall Accuracy (%)	Overall Precision^A (%)
Benzene	NIOSH 1501	4 ppb	32 ppb	75–119	24
Acrolein	EPA TO-11	3 ppb	24 ppb	60–134	30
Formaldehyde	EPA TO-11	6 ppb	48 ppb	65–130	43
Carbon monoxide	ICM 128	0.6 ppm	0.6 ppm	93–108^B	31
Carbon monoxide	OSHA ID 209	1.7 ppm	1.7 ppm	82–116	19
Carbon dioxide	ICM 128	7.6 ppm	7.6 ppm	98–103^B	14
Respirable particulate	NIOSH 0600	0.117 mg/m^3	0.935 mg/m^3	Not available^C	32
Total suspended particulate	NIOSH 0500	0.069 mg/m^3	0.549 mg/m^3	Not available^C	20

^{A}Relative standard deviation.
^{B}Includes only analytical accuracy.
^{C}No accuracy assessment method was available.

Shift- and Fireline-Average Work Durations and Exposures

Among the 45 firefighters monitored at initial attack wildfires, the mean shift length on days with initial attack activity was 13.3 hours (range 12 to 18 hours); the corresponding time these firefighters spent at the fires averaged 3.3 hours (range of 2 to 10 hours). At project wildfires, the 84 firefighters had an average shift length of 13.9 hours (range of 4 to 24) on the days we monitored, with a corresponding time on the firelines of 10.4 hours (range of 2 to 24 hours). At prescribed burns, the average shift duration among 200 of the monitored firefighters was 11.5 hours (range of 6 to 18 hours), and the time at the prescribed burns averaged 7 hours (range of 2 to 13 hours); 21 firefighters were dropped from the prescribed burn TWA analysis because of inadequate data, for example, potential unsampled exposures.

Figure 1 shows the cumulative frequency distribution of carbon monoxide exposures among the 45 firefighters performing initial attack during their shift, and the same data for the 84 firefighters at project fires. For each milieu, the figure shows both shift-average (shift) exposures and time-weighted exposures while at the fire (fireline-average). Firefighters performing initial attack were at fires only during part of their work shift, thus lowering their time-weighted average exposure over the work shift.

The distribution of exposures to respiratory irritants at initial attack and project wildfires is shown in Figure 2. The respiratory irritants acrolein, formaldehyde, and PM3.5 were evaluated together via the standard additive mixture exposure criterion E_m; we used the American Conference of Governmental Industrial Hygienists' (ACGIH®) threshold limit values (TLVs®) as the denominator in Equation 1:

$$E_m = \frac{[\text{acrolein}]}{0.1} + \frac{[\text{formaldehyde}]}{0.3} + \frac{[\text{PM3.5}]}{3} \qquad \textbf{(1)}$$

where E_m = the mixture exposure;
[acrolein] = the acrolein exposure in parts per million;
[formaldehyde] = the formaldehyde exposure in parts per million;
[PM3.5] = the respirable particulate matter exposure in mg/m^3.

If E_m exceeds 1, then the combination of the three irritants exceeds the combined exposure limit. The geometric mean and maximum of the TWA shift- and fireline-duration exposures to acrolein, benzene, CO_2, CO, formaldehyde, PM3.5, total particulate matter, and respiratory irritants for all fire types are summarized in Table II, along with the current permissible exposure limits (PELs).

Figure 3 is the cumulative frequency distribution of the TWA shift- and fireline-duration exposures to CO among 200 firefighters working at prescribed burns in the Pacific Northwest. Figure 4 depicts the cumulative frequency distribution of these firefighters' exposure to the mixture of respiratory

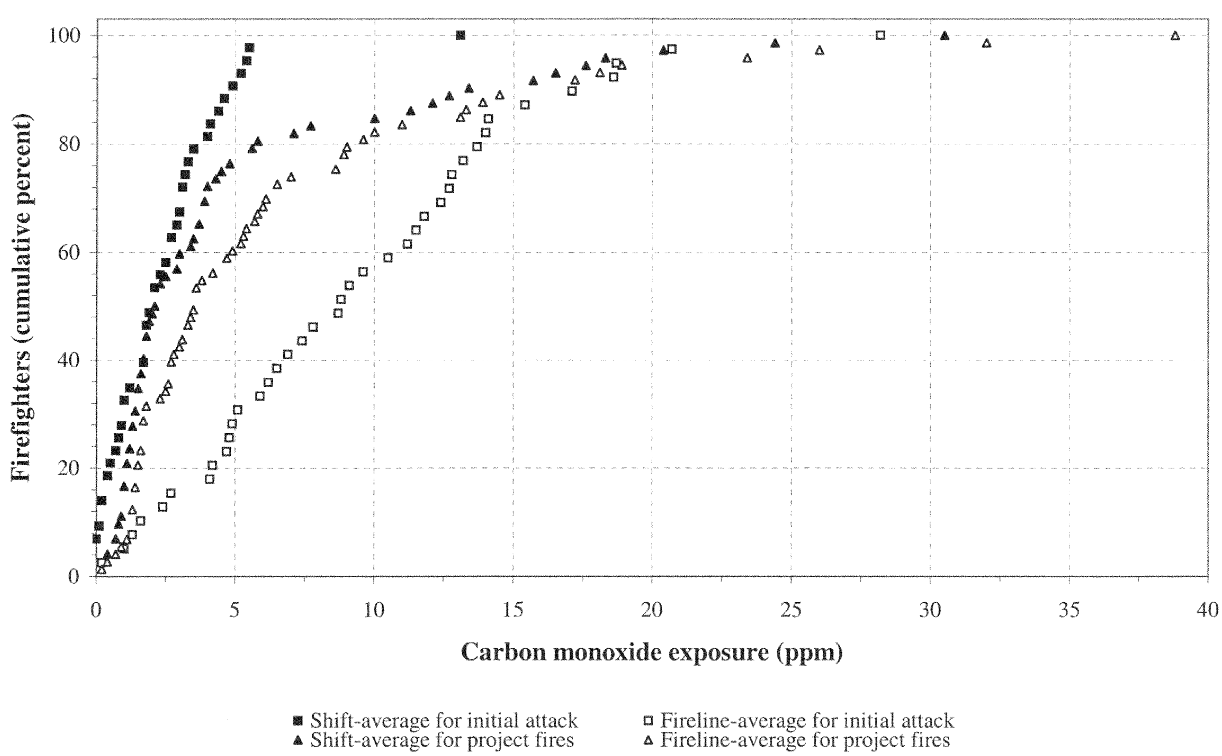

FIGURE 1. Distribution of time-weighted average carbon monoxide exposures at wildfires

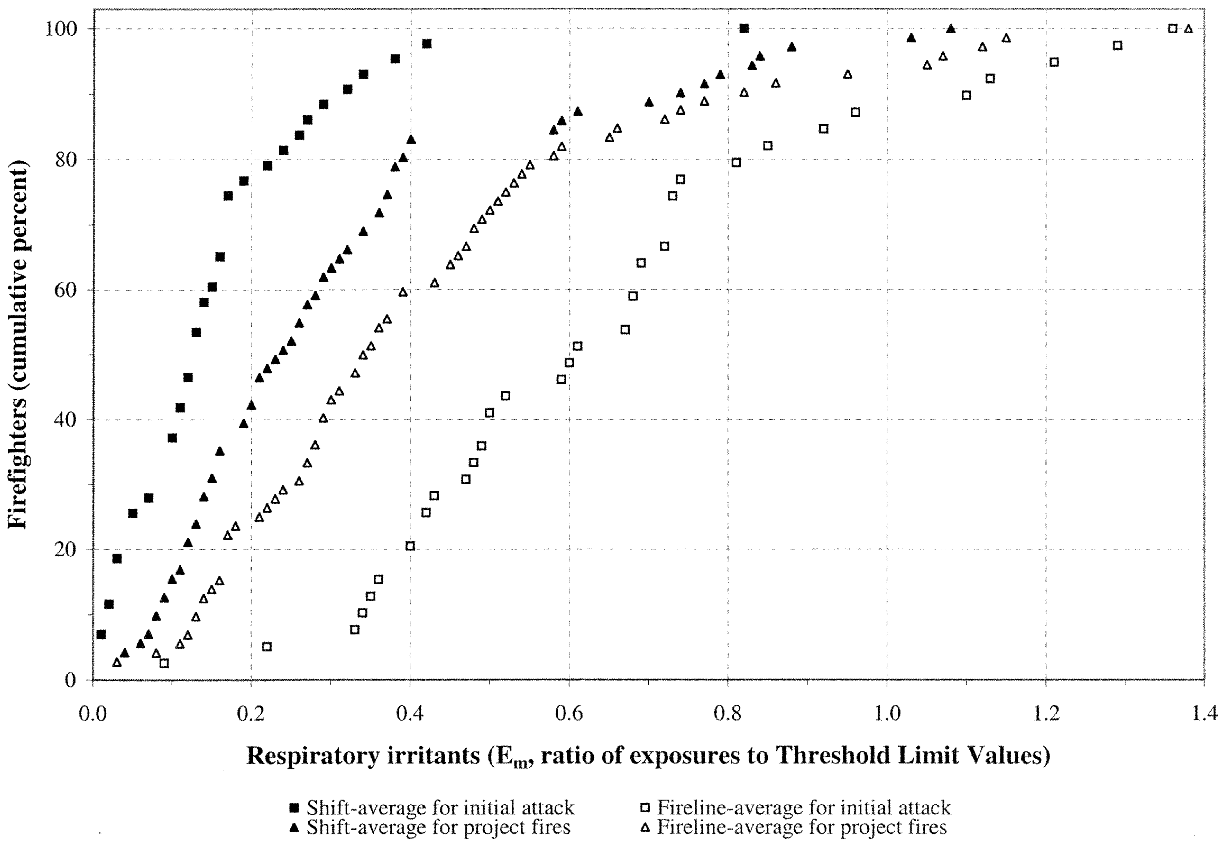

FIGURE 2. Distribution of time-weighted average respiratory irritant exposures at wildfires

irritants at the prescribed burns, using the ACGIH TLVs as our recommended exposure limits.

Peak Smoke Exposures

Integrated short-term exposure limit (STEL) samples for all pollutants were difficult to obtain during peak exposure events. Because of the extended distances between firefighters and long sample durations needed to sample throughout long shifts, we successfully sampled only a handful of peak smoke exposures at project wildfires (with the exception of CO peak exposures, which were obtained in 1995 from datalogger records). Many more peak exposure samples were obtained at prescribed burns (because of the shorter distances) and initial attack wildfires (because sampling began with 15-min sample durations). Table III compares these peak exposure data from prescribed burns and during initial attack of wildfires.

For evaluating short-term exposures to CO and PM3.5, we consider the fast uptake of CO among hard-working firefighters and the uncertain chemical composition of PM3.5 to warrant adopting the most-conservative recommendation of ACGIH.[20] We therefore recommend three times the CO and PM3.5 TLVs as reasonable short-term exposure criteria. Because they differ, both the OSHA PEL and the ACGIH TLV short-term exposure limits are provided for reference. Compared with the data in Table III, our sparse peak exposure sample results from project wildfires averaged 22.4 ppm for CO (n = 29), 0.15 ppm for formaldehyde (n = 4), 0.03 ppm for acrolein (n = 4), and 3.7 mg/m^3 for PM3.5 (n = 2).

Correlations Among Pollutants in Smoke

We found that most of the pollutants measured in smoke were so significantly correlated that one pollutant could be used to estimate exposure to another. There were two exceptions: (1) total particulate matter, probably made airborne when firefighters disturbed soil and ash during their work; and (2) nonfire benzene emissions whenever fuel-powered engines (such as chain saws, pumps, and vehicles) or drip torches were present.

All the initial attack wildfires occurred at locations in the Redding vicinity or in southern California near freeways and urbanized areas. Ambient air at these locations, if impacted by measurable levels of CO, PM3.5, formaldehyde, and benzene (common emissions from many urban sources) would likely confound the correlations among the relatively low-concentration smoke exposure samples. Urban-precursor ozone formation documented by EPA researchers[21] could also cause a possible negative bias in our formaldehyde results at these locations. We also have fewer samples over a shorter concentration range at the initial attack wildfires. These factors

TABLE II. Shift- and Fireline-Average Smoke Exposures Among Wildland Firefighters

		Overall (Shift)		At Fires (Fireline)	
Pollutant (2003 PEL)	**Fire Type (No. of Samples)**	**Mean[B]**	**Maximum**	**Mean[B]**	**Maximum**
Acrolein[A] (100 ppb)	Initial attack (n = 45)	1 ppb	11 ppb	5 ppb	37 ppb
	Project fires (n = 84)	1 ppb	15 ppb	2 ppb	16 ppb
	Prescribed burns (n = 200)	9 ppb	60 ppb	15 ppb	98 ppb
Benzene (1000 ppb)	Initial attack (n = 45)	3 ppb	24 ppb	14 ppb	43 ppb
	Project fires (n = 84)	4 ppb	249 ppb	6 ppb	384 ppb
	Prescribed burns (n = 200)	16 ppb	58 ppb	28 ppb	88 ppb
Carbon dioxide (5000 ppm)	Initial attack (n = 24)[C]	391 ppm	706 ppm	488 ppm	742 ppm
	Project fires (n = 31)[D]	439 ppm	588 ppm	465 ppm	668 ppm
	Prescribed burns (n = 200)	450 ppm	733 ppm	519 ppm	853 ppm
Carbon monoxide (50 ppm)	Initial attack (n = 45)	1.6 ppm	13.1 ppm	7.4 ppm	28.2 ppm
	Project fires (n = 84)	2.8 ppm	31 ppm	4.0 ppm	39 ppm
	Prescribed burns (n = 200)	4.1 ppm	38 ppm	6.9 ppm	58 ppm
Formaldehyde[A] (750 ppb)	Initial attack (n = 45)	6 ppb	58 ppb	28 ppb	92 ppb
	Project fires (n = 84)	13 ppb	84 ppb	18 ppb	93 ppb
	Prescribed burns (n = 200)	47 ppb	390 ppb	75 ppb	600 ppb
Respirable particulate[A] (5 mg/m^3)	Initial attack (n = 45)	0.022 mg/m^3	1.56 mg/m^3	1.11 mg/m^3	2.46 mg/m^3
	Project fires (n = 84)	0.50 mg/m^3	2.30 mg/m^3	0.72 mg/m^3	2.93 mg/m^3
	Prescribed burns (n = 200)	0.63 mg/m^3	6.9 mg/m^3	1 mg/m^3	10.5 mg/m^3
Total particulate (15 mg/m^3)	Initial attack (n = 7)[E]	1.39 mg/m^3	1.81 mg/m^3	5.32 mg/m^3	8.64 mg/m^3
	Project fires (n = 15)[F]	1.47 mg/m^3	4.17 mg/m^3	1.72 mg/m^3	4.38 mg/m^3
	Prescribed burns	Not applicable[G]	Not applicable[G]	Not applicable[G]	Not applicable[G]
Respiratory irritants—PELs[H] ($E_m \leq 1.0$)	Initial attack (n = 45)	0.1	0.5	0.4	0.9
	Project fires (n = 84)	0.1	0.6	0.1	0.8
	Prescribed burns (n = 200)	0.3	2.6	0.4	3.9
Respiratory irritants—TLVs[I] ($E_m \leq 1.0$)	Initial attack (n = 45)	0.1	0.8	0.6	1.4
	Project fires (n = 84)	0.2	1.1	0.3	1.4
	Prescribed burns (n = 200)	0.4	4.3	0.7	6.5

[A] Respiratory irritant that should be evaluated as part of the irritant exposure mixture (E_m).
[B] Geometric mean.
[C] Among 24 engine-crew firefighters (CO_2 was not measured in 1995).
[D] CO_2 was not measured in 1995.
[E] Among only seven Type I hand-crew firefighters (total particulate was not measured before 1995).
[F] Among 15 hand-crew firefighters (total particulate was not measured before 1995).
[G] Not applicable (total particulate was not measured before 1995).
[H] Combined exposure (E_m) to the mixture of respiratory irritants acrolein, formaldehyde, and respirable particulate, calculated as the summed ratios of each to their respective OSHA permissible exposure limits.
[I] Combined exposure (E_m) to the mixture of respiratory irritants acrolein, formaldehyde, and respirable particulate, calculated as the summed ratios of each to their respective 2003 threshold limit values.

may compromise the strength of our interpollutant regressions at the initial attack wildfires. The regression coefficients of determination (r^2) in these conditions ranged from a low of 0.44 for the regression between benzene and CO, with n = 19 sample pairs, up to a high r^2 of 0.82 for acrolein vs. formaldehyde (n = 13).

We obtained stronger interpollutant correlations at the project wildfires, which were at relatively remote locations, with little impact from urban pollutants including the well-known negative bias from ozone on DNPH-based formaldehyde measurements. At project wildfires, we also had many sample pairs covering a wide concentration range. The r^2 values between pollutant pairs at project wildfires ranged from 0.49 (acrolein vs. PM3.5, n = 14 pairs) up to 0.91 (benzene vs. CO, n = 54 pairs).

We found the strongest relationships among pollutants in smoke at Pacific Northwest prescribed burns. These were also in areas removed from urban air pollutants, occurred on good ambient air quality days, and had little likelihood of adverse ozone effects on the formaldehyde results. Figure 5 shows the correlation in our data for formaldehyde and CO. The regression and associated 95-percent confidence bands for a sample estimate are plotted to illustrate detail over the CO range from 1.2 to 100 ppm. The overall regression between

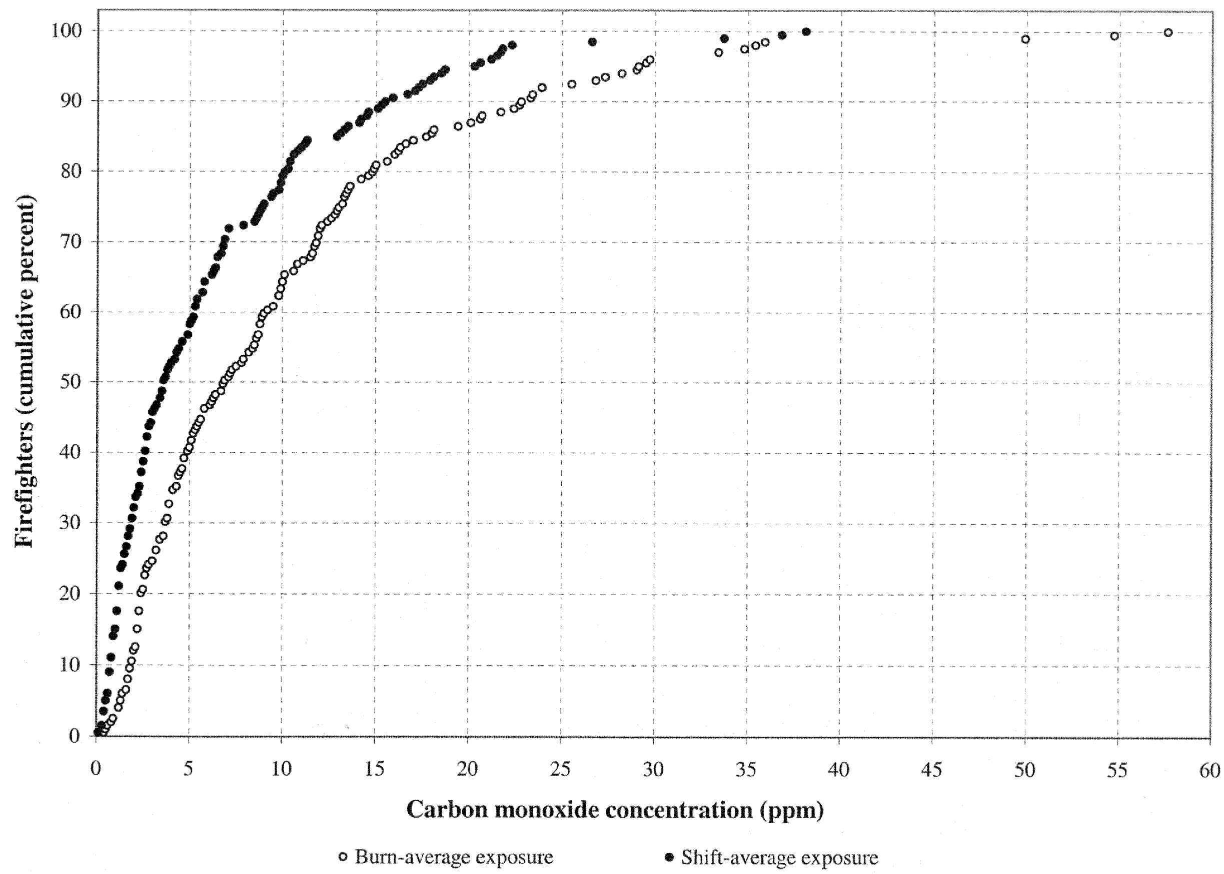

FIGURE 3. Distribution of time-weighted average carbon monoxide exposures at prescribed burns

formaldehyde and CO (between 1.2 and 179 ppm CO) had an r^2 of 0.82 for n = 240 sample pairs.

The correlations at prescribed burns ranged from a low r^2 of 0.62 between PM3.5 and acrolein (n = 74 pairs) up to a high r^2 of 0.86 between formaldehyde and acrolein (n = 127 pairs). The prescribed burn data provide the largest dataset over the widest concentration range. We consider them the most representative regression equations and summarize them in Table IV. For each (arbitrarily) dependent variable (y) pollutant, the slope and intercept is listed for the linear regression between it and the (arbitrarily) independent (x) pollutant, along with the standard errors of the regression terms and the r^2 value for the regression.

Smoke Exposure by Work Activity

Table V summarizes the geometric mean and number of samples obtained for key discrete work types at prescribed burns, which comprised the largest data set of work activity versus exposure. Wildfires include these tasks, plus several others omitted because there were many samples that spanned two tasks, and there were too few samples to characterize the highly variable task-specific exposures. Refer to the research papers (available online) for that information.[4,5] The summary statistical descriptors in Table V represent exposure during these tasks when at least some smoke was observed. Samples were generally around 2 hours in duration, except direct attack, which was on the order of half an hour or less.

To clarify task descriptions: "Burn Boss" and "Holding Boss" supervise prescribed burn ignition and fireline maintenance, respectively; both typically perform the tasks along with supervising them. "Lighting" is the process of igniting the unit with a drip-torch dropping a burning gas/diesel mixture. "Holding" means maintaining the fire inside the firelines with a shovel (and water, when available), sometimes making forays into the surrounding vegetation to extinguish embers and spot fires outside the firelines. When firefighters have to extinguish a large spot fire or "slop-over" of the fire outside the firelines, they are performing "direct attack," often with great urgency. After the flaming phase of the fire dies down, "mop-up" occurs with hand tools and dirt (and water, when available) to extinguish actively smoldering areas. A "sawyer" uses a chainsaw to fell burning snags and cut up downed logs and brush. "Engine" tasks are associated with tending either a truck-mounted or stationary portable water pump, both powered by internal combustion engines.

Smoke Exposure and Ambient Wind Speed

Of the environmental factors examined, only ambient wind speed was correlated to smoke exposure, and not for all job tasks. As an example, Figure 6 shows the positive

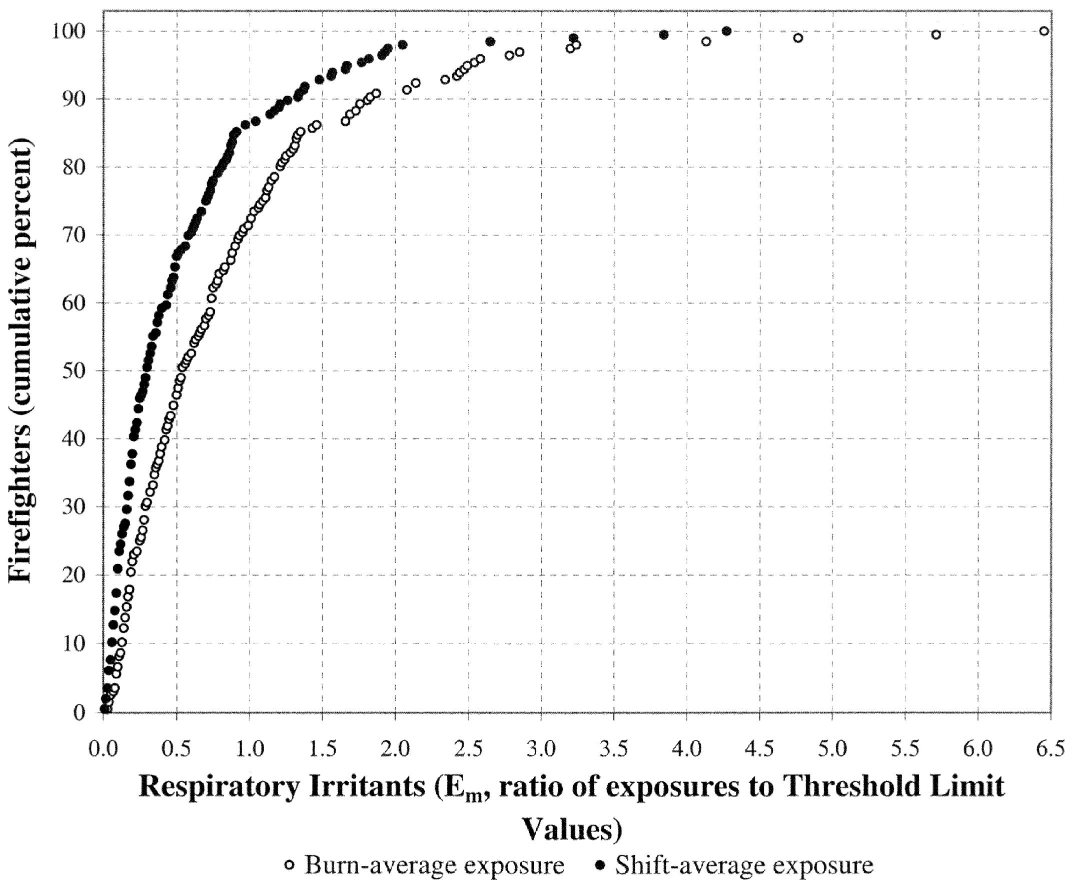

FIGURE 4. Distribution of time-weighted average respiratory irritant exposures at prescribed burns

correlation between CO exposure and wind speed for direct attack activities at prescribed burns. The X axis represents the wind speed adjacent to the burn unit, averaged over the entire duration of the prescribed burn. Direct attack usually is needed only on the downwind side of a prescribed burn, thus wind direction is essentially excluded as a factor by the task subset of the data. Had we noted whether firefighters holding line or conducting mop-up were upwind or downwind of the fires, we

TABLE III. Peak Exposure Samples from Prescribed Burns and Initial Attack Wildfires

Parameter	Short-Term Exposure Limit (PEL/TLV)	Fire Type (No. of Samples)	STEL Sample Result Mean[B]	STEL Sample Result Maximum
Acrolein[A]	100 ppb (TWA)/100 ppb (ceiling)	Initial attack (n = 20)	5 ppb	66 ppb
		Prescribed burns (n = 5)	71 ppb	129 ppb
Benzene	5000 ppb (ceiling)/2500 ppb	Initial attack (n = 19)	19 ppb	82 ppb
		Prescribed burns (n = 14)	64 ppb	277 ppb
Carbon monoxide	50 ppm (TWA)/75 ppm (excursion STEL)	Initial attack (n = 18)	13 ppm	42 ppm
		Prescribed burns (n = 16)	54 ppm	179 ppm
Formaldehyde[A]	2000 ppb/300 ppb (ceiling)	Initial attack (n = 20)	87 ppb	339 ppb
		Prescribed burns (n = 15)	468 ppb	1,460 ppb
Respirable particulate[A]	5 mg/m^3 (TWA)/9 mg/m^3 (excursion STEL)	Initial attack (n = 12)	2.1 mg/m^3	6.9 mg/m^3
		Prescribed burns (n = 12)	7.0 mg/m^3	37 mg/m^3
Sample duration		Initial attack (n = 21)	16 min	20 min
		Prescribed burns (n = 18)	20 min	32 min

[A] Respiratory irritant that should be evaluated as part of the irritant exposure mixture (E_m).
[B] Geometric mean.

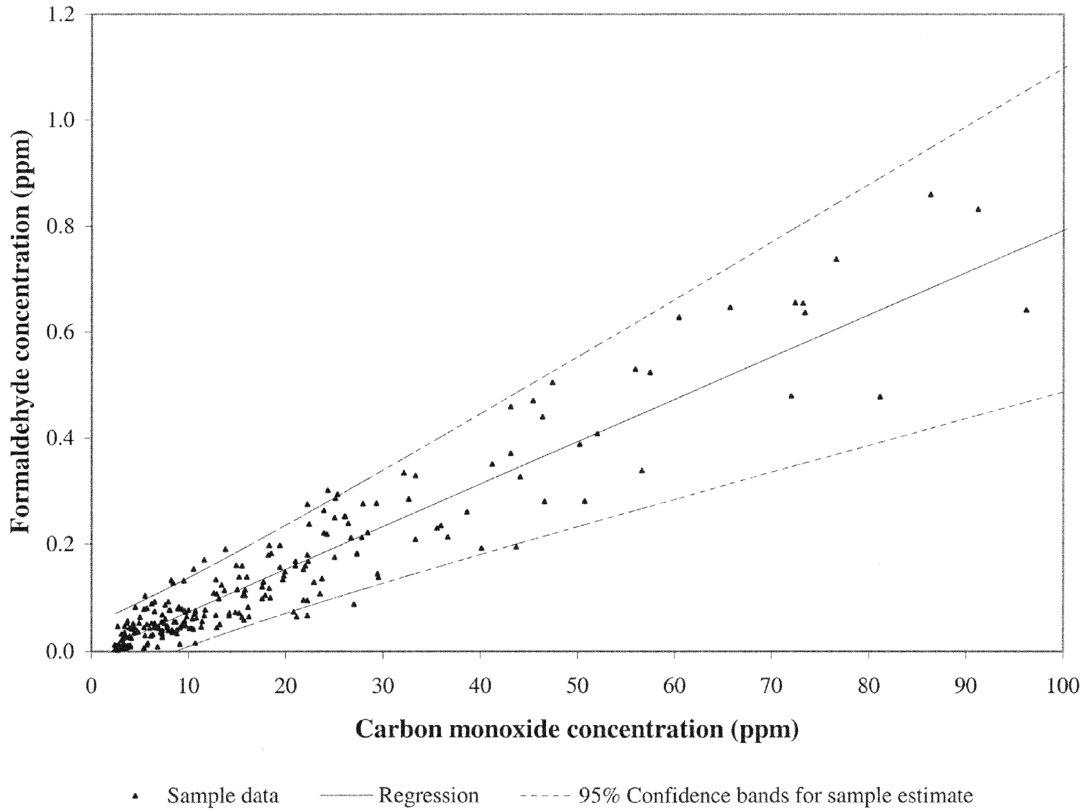

FIGURE 5. Correlation between formaldehyde and carbon monoxide in smoke exposure samples from prescribed burns

are certain that the positive relationship between wind speed and exposure would hold for these tasks as well.

DISCUSSION

Data Quality

The overall accuracy and precision of our measurements (quantified by percent recovery and relative standard deviation results for blind method spike performance evaluation samples, field matrix spikes, and field replicates) were close to the initial data quality objectives defined in the quality assurance project plan,[22] and were reasonably good considering the logistical difficulties involved in data collection. The most significant limitation on the data is that the aldehyde measurements may be biased low by 30–60%, based on results for some of the annual blind performance evaluation samples that

TABLE IV. Interpollutant Linear Regressions Measured at Prescribed Burns

			Regression Coefficients $(y = ax + b)^A$	
Pollutant Pair (x,y)	No. Sample Pairs	r^{2B}	a (± Standard Error)^C	b (± Standard Error)^C
Carbon monoxide, acrolein	87	0.63	9.48×10^{-4} ($\pm 8 \times 10^{-5}$)	4×10^{-3} ($\pm 1 \times 10^{-3}$)
Carbon monoxide, benzene	125	0.74	1.01×10^{-3} ($\pm 5 \times 10^{-5}$)	6×10^{-3} ($\pm 2 \times 10^{-3}$)
Carbon monoxide, formaldehyde	240	0.82	7.99×10^{-3} ($\pm 2 \times 10^{-4}$)	-6×10^{-3} ($\pm 3 \times 10^{-3}$)
Carbon monoxide, respirable particulate	162	0.73	1.14×10^{-1} ($\pm 5 \times 10^{-3}$)	-3×10^{-2} ($\pm 4 \times 10^{-2}$)
Formaldehyde, respirable particulate	154	0.82	1.43×10^{1} ($\pm 5 \times 10^{-1}$)	2×10^{-2} ($\pm 4 \times 10^{-2}$)
Respirable particulate, acrolein	74	0.62	7.49×10^{-3} ($\pm 7 \times 10^{-4}$)	6×10^{-3} ($\pm 1 \times 10^{-3}$)
Formaldehyde, acrolein	127	0.86	1.71×10^{-1} ($\pm 6 \times 10^{-3}$)	2×10^{-3} ($\pm 4 \times 10^{-4}$)
Formaldehyde, benzene	159	0.78	1.20×10^{-1} ($\pm 5 \times 10^{-3}$)	8×10^{-3} ($\pm 1 \times 10^{-3}$)
Respirable particulate, benzene	110	0.71	8.3×10^{-3} ($\pm 5 \times 10^{-4}$)	1×10^{-2} ($\pm 2 \times 10^{-3}$)

^{A}Units are in parts per million for all pollutants except respirable particulate, which is in milligrams per cubic meter.
^{B}Coefficient of determination.
^{C}Standard errors of regression coefficients at 95% confidence level.

TABLE V. Average Sample Concentrations by Work Task at Prescribed Burns

	Geometric Mean Sample Concentration by Task									
	Carbon Monoxide		Benzene		Formaldehyde		Acrolein		Respirable Particulate	
Work Task	(ppm)	(n)[A]	(ppb)	(n)[A]	(ppb)	(n)[A]	(ppb)	(n)[A]	(mg/m^3)	(n)[A]
Burn boss	5.9	14	21	16	77	17	31	9	1.32	17
Lighting	3.7	110	45	98	38	100	5	31	0.75	105
Holding	11.6	75	21	85	127	96	18	33	1.56	82
Holding boss	13.2	22	26	19	119	21	30	11	1.81	17
Direct attack	33.2	16	41	15	464	12	62	1	4.04	10
Mop up	9.2	57	20	62	91	56	12	29	0.75	49
Sawyer	14.2	6	91	3	346	3	10	1	2.93	6
Engine	10.2	5	39	5	98	6	<1	1	1.37	5

[A]Number of samples comprising geometric mean.

our laboratory was challenged with. The PM3.5 data may be biased low, due primarily to electrostatic losses in sampling inherent to the nylon Dorr-Oliver cyclones used.(23) Thus, it is possible that a greater percentage of the firefighters' exposures may have exceeded the combined irritant exposure limits (E_m) for acrolein, formaldehyde, and PM3.5. As well, the actual concentration of any individual pollutant measurement may vary up to ±43% (see Table I). On examining the effect these data quality limitations would have on our findings, we conclude that our conclusions and recommendations do not change significantly—negative or positive biases would only modify the percentage of exposures that exceeded recommended levels, not the fact that exceedences occurred.

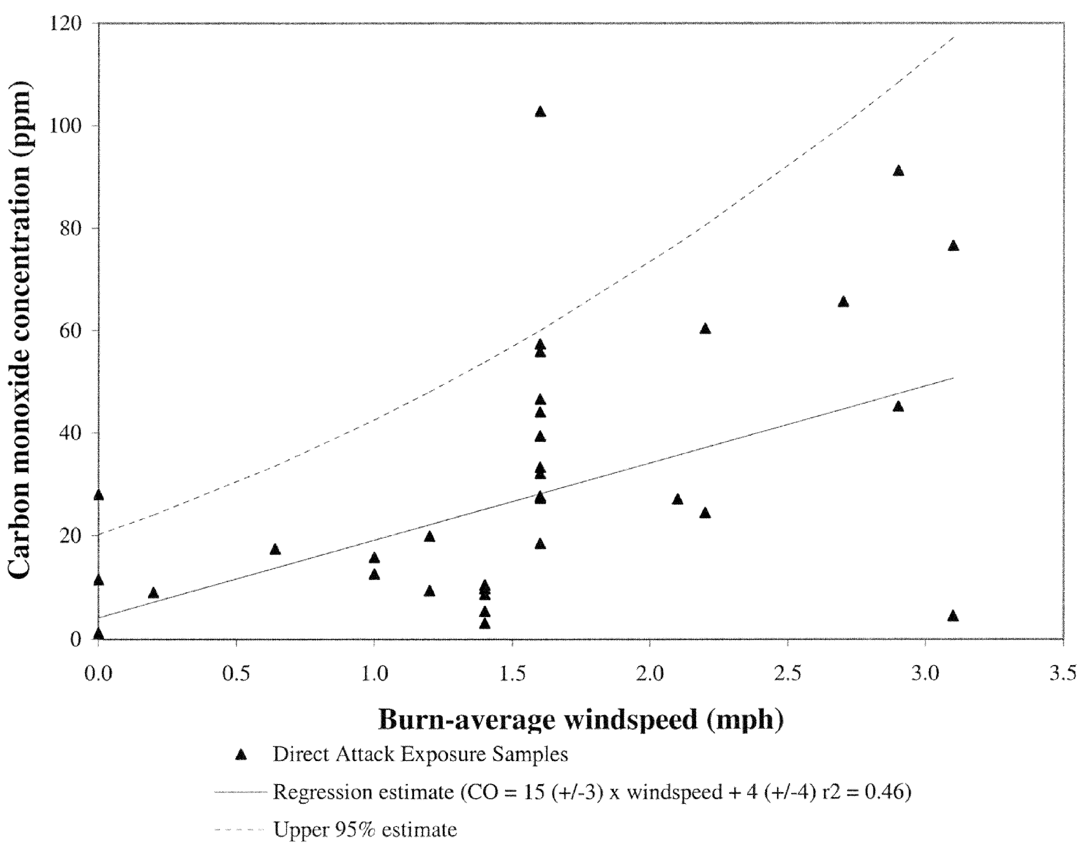

FIGURE 6. Correlation between ambient windspeed and carbon monoxide exposure at prescribed burns

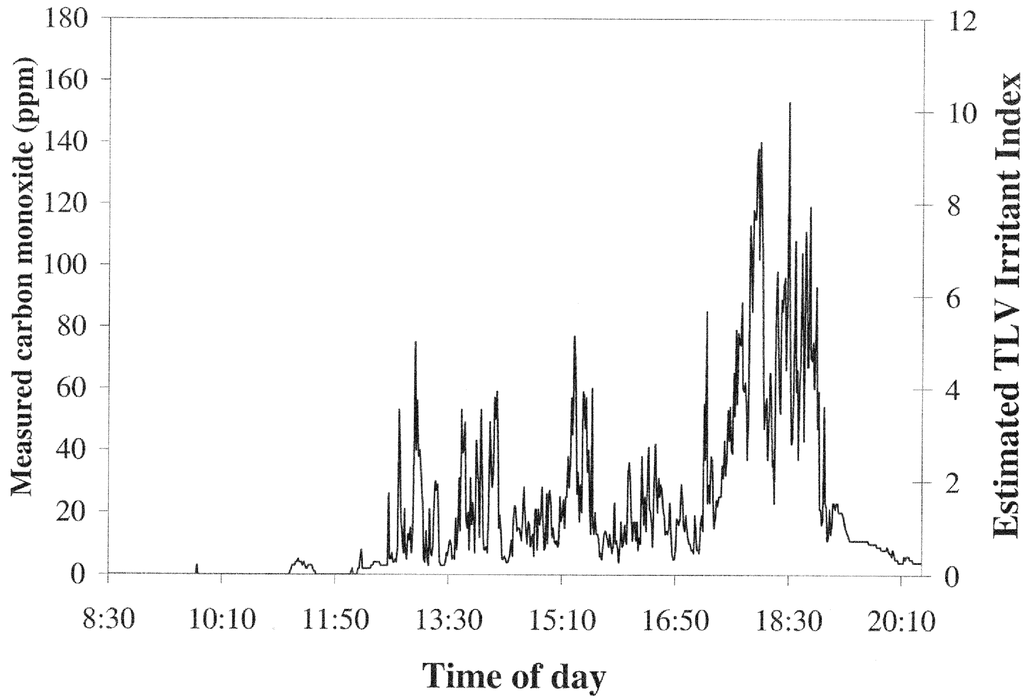

FIGURE 7. Smoke exposure while holding downwind fireline at a project wildfire

KEY FINDINGS

Our baseline measurements from 1991 to 1995 indicate that firefighters work long hours, with shifts ranging up to 24 hours and more at wildfires and over 16 hours at prescribed burns. Smoke exposure at prescribed burns was generally higher than at wildfires (Table II). While working on fire suppression, firefighters are usually able to avoid significant smoke exposure, but we found that the TLVs for CO and the E_m combination of respiratory irritants were both exceeded by approximately 5–10% of the firefighters while on the fireline (Figures 1 and 2). At prescribed burns about 8% of the workers exceeded the TLV for CO while on the fireline (Figure 3), while fully 30% of firefighters exceeded the E_m limit for respiratory irritants based on the TLVs (Figure 4) while on the fireline. The highest TWA exposures at prescribed burns were from 4 to over 6 times the recommended E_m. On a shift-average basis, most exposures do not exceed recommended exposure limits from ACGIH, but 3–5% (depending on the pollutant) at project wildfires and 14% at prescribed burns do exceed recommended exposure limits. Shift-duration exposures seldom exceed OSHA TWA PELs. Often, for much of the time on their shifts, firefighters are mobilizing to or demobilizing from the firelines and are not facing smoke hazards. This lowers their shift-average exposures, especially for firefighters performing initial attack work.

The highest shift- or fireline-TWA exposures were usually driven by one or several peak exposure events, often accompanied by low- to midrange smoke exposures during the rest of the time on the fireline. Firefighters' exposures to pollutants during these peak events were higher during prescribed burns than at initial attack wildfires. Peak exposures during project wildfires appear to be intermediate between the other two situations, but more peak exposure data might modify this conclusion. The brief but intense smoke exposures in peak exposure situations can easily exceed STELs during tasks such as direct attack or holding fireline downwind of an active wildfire or prescribed burn.

The datalogging CO dosimeter facilitates exposure measurements during peak exposure events. As an example, Figure 7 shows CO concentrations for a firefighter holding a fireline during a burnout of unburnt forest at a project fire in Montana. The left axis is the measured CO exposure; the right axis is the estimated corresponding exposure to the E_m for respiratory irritants, calculated using the correlations between CO and the respiratory irritants formaldehyde, acrolein, and PM3.5, and their ratios to TLVs. Firefighters often consider respiratory irritant exposure to be part of their job, but the exposures they endure can be significant.

The occurrence and intensity of peak smoke exposures were often a result of wind-driven shifts of the fire. At a prescribed burn in calm winds (or a planned burnout of unwanted vegetation at a wildfire), clean air is pulled in from the edges of the burn to replace the superheated air that rapidly rises in the convective plume of the fire. This clean air provides ventilation for firefighters manning the perimeter. They will have low smoke exposures because they are effectively upwind of the fire. When the ambient wind is stronger, the plume is displaced downwind; resulting smoke exposure among downwind firefighters increases proportionately with ambient wind speed

(Figure 6). This plume displacement can cause ember-induced spotfires and allow the fire to escape beyond the designated fire perimeter.

Erratic winds also pose fire control difficulties for the firefighters. High smoke exposures are commonly observed in such conditions, for example, when firefighters must work the downwind edge of the fire in a direct attack. Often they are working hard to contain the fire, with the consequence of maximizing their inhalation rate for airborne contaminants. Such ambient conditions were common among the peak exposure data in Table III (although those were relative peaks at a given day, not the absolute maximums we expect occur) and are the primary reason for the differences in holding and direct attack exposures in Table V.

Work task at fires clearly plays a role in controlling exposure. Mop-up exposures, although relatively lower than direct attack or holding on the downwind edge of a fire, can continue for weeks at a large fire. Sawyers and engine operators receive significant pollutant exposures from their engine's exhaust, as well as from the fires. Benzene exposures never exceeded TLVs, but the highest benzene exposures were observed among three work tasks—sawyers, engine operation, and lighting fires using drip torches (Table V).

Along with work activity and wind speed as major factors defining smoke exposure, location at the fire is important. For example, digging a fireline (a task at wildfires) has little smoke exposure when it is remote from the active fire (typical tactics at project fires). In contrast, direct attack, digging a fireline adjacent to the active wildfire (hotline construction), and mobile attack at a fire (manning a fire hose in front of a slowly advancing fire engine on gentle terrain) are tasks likely to occur in smoky areas. Holding line uphill of a fire is another example of a potentially high-exposure situation. Thus terrain, fire behavior, and wind direction all modify the exposure potential of a given task. We lack sufficient space to provide qualitative examples of these interactions here, and we lack quantitative data from an idealized factorial sampling design but refer interested readers to our research summaries.[3–5]

A special situation occurs at wildfires when thermal inversions trap smoke in valleys (prescribed burns are not usually ignited in such conditions). In these circumstances, smoke exposures in the valleys can reach very unhealthful levels for days and even weeks. We observed such conditions at a wildfire in Montana where ambient CO levels ranged consistently between 35 and 55 ppm during the late evening and morning hours.[4]

The correlations we observed between CO, benzene, and the other respiratory irritants were fairly strong and very useful to us in reconstructing TWAs for a work shift where we were missing a result for a pollutant in one of the sampled periods in that shift. Researchers at the Forest Service Fire Sciences Laboratory in Missoula, Montana, have characterized emissions from combustion of forest fuels using real-time spectral methods to show excellent correlations among certain pollutants during specific phases of combustion, indicating a common mechanism of formation in the combustion process.[24] Their research indicates that CO and formaldehyde are associated with different wood combustion mechanisms, and thus they should not track each other well. Perhaps the pollutants we measured among firefighters were relatively well-correlated with each other because more than one mechanism of combustion is operating concurrently on forest fuels at adjacent locations within the fire, and enough mixing and dilution occurs during transport to even out differences in individual emission rates.

RECOMMENDATIONS

Our results are limited to wildfires in the western United States and prescribed burns in the Pacific Northwest. Review of the literature has not identified major differences in exposure data obtained at prescribed burns and wildfires in the southeastern United States, but fires in the southeast and anywhere there are large-diameter fuels or deep soil organic matter layers (which typically have higher moisture contents) may be associated with higher smoke exposures. Smoke exposure among heavy equipment operators is not well-characterized but it should be, given their extensive use at fires. Exposures in fire camps have not been systematically studied, but they are important because CO can interfere with rest and decision making at fire camps in valleys subject to inversions. As well, further effort should be aimed at measuring peak smoke exposure at all types of fires—we believe that our measurements have not identified the upper range of smoke exposures.

Our chromatograms showed dozens of significant peaks; future smoke exposure characterization work should consider attempting to identify and quantify these chemicals and assess their additive impact on human health. Formic acid may be a significant component of smoke.[25] Among the unmonitored compounds: we should assess exposure to urushiol and derivative emissions from the combustion of poison ivy and related plants because they are a significant component of the vegetation in many parts of the country. Free radicals are a poorly characterized but known emission from wood combustion—are they a health hazard at the concentrations that firefighters may encounter? Finally, crystalline silica is present in many soils and exposure can have a long-term impact on health; future measurements of respirable and total dust exposure should include analysis of samples for crystalline silica content. We recommend silica characterization of total dust as well as the respirable fraction because silica should be derived from relatively large particles of airborne soils produced by traffic on dirt roads, hiking firelines, and digging in soils, and the total exposure PEL is likely to be exceeded more easily than the respirable fraction PEL.

For many firefighters, exposure to carbon monoxide would exceed the TLV because exposure limits are adjusted for the unique fire management workplace, which often includes hard breathing, extended hours, and high elevations—all factors that intensify the effects of the health hazards in smoke. Because of the multiple pollutants faced, and the differences from a traditional workplace, an exposure standard specifically for wildland firefighters should be considered. If not an index to account for the multiple components (and uncharacterized components) of smoke, at least an adjusted exposure limit should be considered for CO (exposure duration adjustment is not recommended for irritants because their adverse impacts are rapid). The best method for doing this would be the Coburn-Forster-Kane equation, as modified by Smith et al.[26] Other simplified approaches may be suitable, such as the Brief and Scala model. Using their approach for CO exposure over an 11.5-hour exposure (the mean for prescribed burns) gives a reduction factor of 0.54. Applying this factor to the present OSHA PEL of 50 ppm gives an adjusted PEL of 27 ppm; applying this to the TLV of 25 ppm gives an adjusted TLV of 13.5 ppm.[27]

The NWCG recommended in 1997 that fire managers take measures to control smoke exposure.[1] Measures include: (1) training firefighters on the hazards of smoke; (2) modifying firefighting planning and tactics to emphasize flank attack of wildfires, minimize mop-up efforts, let areas burn if resources are not threatened, and reduce the need for holding firelines and direct attack at prescribed burns; (3) use electronic CO dosimeters to regularly assess smoke exposure; (4) better characterize particulate matter (is it really "inert"?), partially oxygenated reactive gases such as aldehydes, and assess smoke exposures in other regions of the United States; (5) improve health management at wildfires; (6) develop an effective respiratory protection program for certain firefighting situations; and (7) implement medical surveillance and communication of health risks. Some employers have started to implement these ideas but much more needs to be done.

Unless better data are developed, we recommend that our observed correlations among the pollutants be used to predict exposure to several pollutants when resources allow only one (such as CO) to be monitored (Table IV). Using the prescribed burn regressions when estimating exposure provides a measure of conservatism when estimating irritant exposure from CO, since the interpollutant regression slopes measured at project fires were the same or slightly lower. Advances in electronic CO dosimeter technology have largely overcome accuracy problems from radiofrequency interference, ambient temperature swings and dust. We recommend them to those attempting to measure smoke exposure on a routine basis. Researchers from NIOSH have gained valuable experience in using such methods, and we have published a guide to assist others with beginning a smoke monitoring program for wildland firefighters.[28,29]

Respiratory protection is available for irritants such as aldehydes and particulate matter, but not for CO. Airline or SCBA respirators are impractical for all but structure protection tasks. Full-face respirators are problematic due to heat load and fogging. Providing eye protection against irritants via powered air-purifying respirators is no panacea—the irritant symptoms are alleviated but the CO hazard remains and may be greater because comfortable firefighters may remain in smoke that would otherwise drive them away from a secondary CO hazard. Until a respirator is developed that removes CO, we recommend using electrochemical CO dosimeters when wearing an air-purifying respirator to provide instant warnings about the CO levels in a smoky situation.

Smoke exposure is a hazard for firefighters but only some of the time. The hazard is manageable because high-exposure situations are predictable. As forest and range management strategies call for a dramatic increase in prescribed burning over the next 50 years, these findings indicate the need for management steps to control smoke exposures. With implementation of the NWCG recommendations, fire managers can mitigate the hazard and allow firefighters to focus on the job of fire management without the distraction, discomfort, and adverse health impacts of smoke exposure.

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