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Smoke Exposure at Western Wildfires

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Cover

Fire crew wearing smoke exposure instrument packs, Libby Complex wildfires, Montana, 1994. Photo by Roger Ottmar.

Abstract

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Smoke exposure measurements among firefighters at wildfires in the Western United States between 1992 and 1995 showed that although most exposures were not significant, between 3 and 5 percent of the shift-average exposures exceeded occupational exposure limits for carbon monoxide and respiratory irritants. Exposure to benzene and total suspended particulate was not significant, although the data for the latter were limited in scope. The highest short-term exposures to smoke occurred during initial attack of small wildfires, but the shift-average exposures were less during initial attack than those at extended (project) fire assignments because of unexposed time during the shift. Among workers involved in direct attack of actively burning areas and maintaining fireline boundaries, peak exposure situations could be several times greater than recommended occupational exposure limits for short-term exposures. The study found that exposure to acrolein, benzene, formaldehyde, and respirable particulate matter could be predicted from measurements of carbon monoxide. Electrochemical dosimeters for carbon monoxide were the best tool for routinely assessing smoke exposure, so long as quality assurance provisions were included in the monitoring program. Suggested procedures for reducing overexposure to smoke include (1) hazard awareness training, (2) routinely monitoring smoke exposure, (3) evaluating health risks and applicable exposure criteria, (4) improving health surveillance and injury recordkeeping, (5) limiting use of respiratory protection when other mitigation is not feasible, and (6) involving workers, managers, and regulators to develop a smoke exposure management strategy.

Keywords: Smoke exposure, firefighters, occupational health, pollutants, safety, industrial hygiene, smoke hazards.

Summary

This project measured smoke exposure among wildland firefighters in the Western United States between 1992 and 1995. The objectives of the study were to assess firefighter exposure to air pollutants in smoke at wildland fires in the Western United States, determine the average and variability of smoke exposure among wildland firefighters, and observe factors that controlled the exposures. We evaluated the performance of recently available tools, such as dosimeters, to measure smoke exposure. Finally, we determined whether pollutants in smoke were sufficiently correlated with one another for measurements of one pollutant to be used as a surrogate to estimate exposure to the others.

Breathing-zone measurements of acrolein, benzene, carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde, and particulate matter (total and respirable) were obtained concurrently during active firefighting by using personal sampling pumps and sampling media worn by the firefighters. Electrochemical dosimeters also were used to measure CO, thereby providing the advantage of continuous exposure records. Over 1,750 separate measurements of pollutant exposure were collected and analyzed by the project laboratory of the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. The results were validated by an extensive quality assurance program.

Smoke exposure measurements were made at 13 wildfires in California that were successfully controlled by initial attack forces (referred to as “initial attack wildfires”), and during eight multiday wildfires (“project wildfires”) in California, Idaho, Montana, and Washington, for a total of 30 days of firefighting. For the most part, hand crews were monitored at project wildfires and engine crews at initial attack wildfires. The data from the initial attack wildfires and project wildfires were analyzed separately because firefighters at project wildfires usually spend more time at a fire than do initial attack forces, thus the average smoke exposures per shift (“shift-averages”) are very different.

Based on our experience and the observations of experienced firefighters we spoke with, the conditions we monitored were typical of most days of wildland firefighting in the Western United States. We say “most” because we have observed other fires (and heard about more from experienced firefighters) where conditions seemed smokier than those we successfully sampled, by both visual assessment and personal adverse health effects. At the fires we were able to sample, we found that most smoke exposures would not be considered hazardous, but a small percentage routinely exceeded recommended exposure limits at project wildfires. Only CO was shown to occasionally exceed full-shift permissible exposure limits (PELs), as established by the Occupational Safety and Health Administration (OSHA), because the CO exposure limit is adjusted downward by a reduction factor proportional to the shift length, which averaged 14 hours at project wildfires. About 3 percent of the firefighters’ exposures exceeded the adjusted OSHA PEL for CO at project wildfires. None of the exposures exceeded adjusted PELs at initial attack wildfires. The total respiratory irritant exposure (a combination of exposure to acrolein, formaldehyde, and respirable particulate matter) approached the PEL while firefighters were working at project wildfires, but unexposed travel time within the work shifts served to bring the shift-average exposures below OSHA limits. Based on our results, firefighting agencies may want to consider adopting the Threshold Limit Values as occupational exposure criteria (guidelines recommended by the American Conference of Governmental

Industrial Hygienists [ACGIH]), which incorporate more current knowledge of health effects than the Federal OSHA PELs, some of which are based on limited data from the late 1960s. About 3 percent of the shift-average respiratory irritant exposures and about 5 percent of the CO exposures at project wildfires exceeded the recommended ACGIH Threshold Limit Values.

The shift-average exposures to smoke at project wildfires were greater than at initial attack wildfires, but smoke exposure was generally greater during suppression at initial attack wildfires than at project wildfires. The lower smoke exposures among initial attack firefighters at wildfires were due to long periods of unexposed time bracketing their brief exposures during active suppression, thus bringing their shift-average exposures into compliance with both PELs and Threshold Limit Values. Exposure to benzene and CO_2 in smoke was not shown to be a health concern, but the results showed benzene exposure levels were consistently higher among firefighters working with gasoline, such as sawyers and operators of water pumps and drip torches. Exposure to total suspended particulate was within the PELs, but exposure to total suspended particulate was not well characterized because relatively few samples were collected and none were from the higher smoke conditions that occurred during 1992-94. Because of this, future research direction may include further assessment of total suspended particulate exposure as well as exposure to crystalline silica, an uncharacterized hazard that could be cost-effectively assessed through chemical analyses of archived particulate samples.

Samples obtained during peak exposure situations in heavy smoke indicate that these brief but intensely smoky situations are the driving factor behind most shift-average overexposures to smoke, although inversion conditions can cause overexposures at large fires in confined topography. We found that peak exposure samples exceeded the recommended ACGIH short-term exposure limits for the mixture of respiratory irritants (acrolein, formaldehyde, and respirable particulate matter) in about 50 percent of our peak exposure measurements.

Some differences in smoke exposure were apparent among different job tasks: smoke exposure was lower during mop-up and greater during line holding (when downwind or uphill of the fire) and during direct attack of spot fires and flanks of wildfires. Smoke exposures during initial attack were generally higher than at project wildfires, possibly because the firefighters are, in effect, in emergency situations during the former and willing to endure short-term smoke exposure to meet initial attack goals. Increasing ambient windspeeds were positively correlated with higher smoke exposure during fire attack tasks. The firefighters with the highest shift-average smoke exposures were invariably working in peak exposure situations during part of their work shifts. This very important finding indicated that management actions directed at these peak smoke exposure situations will control shift-average smoke exposures as well.

Several results of the study hold promise for minimizing future smoke exposure management costs:

- The known pollutants in smoke were highly correlated with each other. The exceptions were total suspended particulate (because it includes entrained soil dust as well as particles from smoke) and benzene (because firefighters may be working with other sources of benzene, such as gasoline). At this time, respiratory irritants (acrolein, formaldehyde, and respirable particulate matter) and CO are the only well-documented smoke hazards to firefighters. Monitoring for CO therefore can meet most monitoring needs through the use of correlations to estimate exposure to the respiratory irritants.

- Visual estimates hold promise for a low-cost method of determining opportunities for smoke management action. The visual smoke exposure classifications made by an observer with moderate fire experience correlated fairly well with actual smoke exposures.

- The electronic CO dosimeter can give accurate, instantaneous warnings to personnel when CO levels (and correlated respiratory irritants) exceed predefined limits. With data-logging capabilities, this type of instrument can form the basis for a widespread smoke exposure monitoring program with the added advantage of direct feedback to fireline personnel.

If the goal of firefighting agencies is to reduce smoke intake by firefighters because the highest smoke exposures exceed recommended and permissible exposure limits, the management program could include the following elements:

- Hazard awareness training to help managers and firefighters understand why and when smoke exposure is likely to be a concern, what chemicals and physical agents in smoke are involved, how to recognize symptoms of overexposure, and how to manage work to reduce smoke exposures.

- Smoke exposure monitoring, mainly using electronic CO dosimeters (supplemented by occasional comprehensive monitoring), to provide instant feedback to fire personnel, routinely check compliance with occupational exposure limits and evaluate the effectiveness of smoke exposure management strategies by tracking trends in smoke exposure data over many years.

- Evaluation of exposure limits and health risks among wildland firefighters, to assess short- and long-term health consequences and to evaluate whether exposure limits developed for standard industrial workplaces and career patterns are adequate for firefighters.

- Improved recordkeeping of health data to quantify whether smoke-related injuries and illnesses occur, track trends in firefighter health, and enable the assessment of long-term health risks among firefighters.

- Limited respirator use (in accordance with a respiratory protection program and CO monitoring) to reduce respiratory irritant exposure and allow highly trained personnel to work effectively for brief periods in heavy smoke.

- Involvement and consensus building among managers, workers, and regulators to develop a workable smoke exposure management program and maintain continuous improvement.

Contents

Introduction

This paper summarizes measurements of smoke exposure among wildland firefighters in the Western United States. Smoke exposure measurements were taken from over 129 firefighters (both hand crews and engine crews) at 13 initial attack and eight project fires in California, Idaho, Montana, and Washington between 1992 and 1995.

Background

Wildland firefighting presents many hazards to firefighters, including burns, heat stress, tripping and falling hazards, accidents with hand and power tools, being struck by falling rocks and trees, encountering poisonous insects, reptiles, and plants, and inhalation exposure to smoke. Many experienced firefighting personnel consider the last to be only an inconvenience that occasionally causes acute eye and respiratory irritation, nausea, and headache. Others express concern about longer term health impacts, especially when large-scale fires occur in terrain and atmospheric conditions that force firefighters to work for many days in smoky conditions.

Support and coordination of smoke exposure research and information has been provided by the National Wildfire Coordinating Group (NWCG),[1] including an informative quarterly newsletter, “Health Hazards of Smoke,” which received wide distribution from the U.S. Department of Agriculture, Forest Service, Missoula Technology Development Center (MTDC). Several studies of smoke exposure have been undertaken by firefighting agencies since the early 1970s. Since the late 1980s, the National Park Service (NPS) has funded several studies by the National Institute for Occupational Safety and Health (NIOSH). As well, the Pacific Northwest Region of the U.S. Department of Agriculture (USDA), Forest Service, and the Bureau of Land Management (BLM), the California Department of Forestry and Fire Protection (CDF), and NWCG funded the USDA Forest Service, Pacific Northwest Research Station, to conduct a preliminary assessment of smoke exposure at wildfires in the Northwestern United States, which was completed in 1995 (Reinhardt and others 1995b). The USDA Forest Service and CDF also supported another assessment of smoke exposure among initial attack crews in Redding, California, also completed in 1995 (Reinhardt and others 1995a). An overview and summary of some of the relevant literature may be found in Reinhardt and Ottmar (1997a).

This research paper combines additional smoke exposure data obtained in the 1995 wildfire season with the data from the previous two studies for a more complete assessment of smoke exposure at wildfires. It examines smoke exposure in the early stages of fire suppression (initial attack) and during extended attack at project wildfires. Although the results are mainly representative for much of the Western United States, similar results are possible in other regions. Situational factors (such as where the firefighter is in relation to the fire, the ambient wind speed, the fire behavior, the terrain and fuel burning, and the urgency of the work task) ultimately determine whether smoke exposures will be greater or less than what we report here.

Health Hazards in Smoke

Smoke from wildland fires is composed of hundreds of chemicals in gaseous, liquid, and solid forms. The chief inhalation hazards seem to be carbon monoxide (CO), aldehydes, respirable particulate matter with a median diameter of 3.5 micrometers (PM3.5), and total suspended particulate (TSP). Many low- to middle-molecular-weight aldehydes are present in smoke, but formaldehyde and acrolein have been the most studied. Benzene (C_6H_6) is present in wildland fire smoke, but earlier work

[1] All abbreviations are given in a section, “Abbreviations,” on page 67.

Table 1—Selected U.S. occupational exposure limits in 1997

Exposure limit	Acrolein	Benzene	Carbon monoxide	Formaldehyde	Particulate matter
	- - - - - - - - -	- - - - - *Parts per million*	- - - - - - - - -	- - - - - - -	*Mg/m*[3]
OSHA permissible exposure limit	0.1 TWA	1.0 TWA 5.0 STEL-C	50 TWA	0.75 TWA 2.0 STEL	5 TWA (respirable) 15 TWA (total)
NIOSH recommended exposure limit	.1 TWA .3 STEL	.1 TWA 1.0 STEL-C	35 TWA 200 STEL-C	.016 TWA .1 STEL-C	
ACGIH threshold limit value	.1 TWA .3 STEL	.5 TWA 2.5 STEL[a]	25 TWA	.3 TWA-C	3 TWA (respirable)
CAL-OSHA	.1 TWA .3 STEL	1.0 TWA 5.0 STEL-C	35 TWA 200 STEL-C	.75 TWA 2.0 STEL	5 TWA (respirable)

[a]Proposed in ACGIH 1996.

shows that it is not likely to be hazardous unless poor work practices cause exposure to gasoline vapors during engine operations or drip-torch work activities (Reinhardt and others 1995b). Finally, although carbon dioxide (CO_2) is present at relatively high levels in smoke, it is diluted to nontoxic levels by the time it reaches firefighters.

Adverse health effects of smoke exposure begin with acute, instantaneous eye and respiratory irritation and shortness of breath but can develop into headaches, dizziness, and nausea lasting up to several hours. The aldehydes and PM3.5 cause rapid minor to severe eye and upper respiratory tract irritation. Total suspended particulates also irritate the eyes, upper respiratory tract, and mucous membranes, but the larger particles in TSP do not penetrate as deeply into the lungs as the finer PM3.5 particles do. Longer term health effects, lasting days to perhaps months, have recently been identified among wildland firefighters, including very small losses of pulmonary function—unnoticeable in most. These small decrements—on the order of a few percentage points—include a slightly diminished capacity to breathe, constriction of the respiratory tract, and hypersensitivity of the small airways (Letts and others 1991, Reh and others 1994, Rothman and others 1991).

A discussion of particulate inhalation hazards faced by firefighters is incomplete without mentioning crystalline silica, which can be a hazard in the absence of smoke. Because crystalline silica is present in soil dust in many areas of the United States, it is likely to be a component of TSP, but it is unlikely to be significant in PM3.5 because the combustion products dominating the PM3.5 portion of TSP are generally low in silica. Chronic exposure to crystalline silica is well-known to cause silicosis (thickening of the lung tissues), which limits breathing ability. Only one study has attempted to measure crystalline silica in the dust exposures among firefighters, and that study found measurable levels of silica in 25 percent of the samples, ranging up to 9 percent by weight, although the highest sample was just below the Occupational Safety and Health Administration (OSHA) permissible exposure limit (Harrison and others 1992).

Carbon monoxide causes acute effects ranging from diminished work capacity to nausea, headache, and loss of mental acuity. It has a well-established mechanism of action, causing displacement of oxygen from hemoglobin in the blood and affecting tissues that do not stand loss of oxygen very well, such as the brain, heart, and in pregnant firefighters, the fetus. Fortunately, most of these effects are reversible and

CO is rapidly removed from the body, with a half-life on the order of 4 hours. Some studies have linked CO exposure to longer term heart disease, but the evidence is not clear cut.

This research paper summarizes measurements of exposure to acrolein, benzene, CO, CO_2, formaldehyde, PM3.5, and TSP. The other chemicals in smoke seem unlikely to pose a significant health hazard, based on current knowledge. We caution that this conclusion may change as knowledge develops about toxicology and smoke exposure (Dost 1991).

Smoke Exposure Evaluation Criteria

To evaluate occupational exposures to chemicals and other airborne hazards, the line between safe and unsafe exposures requires careful evaluation because individuals differ in their susceptibility to adverse health effects. The OSHA sets legally enforceable permissible exposure limits (PELs) for the United States, and many states have an equivalent occupational safety agency, such as CAL-OSHA in California. These agencies have established PELs that are at least as stringent as OSHA's and may be more so. The PELs have been established for only a small percentage of hazardous chemicals. Where PELs have not been established or are inadequate, OSHA and the state agencies have the authority to require employers to provide a workplace free from recognized hazards likely to cause serious harm.

The procedures for establishing PELs are time consuming and costly, so voluntary guidelines help to fill this gap. One source of current information is NIOSH, which advises OSHA on health hazards in the workplace and establishes recommended exposure limits (RELs) that are based on detailed scientific information. Similarly, the American Conference of Governmental Industrial Hygienists (ACGIH) annually publishes a well-regarded compendium of Threshold Limit Values (TLVs) for worker safety.

Exposure limits for airborne pollutants are defined via three basic time categories. These categories of exposure limits are:

- Time-weighted average (TWA), a concentration for a normal 8-hour day in a 40-hour workweek, to which nearly all workers may be exposed for a working lifetime without adverse effect.

- Short-term exposure limit (STEL), a maximal concentration to which workers can be continuously exposed for up to 15 minutes without adverse effect.

- Ceiling limit (C), a concentration that is unsafe to exceed, for over 1 minute.

A "skin" notation for a chemical indicates that dermal absorption is an important exposure route to consider when developing management strategies. Table 1 summarizes the current regulatory exposure limits for hazards faced by firefighters and the most current (or proposed) guidelines recommended by some key occupational health organizations.

We consider the TLVs to be the best starting point for assessing exposures because they incorporate the latest scientific evidence, whereas the PELs do not. We refer to the ACGIH TLVs as our key evaluation guidelines in this report, although other standards may be appropriate.

Multiple Contaminants

In a situation such as firefighting, where workers face multiple air pollutants, it is prudent to consider the combined effects of the pollutants. Acrolein, formaldehyde, and respirable particulate all cause irritant effects in the same organs: the respiratory tract and mucous membranes. Beyond the physical irritation caused by fine particles, chemical analyses of woodsmoke particulate have shown it to be composed of many organic compounds, some of which are chemical irritants. Without detailed knowledge of the chemical composition of the particulate, it is reasonable to assume that exposure to PM3.5 and the aldehydes produces an additive irritant effect in the respiratory tract and mucous membranes of the eyes, nose, and throat. Following the approach recommended by ACGIH and OSHA, a combined "equivalent irritant exposure" index can be calculated from equation (1):

$$E_m = \left[\frac{\text{conc.}(C_3H_40)}{\text{limit }(C_3H_40)}\right] + \left[\frac{\text{conc.(HCHO)}}{\text{limit (HCHO)}}\right] + \left[\frac{\text{conc.(PM3.5)}}{\text{limit (PM3.5)}}\right], \qquad (1)$$

where

E_m = the equivalent exposure irritant index (a ratio);

conc. = the measured concentration of the irritant;

$[C_3H_4O]$ = acrolein (ppm);

limit = the adopted exposure limit of the irritant—the PEL or TLV;

[HCHO] = formaldehyde (ppm); and

[PM3.5] = respirable particulate (mg/m^3).

The total irritant exposure was an important exposure evaluation criterion in this report. The equivalent exposure (E_m) is required to be maintained below 1.0 for a workplace to be considered in compliance with the criterion. We evaluated the E_m in two ways, by using first the recommended TLVs and then the OSHA PELs as the divisor for each pollutant's exposure. If considering different exposure limits, simply substitute the appropriate exposure limits in the denominators of the calculation to evaluate the combined exposure. Our estimate of E_m probably underestimates the irritant nature of smoke because we have no detailed exposure data for all the irritants (such as other aldehydes, formic acid, and possibly sulfur dioxide). If exposure data for other irritants become available, it may be appropriate to include them in an expanded equation. We considered other common effects of the pollutants, such as carcinogenicity for benzene and formaldehyde, but at this time it is not suggested that these two chemicals be added as an E_m for cancer effects because they affect different organs.

Exposure Duration Considerations

Exposure limits are developed to prevent adverse health effects that occur above a certain dose of pollutant. Dose is the amount of pollutant delivered to a target organ and depends on the level and duration of exposure as well as the rates of pollutant uptake and elimination by the body. Wildland firefighting often requires hard physical labor over extended work shifts. The exposure duration and rate of pollutant uptake in these conditions differ from the assumptions for traditional industrial workplaces used to develop occupational exposure criteria. To account for such differences, adjustments are required to maintain the peak dose below the level that workers would experience in a standard workplace in compliance with the exposure limit. Very complicated models exist to predict doses in given exposure regimes for some pollutants, such as the recently modified Coburn-Forster-Kane (CFK) equation for CO (Smith and others 1996). The simplest approach is to compare the pollutant level during the most exposed 8 hours in the day with the existing standard, while considering the exposure during the rest of the work shift. An alternative and objective method is to multiply the standard exposure limit by a reduction factor to achieve equivalent protection in the nonstandard work environment.

To evaluate compliance of nontraditional work shifts with 8-hour PELs, OSHA uses one of two simple formulas to calculate an exposure limit reduction factor. Knowledge of the toxic effects of the pollutant is needed to assign the pollutant to one of six "work schedule categories," which then determines the correct formula to use (U.S. Department of Labor 1979). Adjustments are not always suggested for all pollutants. Exposure limits for acrolein and PM3.5 are based on the acute irritant effects and do not require adjustment downward for longer work shifts. The ACGIH formaldehyde limit of 0.3 parts per million (ppm) is a ceiling limit, intended to protect most of the work force from irritant effects (American Conference of Governmental Industrial Hygienists 1996); therefore, it does not need to be adjusted downward. The benzene TLV is based on systemic effects, so the exposure limit can be adjusted to account for an increased work shift duration. The CO exposure limit is based on acute toxic systemic effects; thus adjustment is often suggested for work shifts of longer duration.

Equation (2) shows the recommended model from OSHA:

$$\text{adjusted CO exposure limit} = \text{PEL} \times \frac{8}{\text{duration}}, \qquad (2)$$

where

adjusted CO exposure limit = the revised exposure limit to account for the extended work shift,

PEL = the permissible exposure limit (or other exposure limit, such as the threshold limit value), and

duration = the duration of the extended work shift (hours).

Although the OSHA model is straightforward and will be used in this report, the CFK equation is a better model for adjusting the CO exposure limit if detailed exposure, pulmonary function, and site altitude data are available.

Objectives

The objective of this research was to provide useful information about the occurrence and significance of smoke exposure among firefighters at wildland fires. Through better understanding of the extent, magnitude, and reasons for overexposure to smoke, cost-effective and workable measures can be developed to manage the problem. To meet this overall objective, our goals were to:

- Measure firefighters' exposure to the important contaminants in smoke at enough fires to estimate their shift-average smoke exposure at wildfires and to determine the variability of these exposures.

- Observe the work activities, fire behavior, and environmental factors that contribute to high smoke exposures to allow development of targeted exposure management actions.

- Evaluate some techniques, such as CO dosimetry and visual smoke estimating, whereby fire managers could routinely characterize smoke exposure as it occurs, thereby enabling objective assessments of smoke hazards and application of appropriate protective measures.

- Find out whether the ratios among the important hazards in smoke are consistent enough that measurements of a single indicator pollutant could serve as a surrogate to estimate exposure to the rest. If these interpollutant correlations were strong enough, the future costs of routine smoke exposure monitoring could be greatly reduced.

Methods

Data collection took place at two types of wildfires: initial attack wildfires that were successfully suppressed within hours of starting, and project wildfires that took longer to control. Two key differences were considered likely between the two types of wildfires. First, the initial attack crews work at a faster pace for a shorter time because they are in an emergency-response situation; project wildfire crews often take a more measured approach but over a longer timeframe. Second, most of the work shift at project wildfires is spent at the fire, but most of the work shift at initial attack wildfires is spent waiting for a fire to occur. Because of these differences, we expected very different exposure patterns between the two milieus. Thus, the exposure data for initial attack wildfires and project wildfires were analyzed separately. The field and laboratory methodology was essentially the same at both types of wildfires.

Sampling at project wildfires included several types of crews. Most were type I (hotshot) or type II hand crews and included Native American crews, contractor crews, and Federal and state agency crews. Along with the hand crews, two engine crews were monitored at the project wildfires. At the initial attack wildfires, both Forest Service hotshot crews and CDF engine crews were monitored.The CDF crews were based at a fire station in Redding, California, and the Forest Service hotshot crews were from the Angeles National Forest in southern California.

Field Methods

Project wildfires were selected in the Western United States based on logistical feasibility, potential for smoke exposure, and convenience; we opted for fires that were nearby or appeared more difficult to control over fires that seemed unlikely to last very long. During weeks when monitoring was planned at initial attack wildfires, crews were preselected for the study based on their proximity to high fire hazard areas and their willingness to cooperate. Once selected, the initial attack crews were normally dispatched and sampling was done at every daytime fire that occurred.

Our sampling strategy was intended to:

- Select fireline personnel who were representative of crews expected to encounter smoke.
- Maximize the number of firefighters monitored each day to improve the likelihood of including highly exposed personnel.
- Provide data from which smoke exposure can be assessed versus fire characteristics and work activities.
- Assess interpollutant correlations.
- Obtain peak exposure assessment data during brief but intense smoke exposure situations.
- Provide field quality assurance data.

Between two and six firefighters were selected for exposure assessment at each fire, usually by asking for volunteers from within a single fire crew. Although smokers and nonsmokers were included in the sample pool, smokers were asked to refrain from smoking (and generally did) while the samples were being collected. The study team coordinated tracking the firefighters, set up and calibrated sampling equipment, and recorded observations about smoke intensity and job task for each firefighter.

Figure 1—Smoke exposure sampling apparatus.

Firefighters selected for monitoring wore a 4-kilogram sampling apparatus, shown in figure 1. The apparatus consisted of three battery-powered personal sampling pumps held in a web-gear pack or rucksack. The three sampling pumps for a given firefighter were operated concurrently during each sampling period, with each pump dedicated to separate sample collection media:

- An inert gas sampling bag for collection (at a fixed rate between 20 and 200 milliliters/minute) and later analysis of CO and CO_2 by Intersociety Committee Method (ICM) 128 (Lodge 1989).
- Sorbent tubes for collection (on charcoal at 0.15 liter/minute) and later analysis of benzene according to NIOSH method 1501 (National Institute for Occupational Safety and

Health 1989c), and formaldehyde and acrolein (on dinitrophenylhydrazine-coated C-18/silica gel at 0.2 liter/minute) according to EPA method TO-11 (U.S. Environmental Protection Agency 1986).

- A Teflon® 37-millimeter, filter cassette and nylon cyclone assembly for sample collection and later analysis of respirable particulate matter at 1.7 liters/minute according to NIOSH method 0600 (National Institute for Occupational Safety and Health 1989b).[2] In 1995, sampling also was done for total suspended particulate using only the filter-cassette assembly and according to NIOSH method 0500 (National Institute for Occupational Safety and Health 1989a).

In 1995, the gas sampling pump and bag system (for CO and CO_2 analysis) was discontinued in favor of an electronic data-logging dosimeter measuring only CO, according to OSHA method ID-209 (U.S. Department of Labor 1993). The other major change in 1995 was the initiation of monitoring for total suspended particulate.

The air samples were collected consecutively from the breathing zone of each firefighter during discrete time periods of their work shift. Each sample period lasted for the duration of a particular job task, or until the sample media—such as gas sample bags—approached capacity. Peak exposure (STEL) samples lasted for the duration of the peak exposure situation; typically, they were obtained over 15 minutes to ensure that a sufficient sample was acquired for analysis. Each day at project wildfires, sample durations were set up to be about 2 hours, supplemented by STEL samples in obvious peak exposure situations. Conversely, at initial attack wildfires, sampling was planned to begin with STEL samples and switch to 1- or 2-hour samples as the fire was controlled and conditions became less dynamic. After the conclusion of a sample period, a new sample was begun as quickly as possible if smoke exposure continued, but we often did not sample while firefighters were in smoke-free air, thereby allowing us to minimize unnecessary sampling and prevent dilution of CO sample concentrations below detection limits for method 128. Sampling usually did not begin until smoke reached the firefighter. If a firefighter took a work break in clean air or moved out of smoke, sampling often stopped (or paused) and resumed when smoke exposure continued. These clean-air situations often comprised a large portion of the day. Air pollutant exposures during these portions of the day were estimated as equivalent to background levels for the TWA calculations.

Some bias is possible in the results; for example, only volunteers were monitored, yet uncooperative workers who see no harm in smoke exposure may endure higher smoke exposure than volunteers. Another potential source of bias is that crew supervisors may have managed the activities and smoke exposure of their personnel differently when the study team was present. Finally, the added weight of the sampling gear could have diminished the firefighter's work, but as most firefighters were organized into tightly knit squads, the monitored firefighters were unlikely to work at a different pace than the rest of their crew.

The electronic CO dosimeters, along with passive sorbent tube dosimeters for CO, were evaluated for accuracy and practicality in the field during 1992-94. The passive sorbent tubes were not found to be practical in the heat and harsh conditions of

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[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

wildland firefighting. The dosimeters performed adequately enough that they were used as the primary CO data collection method in 1995 after a complete field quality assurance (QA) program was developed for them.

Laboratory Methods

Analytical methods for each pollutant are outlined in this section. For a detailed discussion of each method, refer to the standard operating procedures (SOPs), appendices C through J in the final report (Reinhardt and Ottmar 1997a).

Acrolein and formaldehyde—Minor modifications were made to U.S. Environmental Protection Agency (EPA) method TO-11 to analyze concentrations of formaldehyde and acrolein. This method combines aldehydes and ketones in smoke with 2,4-dinitrophenylhydrazine (DNPH) in the presence of acid to form stable DNPH derivatives. Derivatives were formed during sampling by drawing the air sample through a sorbent tube impregnated with acidified DNPH solution. The sorbent tube (Sep-Pak®) was extracted with acetonitrile in the field to yield a solution of aldehyde-DNPH derivatives. Limiting pre-extraction storage improved acrolein recoveries. The solutions were analyzed in the laboratory by high-performance liquid chromatography (HPLC) with ultraviolet detection.

This method was improved upon for acrolein. Method TO-11 specifies recoveries as low as 40 percent for acrolein. The acrolein-DNPH derivative has a reactive double bond, which causes losses of the acrolein-DNPH derivative immediately upon sampling and during storage. We have found that acrolein-DNPH degrades to several unknown "X-acrolein" DNPH breakdown products, similar to a report by EPA researchers (Tejada 1986). Difficulties with chromatographic resolution masked this problem early in the project. Once good resolution was achieved, the problem and the impossibility of quantitative recovery data became apparent; acrolein data for the 1992 field season therefore were unusable. Chromatography improvements enabled the resolution and measurement (as acrolein) of the acrolein-DNPH degradation products. Quantitative recoveries of known amounts of acrolein spiked on media were regularly achieved with the revised method.

Benzene—A slight modification to NIOSH method 1501 was used for benzene, in which the sampling pump pulled smoke through a small glass tube containing two sections of granular activated charcoal. Hydrocarbons such as benzene were adsorbed on the surface of the front charcoal section. The charcoal tubes were opened and each section desorbed with carbon disulfide (CS_2). The CS_2 extract was analyzed for benzene by gas chromatography with flame ionization detection. Our modification to the method used large-capacity sorbent tubes to prevent benzene breakthrough into the back section of the tube.

Carbon monoxide and carbon dioxide—Both CO and CO_2 were sampled prior to 1995 by filling inert gas sampling bags via a pump. Gas bag samples were analyzed by nondispersive infrared spectroscopy using ICM 128.

In 1995, data-logging electronic dosimeters were used as the primary CO measurement method, under OSHA method ID-209. Laboratory aspects of this method were limited to routine calibrations of the instruments and manipulation of data files. Zero drift in the data-logger results was occasionally observed down to -2 ppm. These were corrected manually by adding a corresponding constant (up to +2 ppm) to all affected results.

Table 2—Method detection limits for pollutants measured at wildfires

Pollutant	Method	Method detection limit: STEL sample[a]	TWA sample[b]
		- - - - - - Parts per million - - - -	
Benzene	NIOSH 1501	0.032	0.004
Acrolein	EPA TO-11	.024	.003
Formaldehyde	EPA TO-11	.048	.006
Carbon monoxide	ICM 128	.6	.6
Carbon monoxide	OSHA ID209	1.7	1.7
Carbon dioxide	ICM 128	7.6	7.6
		--Milligrams per cubic meter--	
Respirable particulate matter	NIOSH 0600	0.935	0.117
Total suspended particulate	NIOSH 0500	.549	.069

[a]Nominal sample duration of 15 minutes.
[b]Nominal sample duration of 2 hours.

Respirable and total suspended particulate—Respirable particulate was selectively sampled from smoke by drawing the air sample through a cyclone device at 1.7 liters per minute and collecting the PM3.5 on a filter, according to NIOSH method 0600. The total suspended particulate method (NIOSH 0500) used in 1995 was essentially the same but omitted the cyclone in the sampling train. The main modification to both these NIOSH methods was that Teflon filters with a 2.0 micrometer (µm) pore size were used to slightly improve capture efficiency for the small particles in smoke and facilitate future chemical analyses of the filters.

Quality Assurance Program

A comprehensive QA program was developed for the project by an independent QA officer not otherwise involved in the project. The data collection effort took place under a QA project plan (Radian Corporation 1993) and its subsequent revision (Radian Corporation 1996). The QA program required calculation and evaluation of many quality control (QC) parameters obtained from laboratory and field QC samples and assessment procedures. All QC results were recorded on control charts, and trends were assessed throughout the project. This QA program enabled identification and correction of many problems before they affected the quality of the data. Chain-of-custody records were maintained from sample collection through laboratory analysis. Comprehensive field and laboratory audits of the project were conducted semiannually by the QA officer. Results of these audits and a complete QA review of the data are presented in detail in appendix H of the final report (Reinhardt and Ottmar 1997a).

Several different types of QC samples were obtained at each fire to assess the variability and accuracy of field data and meet the QA objectives. Systematic problems affecting sample accuracy were tracked through trip blanks, field blanks (unsampled media), field method spikes, and field matrix spikes (media spiked with known amounts of the target pollutants, that were either analyzed directly or used to sample smoke next to unspiked media to determine recovery of the spike). Precision of field data was assessed with field replicates (multiple adjacent samples of smoke in ambient air).

As in the field, QC samples and parameters were used to assess and maintain control in the project laboratory's analytical and data manipulation systems. Blanks and independent calibration checks were used to establish accuracy, and duplicate analyses were used to track analytical precision. The QA plan also included routine evaluation of instrument stability and performance by assessing key calibration parameters. Finally, independent blind (unknown concentration) performance evaluation samples were prepared by outside laboratories and submitted to the USDA Forest Service, Pacific Northwest Research Station, project laboratory—annually for difficult methods such as TO-11.

Method Detection Limits

Method detection limits (MDLs) were periodically evaluated for each analytical method to define the lowest concentration measurable with 99-percent confidence that it was greater than zero. For the first 2 years of the project, permeation tubes and a dilution system were used to generate known atmospheric concentrations of each chemical in a sampling manifold. Replicate samples were then obtained from the manifold by using the field sampling protocol. These sample results were used to determine the MDLs under EPA procedures (U.S. Environmental Protection Agency 1984). Similar tests were done by using National Institute of Standards and Technology (NIST) gases for CO and CO_2 and eight simultaneous low-level field replicate samples from one fire for respirable particulate. By the 1995 season, all MDLs were determined from low-concentration smoke samples in the field. Table 2 lists the 1995 experimentally derived MDLs.

Data Analysis

Many statistical tests and parameters are best suited to data with a normal (bell-shaped) distribution; however, much of the exposure sample data in this project approximated a geometric (lognormal) distribution. Whenever geometric distributions were apparent but the statistical analyses required a normal distribution of data, the concentration data were logarithmically transformed with equation (3) prior to the analyses:

$$\mathrm{Log}X = \mathrm{Log}(X) + 0.05\bar{x} , \quad (3)$$

where $\mathrm{Log}X$ = transformed concentration;

X = concentration of the exposure sample; and

$\bar{x}$ = mean concentration of the data.

The results of the statistical analyses were converted back to the original units by using equation (4):

$$X = e^{\mathrm{Log}X} - 0.05\bar{x} , \quad (4)$$

where e = natural logarithm base.

The addition of the constant (5 percent of the arithmetic mean) allows the use of zero-concentration data to calculate the geometric mean and is preferable to adding a constant of 1 to all observations—commonly done but inappropriate when many of the observations are much smaller than 1 (Liedel and others 1977). Geometric standard

Table 3—Treatment codes for each period in the day comprising the time-weighted average

Code	Treatment	Summary
1	$C_n=C_n$	Concentration of the entire period equals the sample concentration obtained during the period, or portion thereof
2	$C_n=0$	Concentration during the period is assumed to equal zero (background)
3	$C_n=C_{n+1}$	Concentration during the period is assumed to equal the following sampled period
4	$C_n=C_{n-1}$	Concentration during the period is assumed to equal the previous sampled period
5	$C_n=TWAC_{n-1,n+1}$	Concentration during the period is assumed to equal a time-weighted average of the surrounding sampled periods

deviations were calculated as the antilog of the standard deviation of the transformed variables. The geometric standard deviation ranged between 1 for invariant data to 4 for highly variable data. For some data analyses, non-normality remained even after the logarithmic transformation. In the case of small data sets, additional sampling was needed to determine the true data distribution. In other instances, the non-normality suggested additional grouping factors within the populations, which are noted below in the “Results” and “Discussion.”

Pollutant Correlations

Correlations between pollutants were evaluated where pollutant pairs were measured concurrently with a sampling pack, including exposure samples from firefighters and field replicates (which were essentially additional samples of smoke in or near the fire). Linear regression techniques were used to examine the interpollutant correlations. Data were excluded from this analysis if any of the following occurred:

- The two pollutants in question were not successfully sampled at the same place and time (± 2 minutes).

- Bias was indicated for either of the pollutants based on field quality assurance (for example, any PM3.5 samples invalidated by visible nonrespirable particulate matter).

- Either pollutant concentration was below the method detection limit.

Because previous work at prescribed fires showed that benzene does not correlate with the other pollutants in smoke exposure samples if the firefighters have been working with gasoline (Reinhardt and others 1997a), such samples were excluded from the data for benzene regressions. Also, to minimize error in the independent variable (X) relative to Y, data for each regression were limited to instances where the X pollutant was at least twice the MDL. Finally, residuals were examined as a function of possible confounding variables for each regression to ensure that the regression models were unbiased (Neter and others 1983).

Time-Weighted Average Exposures

Time-weighted average (TWA) smoke exposures were calculated for each firefighter to assess shift-average and fireline-average exposure. Each TWA was calculated by:

$$TWA = \frac{C_1 \times T_1 + C_2 \times T_2 + \ldots + C_n \times T_n}{T_1 + T_2 + \ldots + T_n}\ , \qquad (5)$$

where T_n = duration of period n, and

C_n = pollutant concentration during period n.

The shift TWA included the paid hours from the start of the shift until its end. For project wildfires, lunch breaks were excluded from the TWA calculations unless they were taken in smoky situations. Lunch or dinner breaks were assumed to be one-half hour for calculating the TWA, even when work did not resume until somewhat later.

For initial attack wildfire crews, shift TWAs were defined differently. The CDF engine crews technically worked a 96-hour on-call shift, followed by 72 hours off duty. For those crews, a work shift was defined for each day of sampling as the time elapsed between morning wake up and the end of fire-related duties in the evening, including meals. For Forest Service hotshot crews, each shift included the hours from the start of their scheduled shift until the shift ended (in one case, the shift “ended” when the crew was dispatched to another fire out of the region). For these crews, unpaid lunch breaks were excluded from the TWA calculations.

Along with the sampled periods comprising each TWA, unsampled periods occurred; these were treated consistently through a limited set of assumptions about smoke concentrations during such periods. These assumptions were based on field observations about the job task and smoke conditions for each period and expressed as one of five codes defining the best assumption for that time period (table 3). The codes, period time, and relevant pollutant sample data for that firefighter were then used to calculate an estimate of the concentration for the unsampled period.

Where data were missing for one or more pollutants in any sampled periods, the TWA for that firefighter was calculated by using the interpollutant regressions and the sample results for the other pollutants for that period. The best regressions for the missing pollutant, based on r^2 (coefficient of determination), were selected for the relevant fire type (initial attack or project wildfire). As an example, if a PM3.5 sample were invalidated by a pump malfunction between 7:00 and 8:12 a.m., the CO data recorded during that time by the dosimeter on a firefighter would be used to estimate the missing PM3.5 concentration for that period for that firefighter. Regression results were averaged if equally efficient regressor pollutants were available, and the MDL was substituted for any regression results that were below the MDL.

Peak Exposures

Samples from peak exposure situations were obtained in two ways: by using integrated STEL sampling for all pollutants, and by identifying the peak CO exposure from the data-logger results for CO in 1995. Only integrated samples with durations below 20 minutes in peak exposure situations were considered valid as STEL samples. There were too few STEL samples from project wildfires to test whether they were different from STEL samples at initial attack wildfires, so they were summarized separately. A Student’s T-test (Steel and Torrie 1980) showed no significant difference, however, between the log-transformed peak CO exposure data from 1995 at project wildfires versus the data from initial attack wildfires. Because of this, they were combined for an overall peak CO exposure during wildland firefighting.

Job Task

The job task categories we observed (and some common synonyms) were:

- **Attack (direct attack):** Intensive efforts to contain and extinguish the wildfire. This included hotline construction (direct line adjacent to burning or smoldering areas) and spotfire suppression, but not final mop-up. Laying hose to support a direct attack was included in this task.

- **Crew boss:** Supervising a crew's field activities, keeping a lookout, and scouting area if necessary, usually performing tasks as well as managing them.

- **Digging line:** Indirect line construction and direct line construction in blackened areas having few, if any, smoldering combustion sources. The use of hand tools was included in this task, but sawyers and swampers were not included. Deployment of fireline explosives was included in this task.

- **Engine:** This category of work encompassed all work near internal combustion engines, such as fire engine operators and water pump operators. Personnel assigned solely as vehicle drivers were neither sampled nor included in this category. For the initial attack wildfires, fire engine operators and captains that stayed with the engine were included; at project wildfires, this category included only pump operators.

- **Gridding:** This activity involved patrolling systematically to find and extinguish spotfires and hotspots. Some brief direct attack activities were included in this category when hotspots were found.

- **Holding (holding line, patrolling):** Maintaining fire within fireline boundaries. This included using fire hoses and hand tools to maintain firelines and extinguish minor spot-fires along the fireline, periodic forays along and outside sections of fireline to check for spot-fires, and equipment and water supply maintenance work.

- **Lighting:** Use of a hand-held driptorch to ignite fuels during burnout operations.

- **Mobile attack:** This specific type of direct attack occurred only at initial attack wildfires and was characterized by a firefighter working with a firehose in front of a slowly driven fire engine. This is a common tactic in herbaceous fuels and gentle terrain.

- **Mop-up (mopping, dry-mopping, wet-mopping):** This included using fire hoses, portable backpack pumps, and hand tools to extinguish smoldering woody debris after the main flaming phase of the fire had passed. Fire hose line maintenance, installation of branch lines, and equipment and water supply maintenance were included. Patrolling for spot-fires in unburned areas within the firelines was included in this task.

- **Sawyer:** Periodic operation of a chainsaw to fell trees and snags and cut up downed logs during line construction and mop-up.

- **Swamper:** Closely assisting the sawyer during line construction by maneuvering woody material for cutting and clearing cut-up logs and branches from the path of the fireline.

Geometric mean concentrations by job task were calculated for each pollutant. Data were treated separately for initial attack wildfires and project wildfires. The log-transformed pollutant concentration data for each job task were tested for normality by the Shapiro-Wilk procedure (Shapiro and Wilk 1965). Tukey's multiple comparison test was used to examine whether the geometric mean exposures for each work task were significantly different (Steel and Torrie 1980).

Environmental Variables

With the exception of the 1994-95 fireline windspeed observations made with hand-held anemometers, site-specific environmental data from project wildfires were inadequate. Conversely, we were able to obtain useful data from CDF for the initial attack wildfires in Redding, California. Weather, fuel moisture, and National Fire Danger Rating System (NFDRS) predictions of fire behavior (Deeming and others 1977) were paired by time with the smoke exposure data to assess relations among smoke exposure and windspeed, relative humidity, fuel moisture, predicted spread component, predicted burning index, and predicted ignition index. Windspeed data for these initial attack wildfires were obtained from an anemometer 6.1 meters in elevation at the Redding airport. The NFDRS predictions used a single fuel model for the Redding initial attack area, brush model F.

Scatterplots of smoke exposure versus environmental and fire behavior variables were examined for the initial attack wildfires. Based on the patterns observed, only windspeed showed a definitive trend when plotted versus smoke exposure. Linear regression was used to relate smoke exposure concentrations with windspeed for the combined data from initial attack wildfires and project wildfires.

Dosimeters

Three different methods of measuring CO exposure were tested by collecting data concurrently via all three methods for randomly selected firefighters during the 1992 through 1994 fire seasons:

- Infrared analysis of integrated gas samples (ICM 128, the reference method of CO measurement for the project during 1992-94)
- Passive dosimeter tubes from Draeger® and Sensidyne® in 1992-94
- Passive electrochemical dosimeters in 1994 (using the Draeger model 190 data logger via OSHA method ID-209, which became the reference CO measurement method for the project in 1995)

Not enough CO results were within the measurement range of the dosimeter tubes to make meaningful statistical comparisons with those data. The dosimeter tubes may have been adversely affected because the storage requirements of <25 °C could not be met in the field. The CO exposure results from the remaining two methods were compared for each sample period by using linear regression.

Observer Estimates

A visual estimate of the intensity of each firefighter's exposure to smoke was routinely made by the nearest observer during the work shift. These observations were useful for estimating smoke exposure for unsampled periods when calculating the overall TWA exposure for the firefighter's work shifts. Ten different observers recorded smoke classification data during the project. Smoke intensity during each observation was

Table 4—Index to wildfires comprising the study

Fire number	Fire type	Fire name	Date	Fuel species[a]	Location
20	Project	County Line	8/6/92	MC	Lowman, ID
21	Project	County Line #2	8/8/92	MC	Lowman, ID
22	Project	Foothills Fire #1	8/24/92	G	Idaho City, ID
23	Project	Foothills Fire #2	8/26/92	PP/MC	Idaho City, ID
24	Project	Foothills Fire #3	8/27/92	PP/MC	Idaho City, ID
43	Initial attack	Swaysey	8/17/93	CH/O/G	Redding, CA
44	Initial attack	Akritch	8/18/93	G/O	Redding, CA
45	Initial attack	Shawn/Paloma	8/22/93	O/G/CH	Redding, CA
46	Initial attack	Cambridge	8/23/93	O/G	Redding, CA
47	Initial attack	QH Ranch	8/25/93	O/P/G	Redding, CA
48	Initial attack	Silverthorn	8/26/93	O/G	Redding, CA
49	Initial attack	Squaw Grass	8/27/93	PP/MC	Redding, CA
50	Initial attack	Misty Lane	8/29/93	O/G/CH	Redding, CA
55	Project	Tyee Complex #1	8/1/94	MC/LP	Chelan, WA
56	Project	Tyee Complex #2	8/3/94	MC/LP	Chelan, WA
57	Project	Tyee Complex #3	8/5/94	MC/LP	Chelan, WA
58	Initial attack	Virginia	8/13/94	G/O	Redding, CA
59	Initial attack	Chip	8/16/94	G	Redding, CA
60	Initial attack	Shasta View	8/17/94	G/O	Redding, CA
61	Project	Libby Complex #1	8/25/94	MC	Libby, MT
62	Project	Libby Complex #2	8/27/94	MC	Libby, MT
63	Project	Ann #1	8/29/94	MC/LP	Hamilton, MT
64	Project	Ann #2	8/30/94	MC/LP	Hamilton, MT
65	Project	Covington	8/2/95	G/O/CH	Joshua Tree, CA
66	Initial attack	Freeway	8/4/95	G/O	Bear Divide, CA
67	Project	Verbenia #1	8/5/95	CH/O	Cabazon, CA
68	Project	Verbenia #2	8/7/95	CH/O/PP	Cabazon, CA
69	Project	Verbenia #3	8/8/95	CH/O/PP	Cabazon, CA
70	Initial attack	Trask	8/12/95	CH/PP	Monrovia, CA
71	Project	Helester	8/14/95	PP/O	Tahoe, CA

[a]Dominant overstory species listed in descending order of occurrence: **CH**—northern and southern California chaparral (mainly manzanita [*Arctostaphylos* spp.] and oak [*Quercus* spp.] in the north); **G**—western annual grasses such as cheatgrass (*Bromus tectorum* L.), medusahead ryegrass (*Elymus caput-medusae* L.), and fescues (*Festuca* spp.); **LP**—lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.); **MC**—mixed conifers (Douglas-fir, ponderosa pine, white fir [*Abies concolor* (Gord & Glend.) Lindl. ex Hildebr.], grand fir [*Abies grandis* (Dougl. ex D. Don) Lindl.], and western larch [*Larix occidentalis* Nutt.], predominantly on higher elevation sites of the interior West); **O**—oak (*Quercus* spp.);and **PP**—ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.).

classified as none (1), light (2), medium (3), heavy (4), and very heavy (5). If smoke conditions were changing rapidly, the recorded observation consisted of an entry for each appropriate smoke class.

These data allowed us to test how well observers with little previous experience could estimate smoke exposure. Because smoke conditions can change rapidly but our observers were unable to constantly watch the firefighters, we limited the data to sampled periods where the average time between smoke observations was no more than 20 minutes. The smoke intensity observations were averaged for each sample period, and the concentration of each pollutant was plotted against the resulting visual smoke estimate score for the period. After viewing scatterplots of the data, we evaluated linear regressions for each pollutant; measured pollutant concentration was used as the dependent variable, and smoke exposure "class" was the independent variable.

Results

Smoke exposure among firefighters was monitored during 30 days of wildfire suppression between August 1992 and August 1995. Eighty-four 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. A total of 1,763 separate breathing zone samples were collected to measure firefighter exposure to benzene, acrolein, formaldehyde, CO, CO_2, respirable particulate matter, and total suspended particulate during wildfires. Table 4 lists the dates when firefighter exposure to smoke was monitored and the dominant vegetation that burned at each fire.

The results are organized by sections on the following:

- Data quality, to discuss the accuracy, precision and completeness of the exposure measurements as those parameters affect the conclusions
- Pollutant correlations, to show the strong links between exposures to different pollutants
- Exposure assessment at project wildfires, to summarize TWA smoke exposures among firefighters who have the potential for all-day smoke exposure at these multiday fires
- Exposure assessment at initial attack wildfires, to summarize the TWA smoke exposures among initial-attack firefighters who have no smoke exposure until they are called to respond to small wildfires
- Peak exposure assessment, to describe the highest smoke levels monitored at project wildfires and initial attack wildfires
- Factors influencing smoke exposure, to summarize the important determinants of smoke exposure
- Dosimeter performance assessment, to demonstrate the utility of this relatively new and simple procedure for measuring smoke exposure
- Observer estimates, to show the feasibility of visual estimates of smoke intensity for making decisions about the safety of smoke exposure

Data Quality

Samples were analyzed by six methods for the seven pollutants. Some sample results were invalidated owing to technical problems in the field or laboratory. Table 5 summarizes the number of samples attempted in the field, the successful field measurements, the number of results that have potential problems rendering them "qualified" (considered to be estimated values), and the percentage of completeness of the data (how many were valid versus how many were attempted). Only valid data were used to determine smoke exposure and correlations among parameters. Valid data included individual data points that were "qualified."

Table 5—Summary of data collected for each pollutant

Pollutant	Method	Number of samples attempted	Number of valid samples[a]	Number of qualified results	Completeness
					Percent
Benzene	NIOSH 1501	291	208	49	71
Acrolein	EPA TO-11	291	189	129	65
Formaldehyde	EPA TO-11	291	244	12	84
Carbon monoxide	Method 128[b]	259	227	30	78
Carbon monoxide	OSHA ID-209	49	37	0	100
Carbon dioxide	Method 128[b]	259	201	19	78
Total suspended particulate	NIOSH 0500	32	29	8	91
Respirable particulate	NIOSH 0600	291	115	29	40

[a] Includes "qualified" sample results.
[b] Intersociety committee standard methods.

Table 6—Accuracy and precision for smoke exposure assessment measurements

	Overall accuracy (recovery)		Overall precision (relative standard deviation)	
Pollutant	Statistically based[a]	Initial QA plan	Statistically based[b]	Initial QA plan
		Percent		
Benzene	75-119	90-110	24	30
Acrolein	60-134	70-105	30	30
Formaldehyde	65-130	80-110	43	30
Carbon monoxide[c]	93-108[d]	90-110	31	15
Carbon monoxide[e]	82-116	NA	19	NA
Carbon dioxide	98-103[d]	90-110	14	15
Respirable particulate matter	NA	NA	32	20
Total suspended particulate	NA	NA	20	NA[f]

NA = not applicable; analytical or sampling accuracy could not be measured.
[a] Estimated by using liquid method spike recoveries and incorporated into quality assurance project plan (Radian Corporation 1996).
[b] Estimated by using relative standard deviation of field replicates and incorporated into quality assurance project plan (Radian Corporation 1996).
[c] Measured by intersociety committee method 128.
[d] For analytical accuracy only; accuracy associated with sample collection and handling could not be measured.
[e] Measured by OSHA method ID-209.
[f] Analytical method implemented after the original quality assurance project plan was written.

A statistical analysis was performed on the overall set of QC sample data drawn from this project and a concurrent sampling effort using the same methods at prescribed burns (Reinhardt and others 1994). The larger set of QC data that resulted from combining the two data sets produced robust, statistically generated limits for accuracy and precision for the project team's measurements (table 6). These performance-based QC limits were incorporated into the revised quality assurance project plan

(QAPP)(Radian Corporation 1996) and used to evaluate the quality of the wildfire data reported here. The accuracy and precision targets from the initial QAPP (Radian Corporation 1993) are included in table 6 for comparison. The qualified results indicated in table 5 are considered estimated values, which may not be within the statistically based accuracy and precision listed in table 6. Pollutant identification was not affected, only quantitation. In addition, all results within a factor of four of the associated detection limit are estimated because measurement precision decreases at values near the detection limit.

Two sets of performance evaluation (PE) samples were analyzed during the project, as required by the QAPPs. Four additional sets were analyzed for acrolein and formaldehyde because of the difficulty of the method. Three of the six PE samples for acrolein and formaldehyde indicated a low bias, but corrective actions taken to identify the source—including a review of all analytical procedures, method spikes, and certified standard analyses—were inconclusive; therefore, our aldehyde results are to be considered potentially biased low by 50 percent (or a factor of two) and 66 percent (or a factor of three) for formaldehyde and acrolein, respectively. As well, all samples in which acrolein was not detected at the MDL were qualified to indicate the potential for those results to be false negative. The potential of a low bias for formaldehyde and acrolein results and falsely negative acrolein results was considered in our interpretation of the results.

Two laboratory systems audits and two field sampling audits were performed during the course of the project, as required in the QAPPs. The audit results indicated that, overall, the sampling procedures and analytical methods were producing data of sufficient quality for project use.

Pollutant Correlations

We found significant correlations among most of the pollutants. Only total suspended particulate was not well-correlated to other pollutants in smoke. Correlations with CO are especially important because of the ease of measuring CO in comparison to other pollutants. Correlations were expressed as linear regressions between pollutants. For example, figure 2 shows the regression between formaldehyde and CO exposure levels at project wildfires. Each data point represents a sample pair where both pollutants were concurrently sampled from the same firefighter or field replicate at a fire.

All the initial attack wildfires were in or adjacent to urban areas, and project wildfires were in more remote areas with little occurrence of urban pollutants. Strong correlations among the pollutants depended on their arising from a common source (the fires), yet the urban areas surely contributed to measured levels of several pollutants, such as CO. Because of this, the regression data were analyzed and applied separately for project wildfires (table 7) and initial attack wildfires (table 8) to avoid introducing variability to the project wildfire regressions arising from urban source impacts affecting only the samples from initial attack wildfires. In the absence of urban sources of pollutants, we do not expect the regressions to differ significantly between initial attack and project wildfires.

Pollutant correlations at project wildfires—Because the sample durations were usually longer at project wildfires than at initial attack wildfires, more samples from the former exceeded the MDLs. The greater number of available data pairs contributed to stronger regressions at project wildfires than those obtained at initial attack wildfires (see table 7).

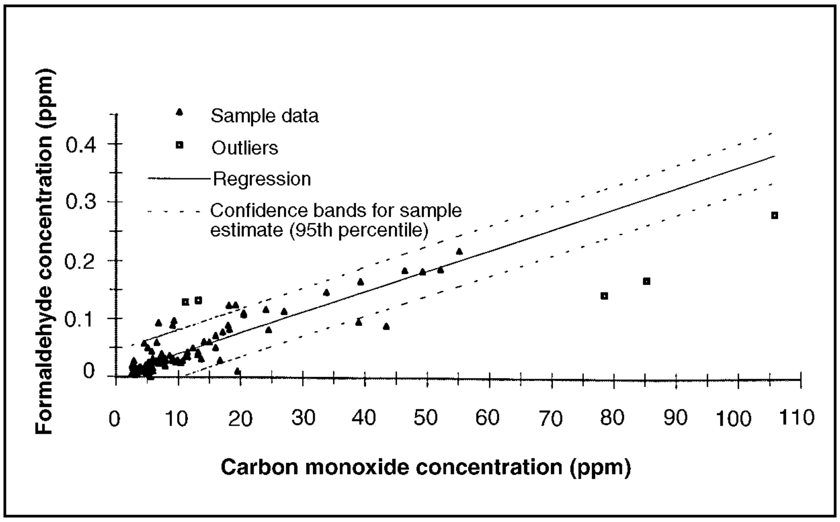

Figure 2—Correlation between formaldehyde and CO in smoke samples at project wildfires. The least squares regression between two pollutants is indicated by the solid line. For predicting formaldehyde levels at a given exposure to CO, 95 percent of the data up to 55 ppm CO will be within the error bands about regression, indicated by the dashed lines above and below the regression line.

Table 7—Interpollutant correlations in smoke samples from project wildfires

			Regression parameters (for the regression equation y=ax+b)			
Pollutants (y,x)	n[a]	r^2 [b]	a	Std.error	b	Std.error
Formaldehyde[c] vs. carbon monoxide[c]	103	0.79	3.598×10^{-3}	1.816×10^{-4}	3.920×10^{-3}	2.911×10^{-3}
PM3.5[d] vs. carbon monoxide	25	.79	4.980×10^{-2}	5.346×10^{-3}	8.135×10^{-1}	1.727×10^{-1}
Benzene[c] vs. carbon monoxide	54	.91	1.089×10^{-3}	4.667×10^{-5}	3.399×10^{-3}	1.085×10^{-3}
Acrolein[c] vs. carbon monoxide	41	.68	4.200×10^{-4}	4.638×10^{-5}	3.260×10^{-3}	1.350×10^{-3}
PM3.5 vs. formaldehyde	31	.68	18.19×10^{0}	2.317×10^{0}	1.705×10^{-1}	2.293×10^{-1}
Benzene vs. formaldehyde	62	.70	2.221×10^{-1}	1.869×10^{-2}	6.698×10^{-3}	1.284×10^{-3}
Acrolein vs. formaldehyde	58	.81	1.841×10^{-1}	1.207×10^{-2}	-1.336×10^{-3}	1.005×10^{-3}
Acrolein vs. PM3.5	14	.49	7.346×10^{-3}	2.184×10^{-3}	2.62×10^{-4}	5.999×10^{-3}

[a] n = number of pairs of samples.
[b] r^2 = coefficient of determination.
[c] Units in ppm.
[d] Units in mg/m^3.

Table 8—Interpollutant correlations for initial attack wildfires

			Regression parameters (for the regression equation y=ax+b)			
Pollutants (y,x)	n[a]	r^{2b}	a	Std.error	b	Std.error
Formaldehyde[c] vs. carbon monoxide[c]	39	0.59	5.638×10^{-3}	7.606×10^{-4}	-1.463×10^{-2}	1.406×10^{-2}
PM 3.5[d] vs. carbon monoxide	16	.46	9.909×10^{-2}	2.852×10^{-2}	6.883×10^{-1}	5.854×10^{-1}
Benzene[c] vs. carbon monoxide	19	.44	1.275×10^{-3}	3.515×10^{-4}	1.199×10^{-2}	7.789×10^{-3}
Acrolein[c] vs. carbon monoxide	20	.53	1.192×10^{-3}	2.626×10^{-4}	6.465×10^{-3}	5.812×10^{-3}
PM 3.5 vs. formaldehyde	14	.79	23.35×10^{0}	3.473×10^{0}	2.889×10^{-1}	4.163×10^{-1}
Acrolein vs. formaldehyde	13	0.82	1.889×10^{-1}	2.654×10^{-2}	7.336×10^{-3}	4.414×10^{-3}

[a]n = number of samples.
[b]r^2 = coefficient of determination.
[c]Units of ppm.
[d]Units of mg/m^3.

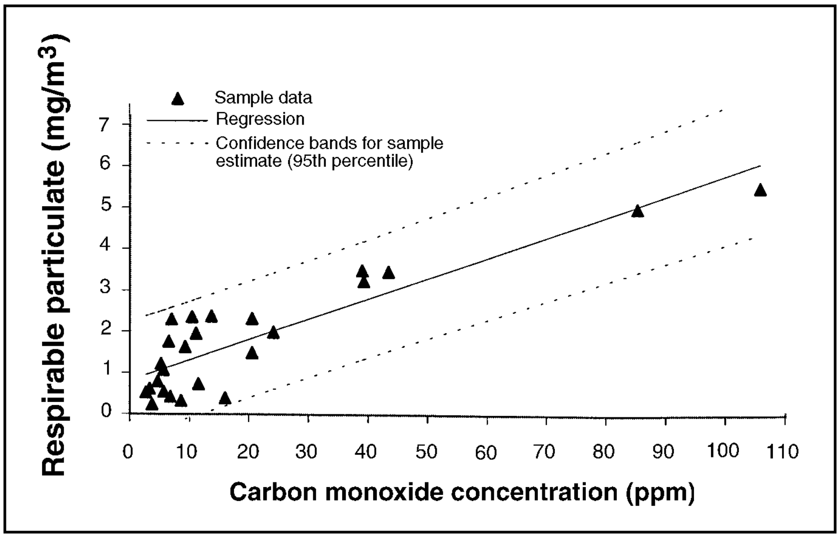

Figure 3—Correlation between respirable particulates and CO in smoke samples at project wildfires.

Figure 3 shows the correlation between PM3.5 and CO exposure among firefighters at project wildfires. As shown in table 5, many data pairs were eliminated from the regression because nonrespirable particulates invalidated the PM3.5 samples.

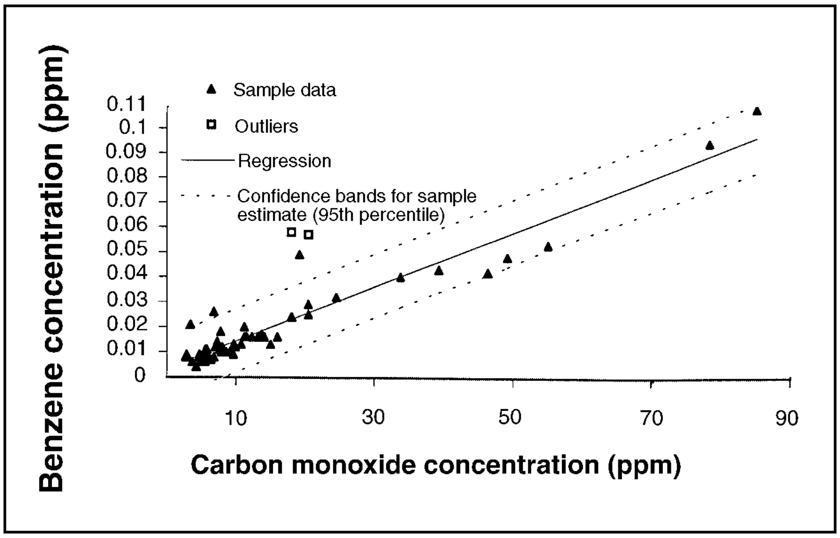

Figure 4—Correlation between benzene and CO in smoke samples at project wildfires.

The correlation of benzene and CO is shown in figure 4. The large number of sample pairs strengthens the association shown between these pollutants.

Pollutant correlations at initial attack wildfires—The strength of the interpollutant regressions was generally lower at initial attack wildfires than at project wildfires. The correlation between benzene and CO was especially low at these fires, which might be expected in an urbanized area because these contain many other sources of CO and benzene that could impact the samples. The few data pairs that met the detection limit criteria showed inadequate correlation to develop useful regressions between benzene and formaldehyde and between acrolein and PM3.5 (see table 8).

Figure 5 shows the correlation between acrolein and CO samples obtained at initial attack wildfires.

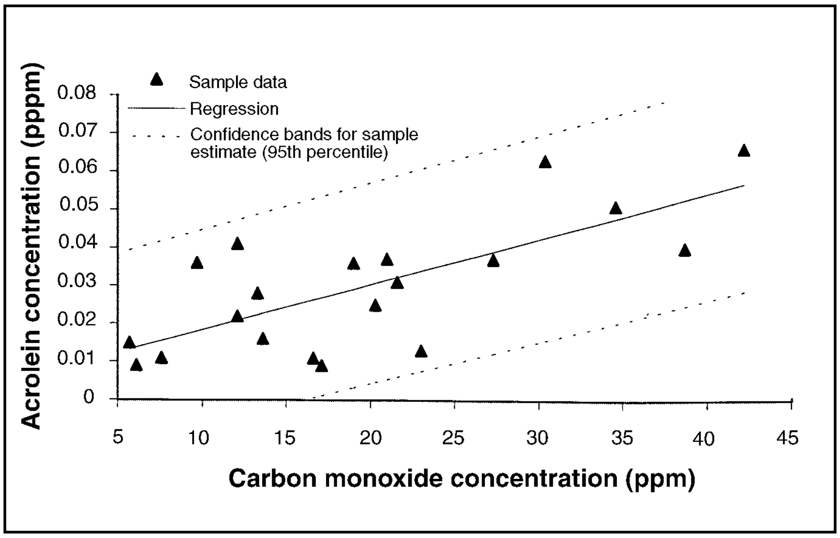

Figure 5—Correlation between acrolein and CO in smoke samples at initial attack wildfires.

Exposure Assessment for Project Wildfires

Time-weighted average exposures were calculated for 84 firefighters at project wildfires, including Forest Service type I (hotshot) crews, type II hand crews from multiple agencies, and three wildland engine crews. Average exposures to smoke for the time that firefighters were at the fire (fire TWA) and for their entire work shift (shift TWA) were calculated from equation (5). The shift TWAs may include time spent in clean, ambient air while in transit between fire camp and fireline, but this usually makes up a relatively small proportion of the day at a project wildfire, whereas it can comprise most of the day among initial attack forces.

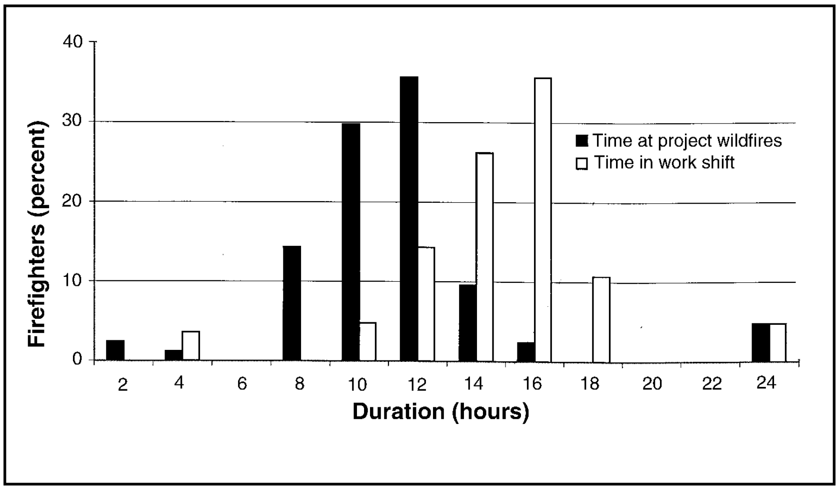

Figure 6—Distribution of work shift duration and time at project wildfires for firefighters.

Work shift durations averaged 13.9 hours for crews on project wildfires; of this, time on the fireline averaged 10.4 hours. Figure 6 shows the distribution of fireline and work shift durations for the crews at project wildfires. Cumulative frequency distributions summarizing the individual TWAs are presented in the following sections.

Acrolein—Acrolein exposure averaged 0.002 ppm on the fireline at project wildfires and 0.001 ppm over the total work shift. The highest TWA acrolein exposure was 0.016 ppm on the fireline and 0.015 ppm over a work shift. The geometric standard

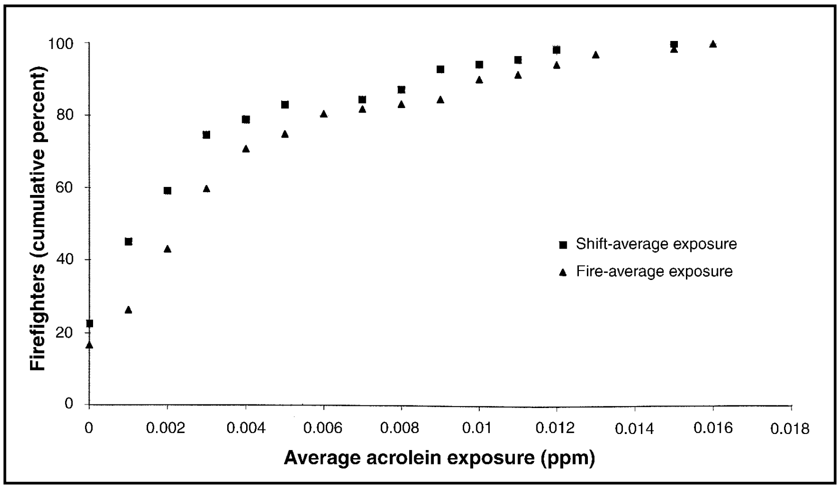

Figure 7—Distribution of shift- and fireline-average acrolein exposure among firefighters at project wildfires.

deviation of the fireline and work shift TWA exposures indicate highly variable exposures at 3.6 and 4, respectively. Figure 7 shows the cumulative frequency distribution of acrolein exposures. Compare these values with the acrolein PEL and TLV of 0.1 ppm.

Benzene—Exposure to benzene averaged 0.006 ppm on the fireline and 0.004 ppm over the work shifts. The highest TWA benzene exposure was 0.249 ppm over the work shift and 0.384 ppm on the fireline. The geometric standard deviation of the TWA exposures of the firefighters for both fire and shift was 3.6. Figure 8 shows the cumulative frequency distribution of benzene exposures for project wildfire crews. Compare these data with the benzene PEL of 1 ppm and the TLV of 0.5 ppm.

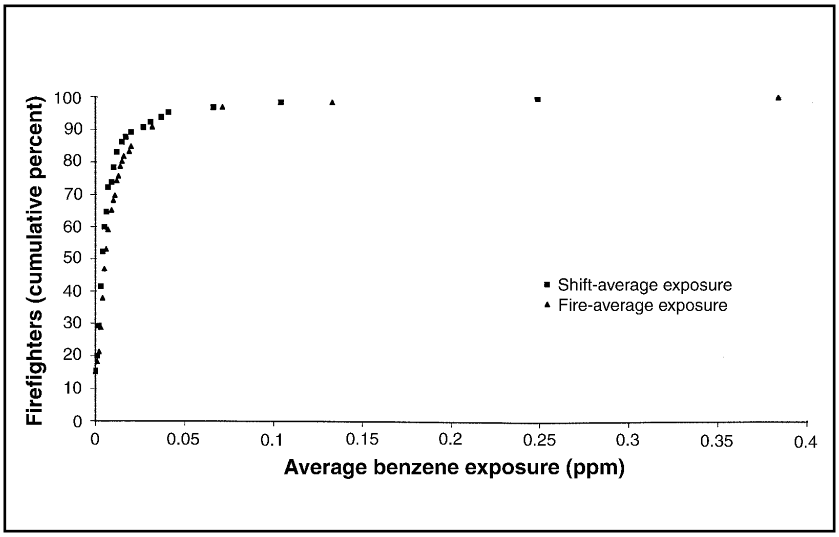

Figure 8—Distribution of shift- and fireline-average benzene exposure among firefighters at project wildfires.

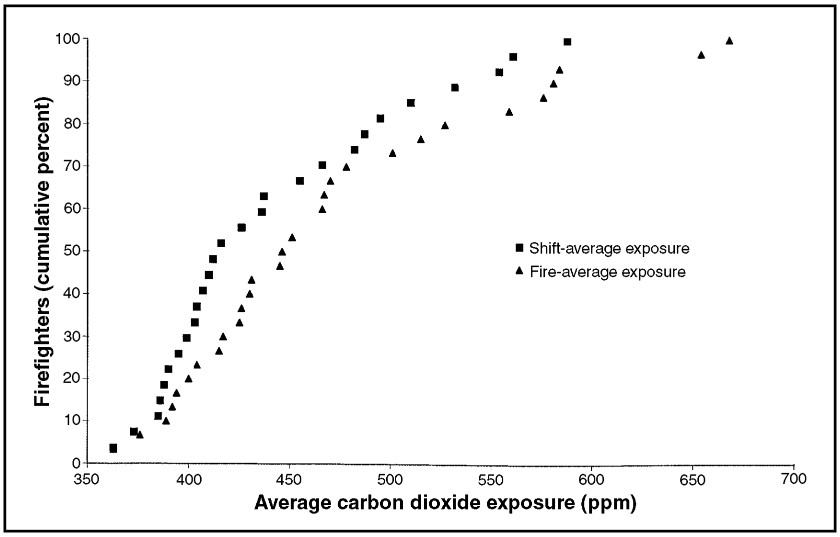

Figure 9—Distribution of shift- and fireline-average CO_2 exposure among firefighters at project wildfires.

Carbon dioxide—Carbon dioxide levels in the firefighters' breathing zones averaged 439 ppm over a work shift and 465 ppm at the project wildfires. The highest CO_2 levels averaged 588 ppm and 668 ppm on the work shift and fireline, respectively. The geometric standard deviation of the shift and fireline TWAs indicated very consistent CO_2 TWAs at 1.1 and 1.2, respectively. Some of the CO_2 measured might have been exhaled breath (CO_2 is a product of normal human metabolism) rather than smoke from the fires. Figure 9 shows the distributions of CO_2 exposure at project wildfires. Compare these data with the PEL and TLV of 5,000 ppm.

Carbon monoxide—Exposure to CO among crews at project wildfires averaged 2.8 ppm over the work shift and 4.0 ppm on the firelines. The maximum TWA exposure to CO was 30.5 ppm over the work shift and 38.8 ppm on the fireline. Geometric standard deviations were 2.5 and 2.6 for fireline and work shift TWAs, respectively. The distributions of shift and fire TWA CO exposures among firefighters are shown in figure 10. Compare these data with the PEL of 50 ppm and the TLV of 25 ppm.

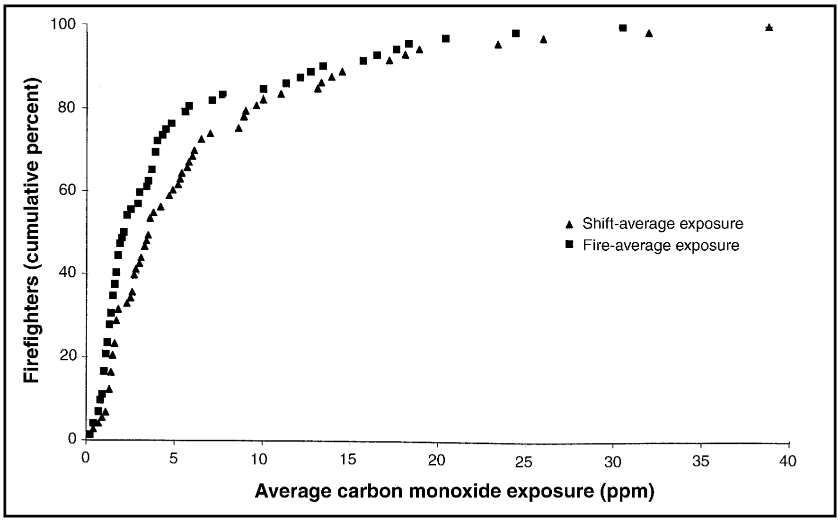

Figure 10—Distribution of shift- and fireline-average CO exposure among firefighters at project wildfires.

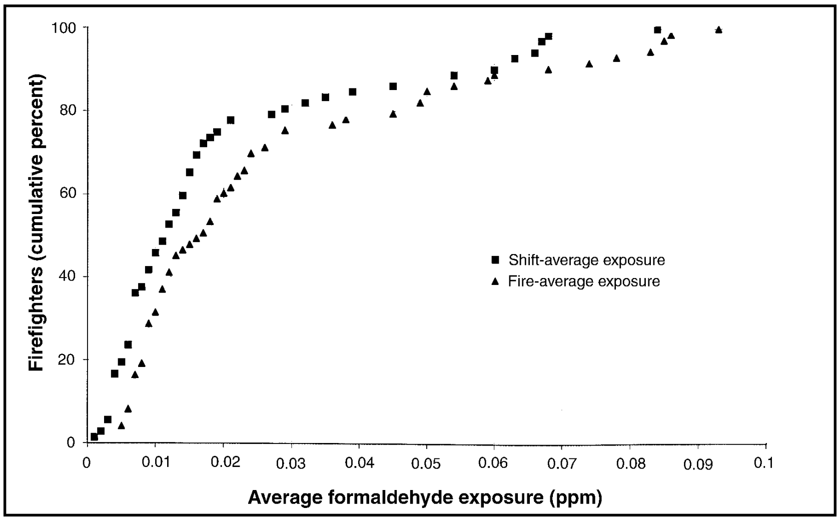

Figure 11—Distribution of shift- and fireline-average formaldehyde exposure among firefighters at project wildfires.

Formaldehyde—Exposure to formaldehyde averaged 0.018 ppm on the fireline at the project wildfires and 0.013 ppm over the work shifts. The maximum exposure was 0.093 ppm on the fire and 0.084 ppm over the work shift. The geometric standard deviations for the TWAs were 2.3 and 2.4 for fireline and work shift exposures, respectively. Figure 11 shows the distributions of shift and fire TWA exposures to formaldehyde at the project wildfires. Compare these data with the PEL of 0.75 ppm and the TLV of 0.3 ppm.

Respirable particulate—Exposure to PM3.5 among firefighters averaged 0.5 milligram per cubic meter (mg/m^3) over the work shifts and 0.72 mg/m^3 on the fireline at project wildfires, with corresponding maximum exposures of 2.93 and 2.3 mg/m^3. Geometric standard deviation of the work shift TWAs was 2.0 and 1.9 for the fireline TWAs. Figure 12 shows the cumulative frequency distributions for PM3.5 exposure among the firefighters. Compare these data with the PEL of 5 mg/m^3 and the TLV of 3 mg/m^3.

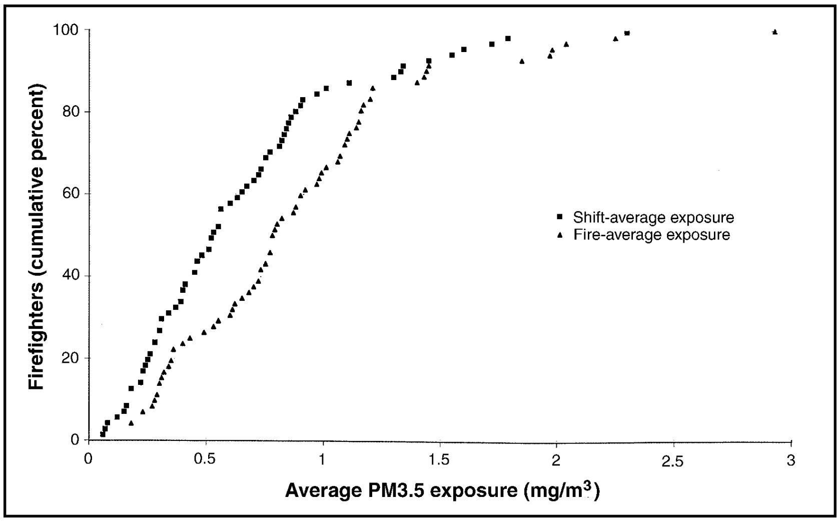

Figure 12—Distribution of shift- and fireline-average respirable particulate exposure among firefighters at project wildfires.

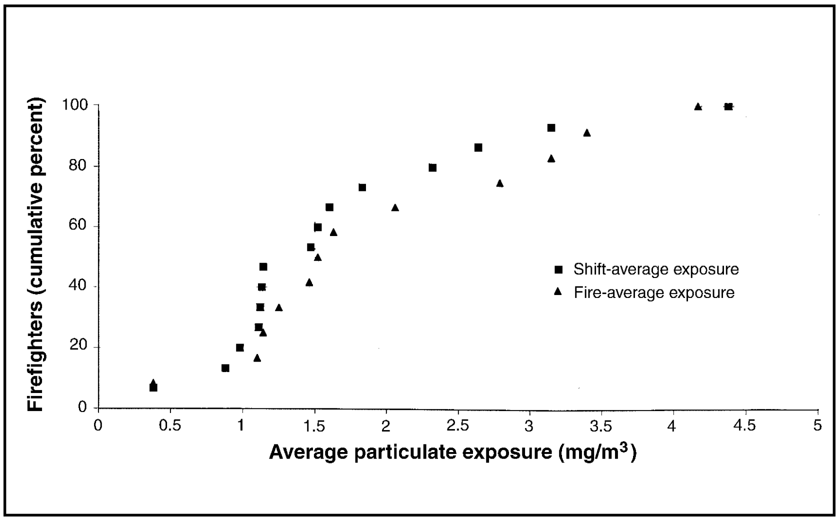

Figure 13—Distribution of shift- and fireline-average total suspended particulate exposure among firefighters at project wildfires.

Total suspended particulate—Exposure to total suspended particulate matter averaged 1.72 mg/m^3 on the fireline at project wildfires and 1.47 mg/m^3 over the work shift. The maximum TWA exposures to total suspended particulate were 4.17 mg/m^3 on the fireline and 4.38 mg/m^3 over a work shift. The geometric standard deviation of the TWAs was 1.8 for the fireline TWAs and 1.7 for the work shift TWAs. Few data are available because total suspended particulate exposure data were not collected until the 1995 fire season. Figure 13 summarizes the particulate matter exposure data. Compare these data with the PEL of 15 mg/m^3.

Respiratory irritants—Exposure to the combination of respiratory irritants (acrolein, formaldehyde, and PM3.5) was calculated according to equation (1). Using OSHA PELs as the divisors in this equation, we calculated that exposure among firefighters averaged 0.1 during the work shift and 0.1 on the fires. Maximum irritant exposures were 0.6 for the work shift and 0.8 on the fireline. Geometric standard deviations were 2.1 (work shift) and 2.0 (fireline). Figure 14 shows the distribution of the TWA exposure data, where the irritant mixture calculations are from the OSHA PELs. The data may be compared with the limit of 1.0 for the ratio, E_m.

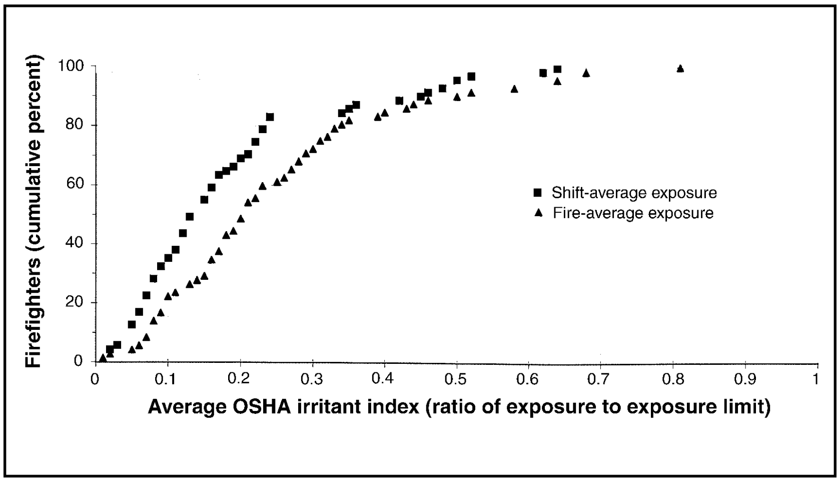

Figure 14—Distribution of shift- and fireline-average respiratory irritant exposure among firefighters at project wildfires (OSHA based).

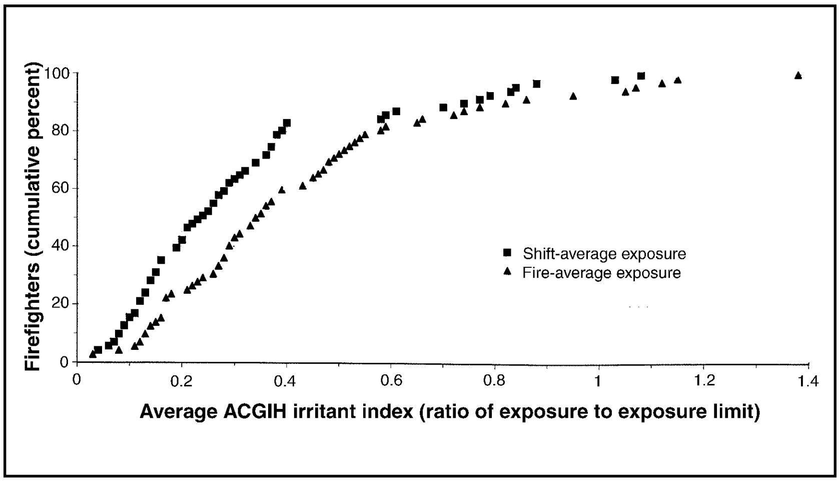

Figure 15—Distribution of shift- and fireline-average respiratory irritant exposure among firefighters at project wildfires (ACGIH based).

Using the recommended ACGIH TLVs as the exposure limits in equation (1) results in a larger value for the irritant index than is calculated from the OSHA PELs. With the TLVs as the basis for calculating E_m, exposure to respiratory irritants averaged 0.3 (with a maximum of 1.4) on the firelines and 0.2 (maximum of 1.1) over the work shift. Figure 15 shows the resulting exposure distribution for the project wildfires. Again, the limit of 1.0 for the ratio, E_m, is the standard against which to evaluate the data.

Exposure Assessment for Initial Attack Wildfires

Firefighters involved in initial attack suppression efforts included CDF wildland engine crews and Forest Service hotshot crews. Average exposures to smoke were calculated for the fire TWA and the shift TWA. The shift TWAs included time spent in clean, ambient air while performing other nonfire duties. This relatively large proportion of the day was the reason that the initial attack wildfire smoke exposure data were analyzed separately from the project wildfire data.

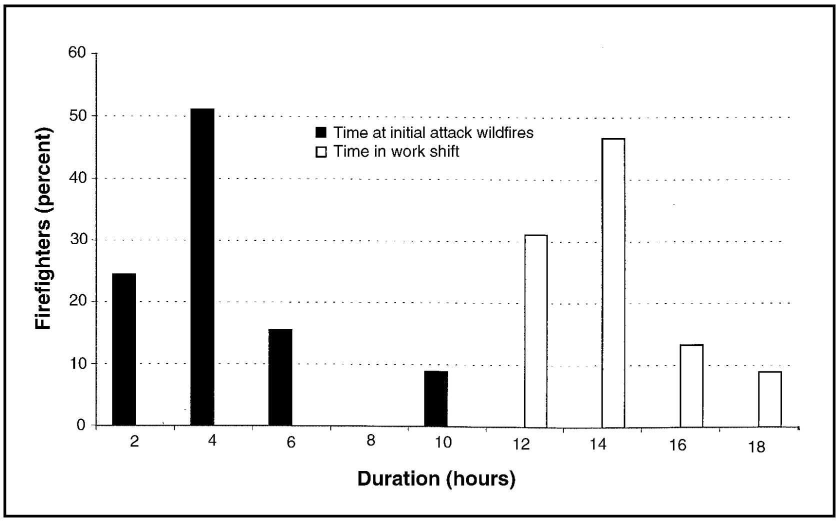

Figure 16—Distribution of time on the fireline at initial attack wildfires and work shift durations for firefighters.

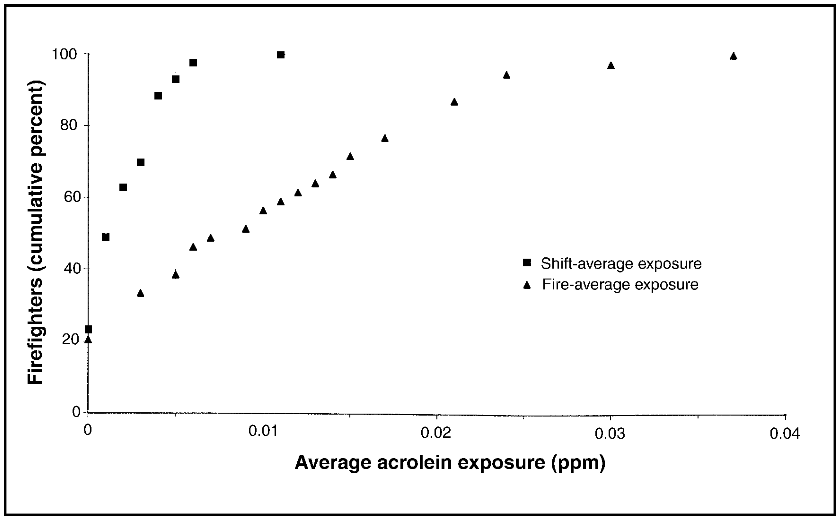

Figure 17—Distribution of shift- and fireline-average acrolein exposure among firefighters at initial attack wildfires.

On days when at least one initial attack event occurred, work shifts averaged 13.3 hours for initial attack crews, and time on the fireline averaged 3.3 hours. Figure 16 shows the distribution of time on the fireline at initial attack wildfires and work shift duration for firefighters.

Acrolein—Acrolein exposure averaged 0.005 ppm (maximum of 0.037 ppm) during initial attack operations, and 0.001 ppm (maximum of 0.011) over a work shift. The geometric standard deviation for both TWA distributions was 4, indicating highly variable exposures. Figure 17 shows the cumulative frequency distributions of acrolein exposures. Compare these data with the PEL and TLV of 0.1 ppm.

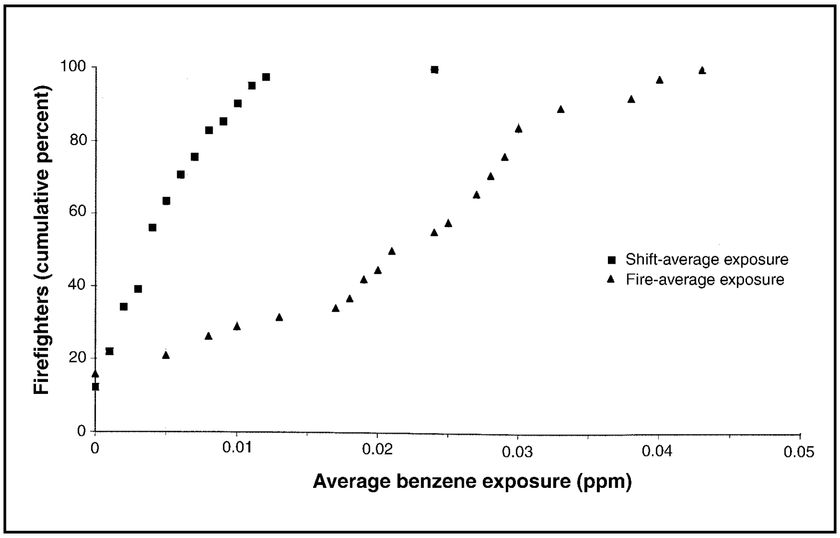

Figure 18—Distribution of shift- and fireline-average benzene exposure among firefighters at initial attack wildfires.

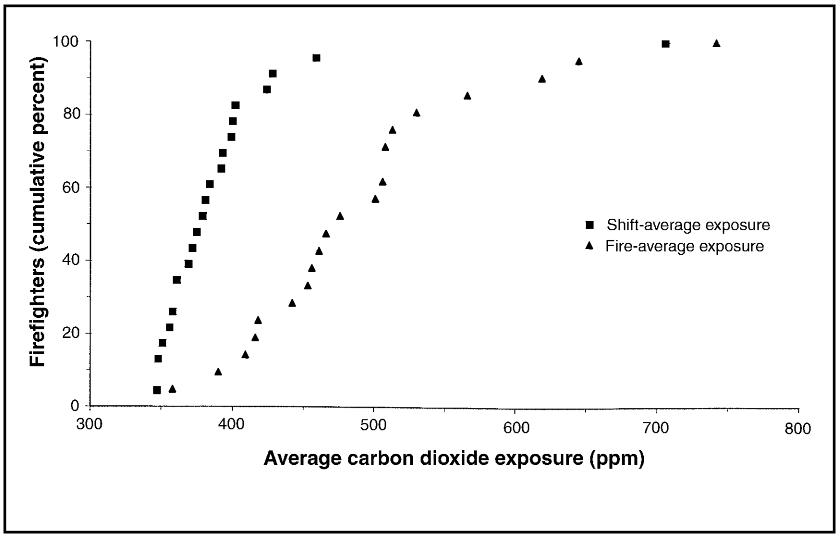

Figure 19—Distribution of shift- and fireline-average CO_2 exposure among firefighters at initial attack wildfires.

Benzene—Exposure to benzene averaged 0.014 ppm on the fireline and 0.003 over the work shifts. The corresponding maximum exposures were 0.043 and 0.024 ppm. Geometric standard deviations were 3.2 for the fireline TWAs and 3.3 for the work shift TWAs. Figure 18 shows the cumulative frequency distributions of benzene exposure among initial attack crews. Compare these data with the PEL of 1.0 ppm and the TLV of 0.5 ppm.

Carbon dioxide—Carbon dioxide levels in the firefighters' breathing zones averaged 391 ppm over a work shift (maximum of 706 ppm) and 488 ppm (maximum of 742 ppm) at the initial attack wildfires. The corresponding geometric standard deviations were both 1.2. These results are limited to CDF engine crews because CO_2 monitoring was not done in 1995. Figure 19 shows the distributions of CO_2 exposure among firefighters at initial attack wildfires. These data can be compared with the PEL and TLV of 5,000 ppm.

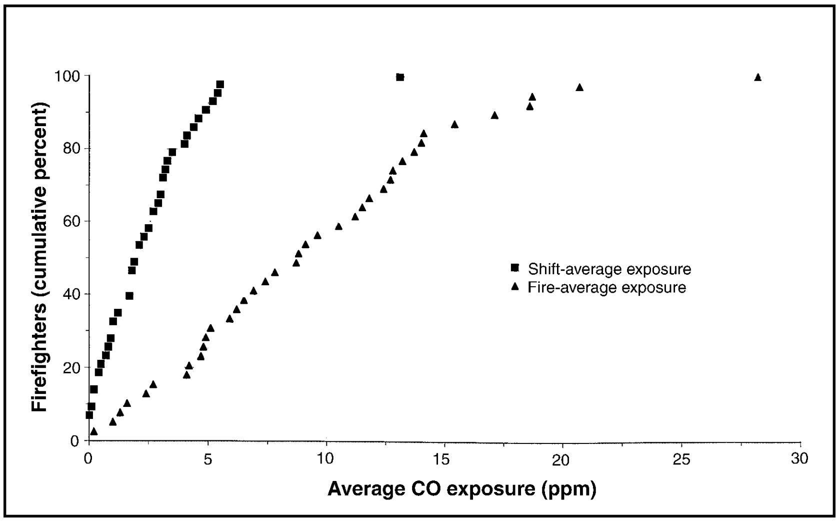

Figure 20—Distribution of shift- and fireline-average exposure to CO among firefighters at initial attack wildfires.

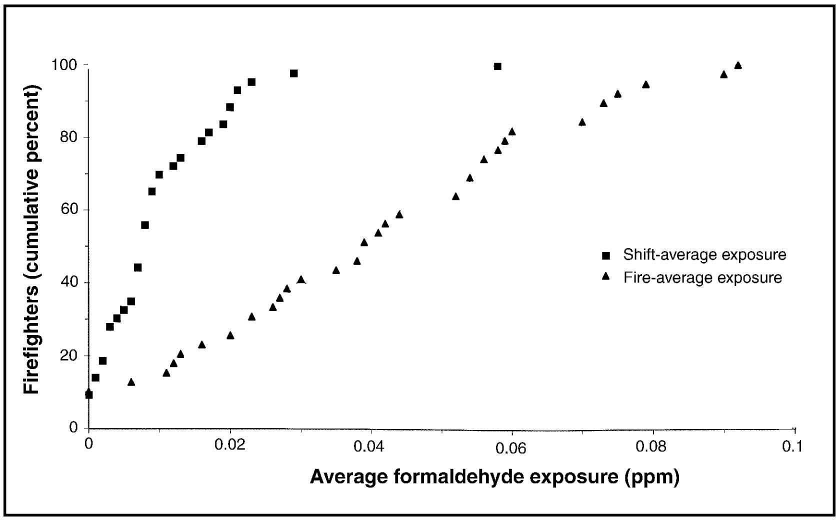

Figure 21—Distribution of shift- and fireline-average exposure to formaldehyde among firefighters at initial attack wildfires.

Carbon monoxide—Exposure to CO averaged 1.6 ppm (maximum of 13.1 ppm) during the work shift among initial attack crews and 7.4 ppm (maximum of 28.2 ppm) at the fires. Geometric standard deviations were 3.0 (work shift) and 2.2 (fireline). The distributions of shift and fire TWA CO exposures among firefighters are shown in figure 20. These data can be compared with the PEL of 50 ppm and the TLV of 25 ppm.

Formaldehyde—Exposure to formaldehyde averaged 0.028 ppm (maximum of 0.092 ppm) at the initial attack wildfires and 0.006 (maximum of 0.058) ppm over the work shifts. The corresponding geometric standard deviations were 3.0 and 3.1. Figure 21 shows the distribution of shift and fire TWA exposures to formaldehyde at the initial attack wildfires. These data can be compared with the PEL of 0.75 ppm and the TLV of 0.3 ppm.

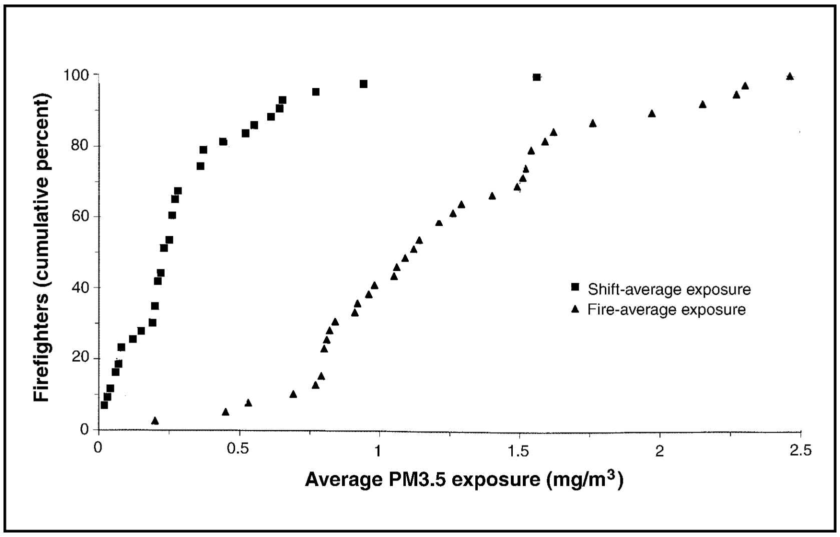

Figure 22—Distribution of shift- and fireline-average exposure to respirable particulates among firefighters at initial attack wildfires.

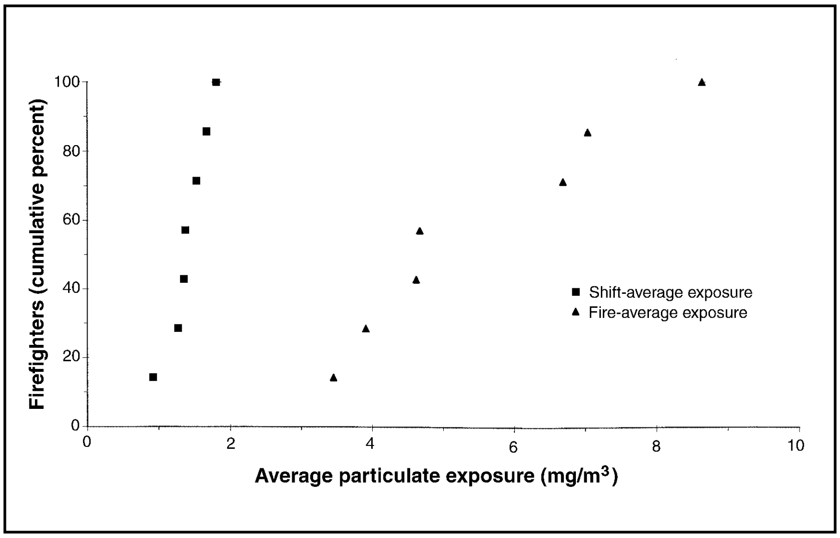

Figure 23—Distribution of shift- and fireline-average exposure to total suspended particulates among firefighters at initial attack wildfires.

Respirable particulate—Exposure to PM3.5 among firefighters averaged 0.022 mg/m^3 over the work shifts and 1.11 mg/m^3 on the fireline at the initial attack wildfires. Maximum TWA exposures were 1.56 mg/m^3 over the work shift and 2.46 mg/m^3 on the fireline. The corresponding geometric standard deviations were 2.5 and 1.6. Figure 22 shows the cumulative frequency distributions for PM3.5 exposure among the initial attack firefighters at wildfires. Compare these data with the PEL of 5 mg/m^3 and the TLV of 3 mg/m^3.

Total suspended particulate—Exposure to total suspended particulate matter averaged 5.32 mg/m^3 (with a maximum of 8.64 mg/m^3) at initial attack wildfires and 1.39 mg/m^3 (maximum of 1.81 mg/m^3) over the work shift, based on only seven data points from Forest Service hotshot firefighters. Data on total suspended particulate exposure were not collected until the 1995 fire season, during which no CDF engine crews were among those monitored. Geometric standard deviations were 1.4 for the fireline TWAs and 1.2 for the work shift TWAs. Figure 23 summarizes the exposure data for the hotshot crews. Compare these data with the PEL of 15 mg/m^3.

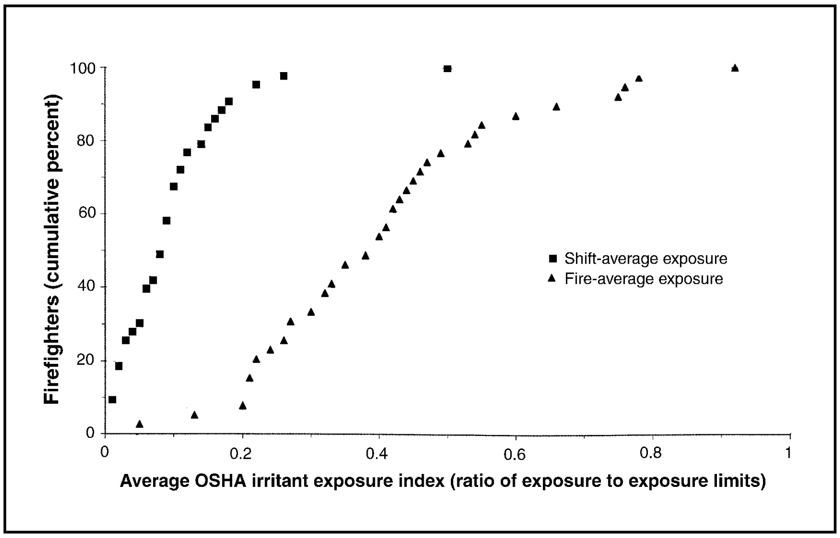

Figure 24—Distribution of shift- and fireline-average respiratory irritants exposure among firefighters at initial attack wildfires (OSHA based).

Respiratory irritants—Exposure to the combination of respiratory irritants (acrolein, formaldehyde, and PM3.5) was calculated according to equation (1). Using OSHA PELs as the divisors in this equation, we calculated that exposure among initial attack firefighters at wildfires averaged 0.1 (maximum of 0.5) during the work shift and 0.4 (maximum of 0.9) at the fires. The corresponding geometric standard deviations were 2.4 and 1.6. Figure 24 shows the exposure data at the initial attack wildfires. Compare these data with the OSHA PEL of 1.0 for the ratio, E_m.

Using the recommended TLVs as the exposure limits in equation (1) resulted in a higher irritant index. With the TLVs as the basis for calculating E_m, exposure to respiratory irritants averaged 0.6 (maximum of 1.4) at the initial attack wildfires and 0.1 (maximum of 0.8) over the work shift. Figure 25 shows the distribution of TWA irritant exposures among initial attack wildfire fighters. Compare these data with the TLV of 1.0 for the ratio, E_m.

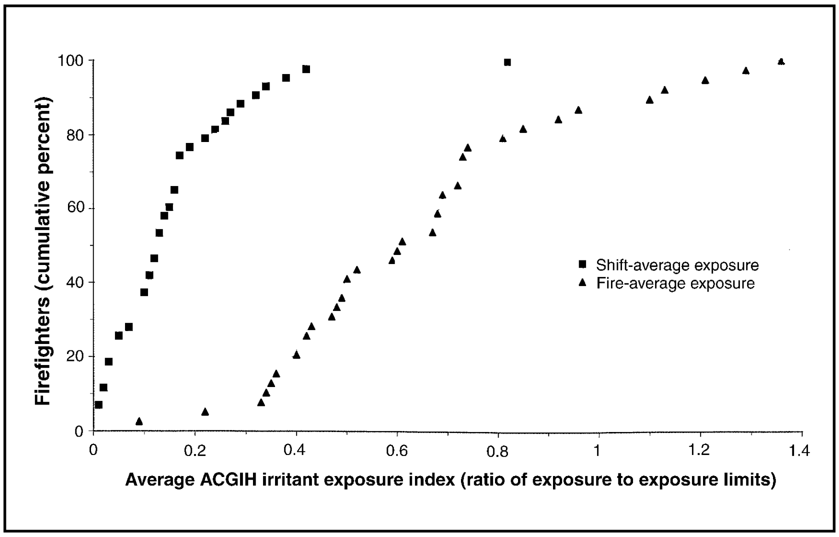

Figure 25—Distribution of shift- and fireline-average exposure to respiratory irritants among firefighters at initial attack wildfires (ACGIH based).

Table 9—Peak carbon monoxide exposures for 1994-95 wildfires

Fire number	Fire type	Time period	Carbon monoxide	Fire number	Fire type	Time period	Carbon monoxide
			Ppm				*Ppm*
59	Initial attack	16:49-17:03	8.1	61	Project	17:22-17:36	77.1
59	Initial attack	17:01-17:15	3.1	62	Project	14:31-14:45	15.9
60	Initial attack	16:53-17:07	23.1	62	Project	14:31-14:45	18.4
60	Initial attack	16:53-17:07	18.5	62	Project	13:21-13:35	23.9
60	Initial attack	16:55-17:09	18.2	64	Project	14:16-14:30	15.5
66	Initial attack	14:06-14:20	39.5	64	Project	14:13-14:27	26.3
66	Initial attack	14:12-14:26	48.6	64	Project	14:12-14:26	30.3
66	Initial attack	14:24-14:38	47.5	65	Project	13:58-14:12	4.9
66	Initial attack	14:23-14:37	39.3	65	Project	14:00-14:14	5.4
70	Initial attack	17:55-18:09	47.1	65	Project	14:00-14:14	5.3
70	Initial attack	17:36-17:50	25.6	65	Project	14:11-14:25	1.4
70	Initial attack	17:29-17:43	11.1	67	Project	16:36-16:50	3.1
70	Initial attack	17:39-17:53	14.9	67	Project	16:22-16:36	2.7
55	Project	10:28-10:42	1.5	67	Project	16:37-16:51	4.1
56	Project	09:51-10:05	31.1	67	Project	16:24-16:38	2.3
56	Project	17:20-17:34	40.7	68	Project	18:51-19:05	12.7
56	Project	14:38-14:52	15.8	68	Project	17:44-17:58	19.5
57	Project	09:39-09:53	11.9	68	Project	18:53-19:07	5.7
57	Project	10:27-10:41	22.8	69	Project	12:43-12:57	10.1
61	Project	17:55-18:09	103.3	69	Project	14:41-14:55	16.9

Table 10—Peak exposure samples from project wildfires

Fire no.	Duration	Job task	Carbon monoxide	Formal-dehyde	Acrolein	Benzene	PM3.5	E_m
	Minutes			*Ppm*			*Mg/m³*	
57	19	Attack	NA	0.142	0.03	0.052	NA	NA
57	16	Attack	17.1	.077	0	.058	NA	NA
61	20	Hold/mop	105.8	.282	.072	NA	5.5	1.8
64	10	Lighting	NA	.084	0	.077	1.8	.5

NA = not available.

Table 11—Peak exposure samples from initial attack wildfires

Fire no.	Duration	Work activity	Carbon monoxide	Carbon dioxide	Formal-dehyde	Acrolein	Benzene	PM3.5	E_m
	Minutes				*Ppm*			*Mg/m³*	
43	16	Attack	14.3	640	0.16	0	0.038	3.17	0.9
43	13	Attack	16.3	532	.04	0	.036	1.26	.3
43	20	Attack	22.1	559	.136	.013	.022	NA	NA
43	19	Attack	30.4	778	.181	.063	.024	NA	NA
46	18	Attack	15.1	583	.038	.009	.019	NA	NA
46	19	Attack	NA	NA	.033	.007	NA	0.88	0.2
46	15	Attack	6.7	548	NA	NA	NA	1.14	NA
46	19	Attack	1.4	496	.031	.009	.022	.91	.2
47	16	Attack	NA	NA	.153	.044	.041	3.05	1
47	13	Engine	NA	NA	.16	.041	.041	2.93	1
47	17	Attack	38.7	1011	.168	.04	.079	5.4	1.3
50	15	Attack	21	759	.189	.037	.032	NA	NA
50	13	Attack	42.2	836	.339	.066	.061	NA	NA
50	18	Engine	34.6	888	.236	.051	.045	6.88	1.7
58	16	Attack	5.2	473	.073	0	.027	NA	NA
58	20	Attack	8.4	863	.217	0	0	2.14	1
58	20	Attack	8.4	1265	.044	0	.022	NA	NA
60	13	Mobile attack	4.7	450	.085	0	0	2.43	.6
60	15	Mobile attack	17.3	491	.032	0	.038	NA	NA
60	16	Mobile attack	10.6	501	.071	0	.082	2.54	.5
60	16	Mobile attack	22.4	467	.05	0	.036	NA	NA

NA = not available.

Peak Smoke Exposure Assessment

Carbon monoxide dosimeters facilitated measuring peak smoke exposures because they recorded data continuously; peak exposure events are easily extracted from the continuous record of exposure. Table 9 shows the peak CO exposure data from each dosimeter record in 1994 and 1995. Data from 1992 and 1993 were not used because of measurement bias, a problem resolved by improving the QA protocol for the instruments in 1994 and 1995. Each observation is the highest 15-minute CO average from the firefighter's work shift. A few peak exposures included periods where the CO levels were briefly above 200 ppm. An overall lognormal mean of 13.7 ppm was calculated for the 40 samples, which had a geometric standard deviation of 2.9.

Project wildfires—Only a few peak exposure samples were collected with the sampling pumps at project wildfires. Many more transient peak exposure situations were observed but could not be sampled. Capturing data during peak exposure periods by using a few observers and traditional sampling methods was much more difficult than using the data loggers because timing and logistics were critical to success. Table 10 lists the results from peak exposure sampling during relatively smoky conditions at the given project fire. The equivalent irritant exposure index (E_m) was calculated from equation (1) and the recommended TLVs: 0.3 ppm formaldehyde, 0.3 ppm acrolein, and an excursion limit[3] for PM3.5 of three times the TLV of 3.0 mg/m^3 (American Conference of Governmental Industrial Hygienists 1996).

Initial attack wildfires—More peak exposure samples were collected at initial attack wildfires because the sampling plan called for short-term sample durations to capture brief but intense exposures during the initial attack. Table 11 lists the peak exposure samples obtained during the smokiest conditions observed at the initial attack wildfires. The irritant exposure index (E_m) was calculated as described above for project wildfires.

Factors Influencing Smoke Exposure

Job task—Table 12 lists the geometric mean exposures during each major job task at project wildfires. The duration of most samples was 1 to 2 hours. Because few samples were obtained during some work activities, the means may not be truly representative of exposure during that activity. Refer to the number of samples (n) in the tables to evaluate the significance of the means.

Table 12—Average smoke exposure by job task at project wildfires

	Carbon monoxide		Carbon dioxide		Benzene		Formaldehyde		Acrolein		PM3.5		Total suspended particulate	
Job task	$\bar{x}_G$[a]	n[b]	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n
	Ppm		*Ppm*		*Ppm*		*Ppm*		*Ppm*		*Mg/m^3*		*Mg/m^3*	
Direct attack	5.6	9	477	9	0.018	12	0.039	11	0.002	11	0.51	3	NA	0
Crew boss	7.0	5	612	5	.010	4	.019	6	0	6	NA	0	NA	0
Dig and attack	5.8	5	400	2	.000	2	.023	5	0	3	NA	0	12.00	4
Digging line	3.9	21	472	21	.004	22	.022	21	.001	11	.99	7	NA	0
Engine operator	13.7	2	586	2	.130	3	.079	3	.009	3	.42	1	NA	0
Gridding	4.8	11	452	11	.004	12	.015	14	.002	9	.50	4	NA	0
Hold and mop-up	45.1	7	750	7	.058	5	.098	9	.017	9	.71	5	NA	0
Holding	3.2	15	465	10	.005	12	.015	17	0	12	3.75	10	1.43	4
Lighting	8.7	6	569	6	.071	5	.094	8	.004	8	.34	6	NA	0
Mop-up	4.4	52	477	46	.004	44	.022	54	0	33	1.84	24	4.33	9
Sawyer	4.2	13	469	13	.021	9	.031	9	.001	3	.65	5	NA	0
Swamper	3.7	3	469	3	.015	3	.027	3	.002	3	.67	1	6.44	1

NA = not available.
[a]$\bar{x}_G$ = geometric mean.
[b]n = number of samples.

[3] An excursion limit is a short-term exposure limit for pollutants not having an otherwise-defined STEL or ceiling limit.

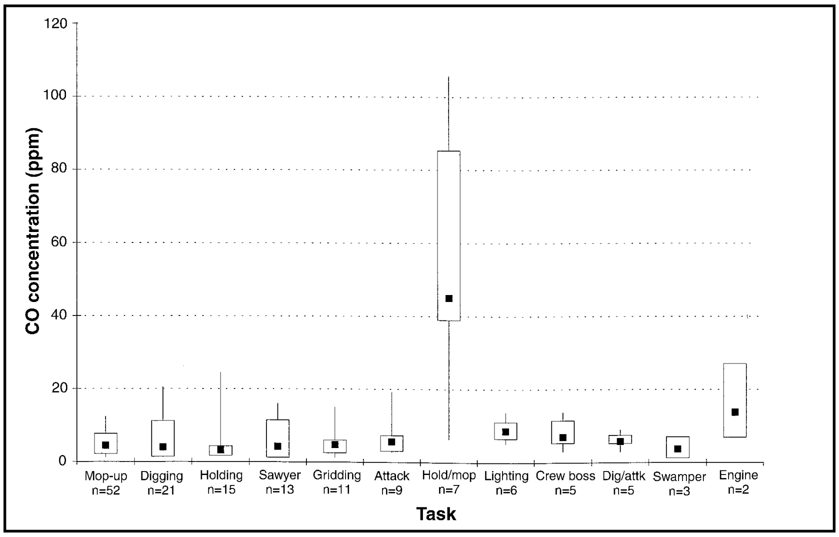

Figure 26—Distribution of CO exposure among firefighters by job task at project wildfires. The "box and whisker" plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers" represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

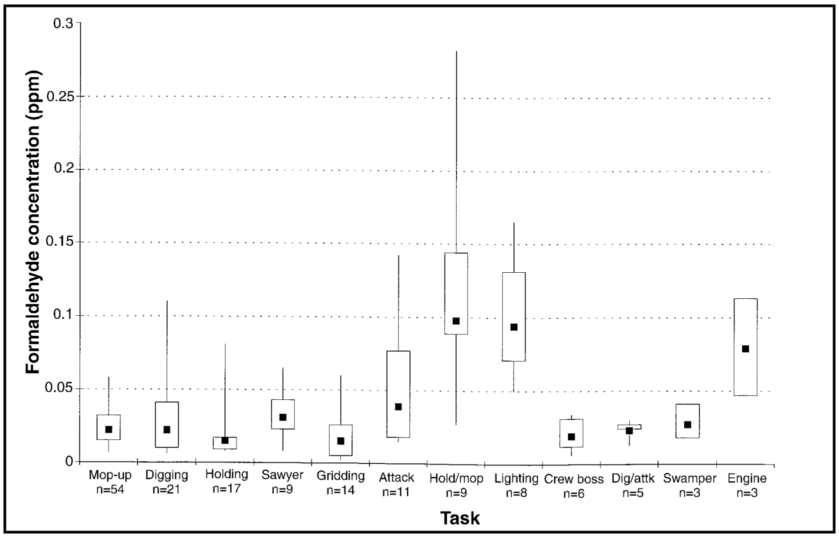

Figure 27—Distribution of formaldehyde exposure among firefighters by job task at project wildfires. The "box and whisker"plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers"represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

Figure 26 compares the distribution of CO exposures for workers during each job task at project wildfires. The statistics were calculated on the logarithmically transformed data, but these graphs show the data in original units. Figure 27 shows the distribution of formaldehyde exposures by job task at project wildfires.

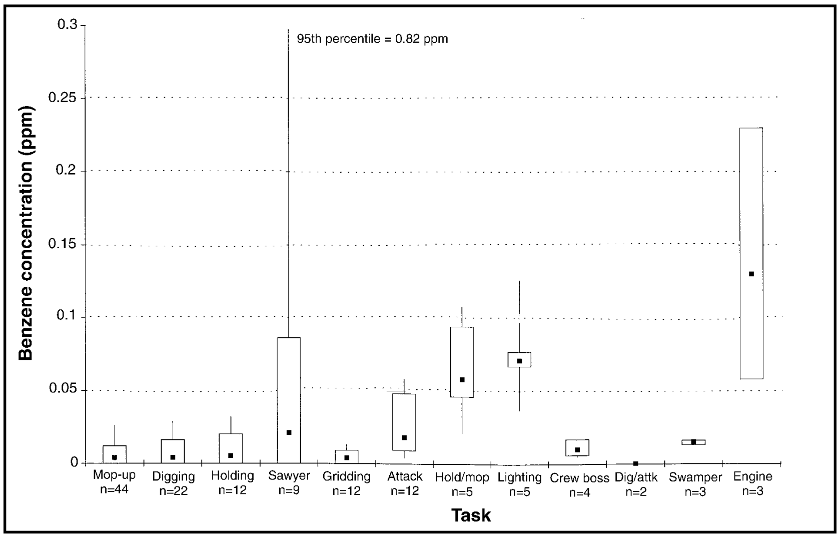

Figure 28—Distribution of benzene exposure among firefighters by job task at project wildfires. The "box and whisker"plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers" represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

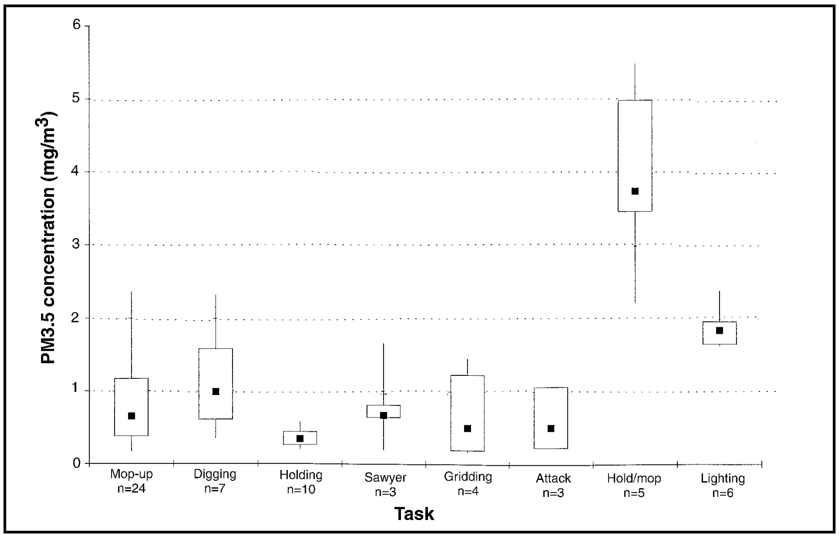

Figure 29—Distribution of respirable particulate exposure among firefighters by job task at project wildfires. The "box and whisker"plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers" represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

Figure 28 compares exposure to benzene among different work activities at project wildfires. At these project wildfires, the "engine" task was represented only by workers tending portable gas-powered water pumps.

Figure 29 compares exposure to PM3.5 by job task at project wildfires.

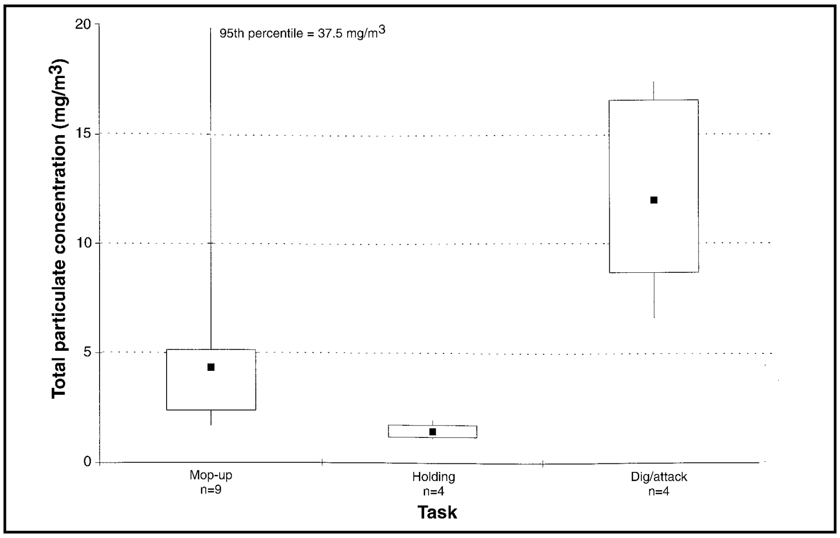

Figure 30—Distribution of total suspended particulate exposure among firefighters by job task at project wildfires. The “box and whisker” plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical “whiskers”represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

Table 13—Average smoke exposure by job task at initial attack wildfires

Job task	Carbon monoxide		Carbon dioxide		Benzene		Formal-dehyde		Acrolein		PM3.5		Total suspended particulate	
	$\bar{x}_G$[a]	n[b]	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n	$\bar{x}_G$	n
	Ppm		*Ppm*		*Ppm*		*Ppm*		*Ppm*		*Ppm*		*Ppm*	
Attack	11.6	22	653	21	0.021	22	0.069	21	0.004	22	1.74	12	12.19	1
Crew Boss	9.6	2	NA	0	NA	0	.053	2	0	2	1.02	2	2.57	2
Dig and attack	14.1	2	NA	0	NA	0	.045	2	0	2	NA	0	11.15	1
Engine	8.7	6	547	6	.028	7	.041	8	0.003	7	1.77	6	NA	0
Mobile attack	12.3	5	483	5	.020	5	.045	5	0	5	2.49	2	NA	0
Mop-up	8.4	25	540	24	.007	29	.024	8	.003	26	1.05	19	1.00	1
Sawyer	16.3	2	NA	0	.056	1	.059	2	0	3	NA	0	8.13	2
Swamper	10.3	3	NA	0	NA	0	.035	3	0	2	.61	2	5.81	3

NA = not available.
[a]$\bar{x}_G$ = geometric mean.
[b]n = number of samples.

Figure 30 shows total suspended particulate exposure during the work activities where it was sampled. Fewer data are available for this comparison because TSP exposure data were not collected before 1995.

Table 13 summarizes the exposure to pollutants during the work activities at initial attack wildfires. The geometric mean and number of samples are listed for each activity at initial attack wildfires.

Figures 31 through 36 compare the CO, formaldehyde, benzene, respirable particles, acrolein, and total suspended particulate exposure among firefighters during different work activities at initial attack wildfires.

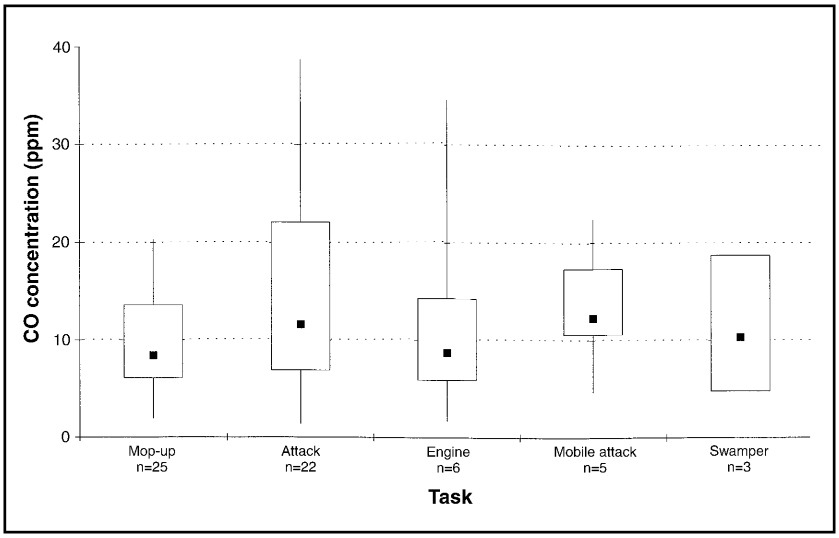

Figure 31—Distribution of CO exposure among firefighters by job task at initial attack wildfires. The "box and whisker" plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers" represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

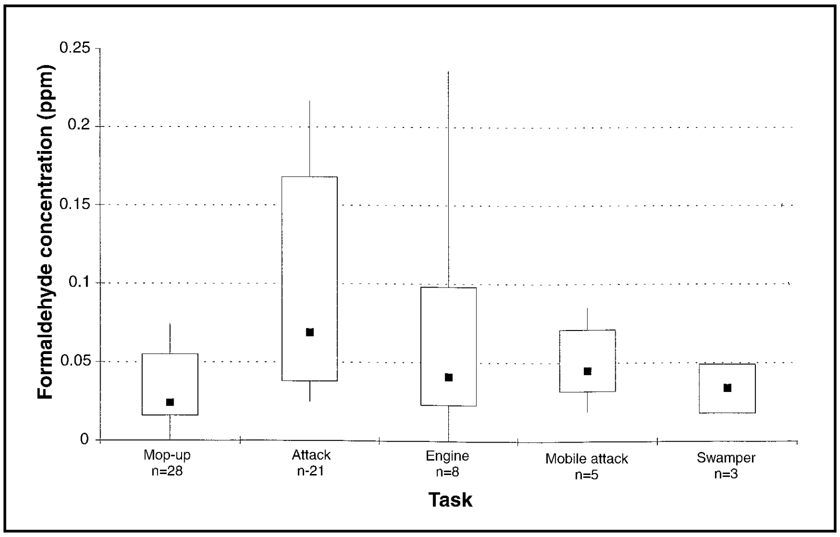

Figure 32—Distribution of formaldehyde exposure among firefighters by job task at initial attack wildfires. The "box and whisker" plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers"represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

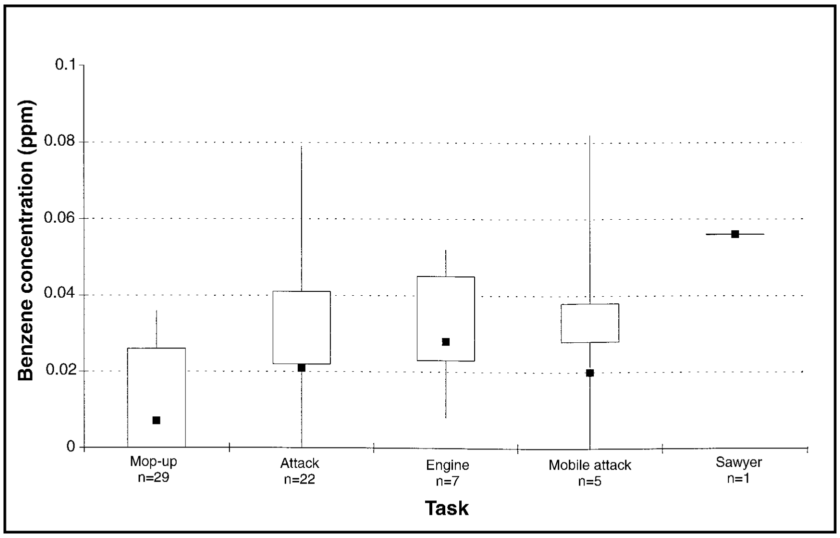

Figure 33—Distribution of benzene exposure among firefighters by job task at initial attack wildfires. The "box and whisker"plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers"represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

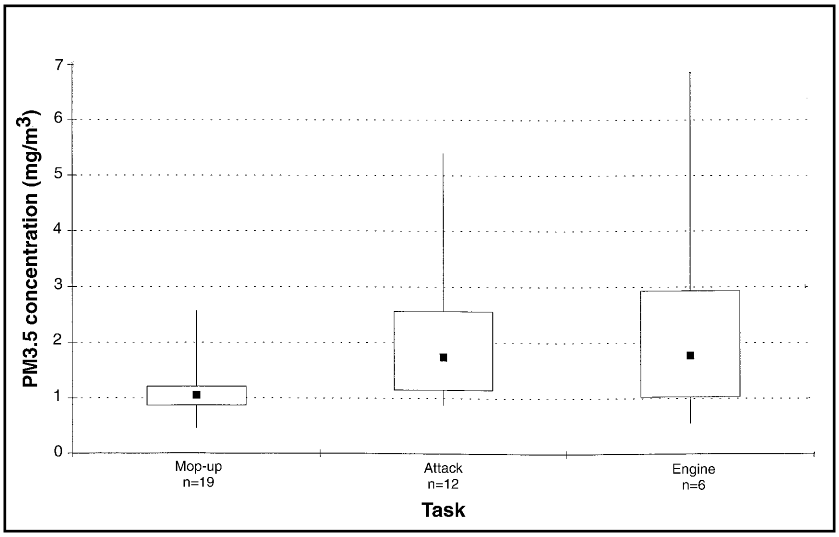

Figure 34—Distribution of respirable particulate exposure among firefighters by job task at initial attack wildfires. The "box and whisker" plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical "whiskers" represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

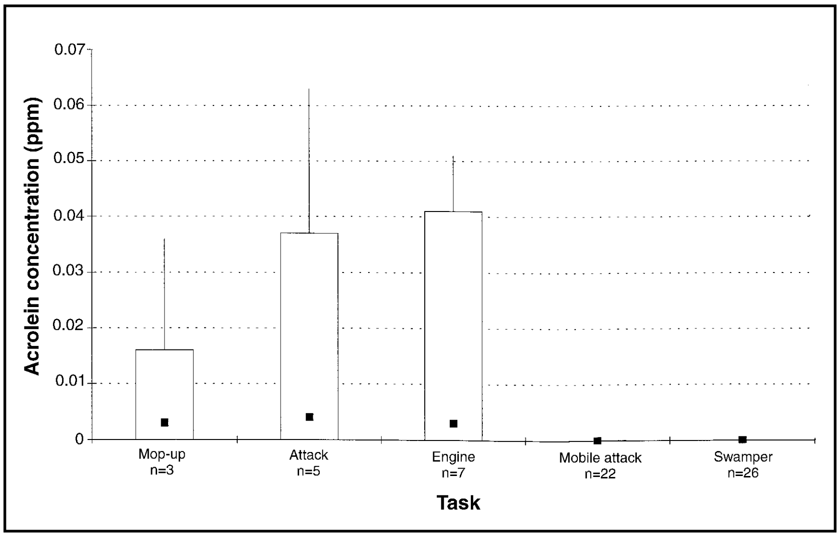

Figure 35—Distribution of acrolein exposure among firefighters by job task at initial attack wildfires. The “box and whisker”plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical “whiskers”represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

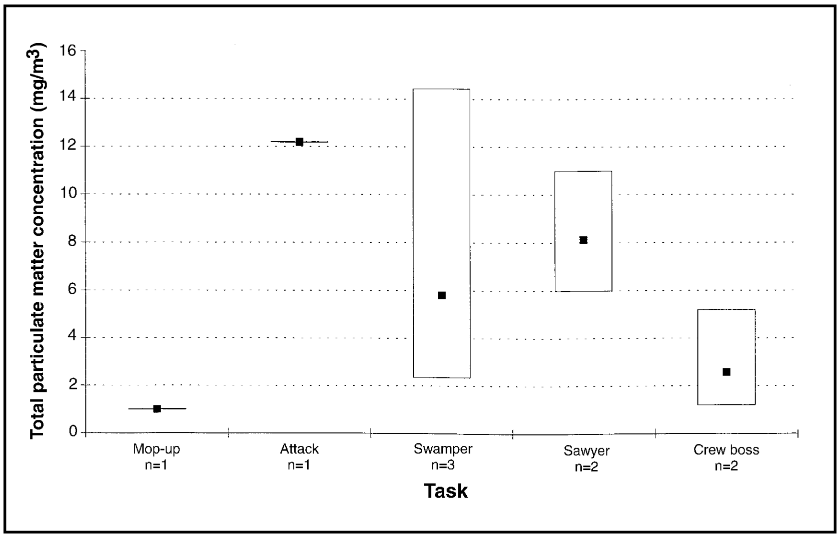

Figure 36—Distribution of total suspended particulate exposure among firefighters by job task at initial attack wildfires. The “box and whisker” plots use a box to show the data lying within the upper and lower quartiles (the middle 50 percent of the range). The solid square is the geometric mean of the samples, and the upper and lower vertical “whiskers”represent the data between the quartiles and the 95th and 5th percentiles. The relative length of the whiskers and the location of the mean depict the skew in the distribution (a symmetrical arrangement of the box and whiskers indicates a normal distribution).

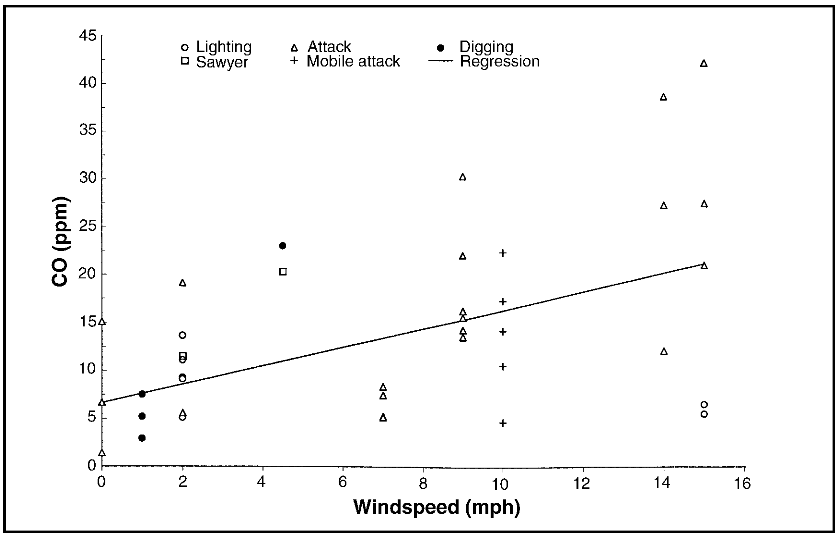

Figure 37—Correlation between CO exposure among firefighters and ambient windspeed.

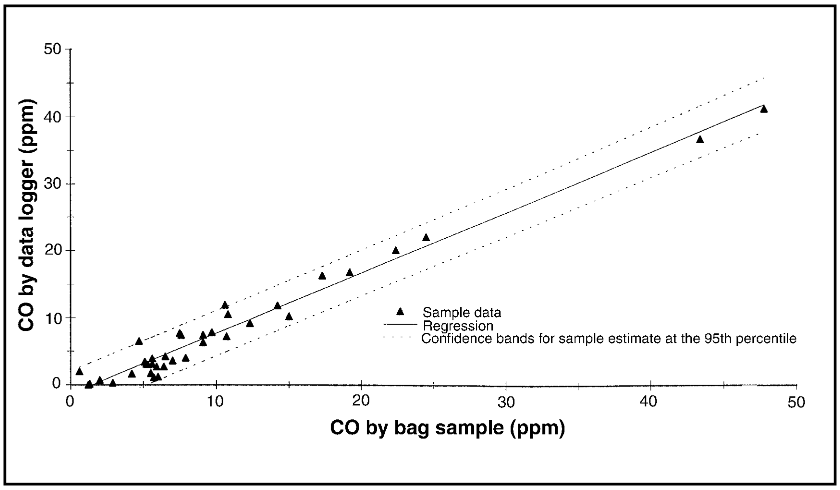

Figure 38—Correlation between carbon monoxide data from integrated bag samples and electronic dosimeters.

Windspeed—Pollutant exposure levels were plotted against the corresponding ambient windspeed at or near the fire to examine the relation between windspeed and smoke exposure. Figure 37 shows the observed trend between ambient windspeed and CO exposures for firefighters engaged in various activities. Most of the data were frominitial attack wildfires. Samples collected during mop-up did not show a trend relative to windspeed and are not plotted.

Other site factors—Carbon monoxide and formaldehyde exposure for the 11 initial attack wildfires in Redding, California, were plotted versus local data for relative humidity, 1- and 10-hour fuel moisture, predicted rate of spread, burning index, and ignition index. None of the plots indicated a trend between smoke exposure and these site factors.

Dosimeter Performance

Carbon monoxide measurements obtained at several wildfires in 1992-94 by using ICM 128 (Lodge 1989) were compared against concurrent data obtained with electronic dosimeters by using OSHA method ID-209. The results indicate good linearity (the r^2 is 0.97 for 38 sample pairs) but a negative bias in the dosimeter data relative to the reference method 128 (fig. 38).

Figure 39 shows the response of the data loggers to a reference gas standard (a known level of CO in air).Whenever possible, this QC check was performed before and after each work shift monitored. Each point on the x-axis represents a single data logger at the given fire (from table 4); for example, two data loggers were used at fire 55 and three at fire 56. Each point on the x-axis represents a single data logger at a given fire (table 4). In most cases, the postsampling response (the empty triangles) was lower.

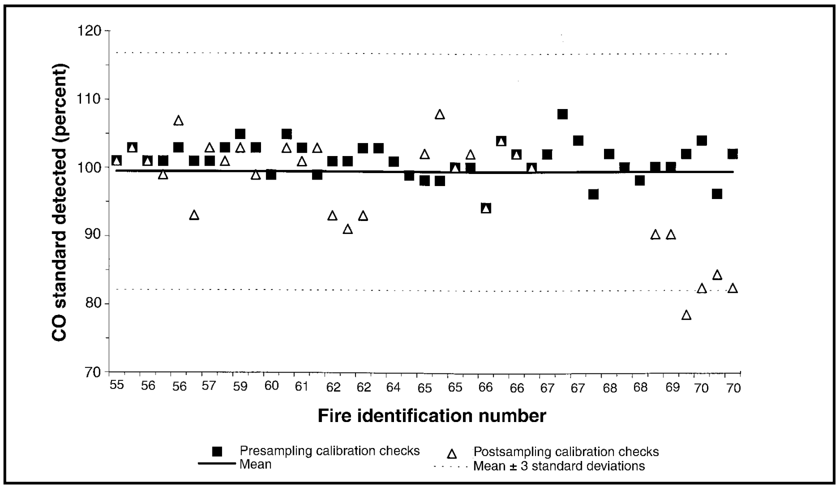

Figure 39—Field calibration check results for data logging CO dosimeters. Each point on the x-axis represents a single dosimeter at a given fire. The squares show the response of the dosimeter to the QC check gas before sampling a work shift, and the triangles mark the response at the end of a work shift.

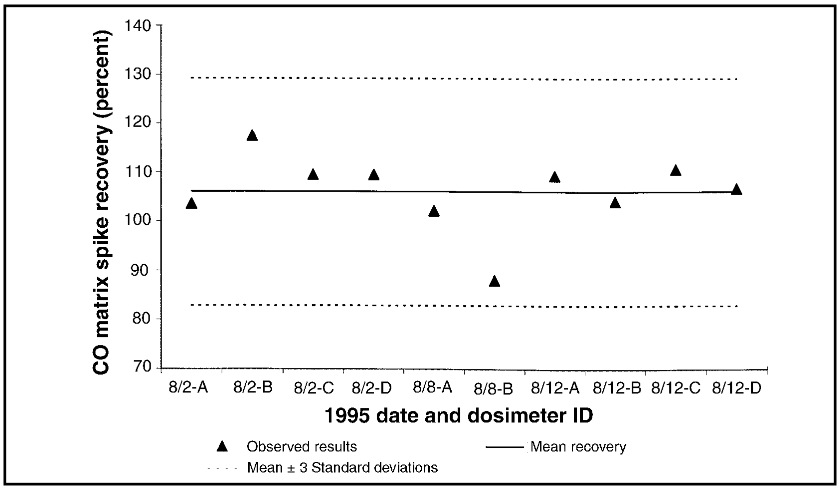

Figure 40—Amount of CO standard gas measured by dosimeters in a smoke matrix. A = dosimeter A; B = dosimeter B;C = dosimeter C; and D = dosimeter D.

The 1995 QA protocol included testing the response of each dosimeter in the field to a known amount of CO mixed with a sample of smoke obtained from the fire. After subsequent lab analysis of the CO level in the smoke sample (using ICM 128), we were able to evaluate whether the dosimeter could accurately determine the amount of the "spiked" CO in the presence of the smoke matrix. We accomplished this test on several days of sampling; the data from the four dosimeters (identified as A through D) are summarized in figure 40.

Observer Estimates

The field observers' classifications of firefighter smoke exposure were compared against the actual concentration data (figs. 41-43). Linear regression was used to evaluate the ability of the observers to classify smoke exposure. The accuracy of their estimates was measured by the fit of the regression line to the observed points (figs. 41-43). The precision of their estimates is depicted by the envelope of the upper and lower 95-percent confidence intervals (for any given smoke exposure class estimate on the x-axis, 95 percent of the exposure samples would be within the band defined by the two confidence lines). Regressions were developed for CO, PM3.5, and formaldehyde. Insufficient data were available to develop a useful regression for total suspended particulate, and the data for acrolein were too widely scattered to make this approach a useful tool.

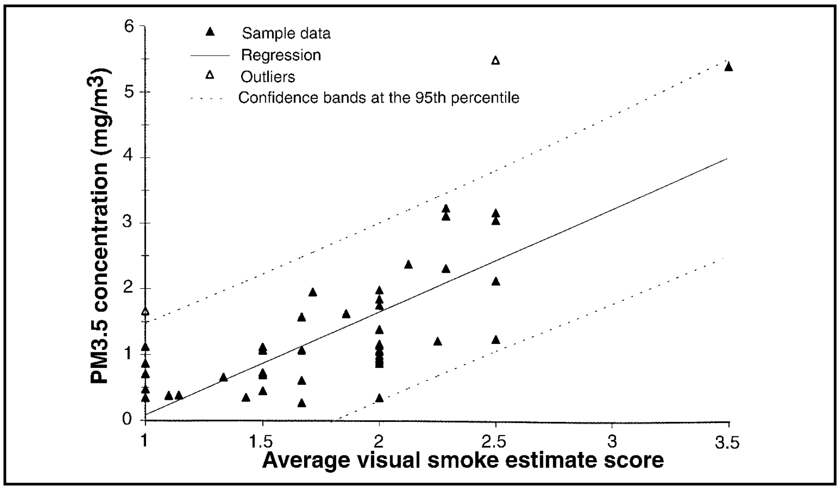

Figure 41—Correlation between visual estimate and sampled respirable particulate exposure.

Figure 41 shows how the actual PM3.5 exposure of the firefighters compared to the observers' smoke classifications. A total of 46 PM3.5 samples were used in the smoke classification regression analysis (two outliers were not used). For the smoke classes ranging between none and medium-heavy (1 to 3.5), the r^2 of the linear regression was 0.60. Equation (6) thus provides a very basic tool to estimate firefighter exposure to PM3.5:

$$PM3.5(mg / m^3) = \text{class} \times 1.57(\pm 0.19)-1.49(\pm 0.37) , \qquad (6)$$

where class = average smoke intensity classification for the observation period.

The standard error of the slope and intercept are given in parentheses after equation parameters. Figure 42 shows how the firefighters' CO exposure associated with the observers' smoke intensity classifications. A total of 70 sample periods were used (two outliers are shown). The r^2 for the regression was 0.37. Equation (7) provides users with another basic tool to estimate CO exposure among wildland firefighters:

$$CO(ppm) = class \times 14.5(\pm 2.3) - 14.2(\pm 4.4)\ , \qquad (7)$$

Figure 43 shows how the firefighters' exposure to formaldehyde differed compared to the observers' smoke intensity ranking. A total of 68 sample periods were used for the regression analysis (omitting two outliers).The r^2 for the regression was 0.39. Equation (8) summarizes this basic tool for estimating firefighter exposure to formaldehyde:

$$HCHO(ppm) = class \times 0.08(\pm 0.01) - 0.09(\pm 0.02)\ , \qquad (8)$$

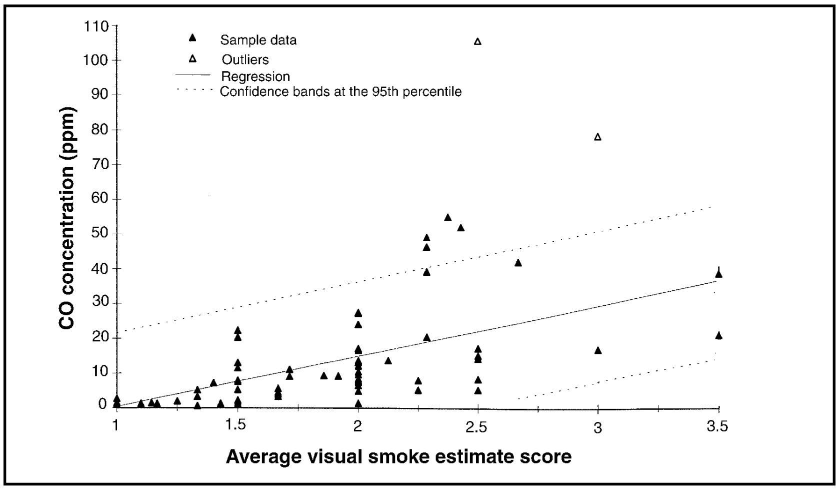

Figure 42—Correlation between visual estimate and sampled CO exposure.

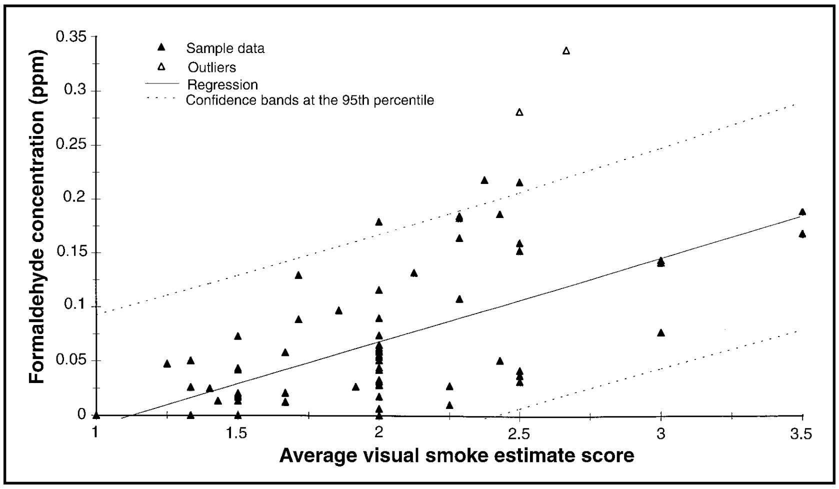

Figure 43—Correlation between visual estimate and sampled formaldehyde exposure.

Figures 44 through 48 show examples of our observers' consensus rankings of smoke exposure—ranging from none to very heavy smoke exposure. Figure 44 shows a fire crew during a brief break in fireline construction at the Foothills wildfire in Idaho during 1992, when no smoke was apparent to the observers. Equations (6) through (8) were used to predict the average exposures for the no-smoke classification:

Carbon monoxide	Formaldehyde	Respirable particulate
0 ppm	0 ppm	0 mg/m^3

Figure 44—Fire crew at the Foothills wildfire in Idaho, 1992.There was no smoke apparent to the observers.

Figure 45—Fire crew during the Libby Complex wildfires in Montana, 1994.The observers classified this as a light smoke exposure situation.

Figure 45 shows a firefighting crew preparing to disembark down the fireline at the Libby Complex wildfires in Montana during 1994.The very weak inversion coupled with little fire activity resulted in this light smoke exposure situation. Equations (6) through (8) were used to predict the average exposures for the light-smoke classification:

Carbon monoxide	Formaldehyde	Respirable particulate
15 ppm	0.1 ppm	2 mg/m^3

Figure 46 shows a crew holding line and mopping up during a late-afternoon burnout operation at the Libby Complex wildfires in Montana during 1994. The smoke exposure was classified as medium intensity by the observers. Equations (6) through (8) were used to predict the average exposures for the medium-smoke classification:

Carbon monoxide	Formaldehyde	Respirable particulate
30 ppm	0.15 ppm	3 mg/m^3

Figure 46—Firefighting crew holding line during a late afternoon burnout operation in the Libby Complex wildfires in Montana, 1994. The observers classified this as a medium smoke exposure situation.

Figure 47—Firefighter holding a fireline. The observers classified this as a heavy smoke exposure situation.

Figure 47 shows a firefighter holding a fireline in heavy smoke. The smoke concentration continued to increase during the observation period. Equations (6) through (8) were used to predict the average exposures for this smoke classification, based on data from this study. Because the heavy-smoke classification extrapolates beyond the sample data of this study (none of our samples were from a period classified as "heavy smoke" for the entire period), they may be inaccurate:

Carbon monoxide	**Formaldehyde**	**Respirable particulate**
44 ppm	0.2 ppm	5 mg/m^3

Figure 48—The same firefighter as in figure 47 holding a fireline. The observers classified this as a very heavy smoke situation.

Finally, figure 48 shows the same firefighter as shown in figure 47 but in a very heavy smoke situation.The smoke exposure was relatively long and the firefighter suffered from extreme nausea. Air sampling data from this study were used to predict the approximate average exposures for this smoke classification from equations (6) through (8). Again, because these predictions extrapolate beyond the sample data of this study, they may be inaccurate:

Carbon monoxide	**Formaldehyde**	**Respirable particulate**
58 ppm	0.3 ppm	6 mg/m^3

Discussion

Most of the time, firefighters are not overexposed to smoke because they can remain upwind of fires during suppression. Work occasionally occurs, however, in thicker smoke, and these exposures can easily exceed STELs recommended by ACGIH. When peak exposures repeatedly occur, or are combined with extended work in moderate smoke, shift-average smoke exposure also can exceed recommended exposure limits for the work shift.

Figures 10 and 15 show that up to 5 percent of the firefighters' shift-average exposures to CO and the sum of respiratory irritants (acrolein, formaldehyde, and respirable particulate matter) exceeded ACGIH TLVs, and up to 10 percent of the firefighters exceeded these TLVs while working on a fireline. The CO and respiratory irritant exposures summarized in figures 10 and 14 seem to be within the current OSHA PELs, unless the allowed CO PELs are adjusted downward to account for the long work shifts at wildfires. This adjustment results in a lower PEL, one exceeded by some of the measured exposures. The adjustment factor is obtained by dividing 8 hours by the actual shift length (14 hours, based on our data for project wildfires). This results in an adjusted PEL of 29 ppm CO, an enforceable limit that was exceeded by about 3 percent of firefighters at project wildfires. Finally, considering the study's QA results, up to 2 percent of the shift-average respiratory irritant exposures also could exceed the PELs because the imprecision of the irritant exposure measurement ranges between 30 and 40 percent (table 6), and the aldehyde measurements may be biased low by a factor of two to three.

The TSP data we began to obtain in 1995 were from conditions representing only the lower to middle range of smoke exposures, based on concomitant levels of the other characteristic pollutants in smoke. The TSP data indicated compliance with the OSHA PEL, but the true range of TSP exposure can be further assessed by additional monitoring to ensure that TSP is not an overlooked problem. Benzene was not an inhalation hazard among firefighters, even among those occasionally working with gasoline.

Most of the firefighters'TWA pollutant exposures were brought into compliance by long periods in the day without significant smoke exposure, but work on the fireline can be in high-exposure conditions—especially during direct attack, at initial attack wildfires, and while holding a fireline during burnout operations. As shown in tables 10 and 11 and figure 26, peak exposures to CO and respiratory irritants are likely to exceed recommended STELs in these situations. The probability of overexposure to smoke is enhanced when firefighters are on the flanks or downwind of a fire in high ambient winds, or when inversion conditions prevent smoke dispersal by trapping emissions from a large fire within a valley.

The exposure data we report are similar to results of other researchers. Results of carboxyhemoglobin (COHb) monitoring at 11 western wildfires in 1974-76 showed that 9.4 percent of firefighters had postfire COHb levels above 5 percent (Jackson and Tietz 1979). This value ranged from 0 to 100 percent of the firefighters tested at each fire, highlighting the variability of smoke exposures. These COHb results would correspond to somewhat higher CO exposures than we measured, which could be due to inherently smokier situations at the fires monitored by Jackson and Tietz, and they also may be explained if there was, as some suggest, less concern about the adverse effects of smoke in that era. More recently, Reh and Deitchman (1992) obtained breathing zone samples of CO during the 1988 project wildfires in Yellowstone National Park that ranged between 3.6 and 7.8 ppm during mop-up and between 1.9 and 3.9 ppm during a day of fireline construction—ranges consistent with our results. They also obtained area samples for total particulate matter, which were mostly below 1.2 mg/m^3, although one 5-hour sample was 15.9 mg/m^3, and a 4-hour sample was 47.6 mg/m^3. Our results, again, are consistent with those and highlight the potential for occasionally high exposure levels. A few area samples for aldehydes detected formaldehyde levels averaging between 0.02 and 0.03 ppm; benzene samples were all below 0.03 ppm. Their results are very consistent with our project wildfire results, especially for activities with lower smoke exposure potential and no gasoline exposure.

Finally, a summary of results from exposure monitoring in northern California between 1986 and 1989 found that 46 samples of firefighter exposure to CO averaged 14.4 ppm during fireline and mop-up activities at prescribed burns and wildfires; range, 1.4 to 38 ppm (Materna and others 1992). Their mean CO exposure is higher than our data, but the range is consistent. They also found that 22 samples of respirable particulate exposure averaged 1.75 mg/m^3 (range, 0.327-5.14 mg/m^3), and total particulate averaged 9.46 mg/m^3, (range, 2.7 to 37.4 mg/m^3). Again, the ranges of these values are consistent with our results and point out the possibility of higher exposures.

Our data show that the respiratory irritants, formaldehyde, acrolein, and respirable particulate, are well-correlated with CO, and that electronic dosimeter technology can be an effective basis for a routine smoke exposure monitoring program on a broad scale. Our experience also was that observers can roughly estimate smoke exposure with sufficient precision to determine whether administrative controls or respiratory protection should be used to reduce smoke exposures.

Pollutant Correlations

Exposure of firefighters to the key respiratory irritants in smoke can be predicted from measurements of CO, at least in the Western United States. Carbon monoxide levels in smoke at project wildfires were strongly correlated to concentrations of formaldehyde, PM3.5, and acrolein, as indicated by the r^2 values (range, 0.44 to 0.91; tables 7 and 8). This opens up a cost-effective way to routinely assess exposure to many pollutants in smoke that are difficult and expensive to measure. Benzene and CO exposure are especially well correlated when there is no exposure to other benzene sources such as gasoline or engine exhaust.

Although few samples were obtained, TSP was not significantly correlated to PM3.5 either at project wildfires or during initial attack. If further assessment of TSP exposure indicates a significant hazard in more intense smoke exposure situations, it will be a key pollutant to routinely monitor because of the lack of correlation to CO. Emission measurements collected in the plume of prescribed burns (Sandberg and others 1989) have shown strong correlations between concentrations of TSP and fine particles (PM2.5); thus the correlation of TSP and PM3.5 in smoke also may be relatively strong. The lack of a similar correlation in our data is clearly due to entrained soil dust from firefighters' activities dominating the samples in the absence of high levels of smoke.

To provide the best fit to the most data in each regression, we excluded a few outliers from the final regressions, based on poor fit compared to the overwhelming balance of the data; this is rightly of concern to statisticians. However, in so much as any of the samples could be inaccurate because of indeterminate errors in the rugged field environment (such as unobserved temporary kinks in air sampling lines), we are confident that excluding the few outliers (from none to five excluded from up to 103 sample pairs, depending on the correlation) did not bias the accuracy and provided appreciably more precise fits to the data. We used the Cook's D and DFFITS statistics to identify observations for possible exclusion (SAS Institute 1989).

The regressions with CO provide a useful quantitative tool to estimate E_m, proven over a range of 1.5 times the PEL for E_m (the mixture of acrolein, formaldehyde, and PM3.5). Fire managers may want to consider using the project wildfire regressions for this purpose rather than the initial attack data from urban interface fires, because the project wildfire regressions (1) are based on a larger number of samples, (2) cover a greater geographic range, and (3) provide greater precision than the initial attack regressions, which were likely to have been compromised by urban sources of pollutants. Fire managers may want to consider using these interpollutant correlations to cost-effectively monitor smoke exposure, but we caution that data from other regions are necessary to determine whether the correlations are consistent over a broader geographic scale.

Project wildfires—The interpollutant regressions at project wildfires were surprisingly strong. The correlations between CO and each of the respiratory irritants can be used to effectively estimate total irritant exposure from simple CO measurements in the field. To do this, equation (9) may be conveniently programmed into a calculator or distributed to crew supervisors as a nomogram:

$$E_m = \frac{([CO] \times 3.598 \times 10^{-3} + 4 \text{ x } 10^{-3})}{(\text{formaldehyde exposure limit})} + \frac{([CO] \times 4.98 \times 10^{-2} + 0.8)}{(\text{PM 3.5 exposure limit})} + \frac{([CO] \times 4.2 \times 10^{-4} + 3 \times 10^{-3})}{(\text{acrolein exposure limit})}, \qquad (9)$$

where E_m is the total irritant exposure, and the appropriate exposure limit for each pollutant is chosen from table 1. A numerical example using the OSHA PELs is given below. At a firefighter's TWA CO concentration of 43 ppm over 8 hours, the estimated total irritant exposure at a project wildfire would be:

$$E_m = \frac{(43 \times 3.598 \times 10^{-3} + 4 \times 10^{-3})}{(0.75)} + \frac{(43 \times 4.98 \times 10^{-2} + 0.8)}{(5)} + \frac{(43 \times 4.2 \times 10^{-4} + 3 \times 10^{-3})}{(0.1)}$$

$E_m = 1.01.$

This example assumes that the PELs are adequate exposure limits for firefighters, and shows that a CO exposure for 8 hours that is below the current PEL of 50 ppm results in an irritant exposure just exceeding the OSHA PEL of 1.0. Here is another example with the recommended ACGIH TLVs as the evaluation criteria and an assumed TWA CO exposure of 21 ppm over 8 hours:

$$E_m = \frac{(21 \times 3.598 \times 10^{-3} + 4 \times 10^{-3})}{(0.3)} + \frac{(21 \times 4.98 \times 10^{-2} + 0.8)}{(3)} + \frac{(21 \times 4.2 \times 10^{-4} + 3 \times 10^{-3})}{(0.1)}$$

$E_m = 1.00.$

When using the ACGIH TLVs as the evaluation criteria, CO exposure must be maintained below 21 ppm to keep the irritant exposures within acceptable limits. When selecting a CO exposure to use as an action level to prevent overexposure to irritants, keep in mind that the equations above are for the best-fit linear regression; therefore, some irritant exposure samples would be above as well as below the regression line. Also, if the formaldehyde and acrolein results we obtained are actually biased low, as indicated by some of our QA data, the actual irritant sum will be higher as the regressions would underpredict the true formaldehyde and acrolein levels.

Initial attack wildfires—Pollutant correlations at initial attack wildfires were not as strong as at project wildfires. Compare the regressions in tables 7 and 8. Three reasons could explain the differences between the two sets of regressions: (1) more samples were obtained at project wildfires, which increases the r^2 for a regression if other factors are held constant; (2) the range of sample concentrations at project wildfires was broader than at initial attack wildfires for all regression pairs except formaldehyde and acrolein, which also tends to increase an r^2; and (3) the project wildfires were much further removed from urban sources of air pollution, so the relations among the pollutants in smoke were not obscured by contributions from urban sources. This latter possibility exists with the data from initial attack wildfires. For example, at lower smoke concentrations, a small amount of background, urban CO (3 or 4 ppm) is a relatively large proportion of the total CO in the sample, which obscures true correlations among the pollutants in biomass smoke. If further data without these limitations were obtained, the resulting regressions from initial attack wildfires and project wildfires might be equivalent.

Exposure Assessment

Averaged over a work shift, smoke exposure at these wildfires was usually below the OSHA PELs, but a small percentage of work shifts exceeded the PEL for CO after adjustment for the longer work shifts, under the OSHA approach. More would likely exceed the 5 percent COHb criterion if the CFK equation were applied. The ACGIH recommended TLVs were occasionally exceeded outright for CO, as well as for the sum of the respiratory irritants (acrolein, formaldehyde, and PM3.5). All benzene exposures were well below the OSHA PEL, and only one exposure by a firefighter to benzene exceeded the benzene TLV while that person was on the fireline. The peak smoke exposure samples from project wildfires and initial attack wildfires were similar in concentration: all were below the OSHA STELs, but roughly half of the samples exceeded an E_m based on the TLV STELs for respiratory irritants. We can conclude that smoke exposure is more often a problem for brief periods within a day than over an entire work shift. In most cases where the shift-average exposure limits are exceeded, the exposures could be brought into compliance by focusing control efforts to reduce the peak exposures within the work shift.

Exposure Assessment for Project Wildfires

Firefighters work long days at project wildfires, and their extended work shifts are inconsistent with the 40-hour workweek on which the PELs are based. The firefighters we observed spent, on average, over 10 hours on the fireline within their 14-hour work shifts (fig. 6). Firefighters routinely labor through extended work shifts at project wildfires and seldom receive optimum work and rest cycles. Such conditions warrant adjusting the exposure limit to achieve adequate protection against chemical hazards, especially CO.

Respiratory irritants—Although each respiratory irritant was individually below its respective PEL and TLV, the collective irritation of the eyes and respiratory system by these smoke components was significant (figs. 14 and 15). Compared with the PELs, the highest TWA fireline and work shift exposures to irritants were about 80 percent and 65 percent of the PEL (E_m=1.0), respectively. Using the ACGIH-recommended TLVs as the evaluation criteria, about 8 percent of the firefighters' fireline TWAs and 3 percent of the work shift TWAs exceeded the respiratory irritant TLV.

As discussed under "Data Quality," above, some performance evaluation audit samples indicated that the aldehyde measurements may be biased low. Review of our data, calculations, and procedures could not explain the discrepancy between low performance-evaluation audit results for the aldehydes and the adequate results of field matrix spike recoveries (accuracy data from table 6). If a bias was present it was consistent, because the interpollutant correlations showed consistent ratios between the aldehydes and the other pollutants in smoke that were accurately measured. If this bias existed, it is probable that a small percentage of the exposures would have exceeded the OSHA irritant PEL at project wildfires, and a larger percentage would have exceeded the ACGIH irritant TLV. To evaluate this, we corrected for the effect of a potential bias in our measurements of formaldehyde and acrolein and produced the results illustrated in figure 49, which may be compared with figure 14 (in which the data are assumed to have no bias).

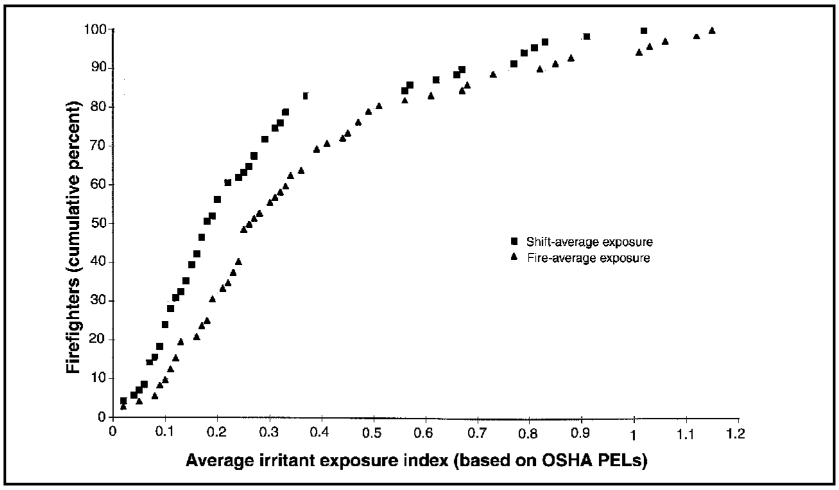

Figure 49—Shift- and fireline-average respiratory irritant exposure at project wildfires, assuming biased aldehyde data.

Simultaneous measurements of the three respiratory irritants were successful only during one of three peak exposure samples at project wildfires (table 10). This sample was obtained from a firefighter holding fireline and mopping-up during a burnout. The sample data indicated a peak exposure about twice the ACGIH guidelines but just 75 percent of a PEL-based STEL for E_m. We note that exposure during the smokiest 15 minutes of this 20-minute sample (consistent with the STEL definition) may have been greater than the sample obtained. In spite of our incomplete data, we can state that peak irritant exposures at project wildfires can reach levels that are very irritating to workers. To summarize exposure to irritants at project wildfires, the data we have indicated that the highest exposures are probably compliant with the current PELs, but they do not meet the guidelines established by ACGIH to prevent adverse effects, primarily irritation of the eyes and mucous membranes and temporary depression of respiratory system functions.

Benzene—Only one TWA benzene exposure for a firefighter exceeded the ACGIH TLV of 0.3 ppm at project wildfires. This exposure was estimated at 0.384 ppm over 9 hours on the fireline (fig. 8). No benzene exposures exceeded the OSHA PEL. The firefighter with the highest benzene exposure was igniting a burnout with a drip torch in the morning and alternately carrying fuel, operating a chainsaw, and mopping-up during the afternoon. His average benzene exposure over the entire shift was 0.249 ppm, but his benzene exposure was 0.824 ppm during one 90-minute period of chainsaw operation. The firefighter with the next highest benzene exposure (0.104 ppm for the shift, 0.133 ppm on the fireline) was tending a portable water pump during most of the work shift, well removed from the fire smoke. The third highest benzene exposure (0.066 ppm during the shift, 0.071 ppm on the fireline over 14 hours) was another sawyer, who operated or carried a chainsaw most of the day. These results indicated that sawyers and other engine operators are most likely to have the highest benzene exposures among fire crews. Workers involved in large refueling operations, such as those preparing drip torches or helitorches, could have more significant benzene exposures. Such workers were not sampled in this study, but based on our results, fire management agencies may wish to target them for future benzene exposure assessment. We can conclude from these data that the benzene exposure of a typical firefighter working with hand tools is unlikely to exceed the current PELs or TLVs.

The two peak exposure samples from project wildfires that had successful benzene results were both around 0.055 ppm (table 10), well below either ACGIH or OSHA STELs. Those peak exposure samples were identified by their match to a peak smoke exposure situation, not by peak benzene exposure caused by gasoline vapors. The low benzene levels in the peak smoke samples reinforced our conclusion that neither the OSHA or ACGIH STELs for benzene are likely to be exceeded in the absence of gasoline vapors.

Carbon dioxide—Carbon dioxide was not sampled in 1995, but the data from 1992-94 show that levels of CO_2 measured in the breathing zone were relatively low, much less than the OSHA PEL of 5,000 ppm (fig. 9). Some of the CO_2 measured may be from normal metabolic waste (exhaled breath) rather than forest fires. We did not expect CO_2 to be a health concern among firefighters, and the data bear this out. The data may be useful to future investigators interested in the effects of low-level CO_2 exposure. To that end, we note that background CO_2 levels were not measured, and a background concentration of 346 ppm was assumed for estimating TWA CO_2 exposures.

Carbon monoxide—Carbon monoxide exposures among firefighters have a pattern similar to respiratory irritants. The distribution of exposures is skewed, with most at low concentration and a small percentage of higher exposures (fig. 10). No measured exposure exceeded the current unadjusted OSHA PEL (50 ppm), one exceeded the former OSHA PEL (35 ppm) while the firefighter was on the fireline, and less than 5 percent of the CO exposures exceeded the ACGIH TLV of 25 ppm.The OSHA requires that the OSHA PEL be adjusted to account for the potential COHb buildup during a long work shift. One simple method is to use equation (2). For a 14-hour work shift, this results in an adjusted CO PEL of 29 ppm, a limit exceeded for about 3 percent of our firefighters. The best method of adjusting the CO PEL uses the CFK equation to arrive at the equivalent limit to prevent a COHb level above 5 percent. The CFK equation gives a much lower exposure limit for a long work shift, especially in high-altitude conditions; an exposure limit of around 20 ppm would typically be calculated. In such a scenario, about 10 percent of the observed CO exposures would exceed the adjusted CO exposure limit.

Among the peak exposure data, the highest CO sample was just over 100 ppm, with most samples in the range of 10 to 50 ppm. The CO values on the data logger for the more highly exposed firefighters were occasionally above 200 ppm for brief periods; if maintained for 5 minutes, they would exceed the former OSHA ceiling limit for CO. When peak CO exposures occur while firefighters are exerting maximum effort, COHb levels in the bloodstream can rise rapidly, on the order of 1 percent per minute. Because CO alone has no odor or warning properties, it is probably the best pollutant to be monitored in any routine exposure monitoring program. Carbon monoxide is easy to monitor in high-exposure situations with electronic dosimeters; these devices can sound alarms when CO levels exceed preset limits, and the strong correlations with the respiratory irritants can be used to manage exposures to respiratory irritants.

Total suspended particulate—The firefighters'TWA exposures to TSP were all less than half of the exposure limits for nuisance dust (fig. 13). Based on these data, total suspended particulate exposures are not significant. The TSP data were collected, however, for only a small subset of the monitored firefighters (at 3 days of wildfire suppression in southern California), a set that was obtained in relatively smoke-free conditions, based on the other pollutants measured among the same firefighters. The smoke exposure data obtained from 1992 to 1994 included much higher levels of PM3.5 and CO (figs. 10 and 12) than were found in the data from 1995. For example, among those firefighters for whom both TSP and CO exposures were measured in 1995, the highest TWA CO exposure was only 2.3 ppm on the fireline and 1.8 ppm over the work shift. The corresponding PM3.5 levels were all below 1 mg/m^3. Thus, the TSP values that exceeded the PM3.5 levels (ranging up to 4.5 mg/m^3) were associated with large particles of disturbed ash and soil dust rather than smoke.

We believe it is reasonable to assume that higher levels of smoke will be associated with higher levels of TSP. Fire emissions research has sampled concentrations of fine particles (PM2.5) and TSP in smoke plumes above operational prescribed burns (Sandberg and others 1989). The PM2.5 comprised about 56 percent of the TSP. Because the PM2.5 and PM3.5 portions of TSP in smoke are of similar size (and thus concentration), firefighters exposed to 2.5 mg/m^3 of PM3.5 are expected to have TSP exposures from smoke on the order of 5 mg/m^3. Similarly, the correlation between CO and TSP found by Sandberg and others (1989) suggests that the higher TSP exposures from smoke are about 6 mg/m^3. When these estimates of the TSP contributed from smoke were added to the observed TSP levels from 1995 (which ranged up to 4.5 mg/m^3), an estimated exposure to TSP in a smoky environment was about 10 mg/m^3, which is two-thirds the PEL for TSP.

The results suggested that further monitoring of TSP exposure is warranted to establish whether compliance with the PEL is a problem during work shifts when smoke levels are higher. The health significance of exposure to nonrespirable dusts without fibrogenic or chemical irritant properties is limited to irritation so far as we know; but the dust samples have not been analyzed for crystalline silica, and other investigators have found significant levels of crystalline silica in similar samples from firefighters in northern California (Materna and others 1992).

We believe that our data are representative of average conditions, especially for CO and PM3.5. The aldehyde data may be biased low, but we are not convinced of this because of the strength of the interpollutant correlations. We emphasize that the distribution of smoke exposures is skewed (there are many more low-exposure hours than high-exposure hours in a firefighter's career); therefore, we are unlikely to have measured the highest exposures that occur. To do so would take a substantial monitoring effort because the lag time to arrive on-site is separate from the incident response. Further research-scale collection of smoke exposure data, even if it captures the occasional very high exposure, is unlikely to change smoke management direction for minimizing exposure levels.

We point out that our data are not without potential internal biases. Multiple firefighters were sampled each day, but the exposures we measured were not completely independent because (1) the firefighters were mostly from the same crew and working the same area of the wildfire, and (2) we expect that smoke exposures are more similar within a crew working in one area of a fire than between crews in different areas. Because of this, we believe that more broadly based sampling is better suited to define the distribution and upper bound of smoke exposures.

Although we monitored smoke exposure during 17 days at project wildfires, the data from project wildfires were obtained at only eight separate fires. Most of the project wildfire sampling occurred on sequential days at the fires. It seems apparent from our observations that the urgency of firefighting efforts generally declines to a more measured pace as a fire progresses from initial attack through days and weeks of containment efforts and, finally, control and mop-up. As a fire progresses from a flaming phase to a smoldering phase, the smoke production rate declines as well. Because most of our sampling data from project wildfires were in the mid to latter phases of the fires, the exposure distributions we found may be biased low if higher exposures occur earlier in the fires. Future monitoring programs should strive to obtain enough data over the course of a fire to assess the time series trend of smoke exposure over multiple days.

Exposure Assessment for Initial Attack Wildfires

Initial attack crews had lower TWA smoke exposures than crews on project wildfires (figs. 6 and 16). Firefighters have about the same working shift length at initial attack and project wildfires, but the initial attack forces spend much less time on the fireline–an average of only 3.3 hours at initial attack wildfires compared with 10.4 hours at project wildfires. Because the amount of time spent at the wildfire scene is so much lower, shift-average exposure limits are less likely to be exceeded among initial attack crews, at least when only one or two small fires occur per day. The data showed that overexposure to respiratory irritants and CO is possible for initial attack crews on the fireline, primarily from peak smoke exposure situations.

Respiratory irritants—Exposure to the individual respiratory irritants (acrolein, formaldehyde, and PM3.5) was slightly greater than at project wildfires (compare figs. 15 and 25). At initial attack wildfires, the total irritant exposure (E_m) on firelines exceeded the recommended TLVs for about 10 percent of the firefighters and was about 90 percent of the PEL (fig. 24). These results were consistent with our observation that the urgency of initial attack to fight wildfires entices fire crews to work through intense smoke exposures.

In spite of the relatively high smoke exposures on the fireline, the long periods that initial attack crews spend on-call between fire dispatches lowered their shift-average exposures. Compare the shift-average irritant exposure data at project wildfires and initial attack wildfires (figs. 15 and 25). The initial attack crews had consistently lower shift-average irritant exposures than the firefighters at project wildfires. During the days when we tracked the initial attack crews, fires rarely occurred until the afternoon. As shown in figure 50, initial attack firefighters at wildfires had so much unexposed time in their shift that no shift-length irritant exposures exceeded the PELs, even after recalculating the irritant exposures to compensate for potentially biased aldehyde measurements.

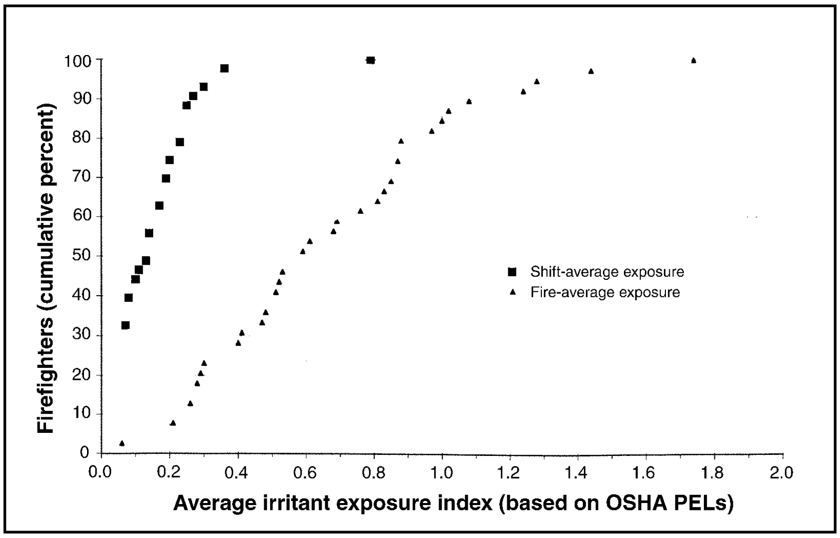

Figure 50—Shift- and fireline-average respiratory irritant exposure at initial attack wildfires, assuming biased aldehyde data.

Peak exposures to respiratory irritants at initial attack wildfires (table 11) were similar to those at project wildfires. The large number of peak exposure samples at initial attack wildfires provided enough replication to conclude that peak exposure situations cause overexposure to respiratory irritants in about 50 percent of the firefighters, based on E_m STELs calculated by using the TLVs, although none of the samples exceeded the current PELs. If our aldehyde data were actually biased low, adjusting them upward by a factor of 2 to 3 may change this conclusion. Similar results are possible at project wildfires, although not enough peak exposure samples were obtained at project wildfires to evaluate the possibility.

Benzene—There was little exposure to benzene at initial attack wildfires. All the benzene exposures on the fireline were less than 0.045 ppm (fig. 18). It was apparent that smoke alone is not likely to cause an overexposure to benzene at initial attack wildfires. In the benzene data from initial attack wildfires, three of the four firefighters with the highest fire-average exposures were working as sawyers or swampers, engine captains, or in mobile attack. The fourth was working directly adjacent to the sawyers on a tightly spaced hand crew. The highest peak benzene exposure samples at initial attack wildfires also were among firefighters conducting direct attacks or mobile attacks or the engine captains (table 11). As for project wildfires, these data showed that working near gasoline engines caused the largest benzene exposures. None of the peak benzene exposures approached ACGIH STEL recommendations.

Carbon dioxide—Levels of CO_2 in the breathing zone were all much less than the 5000-ppm OSHA PEL (fig. 19). We had about as many TWA CO_2 exposure estimates at initial attack wildfires as at project wildfires. The distribution was skewed at initial attack wildfires by a few exposures that were substantially higher than the rest. This pattern contrasted with results from project wildfires (fig. 9), where the exposures were more evenly distributed across a narrower concentration range. Urban combustion sources possibly contributed to the higher CO_2 levels at these initial attack wildfires.

Carbon monoxide—Only one firefighter had a fire-average CO exposure exceeding the recommended TLV (fig. 20). As well, no firefighter had a shift-average CO exposure that exceeded the PEL when adjusted by using equation (2). Fewer shift-average exposure measurements were obtained at initial attack wildfires. If the true distribution of exposures is such that only a small percentage of them exceeds the TLV, the apparent compliance with the TLV may be an artifact of a small sample size. Shift-average overexposures to CO probably occur on extended initial attacks, but clearly, the higher CO exposures that we found on the fireline often were diluted by the large proportion of time between fire dispatches.

Total suspended particulate—It is interesting that the total suspended particulate exposures at initial attack wildfires in southern California (fig. 23) were consistently higher than at the project wildfires (fig. 13). The corresponding CO exposures explain this result, because there is some correlation between the two pollutants in smoke (Sandberg and others 1989). The highest fireline-average CO exposure co-obtained with the TSP data was only 2.3 ppm at project wildfires compared to 11.8 ppm at the initial attack wildfires. In fact, all the initial attack wildfire fireline CO exposures were above 4.8 ppm CO. The correspondingly higher TSP levels reinforced our conclusions about the potential TSP results for project wildfires and the need to further assess this hazard.

As is shown in the CO data, the initial attack TSP samples were all from firefighters who had moderate smoke exposures. The highest TSP exposures on the fireline were only 60 percent of the OSHA PEL, and the TSP exposure levels we measured were not significant when averaged over the work shift. Further sampling in a variety of fuel types and lengths of initial-attack assignments might result in the occasional shift-average overexposure.

Factors in Smoke Exposure

Our observations showed that overexposure to smoke is most likely to occur when firefighters are required to accomplish a task in spite of potential smoke levels and when weather or fire behavior causes smoke to be brought to the firefighter in high doses. For example, a job task such as direct attack is inherently urgent, causing many firefighters to ignore the irritation from smoke exposure as they focus on responding successfully to the emergency. Some weather conditions such as strong, gusty, or erratic winds contribute to smoke exposure by causing unanticipated fire behavior or transporting smoke across firelines. A firefighter's position (uphill or downhill) and direction (upwind or downwind) relative to a fire are obvious factors contributing to smoke exposure potential. Proving these concepts with statistical certainty is difficult with the available data, but some patterns were apparent in the data. We were able to evaluate two main factors thought to control smoke exposure potential: job task and windspeed.

Job task, project wildfires—The job of putting out a large wildfire entails different tasks. Our exposure measurements point to some differences in exposure among these work activities, but these differences were not proven to be statistically significant. There were not enough samples from many of the tasks to represent the associated range of exposures (table 12), and further sampling will be required to evaluate differences. For many samples, other factors such as wind, fire behavior, or firefighter positions relative to the fire seem to have defined the exposure during the sample more than the work task itself. For example, a strong atmospheric inversion occurred one morning at the County Line fire (fire 20), during which all the sampled firefighters worked in very smoky conditions regardless of their task. In this obvious instance, these data were excluded from the work-type exposure comparison. Statistics aside, a few differences among work activities that were apparent to us are discussed below.

Digging fireline—Building firelines was a relatively low-exposure activity in most instances, as indirect firelines often were placed far from actively burning areas. When a direct fireline was constructed adjacent to rapidly burning fuels (for example, at fire 57) much higher exposures were sometimes observed. This scenario overlapped what was categorized as "direct attack." More often, the direct fireline construction that we observed was either around blackened areas where few hotspots were actively burning or on the upwind or downhill edge of burning areas, where most smoke was carried away from the firefighters. In those cases, only intermittent periods of smoke exposure occurred, with the overall average of moderate smoke exposure occurring while firefighters were digging line (see for example figs. 26 and 29).

Holding fireline—Firefighters at project wildfires generally had the lowest exposures while "holding" firelines. At large project wildfires, "holding" personnel often were assigned to a division or section of line with the task of being on guard for flare-ups or runs by the fire in that area. Because they were essentially waiting for something to happen, their smoke exposures were usually low, as is apparent from figures 26 and 27, where the asymmetrical shapes of the boxes and whiskers show that most of the holding personnel had low smoke exposures and only a few had higher exposures. These higher exposures (when something happened!) were due to wind-driven smoke as the fire tested the staffed section of fireline. Earlier results from prescribed burns show that holding personnel are among the more highly exposed groups (Reinhardt and others 1994), but the key difference was that the holding forces at prescribed burns were more often in a situation where the fireline was tested. At the project wildfires, holding personnel were seldom as near to actively burning fuels. However, as can be seen by the high exposures during the holding and mop-up job tasks (for example, fig. 26), holding forces at project wildfires do endure the higher exposures measured at prescribed fires. Most of the holding and mop-up job task data were obtained from a single crew at the Libby complex fires in Libby, Montana, in 1994. This contract fire crew was assigned to hold a fireline during an afternoon burnout operation aimed at removing the hazard from a large area of unburned forest within the main firelines. Figure 51 shows a plot of the equivalent respiratory irritant levels calculated by using equation (9) and the CO dosimeter data from one firefighter. The local winds increased midway through the burnout, and smoke exposures increased during the afternoon as the winds transported smoke across the firelines.

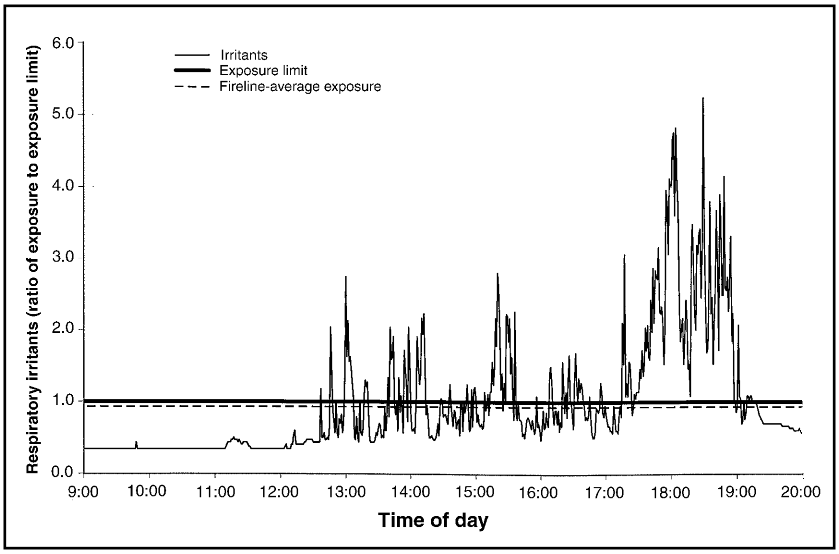

Figure 51—Respiratory irritant exposure from one firefighter as that person was holding the fireline during a burnout operation.

The smoke exposure among holding forces can easily be three times the ACGIH recommended peak exposure limits for respiratory irritants and CO. At such levels, most workers will have adverse short-term health effects. Our limited sampling of wildfires did not have a chance to further measure these conditions.

Lighting—Exposure to smoke during lighting was higher than we might have expected, based on data for the task obtained during prescribed burns, where the exposures were low for all pollutants except benzene (Reinhardt and others 1994). All the samples of this job task were obtained during a burnout at fire 64 (Ann fire, Hamilton, Montana, 1994), where very erratic winds contributed to the smoke exposure. Such conditions can occur at any time, but we believe that further sampling from a variety of wildfires would indicate a lower average exposure to CO and respiratory irritants during lighting. Benzene exposures may remain relatively high in any case because the drip torch is a constant exposure source during this task.

Mop-up—We found that particulate matter (total and respirable) were the only pollutants likely to be a significant health hazard during mop-up, with total suspended particulate comprising the greatest concern with an average of nearly half the PEL (fig. 30). These results were intuitive, because the task involves digging and stirring of ashes and dirt, which cause particulates to become airborne. Smoke exposure during mop-up is the best characterized activity at project wildfires. With the exception of TSP, we are confident that the distribution of smoke exposure data for mop-up at project wildfires accurately represented what most firefighters experience. From a health consequence standpoint, the respirable particulate exposure is the main concern, averaging over half the ACGIH recommended TLV of 3.0 mg/m^3 (fig. 29). One goal for future monitoring efforts could be to augment the total suspended particulate data because our nine samples are inadequate to define the exposure potential.

Sawyer—Smoke exposure among sawyers at project wildfires was not especially high for any pollutant except benzene. One 93-minute benzene sample result from fire 64 was 0.82 ppm, which is above ACGIH recommended TLV but below the PEL. Because the other pollutants were at low concentrations during the sample period, yet they normally are well correlated to benzene in smoke, this high benzene sample was most likely due to gasoline exposure. Sawyers, pump operators, and fueling personnel share this potential for greater benzene exposures.

The 13 exposure samples obtained from sawyers at project wildfires did not document elevated CO exposures. We expected to see greater CO levels among those working so near to the exhaust of a chainsaw, especially if ambient winds were low or firelines were being constructed in dense fuels, such as chaparral, so that the engine exhaust was not well dispersed. The sawyers that we monitored were not in such conditions at the project wildfires. The same comments apply to swampers, and our three exposure samples from swampers at project wildfires did not show significantly elevated CO exposures.

Direct attack—The formaldehyde data provided a good indication of smoke exposures during direct attack relative to the other work activities (fig. 27). The 11 exposure samples from this task indicated slightly higher formaldehyde exposure than the other tasks. The smoke samples from direct attack at project wildfires were not obtained in especially smoky conditions, but for a given firefighter they showed higher smoke concentrations during the direct attack of spot fires and while digging line in a direct attack action than during bracketing periods of mop-up or line construction.

Engine—At project wildfires, all smoke exposure samples for the "engine" job task were obtained from a firefighter assigned to tend a portable gas-powered pump serving a fireline. This firefighter had minor exposure to drifting smoke from the fire, but remained at the road away from the fire for the entire work shift. We surmise that his relatively high CO and benzene exposures were mostly from the pump exhaust and exhaust from passing vehicles. The relatively high benzene levels were consistent with gasoline fumes. One 155-minute CO sample averaged 27 ppm, which underscored the point that workers may not always be aware of the hazards of working near operating engines.

Job task, initial attack wildfires—As at project wildfires, smoke exposure seemed to differ among firefighters depending on their job task. The differences were not statistically significant. More samples would be needed to evaluate statistical significance.

Attack—Smoke exposure among firefighters at initial attack wildfires reached the highest levels during direct attack and mobile attack and while digging line in a direct attack action (table 13). The average exposure to CO during these activities was about half the ACGIH recommended TLV, and respiratory irritant exposures averaged about 85 percent of the ACGIH recommended TLV standard. The highest exposures to both were above the ACGIH recommended TLVs, but few firefighters spent more than 8 hours on the fireline. Considering the variability of the exposures during these three tasks, adverse short-term health effects were expected, especially among workers sensitive to smoke.

The average smoke exposures during “attack” activities were somewhat higher at initial attack wildfires than at project wildfires. Three explanations may apply: (1) at small fires, firefighters often work in closer proximity to actively burning areas with less risk of entrapment than is possible at project wildfires and thus may receive higher smoke exposures; (2) fire crews during initial attack may endure brief, intense smoke exposures because they are in an emergency-response situation with the opportunity to control an incipient fire before more valuable resources are destroyed; and (3) relatively fewer direct attack samples were available from project wildfires and we may not have captured the range of exposures during this activity. A well-planned, routine smoke exposure monitoring program could show whether smoke exposures during direct attack differ between large and small fires.

Mop-up—Smoke exposure among firefighters during mop-up was low relative to the other work activities at initial attack wildfires, averaging about 45 percent of AGCIH recommended TLV for respiratory irritants (table 13). Respiratory irritant exposures among firefighters was similar at both initial attack wildfires and project wildfires, but the CO exposures were somewhat higher at the initial attack events (compare figs. 26 and 31).

Engine—The engine job category at initial attack wildfires included wildland fire engine operators and captains, rather than the pump operators represented at project wildfires. The initial attack “engine” individuals had low to moderate smoke exposures relative to the other work activities. They were either driving the fire engines during mobile attack or operating their engine’s pumps and directing their crew’s efforts.

Sawyer and swamper—The sawyers and swampers at the initial attack wildfires were working at close quarters within their hotshot crews to construct fireline adjacent to burned areas. Their CO exposures were greater than those for individuals performing the same tasks at project wildfires. As discussed above, the ability to work closely with small fires may cause higher smoke exposures at initial attack wildfires. Another factor in our data may be that the sawyer-swamper teams at initial attack wildfires were working either in dense brush (fires 66 and 70) or a narrow draw (fire 66); both situations could increase worker exposure by limiting the dispersion of exhaust from chainsaws.

Wind speed—Smoke exposure among firefighters engaged in mop-up showed no trend relative to ambient wind speed, but a correlation with wind was apparent among those working in “attack” activities. Figure 37 shows the relation. Smoke exposure rose by about 1 ppm CO with each additional mile per hour of windspeed. The r^2 for the regression was only 0.23, which limited its value as a predictive tool, but the correlation supports the observation that firefighters encounter smokier conditions near the head of the fire when the winds are strong. This result might be expected because fire intensity and rate of spread increases with ambient windspeed, as does the difficulty of suppressing the fire. Most of the samples represented in this graph were from initial attack wildfires, because wind data were not available for the project wildfires. A similar correlation may exist at project wildfires, however, because the highest sustained smoke exposures we measured at those occurred when an increasing afternoon wind transported smoke from a burnout operation into a crew of firefighters (fire 61, discussed above under holding and mop-up exposures at project wildfires). In future studies, data about whether a firefighter was upwind or downwind of a fire would help to clarify the role of windspeed: a high wind does not increase smoke exposure when firefighters are upwind of the fire.

Atmospheric inversions that limit dispersion of smoke provide another set of conditions where widespread and consistently high smoke levels are possible (as evidenced by several exposures at 35 to 55 ppm CO measured over 3 hours in such conditions at fire 20). Similar conditions are reported to have occurred at the Happy Camp wildfire complex in the Klamath National Forest in 1987 (Sutton and others 1988).

Other site factors—We believe that site factors are likely to exert influence on smoke exposure, but our data were inadequate to test this. Combustion research has shown that fires in heavier or wetter fuels produce more pollutants per ton of fuel consumed than those in dry or light fuels, which burn more completely (Ward and Hardy 1991). Because fuel moisture is a key determinant of fire behavior and intensity, a fire in fuels with high moisture content will burn more slowly and less completely, thereby increasing pollutant production. If such a slow-moving fire must be approached closely or from the downwind side, then firefighters would seem likely to have significant smoke exposures.

Differences in smoke exposure may exist among firefighters working in different fuel types due to differences in emission factors for the pollutants and because of different tactics employed for the specific fuel. For example, firefighters working with tractor and plow equipment in grass and brush in the Southeastern United States may have very different smoke exposure patterns than hand crew personnel working in steep timber in the Western United States. We do not have enough data from other regions and diverse vegetation types to evaluate these factors.

Dosimeter Performance

The electronic data-logging dosimeter is the best way to collect widespread CO exposure data. Our decision to rely exclusively on electronic data loggers in the 1995 season was based on our comparisons of the CO results from our reference method (ICM 128) with those obtained by the dosimeters during 1993-94 (fig. 38). Although the dosimeter data were slightly lower than those from the reference method, we were confident that rigorous quality assurance could overcome this problem. The dosimeters tended to become less sensitive to CO over a work shift (fig. 39), but the occurrence of this bias could be tested by presampling and postsampling QC checks of the sensor accuracy. Adhering to strict QC limits for the amount of acceptable bias yielded CO exposure data that are comparable among groups and methods. Figures 38 and 39 suggest that dosimeter data obtained without frequent objective checks of instrument performance are considered estimates. Such data would be of no value to a long-term, routine smoke exposure monitoring program.

Our QA program included evaluation of matrix effects on the data-logger sensors arising from interferences from the other components of smoke. By spiking known amounts of CO into whole-air samples of smoke, we showed that the accuracy of the Draeger dosimeter was not unduly affected by the smoke matrix at the levels we routinely monitored (fig. 40). We suggest that such an evaluation occur before a dosimeter model is selected for routine use at fires.

After our experience with the Draeger 190 data loggers, we concluded that the manufacturer's recommendations for calibration frequency were insufficient to obtain adequate accuracy in wildland fire conditions. We suggest twice-daily QC checks and a calibration frequency based on the QC check results. We also observed temperature sensitivity in the Draeger 190 data logger. Placing a dosimeter in direct sunlight on a hot day caused the data logger to falsely indicate up to 5 ppm CO; moving the dosimeter to the shade corrected the problem. The Draeger data loggers we evaluated were highly susceptible to water contacting the inlet filter and disabling the instrument, a consideration when evaluating product suitability to the rugged field conditions of firefighting. Radio-frequency shielding is another beneficial feature of many models. There are now many brands of electronic dosimeters available, with and without data-logging capability. With appropriate QC programs in place, most brands are capable of providing reliable information to the user.

A beneficial aspect of data-logging dosimeters is the ease of data collection and the rich information content of the exposure profiles, which provide continuous traces of CO levels throughout the monitoring period (refer to fig. 51). Detailed observations and timekeeping allow for postexposure debriefings on the smoke exposures that a fire crew encounters. Printing the graphs and data summaries provides permanent records of CO exposure, and the transfer of data to personal computers is simple. We were even able to accomplish this in the field at remote spike camps by using a notebook computer and a small 9-volt battery to power the Draeger data transfer adapter. With two small gas cylinders (a calibration gas and a QC check gas) and a portable computer, monitoring equipment adequate for weeks of data collection among several crews can weigh less than 3.6 kilograms and be as mobile as any fireline situation requires.

Most importantly, dosimeters provide the alarm capability to warn users of unhealthful CO levels and provide crew foremen or safety officers with an objective indicator of smoke intensity. Even though the combination of respiratory irritants reaches critical levels for crew health before CO does, CO can be monitored and related to the sum of respiratory irritants by a simple formula. By relying on dosimeters for a monitoring program, fire managers can decide objectively when action should occur, such as donning respiratory protection against irritants or evacuating when CO becomes hazardous.

Assume, for example, that the TWA CO exposure of a firefighter at a project wildfire is 23 ppm. This is within the AGCIH recommended exposure limit of 25 ppm. From the interpollutant regression equations in table 7, the corresponding irritant exposures are as follows:

Pollutant	**TWA exposure regression result**	**Recommended exposure limit**
Formaldehyde (HCHO)	0.087 ppm	0.3 ppm
Respirable particulate (PM3.5)	1.94 mg/m^3	3 mg/m^3
Acrolein (ACRO)	0.010 ppm	0.1 ppm

The combined irritant exposure is derived as follows from equation (1):

$$E_m = \frac{[HCHO]}{0.3} + \frac{[PM3.5]}{3} + \frac{[ACRO]}{0.1}$$

$$E_m = \frac{[0.087]}{0.3} + \frac{[1.94]}{3} + \frac{[0.01]}{0.1}$$

Because the irritant exposure exceeds 1.0, it does not meet AGCIH irritant exposure limits, and mitigating measures may need to be implemented to fall within compliance. At 23 ppm, the firefighter was not overexposed to CO. By wearing lightweight respiratory protection, the firefighter could continue to work without incurring harm from respiratory irritation. With proper advance training in respirator use, a lightweight respirator for fine particles could achieve this irritant control, providing CO is monitored closely. Carbon monoxide monitoring is important when using respirators because they do not protect against CO exposure even though they afford relief from respiratory tract irritation.

Observer Smoke Estimates

Observers' estimates of smoke exposure were variable but still seemed to be a practical tool for exposure management in the absence of real data. Based on our limited data, we believe that with further data from a broader range of exposures, observers' estimates may be widely useful for smoke exposure management. In situations such as those depicted in figures 41 through 45, our observers classified the actual exposure fairly well (see figs. 46 through 48). Although there is variation in the results, we found that a smoke class of 3 (medium) related to a CO exposure of about 30 ppm. Based on this, it is suggested that firefighters limit their work in "medium" smoke to keep smoke exposures within recommended limits. The regression for PM3.5 was the best among those examined, with an r^2 of 0.6 for 46 pairs of observer estimates and PM3.5 samples. The regressions for CO and formaldehyde were not as precise, probably because only particulate matter reflects, scatters, or absorbs visible light—all effects detectable by eye. Not enough data were obtained for total suspended particulate or acrolein to provide useful regressions, and none of the regressions contains enough data for high concentrations to determine the utility of this approach in very smoky conditions. For fire managers without access to monitoring equipment, the smoke classifications provide an interim approach to assess and control smoke exposure.

Management Implications

If the goal of managers is to minimize the exposure of firefighters to unhealthful levels of smoke that could exceed legal and recommended limits during wildfires, then managers could implement a program to manage smoke, composed of the following elements: (1) training in hazard awareness, (2) monitoring of routine smoke exposure, (3) evaluating exposure limits, (4) improving recordkeeping, (5) assessing health risks, (6) deploying respirators, and (7) involving workers and regulators.

The data we have indicate that firefighters mostly work in smoke levels that are not expected to cause health problems or exceed legal and recommended limits. Existing work practices are adequate to protect firefighters' health in those situations. Our data show, though, that firefighters occasionally work in situations where they endure smoke levels that exceed guidelines recommended by occupational health experts, levels that can even be higher than U.S. occupational safety regulations allow. Reducing such overexposures will reduce organizational liability and is expected to increase work force productivity and health. Wildland fire agencies could consider controlling these high-exposure situations through a focused program to reduce overexposure to smoke. Wildland fire agencies such as the Forest Service, BLM, and CDF already have in place many of the elements of a successful program. With minor revisions, development of pieces missing from the strategy, and appropriate technical and administrative oversight, overexposures to smoke can be reduced. The basic outline of a smoke exposure management program follows.

Training in Hazard Awareness

For change to occur, there must be consensus that change is needed. The work force must understand the hazards of smoke exposure, the short- and long-term health effects, the situations that cause overexposure to smoke, and methods to assess and avoid overexposure. The education must begin in the classroom, before firefighters are assigned to the field, but should be routinely refreshed to maintain a positive safety attitude. Field education about the hazards of firefighting is also important, and smoke hazards should be reviewed when they occur. The visual smoke exposure classifications we developed are a simple start to heighten worker and manager awareness of smoke exposure on the fireline, but it is important to include objective CO dosimetry and routinely inform firefighters of monitoring results.

Monitoring of Routine Smoke Exposure

Data gathered widely in a manner well integrated with the incident command system will allow adequate tracking of existing conditions and future trends in smoke exposure. Personal smoke exposure assessment could be added to the objectives of wildfire and prescribed fire safety management planning. A cache of equipment could be obtained, and safety officers or other personnel trained and held accountable for implementation of a well-designed monitoring plan at some representative percentage of fires. The sampling plan could achieve regional balance and capture smoke exposure data at initial attacks, during extended attack at project wildfires, and at prescribed burns. The program could be based on CO data loggers, after evaluation of the available products to select the best suited dosimeters. The monitoring could be done with strict adherence to protocol so that all data are comparable and of known quality. A small percentage of the monitored crews could be randomly selected for further evaluation of the correlations between CO and the respiratory irritants, and TSP could be monitored widely until that hazard is adequately assessed. The data could be evaluated at least annually to detect trends in exposure and refine exposure management strategies. The program could include periodic third-party data evaluation to validate data quality. A well-designed program can be done with little adverse impact on fire operations, provide many benefits, and cost surprisingly little.

Evaluating Exposure Limits

An independent panel of expert toxicologists could be convened to evaluate exposure data and the potential health effects among firefighters. This evaluation process could be used to determine whether the existing OSHA PELs are adequate or whether alternative standards should be derived. Consensus standards can then be set. The wildland fire workplace is very different from an industrial or office environment, and limits appropriate for firefighting may differ from those taken “off-the-shelf.” Depending on the pollutant, current exposure limits may be inappropriate.

Improving Recordkeeping

The existing accident reporting system at wildland fires does not enable efficient and confidential tracking of smoke-related illnesses among fireline personnel. Computers could enable better tracking of all work-related injury data to ultimately provide epidemiological data for those involved with the long-term health of the work force. Good recordkeeping is needed to measure progress in meeting injury and illness reduction goals.

Assessing Health Risks

Risk assessment is a valuable tool to evaluate the long-term health risks to firefighters from smoke exposure. A preliminary assessment has been done (Booze and Reinhardt 1996), but a refined risk assessment would be helpful if it included exposure data for all pollutants that firefighters face, including entrained dust exposures. This would improve upon existing toxicological dose-response data for fine particles and use realistic exposure assumptions.

Deploying Respirators

Our exposure data for respiratory irritants indicated that exposure to these may need to be reduced in peak exposure situations. Respirators are an effective way to do this. Most firefighters will seldom need to wear a respirator and may need them only for brief periods to mitigate the hazards. By donning respiratory protection on those occasions when the acute hazards would be reduced (except CO, with present technology), the firefighters still could be effective at their jobs—perhaps more so if the irritants were becoming incapacitating. Even though current respirator technology is not ideal, it is light and comfortable enough to enable firefighters to protect their lungs and maintain productivity in irritating and possibly damaging conditions.

Because respirator use is regulated by OSHA and equivalent state agencies, respirator deployment should occur only in the context of a respiratory protection program. Key elements in these programs include assessing the ability of individuals to work with respirators, training employees on the limits of respirator protection, and describing the implementation of medical surveillance procedures. Our data also suggest that current respirators for organic vapors and particulates should be worn in conjunction with CO alarm dosimeters to warn of concomitant CO overexposure. This is only an interim solution. New respirator technologies are needed to protect against CO exposure as well. Such a respirator design once was used by urban firefighters but was banned after being implicated in structural firefighting deaths. Because wildland fire atmospheres have not been shown to be immediately dangerous to life and health (without risking severe burns), it makes sense to develop a new lightweight respirator that protects against CO as well as the irritants. The main barrier is the lack of warning properties for CO overexposure. Reliable service-life indicators could be developed, however, for respirator cartridges to afford adequate protection for wildland firefighters.

Involving Workers and Regulators

Regular dialogue with OSHA or the responsible state agency, as well as employee representatives, is a key to ensuring that the smoke exposure management plan is workable and meets consensus goals. If the plan is not accepted by workers and managers, then it will not succeed. Finally, the regulatory agencies could be consulted for interpretations and clarifications on legal aspects and early review of the smoke exposure management plans.

Our study found that smoke exposure among firefighters is a problem that is not widespread but does warrant management action to improve current conditions. We believe we have identified the conditions associated with overexposure to smoke and have found that they are amenable to control through carefully designed management strategies. By implementing a smoke exposure management plan, fire management agencies will enhance their workers' health and productivity.

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
BLM	Bureau of Land Management
C	Ceiling limit
C_3H_4O	Acrolein
C_6H_6	Benzene
CDF	California Department of Forestry and Fire Protection
CFK	Coburn-Forster-Kane
CO	Carbon monoxide
CO_2	Carbon dioxide
COHb	Carboxyhemoglobin
CS_2	Carbon disulfide
DNPH	2,4-dinitrophenylhydrazine
E_m	Equivalent exposure limit for a mixture
EPA	U.S. Environmental Protection Agency
HCHO	Formaldehyde
HPLC	High-performance liquid chromatography
ICM	Intersociety Committee Method
MDL	Method detection limit
mg/m^3	Milligrams per cubic meter
µm	Micrometer
MTDC	Missoula Technology Development Center
NFDRS	National Fire Danger Rating System
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NPS	National Park Service

NWCG	National Wildfire Coordinating Group
OSHA	Occupational Safety and Health Administration
PE	Performance evaluation
PEL	Permissible exposure limit
PM3.5	Respirable particulate matter
ppm	Parts per million
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality control
r^2	Coefficient of determination
SOP	Standard operating procedure
STEL	Short-term exposure limit
TLV	Threshold limit value
TSP	Total suspended particulate
TWA	Time-weighted average
USDA	U.S. Department of Agriculture

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References

American Conference of Governmental Industrial Hygienists. 1996. 1996 TLVs® and BEIs®: Threshold Limit Values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH. 138 p.

Booze, T.F.; Reinhardt, T.E. 1996. Assessment of the health risks of chronic smoke exposure for wildland firefighters. [Place of publication unknown]: [Publisher unknown]. Unpublished report. Available from: Radian Corporation, 8501 N. Mopac Blvd., Austin, TX 78759.

Deeming, J.E.; Burgan, R.E.; Cohen, J.D. 1977. The national fire-danger rating system—1978. Gen. Tech. Rep. INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 63 p.

Dost, F.N. 1991. Acute toxicology of components of vegetation smoke. In: Reviews of environmental contamination and toxicology. New York: Springer-Verlag: 2-46. Vol. 119.

Harrison, R.; Materna, B.; Liu, D. [and others]. 1992. Respiratory effects of smoke exposure in wildland firefighters: methacholine challenge testing and exposure monitoring. [Place of publication unknown]: [Publisher unknown]. 30 p. Available from: California Occupational Health Program, California Department of Health Services, 2151 Berkeley Way, Rm. 504, Berkeley, CA 94704.

Jackson, G.;Tietz, J.G. 1979. Preliminary analysis: firefighters' exposure to carbon monoxide on wildfires and prescribed burns. Project Record. Missoula, MT: U.S. Department of Agriculture, Forest Service, Equipment Development Center.

Letts, D.; Fidler, A.T.; Deitchman, S. [and others]. 1991. Health hazard evaluation report, U.S. Department of the Interior, National Park Service, southern California. HETA 91-152-2140. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. 16 p.

Liedel, N.A.; Busch, K.A; Lynch, J.R. 1977. Occupational exposure sampling strategy manual. Cincinnati, OH: U.S. Department of Health, Education and Welfare, National Institute for Occupational Safety and Health: 125.

Lodge, J.P., ed. 1989. Method 128. In: Methods of air sampling and analysis. 3d ed. Chelsea, MI: Lewis Publishers, Inc.: 296-302.

Materna, B.L.; Jones, J.R.; Sutton, P.M. [and others]. 1992. Occupational exposures in California wildland fire fighting. American Industrial Hygiene Association Journal. 53 (1): 69-76.

National Institute for Occupational Safety and Health. 1989a. Manual of analytical methods. 3d ed. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control: 0500-1 to 0500-3.

National Institute for Occupational Safety and Health. 1989b. Manual of analytical methods. 3d ed. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control: 0600-1 to 0600-6.

National Institute for Occupational Safety and Health. 1989c. Manual of analytical methods. 3d ed. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control: 1501-1 to 1501-7.

Neter, J.; Wasserman, W; Kutner, M.H. 1983. Applied linear regression models. Homewood, IL: Irwin Publishers: 111-122.

Radian Corporation. 1993. Smoke exposure assessment quality assurance project plan. Austin, TX.

Radian Corporation. 1996. Smoke exposure assessment at wildfires and prescribed burns quality assurance project plan. Austin, TX.

Reh, C.M.; Deitchman, S.D. 1992. Health hazard evaluation report, U.S. Department of the Interior, National Park Service, Yellowstone National Park, Wyoming. HETA 88-320-2176. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

Reh, C.M.; Letts, D.; Deitchman, S. 1994. Health hazard evaluation report, U.S. Department of the Interior, National Park Service, Yosemite National Park, California. HETA 90-0365-2314 (2415). Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health. 33 p.

Reinhardt, T.E.; Black, J.; Ottmar, R.D. 1995a. Smoke exposure at northern California vegetation fires: [Place of publication unknown]: [Publisher unknown]; final report. Available from: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 4043 Roosevelt Way NE, Seattle, WA 98105.

Reinhardt, T.E.; Black, J.; Ottmar, R.D. 1995b. Smoke exposure at Pacific Northwest wildfires. [Place of publication unknown]: [Publisher unknown]; final report. Available from: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 4043 Roosevelt Way NE, Seattle, WA 98105.

Reinhardt, T.E.; Hanneman, A.H.; Ottmar, R.D. 1994. Smoke exposure at prescribed burns: [Place of publication unknown]: [Publisher unknown]; final report. 123 p. Available from: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 4043 Roosevelt Way NE, Seattle, WA 98105.

Reinhardt,Tim; Ottmar, Roger D. 1997a. Smoke exposure at western wildfires. [Place of publication unknown]: [Publisher unknown]; final report. 149 p. Available from: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 4043 Roosevelt Way NE, Seattle, WA 98105.

Reinhardt,Timothy E.; Ottmar, Roger D. 1997b. Smoke exposure among wildland firefighters: a review and discussion of current literature. Gen. Tech. Rep. PNW-GTR- 373. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 61 p.

Rothman, N.; Ford, D.P.; Baser, M.E. [and others]. 1991. Pulmonary function and respiratory symptoms in wildland firefighters. Journal of Occupational Medicine. 33(11): 1163-1169.

Sandberg, D.V.; Ward, D.E.; Ottmar, R.D. [and others]. 1989. Mitigation of prescribed fire atmospheric pollution through increased utilization of hardwoods, piled residues, and long-needled conifers. [Place of publication unknown]: [Publisher unknown]; final report. 160 p. Available from: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 4043 Roosevelt Way NE, Seattle, WA 98105.

SAS Institute, Inc. 1989. SAS/STAT® user's guide, version 6, 4th edition. Cary, NC. 846 p. Vol. 2.

Shapiro, S.S.; Wilk, M.B. 1965. An analysis of variance test for normality (complete samples). Biometrika. 52: 591-611.

Smith, S.R.; Steinberg, S; Gaydos, J.C. 1996. Errors in derivations of the Coburn-Forster-Kane equation for predicting carboxyhemoglobin. American Industrial Hygiene Association Journal. 57: 621-625.

Steel, R.G.D.; Torrie, J.H. 1980. Principles and procedures of statistics—a biometrical approach. 2d ed. New York: McGraw Hill. 633 p.

Sutton, P.; Castorina, J.; Harrison, R.; Ford, D.P. 1988. Carbon monoxide exposure in wildland fire fighters. Field Investigation FI-87-008. [Place of publication unknown]: [Publisher unknown]. Available from: California Department of Health Services, Epidemiologic Studies and Surveillance Section and Occupational Health Surveillance and Evaluation Program, 2151 Berkeley Way, Rm. 504, Berkeley, CA 94704.

Tejada, S.B. 1986. Evaluation of silica gel cartridges coated in-situ with acidified 2,4-dinitrophenylhydrazine for sampling aldehydes and ketones in air. International Journal of Analytical Chemistry. 26: 167-185.

U.S. Department of Labor. 1979. Compliance officer's field manual. Washington, DC: Occupational Health and Safety Administration.

U.S. Department of Labor. 1993. Carbon monoxide in workplace atmospheres (direct-reading monitor). Method No. ID-209. Salt Lake City, UT: Occupational Safety and Health Administration, Technical Center. 49 p.

U.S. Environmental Protection Agency 1984. Code of federal regulations, title 40, chapter I, part 136, appendix B: definition and procedure for the determination of the method detection limit–revision 1.11. Washington, DC: 198.

U.S. Environmental Protection Agency, Research and Development. 1986. Supplement to EPA/600/4-84/041: compendium of methods for the determination of toxic organic compounds in ambient air. Research Triangle Park, NC: Environmental Monitoring Systems Laboratory. 38 p.

Ward, Darold E.; Hardy, Colin C. 1991. Smoke emissions from wildland fires. Environmental International. 17: 117-134.

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