United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-526
October 2000

Smoke Exposure Among Firefighters at Prescribed Burns in the Pacific Northwest

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Abstract

Reinhardt, Timothy E.; Ottmar, Roger D., Hanneman, Andrew J.S. 2000. Smoke exposure among firefighters at prescribed burns in the Pacific Northwest. Res. Pap. PNW-RP-526. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 45 p.

Smoke exposure measurements among firefighters during prescribed burns in the Pacific Northwest between 1991 and 1994 showed that a small but significant percentage of workers experienced exposure to carbon monoxide and respiratory irritants that exceeded occupational exposure limits. This most often was caused by unfavorable winds or fire behavior and occurred mostly among workers involved in maintaining the fire within the prescribed boundaries. Smoke exposure in such peak exposure situations was up to three times above recommended limits. Exposure to acrolein, benzene, formaldehyde, and respirable particulate matter could be predicted from measurements of carbon monoxide. Electronic dosimeters were the best tool to assess smoke exposure routinely, so long as quality assurance concepts were included in the monitoring program.

Keywords: Smoke hazards, firefighters, health effects, pollutants, Pacific Northwest.

Summary

Smoke exposure at prescribed burns was studied by the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, and Radian Corporation between 1991 and 1994 to assess the significance of exposure to smoke among firefighters during prescribed burns in the Pacific Northwest. The study measured smoke exposure among over 200 firefighters to determine their average exposure to smoke during burns, and over entire work shifts. Samples were obtained to compare the relative smoke exposure potential of each job task at a prescribed fire and identify whether certain site-specific or environmental conditions were associated with high smoke exposures. The study examined the correlations among pollutants in smoke to determine whether exposure to many pollutants might be estimated from measurements of a single surrogate pollutant and thus lower future monitoring costs. The study also evaluated simple dosimeter technology for routine monitoring of carbon monoxide (CO) exposure.

The study found that among firefighters, up to 14 percent of the exposures to respiratory irritants (respirable particles, formaldehyde, and acrolein) and 8 percent of the exposures to CO were above limits recommended by occupational health advisory organizations to protect worker health. Benzene exposure was found to not be significant. About 2 percent of the CO exposures and 5 percent of the respiratory irritant exposures exceeded permissible exposure limits set by the Occupational Safety and Health Administration (OSHA), which are less stringent than the recommended limits but legally applicable to federal agencies. Average exposures were higher during the burns, but in most cases the unexposed time spent in traveling and setting up the burn reduced the overall work shift exposure below permissible exposure limits. The highest respiratory irritant exposures were about six times the recommended exposure limits. These high levels of smoke exposure occurred during line holding, line supervision, and direct attack activities. Such peak exposures exceeded recommended limits for short-term exposures. Excessive smoke exposure during these work tasks were significantly correlated with burning under higher windspeed conditions.

Several suggestions are presented for managing smoke exposure at prescribed burns. First, a risk assessment is underway and, when completed, could be used to assess the long-term health risks among prescribed burners. Second, a smoke exposure management program could be implemented to reduce overexposures to smoke at prescribed fires. This program would include the following elements:

- Improve smoke exposure hazard awareness training.

- Monitor CO exposure routinely at prescribed burns by using electronic dosimeters that record CO exposure data for later retrieval with a computer.

- Use interpollutant correlations to estimate exposure to irritants based on CO measurements.

- Develop a health surveillance program to identify individuals at risk of adverse health effects from smoke exposure and track the health of workers chronically exposed to smoke.

- Modify prescribed burning practices to reduce exposure to smoke through better preburn planning and strategic water application, burning under wet conditions, limiting burning in windy conditions if adjacent resources are at risk, and accepting minor prescribed burn escapes and managing them when conditions abate.

- Implement training and fit-testing for an OSHA-compliant respirator program that includes outfitting core firefighters with respiratory protection against irritants and electronic CO dosimeters to protect against CO, which is not removed by currently available respirators.

The adverse health effects of smoke exposure at prescribed fires seem to be manageable. With some planning, existing programs could be improved and new programs established that would effectively manage smoke exposure with minimal effort and cost.

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Figure 1—Firefighters exposed to smoke from prescribed fire in grass.

Introduction

Wildland firefighters commonly experience some degree of smoke exposure during prescribed burning operations (fig. 1). Prescribed burns are beneficial uses of fire planned to achieve land management objectives, such as forest and grassland regeneration, forage production for wildlife, timber stand improvement, and wildfire hazard reduction. Although prescribed burning has been practiced for many years, the significance of the smoke exposure faced by fireline personnel had not been assessed previously. It is important to understand the frequency and magnitude of smoke exposure to determine the potential for adverse health effects among firefighters and to assess compliance with occupational safety regulations. By understanding the causes of overexposure to smoke, we can maintain smoke exposure below levels causing adverse health effects. This paper summarizes measurements of smoke exposure among wildland firefighters conducting prescribed burns in Washington and Oregon between 1991 and 1994.

Background

The U.S. Department of Agriculture, Forest Service, lists occupational smoke exposure among the potential adverse environmental effects of prescribed fire in an environmental impact statement for vegetation management (U.S. Department of Agriculture 1988). In 1988 and 1989, the U.S. Department of Agriculture, Forest Service, Pacific Northwest Region (Region 6), the U.S. Department of the Interior, Bureau of

Land Management (BLM), and the State of California Department of Forestry and Fire Protection (CDF) funded the Pacific Northwest Research Station (PNW) to conduct a pilot study of smoke exposure among firefighters at prescribed fires (Reinhardt 1991). Based on the pilot study results, Region 6 asked PNW to perform a 3-year comprehensive smoke exposure assessment at prescribed fires in the Pacific Northwest (Reinhardt and others 1994). The assessment work was carried out by Station staff and Radian Corporation. The results of the comprehensive smoke exposure assessment are summarized in this paper.

Health Hazards in Smoke

Smoke exposure among wildland firefighters has been associated with adverse health effects ranging from acute irritation and shortness of breath to headaches, dizziness, and nausea lasting up to several hours. What causes this? Smoke from vegetative biomass is composed of hundreds of chemicals in gaseous, liquid, and solid forms. Of these, we considered the chief inhalation hazards to be carbon monoxide (CO), aldehydes, benzene, and respirable particulate matter with a median aerodynamic equivalent diameter of 3.5-µm (PM3.5). This conclusion was reached on the basis of the presence of these hazards in smoke and their relative toxicity data. Of the aldehydes, formaldehyde (HCHO) and acrolein were considered the most likely hazards, but many other low- to middle-molecular weight aldehydes also are present in smoke.

Exposure to these aldehydes causes immediate eye and upper respiratory tract irritation, as does exposure to PM3.5. These gases and PM3.5 also can penetrate far into the lungs of unprotected workers. This is a concern because long-term health effects, lasting from days to perhaps months, recently have been identified among wildland firefighters, including losses of pulmonary function (such as slightly diminished capacity to breathe, constriction of the respiratory tract, and hypersensitivity of the small airways).

The University of Washington conducted an evaluation of respiratory effects of smoke exposure among firefighters in the Pacific Northwest (Betchley and others 1997). They measured spirometric parameters (measurements of lung function) and the prevalence of adverse respiratory health symptoms among 76 firefighters before and after work shifts (cross-shift) in 1992 and 1993, and among 53 firefighters before and after the 1992 fire season (cross-season). Except for coughs, symptoms of respiratory distress increased in the cross-shift analysis; however, none of the symptoms increased significantly. The cross-shift analysis found small but statistically significant average individual declines in forced vital capacity of the lung (FVC), forced expiratory volume in one second (FEV1), and forced expiratory flow in the midrange of the exhalation (FEF25-75). These declines were on the order of 1 percent for FVC, 3 percent for FEV1, and 6 percent for FEF25-75. Across a firefighting season, the declines were slightly lower, and only declines in FEV1 and FEF25-75 were statistically significant. A small subset of 10 firefighters from the 1992 season were followed at the beginning of the 1993 season. The lung function of 9 out of 10 of these firefighters had returned to their preseason 1992 values.

In another project, the National Institute for Occupational Safety and Health (NIOSH) studied six highly trained type I crews for the National Park Service (NPS). The firefighters had small declines in lung function between the beginning and end of the summer wildfire season, but the declines were not statistically significant. In spite of the lack of statistical power, it is suggestive that the study found the greatest lung function decreases among those firefighters who reported working the most hours (Letts and others 1991). A similar study among 69 CDF firefighters found that firefighters reported a significant increase in eye and nose irritation, cough, phlegm, and wheezing at the end of the fire season. Small declines in lung function also were found, and although these were statistically significant, high smoke exposures in the last week of the study made it impossible to determine whether the lung function changes were due to smoke exposures in the last week or over the whole fire season (Rothman and others 1991). Another study of smoke exposure and cross-shift health effects among type I and lesser trained type II crews on behalf of the NPS found small but significant declines in lung function among the type I crews and lesser declines among the type II crews (Reh and others 1994). Because of confounding factors and the lack of actual exposure data, cause and effect relations between respiratory irritants in smoke, such as formaldehyde, acrolein, or PM3.5, and these relatively short-term pulmonary effects have been difficult to prove. Long-term adverse effects on respiratory health remain unstudied.

Carbon monoxide has acute effects on the body, ranging from slightly diminished work capacity to a loss of mental acuity, acute nausea, and severe headache at levels that have been measured at prescribed burns (Reinhardt and others 1994). Death can occur during extreme exposure levels; however, these levels are unlikely to exist outside enclosed spaces. Carbon monoxide has a well-established mechanism of action, displacing oxygen from hemoglobin in the blood to form carboxyhemoglobin (COHb), which damages tissues that do not stand loss of oxygen very well, especially the brain and heart. This oxygen deprivation effect poses a significant hazard to the developing fetus of a pregnant firefighter. Fortunately, most of these effects are reversible and CO is rapidly removed from the body (after evacuation of a victim to clean air, CO has a half-life in the body of about 4 hours). Circumstantial evidence among exposed populations has linked CO exposure to longer term heart disease, but the evidence is equivocal.

At the low levels of benzene observed among firefighters (Reinhardt and others 1994), adverse health effects are not likely, although gasoline-handling activities could cause exposures an order of magnitude or more higher—levels at which sustained career exposures are associated with leukemia and other blood disorders. Carbon dioxide (CO_2) is present at relatively high levels in smoke, but its toxicity is relatively low and thus it is not considered a significant hazard. The hundreds of other chemicals in smoke are unlikely to pose a significant health hazard, but this conclusion could change as our knowledge of toxicology and smoke exposure improves (Dost 1991). The study summarized in this research paper (also see Reinhardt and others 1994) measured exposure to acrolein, benzene, CO, CO_2, formaldehyde, and PM3.5.

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

Exposure limit	Acrolein	Benzene	Carbon monoxide	Formaldehyde	Respirable particulate matter
	- - - - - - - - - - - -*Parts per million*			- - - - - - - - - - - - - -	*Mg/m³*
OSHA permissible exposure limit	0.1 TWA	1.0 TWA 5.0 STEL-C	50 TWA	0.75 TWA 2.0 STEL	5 TWA
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 .1 STEL-C	.5 TWA 2.5 STEL	25 TWA	.3 TWA-C	3 TWA
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

Smoke Exposure Evaluation Criteria

How does one decide whether smoke exposure is acceptable or not? There are several evaluation criteria for occupational inhalation exposures. The Occupational Safety and Health Administration (OSHA) sets permissible exposure limits (PELs) for federal employees in the United States and for public and private sector employees in states having no state equivalent of OSHA. Twenty-three states currently have designated equivalent state agencies, such as the California Occupational Safety and Health Administration (CAL-OSHA), Oregon OSHA, and the Washington Department of Labor and Industries, that have legal jurisdiction over all state and private industry workers. These state agencies have established PELs at least as stringent as those of OSHA. The PELs are enforceable by law.

There are relatively few PELs in spite of the many thousands of chemical compounds known to cause adverse health effects. Where PELs have not been established or are inadequate, OSHA and the state agencies often rely on other sources to determine exposure standards for inhalation hazards. 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 thorough reviews of available scientific information. Similarly, the American Conference of Governmental Industrial

Hygienists (ACGIH) maintains an annually updated, well-regarded compendium of threshold limit values (TLVs) for worker safety (ACGIH 2000).

Each organization expresses the exposure limits for airborne pollutants 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 work week, 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 (C), a STEL concentration that should not be exceeded, even instantaneously.

Table 1 summarizes the current regulatory exposure limits for hazards faced by firefighters and the most current (or proposed) guidelines recommended by occupational health organizations. In our opinion, the ACGIH TLVs are the best guideline for assessing exposures because they incorporate the latest scientific evidence, unlike the PELs.

Multiple Contaminants

Where workers face multiple air pollutants in a workplace, the combined effect of the pollutants is considered. Acrolein, formaldehyde, and PM3.5 all cause irritant effects in the same organs: the respiratory tract and mucous membranes. Following the approach recommended by ACGIH and OSHA, a combined “equivalent irritant exposure” index can be calculated from equation (1):

$$E_m = \frac{\text{conc.}[C_3H_4O]}{\text{limit }[C_3H_4O]} + \frac{\text{conc.}[HCHO]}{\text{limit }[HCHO]} + \frac{\text{conc.}[PM3.5]}{\text{limit }[PM3.5]} , \qquad (1)$$

where E_m	=	the equivalent exposure irritant index (unitless);
conc.	=	the measured concentration of the irritant;
limit	=	the selected exposure limit of the irritant; i.e., the PEL or TLV;
$[C3H_4O]$	=	acrolein (parts per million [ppm]);
[HCHO]	=	formaldehyde (ppm); and
[PM3.5]	=	respirable particulate (mg/m^3).

This irritant exposure calculation was used as an important exposure evaluation criterion in this research. The equivalent exposure (E_m) must be maintained below 1.0 for a workplace to be considered in compliance with the criterion. Other unsampled irritants are likely present in smoke, including many other aldehydes, formic acid, and possibly sulfur dioxide (Dost 1991, Reh and others 1994). Our estimate of E_m probably underestimates the irritant nature of smoke because we have no detailed exposure data for the other irritants. If such exposure data become available, other irritants can be included by expanding equation (1). We considered other common effects of the pollutants, such as carcinogenicity for benzene and formaldehyde, but we do not suggest an additive model for those two chemicals because the sites of carcinogenesis differ.

Exposure Limit Adjustments

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. Prescribed burning 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 8 hours of highest exposure 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 are 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 necessary for all pollutants in smoke. Exposure limits for acrolein and PM3.5 are based on acute irritant effects and do not need to be adjusted downward for longer work shifts. The ACGIH formaldehyde limit of 0.3 ppm is a ceiling limit, intended to protect most of the work force from irritant effects (American Conference of Governmental Industrial Hygienists 1992); therefore, adjustment downward is not required. 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, and adjustment is thus necessary for longer duration work shifts.

Equation (2) shows the recommended model from OSHA:

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

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 TLV), 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 the better model for adjusting the CO exposure limit if detailed exposure, pulmonary function, and site altitude data are available.

Objectives

A logical way to manage the problem of smoke exposure is to (1) first assess the exposure to smoke, (2) then assess the likely health risks based on the exposure data, and (3) develop a risk management strategy to control any unreasonable risks and maintain a safe and healthy workplace. The technical approach of our study was designed to meet the exposure assessment need while providing important data for risk assessment and developing risk management strategies. The following objectives were defined:

- Exposure assessment—evaluate the average and peak exposures to the important components of smoke among firefighters at prescribed burns.

- Exposure determinants—identify the important variables that contribute to low or high smoke exposures.

- Dosimeter evaluation—try several models of inexpensive dosimeters that measure CO to see if they are useful tools to gather data about smoke levels at prescribed burns.

- Pollutant correlations—evaluate whether the important pollutants in smoke are sufficiently correlated such that exposure to all could be estimated from measurements of only one or two surrogate pollutants.

Shift-Average Exposure Assessment

The main project objective was a comprehensive assessment of inhalation exposures to smoke among firefighters at prescribed burns in the Pacific Northwest. “Smoke exposure” includes the most likely hazards in smoke: acrolein, benzene, CO, formaldehyde, and PM3.5. This assessment of smoke exposure included information about the average level of contaminants that firefighters breathe while on the fireline, the peak levels during intense exposures, and the average exposures during a work shift. The average work shift was considered as the average number of hours an individual was in work status, including onsite work and travel hours. Monitoring was originally planned only at broadcast burns of “activity fuels” (in this paper, the term “fuel” refers to the combustible woody debris and herbaceous vegetation on a site; “activity fuels” are those produced by human disturbance, such as timber harvest residues, or slash). Over time, monitoring was expanded to include some underburns in natural and activity fuels because of the shifting emphasis by land managers toward those types of prescribed burns.

Exposure Determinants

A second project objective was to identify the key variables influencing smoke exposure. Ultimately, risk management strategy depends on understanding the factors that come together to produce overexposures to smoke. The following factors were tentatively identified in a preliminary study by PNW (Reinhardt 1989):

- Work activity, which influences smoke exposure because proximity and duration of exposure to smoke differs among workers performing different tasks at a fire.

- Fuel loading, which influences fire behavior and the techniques used to ignite the burn.

- Fuel moisture, which has a strong influence on fire behavior.

- Ambient windspeed, which affects both fire behavior and smoke transport across firelines.

Dosimeter Performance Evaluation

Smoke exposure data collection using approved sampling and analysis methods for the important pollutants in smoke is time consuming and costly, and it does not provide quick feedback to fire managers. Recent advances have been made in chemical sorbent and electrochemical dosimeters, especially for CO. An important objective of our study was to evaluate the performance of these devices, including their accuracy, precision, and feasibility in the field environment.

Pollutant Correlations

The project objectives included concurrent sampling of all pollutants to find out whether the level of each pollutant in a sample was related to the levels of the others in that sample. If so, measurements of a single pollutant could serve as a surrogate to estimate exposure to the rest of the hazards in smoke. A strong set of relations could allow fire management organizations to reduce the costs of effectively monitoring smoke exposure.

Methods

An overview of the field and laboratory methods used in this project is given in this section. Details of the standard operating procedures and an overview of the quality assurance plans are contained in the project report (Reinhardt and others 1994).

Prescribed burns were selected from a variety of areas in the Northwestern United States. Burns were selected to cover the range of fuel loading and fuel moisture regimes typical for this region, within logistical limitations. Six firefighters generally were selected for sampling each day, usually by random draw; but at some burns, volunteers were requested from those present for the burn. Most of the crews at the burns were hand crews, ranging in experience from part-time burners at their first burn to highly experienced hotshot or smokejumper crew leaders and fire management officers. Although smokers were included among the sampled firefighters, they were asked to refrain from smoking while the samples were collected. Where more than one prescribed burn occurred in a day, the same firefighters were monitored at each burn.

Firefighters wore a 9-pound sampling apparatus during monitoring (fig. 2). The apparatus consisted of three battery-powered personal sampling pumps attached to a web-gear pack or backpack. The pumps pulled air into the following sample collection devices:

- An inert gas sampling bag for collection of CO and CO_2 followed by analysis in the laboratory according to intersociety committee method 128 (Lodge 1989).

Figure 2—Sample-collection apparatus worn by firefighters.

- Sorbent tubes for benzene (charcoal), formaldehyde, and acrolein (coated C-18 Sep-Paks®[1]). The benzene was analyzed in the laboratory according to NIOSH method 1501 (National Institute for Occupational Safety and Health 1989), and the formaldehyde and acrolein were measured via modified EPA method TO-11 (U.S. Environmental Protection Agency 1986).

- A filter-cassette assembly with a nylon cyclone to achieve a 3.5-µm cutpoint for respirable particulate matter, followed by analysis in the laboratory according to NIOSH method 0600 (National Institute for Occupational Safety and Health 1989).

All laboratory analyses were performed at the Pacific Northwest Research Station, Forestry Sciences Laboratory, Seattle. Samples were stored and transported in accordance with established procedures to prevent sample degradation. Chain-of-custody procedures were maintained throughout sample transport and laboratory analysis.

[1] 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.

For each firefighter, air samples were collected near the face (in the breathing zone) consecutively during the work shift. The three pumps in each sample pack were operated concurrently. Each sampled period for a firefighter lasted the duration of a given work activity, or as limited by the capacity of gas sample bag. Peak exposure samples lasted for the duration of the peak exposure situation, with a typical minimum duration of 15 minutes to ensure collection of sufficient sample volume.

During each burn, observers tracked the firefighters, calibrated sampling equipment, and recorded observations about the smoke intensity and work activity for each firefighter being monitored. After the conclusion of a sample period, the observer began a new sample as quickly as possible if smoke exposure continued. Because a spare sampling pack was not always available to resume sampling, unsampled time would accrue for the firefighter while the sample media were changed. Change of sampling equipment took at least 8 minutes, and logistical problems sometimes delayed redeployment of the sampler on the firefighter for several hours.

Sampling usually did not begin until smoke actually reached the firefighter, to minimize unnecessary dilution of CO samples to levels below our method detection limits. If a firefighter took a work break in clean air or moved out of smoke, sampling often was halted 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.

Because some firefighters were selected by the volunteer approach, the results may be biased; for example, uncooperative workers who see no harm in smoke exposure may endure higher smoke exposure than volunteers who consider smoke harmful. Another potential source of bias is the presence of the study team. Crew supervisors may manage their personnel differently with the study team present; this could cause higher or lower smoke exposures, depending on the supervisor.

Fuel moisture data were obtained from either the local fuels management staff or from an electronic moisture probe. With the moisture probe, at least nine separate preburn fuel moisture measurements were obtained across the unit and averaged for each site. Ambient wind data were obtained by using a cup anemometer located 5 feet above ground at a convenient location adjacent to the burn. Local windspeeds at ridgetops or at a higher elevation above ground likely would be greater than we measured.

Electronic dataloggers were calibrated at least monthly according to the manufacturer's recommendations. Immediately after calibration they were checked against a second calibration gas mixture and were within 1 percent of theoretical values. The performance of the instruments in the field was assessed by challenging the instrument with the second calibration gas mixture before and after the burns. During sampling, the dataloggers were deployed in the breathing zone of the firefighters along with the passive dosimeter tubes.

Quality Assurance

A comprehensive quality assurance (QA) program was developed for the project by an independent QA officer not otherwise involved in the project. The QA program is documented in the quality assurance project plan (Radian Corporation 1993). In accordance with the QA program, many measurements of quality control (QC) parameters were obtained from laboratory and field QC samples and procedures that included trip blanks, field blanks, lab blanks, method and matrix spikes, field replicates (collocated ambient smoke samples obtained at each fire), lab duplicates, calibration check samples, evaluation of response factors and calibration parameters, and performance evaluation samples prepared by an independent laboratory. All QC results were recorded on control charts, and trends were assessed throughout the project. This QA program enabled identification and correction of problems before they affected data quality. Comprehensive field and laboratory audits of the project were conducted semiannually by the QA officer. These audits and a complete QA review of the data are summarized in the original report (Reinhardt and others 1994).

Data Analysis

The smoke sample concentration data were not distributed normally (in a bell-shaped curve) around a central value but were logarithmically distributed (skewed to one side, with many low-concentration data and few high-concentration data). Analytical results for values below the method detection limits were used rather than replaced by some other value, such as the detection limit or one-half the detection limit. Values below the detection limit constituted 22 percent of the valid acrolein data, 35 percent of the benzene data, 0 percent of the CO_2 data, 5 percent of the CO data, 12 percent of the formaldehyde data, and 17 percent of the PM3.5 data. To calculate average values for exposures, the data were logarithmically transformed before the mean was calculated. We used an initial addition of 1 to all values to enable the use of zero-concentration data (data below method detection limits, with analytical results of zero) (Steel and Torrie 1980). Equation (3) provides the formula for this transformation:

$$\mathrm{L}X = \mathrm{LN}\ (X+1) \quad , \tag{3}$$

where
X = the pollutant concentration, and
LX = the natural logarithm-transformed concentration.

Each mean concentration was obtained by calculating the mean of the logarithmically transformed data, then converting that data back to the original units through equation (4):

$$\mathrm{X} = (e^{\mathrm{L}X} - 1) \quad , \tag{4}$$

where
e = natural logarithm base.

Correlations among pollutants were evaluated from samples and field replicates that successfully measured the different pollutants over the same period for a given sampling pack. Linear regressions between individual pollutants were calculated in SAS®

(SAS Institute, Inc. 1989). Residuals of the regressions were examined for goodness-of-fit and, trends versus other independent variables, such as sampling or analysis date, associated field blank level, etc. Regressions on the log-transformed data also were evaluated but did not offer substantial improvement. Higher order equations were not attempted. The regressions between benzene and the other pollutants did not use data from sample periods where the smoke was likely to have additional benzene from gasoline sources, such as during chainsaw operation or lighting fires with a drip torch.

Time-weighted averages were calculated for each firefighter to assess smoke exposure over the duration of a work shift and while on the fireline. Each TWA was calculated by the following formula:

$$\mathrm{TWA} = \frac{C_1 \times T_1 + C_2 \times T_2 + \ldots + C_n \times T_n}{\mathrm{T}_1 + \mathrm{T}_2 + \ldots + \mathrm{T}_n}\ , \tag{5}$$

where

T_n = the time in minutes of period *n*, and
C_n = the pollutant concentration during period *n*.

Meal breaks were excluded from the TWA calculations unless smoke exposure continued during the break. Where lunch breaks were in clean air, only the standard half-hour lunch was excluded when the de facto lunch extended beyond the allotted half-hour. If the lunch was less than one half-hour, only the actual time was excluded from the TWA calculations. Travel to and from the unit was in most cases compensated time and therefore was included in the TWA calculations.

The TWA smoke exposure assessment had to incorporate both the sampled and unsampled portions of the workday. We picked one of five methods to calculate the sample concentration during each distinct period that made up the TWA for the firefighter. These methods are summarized in table 2 as five codes describing the possible treatments applied to the TWA period.

For sampled periods for which we did not have valid data for a pollutant, the missing concentration datum was calculated by regression from the other pollutants successfully measured from the firefighter during that period. The pollutant chosen as the regressor was selected from those available for the sample period based on the best coefficient of determination (r^2) value for the regression. When more than one regressor pollutant with an equivalent r^2 value was available, the regression results were averaged.

The resulting TWA exposures (fireline-duration and shift-duration) calculated for each firefighter were combined into fireline and work shift TWA data sets. For each data set, cumulative frequency distributions were plotted to show the percentage of firefighters exposed at a given pollutant level.

Peak exposure samples were identified based on a sample duration of less than 30 minutes and field notes from the observers indicating that the sample was for a relatively smoky situation. The mean concentrations of the peak exposure samples were calculated in SAS by using logarithmic transformations as described above.

Table 2—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.
2	$C_n=0$	Concentration during the period is assumed to equal zero.
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 bracketed sampling periods.

Exposure determinants were evaluated in two ways: by comparison of mean exposure for each work activity, and by examining regressions between exposure (dependent variable) and the independent environmental variables of windspeed, fuel moisture, and preburn fuel loading. The discrete work activities we identified were:

- Burn boss—This job involved the overall ground supervision of the prescribed burn. This individual often used a drip torch in the course of their duties.

- Lighting—This involved using a hand-held drip torch to ignite woody fuels in the unit. At two burns, the sampled individuals supplemented the standard drip torch teams by using an all-terrain vehicle with a tank-fed drip torch on the back, and at one unit, by forming balls of AlumaGel by hand and throwing the ignited balls into the unit.

- Holding—Workers at this task maintained the fire within the unit boundaries by patrolling the fireline and areas outside the unit, used a fire hose and hand tools to extinguish small spot-fires outside the unit, and managed water supplies and equipment along the fireline.

- Holding supervisor—The employee in this position oversaw line holding activities, resolved problems that arose during the burn, and often performed holding tasks as well.

- Attack—This activity was similar to holding but was a more focused, high-intensity effort to contain larger spot fires and extinguish flaming and smoldering combustion that had escaped the prescribed unit boundaries.

- Engine—The engine activity included anyone who was driving or working from a vehicle, such as a pickup truck or wildland fire engine. These were incidental assignments that arose during the shift, because designated vehicle drivers that periodically left the unit were excluded from the pool selected for sampling at the start of the day.

- Sawyer—This work activity describes those using and maintaining a chainsaw.

- Mop-up—Any workers using hand tools or fire hoses to extinguish smoldering woody debris and duff after the flaming phase of the fire had passed. This task included maintenance of a hose system to supply water at the burn unit.

The individual sample data were assigned to each work activity, and the log-transformed data distributions for each work activity were tested for normality by using a Shapiro-Wilk's Test (Shapiro and Wilk 1965). Because the transformed data approximated a normal distribution, geometric mean concentrations were calculated for each work activity from the transformed data. Tukey's Multiple Comparison Test was applied to test the transformed data for significant differences in smoke exposure among the work tasks (Steel and Torrie 1980).

Windspeed data were obtained as average values over various time periods for each unit burned in the day. For days where multiple units were burned by the fire crew, the individual unit averages or single values for windspeed or fuel moisture were time weighted by the amount of time the firefighters spent at each unit. Fuel loading data were obtained from each fire manager's preburn inventory data for each unit. These data were also time weighted by the amount of time the firefighters spent at each unit. If duff loading was reported in inches by the burn managers, these were converted to tons per acre by one of three conversion factors:

- East side of Cascade Range: 12.1
- West side of Cascade Range: 18.7
- East side of Cascade Range, litter: 3

Where duff data were given in inches of litter plus duff, we assumed a distribution of 50 percent litter and 50 percent duff.

The site variables were used as independent linear regressors against the burn-TWA smoke exposure, as well as together in a multiple linear regression model. The models also were calculated versus individual CO samples for each main work task to determine whether smoke exposure during each work task was affected by the site variables. Finally, to determine whether brief increases in windspeed had an effect on the exposure to smoke, individual CO samples were paired with the nearest observation of windspeed. Where a sample period extended over more than one windspeed observation, the time-weighted average windspeed was used as the regressor variable.

Several analyses were made with the dosimeter and datalogger results. Datalogger accuracy was assessed by a calibration check performed before and after the burns with a standard mix of CO. Some of the dataloggers had a negative or positive signal drift during the monitoring period. Data showing obvious zero drift up to ±3 ppm were adjusted by adding an equivalent offset to all readings across the monitoring period. All CO results from the dosimeter tubes were corrected for temperature and pressure according to the manufacturer's instructions. Dosimeter tube results below the minimum scale mark (50 ppm-hr) were excluded from the data to ensure that only detectable values were used. The remaining CO data from the dosimeter tubes and the CO data from the electronic dataloggers were separately compared with the CO results from the reference method (method 128) for individual sample periods. Similarly, the calculated burn TWAs were compared with the dosimeter and datalogger results.

Table 3—Prescribed burns in this study

Burn name	Burn number	Date	Location
Jordan Creek #2	1	7/22/91	Packwood, WA
Niagara Bend #6	2	8/7/91	Hebo, OR
Cove Corner #2	3	9/5/91	Alsea, OR
Klickitat #1	4	9/10/91	Alsea, OR
Redlands #3	5	3/11/92	Clackamas, OR
Sheep #12 & #22	6	3/12/92	Clackamas, OR
Dry Lake #1	7	3/24/92	Silver Lake, OR
Dry Lake #2, Hog Leg	8	3/25/92	Silver Lake, OR
South First Sale #32-41	9	4/6/92	Chelan, WA
South First Sale (day 2)	10	4/7/92	Chelan, WA
Black I #32	12	4/21/92	Twisp, WA
Black I #3 & #7	13	4/22/92	Twisp, WA
Black I #7 & #3	14	4/23/92	Twisp, WA
Flagg Mountain #7	15	4/24/92	Winthrop, WA
Monroe 5 #3	16	5/15/92	Randle, WA
Bear Prairie 3 #10	17	5/18/92	Packwood, WA
Sardine Boundary #6	18	6/2/92	Blue River, OR
Bobcat #9	19	6/4/92	Twisp, WA
Ruby #6	25	10/6/92	Newport, WA
Russian #3	26	10/7/92	Sullivan Lake, WA
Gold #18	27	10/14/92	Republic, WA
Coal Dust #9 & #7, Fishnest #15	28	10/16/92	Mount Adams, WA
Cow Camp #10 & #24	29	10/23/92	John Day, OR
Thompson #3	30	10/24/92	John Day, OR
Fawn #3	31	10/26/92	Naches, WA
Shamel Creek #19	32	5/9/93	Entiat, WA
Black I #16 & #17	33	5/10/93	Twisp, WA
Slim #12	34	5/12/93	Twisp, WA
Slim #7	35	5/13/93	Twisp, WA
Acorn #6	36	5/18/93	Ripple Brook, OR
McCoy #4	37	5/19/93	Detroit, OR
Horseberry Flat #5	38	5/25/93	Packwood, WA
Dry Creek #22	39	6/16/93	Silver Lake, OR
Granite Boulder #4	40	6/18/93	Long Creek, OR
LP #2 & #3	41	7/1/93	Winthrop, WA
Uncle Condon #5	42	7/8/93	Mapleton, OR
LP #5	51	10/18/93	Winthrop, WA
Hardt #20 & #17	52	10/19/93	Winthrop, WA

Results

A brief summary of the data quality is given, then the results are presented for the shift- and burn-average exposure to smoke among firefighters, the peak smoke exposures, the variables determining smoke exposure levels, and the dosimeter evaluations. Finally, the interpollutant regressions are presented. Table 3 lists the prescribed burns where sample collection occurred.

Data Quality

Between July 1991 and May 1994, sampling for acrolein, benzene, CO_2, CO, formaldehyde, and respirable particulate matter was attempted in the breathing zone of firefighters at prescribed burns. Some sample results were questionable for various reasons, such as insufficient sample volume, inconsistent sample flow rates before and after sampling, spilled or damaged samples, sampling pump malfunctions, blank contamination, or analytical problems; such data were not used to derive project results. Of the resulting validated sample data, some of the data are considered “qualified” because one or more QA measures associated with the sample indicated that they may not meet quantitation criteria. Table 4 summarizes the valid and qualified data by pollutant.

Table 5 lists the overall accuracy and precision for the samples. It shows the original data quality targets defined in the quality assurance project plan (Radian Corporation 1993), as well as the actual data quality results based on a statistical summary of all QA results obtained by the project laboratory through May 1994. About 75 percent of the smoke exposure data obtained by the project laboratory during this period was collected at prescribed burns and another 25 percent was collected at wildfires, both with the same equipment and methods.

Table 4—Summary of sample numbers and completeness by pollutant

Pollutant	Method	Samples attempted	Valid samples	Qualified results	Completeness[a]
					Percent
Benzene	NIOSH 1501	481	349	53	85
Acrolein	EPA TO-11	481	140	11	92
Formaldehyde	EPA TO-11	481	397	182	54
Carbon monoxide	ICM 128	481	357	90	75
Carbon dioxide	ICM 128	481	356	85	76
Respirable particulate	NIOSH 0600	481	338	26	95

[a] Percentage of valid samples without qualifying constraints.

Table 5—Accuracy and precision for pollutants measured at prescribed burns

Pollutant	Overall accuracy		Overall precision	
	Target	Actual	Target	Actual[b]
	- - - - - - - - - - - - - *Percent* - - - - - - - - - - - - -			
Benzene	90-110	77-126[a]	30	25
Acrolein	70-105	70-136[a]	30	33
Formaldehyde	80-110	70-128[a]	30	45
Carbon monoxide	90-110	92-107[c]	15	32
Carbon dioxide	90-110	97-103[c]	15	14
Respirable particulate matter	NA	NA	20	35

NA = not available, sampling accuracy could not be measured.
[a] Calculated from liquid method spike recoveries.
[b] Calculated from relative standard deviation of field replicates.
[c] For analytical accuracy only; accuracy associated with sample collection and handling was not measured.

Table 6—Method detection limits for pollutants measured at prescribed burns

Pollutant	Method	Method detection limit	
		STEL sample[a]	TWA sample[b]
		- - - - - *Parts per million* - - - - -	
Benzene	NIOSH 1501	0.028	0.0035
Acrolein	EPA TO-11	.017	.002
Formaldehyde	EPA TO-11	.033	.004
Carbon monoxide	ICM 128	.6	.6
Carbon dioxide	ICM 128	7.6	7.6
		Milligrams per cubic meter	
Respirable particulate matter	NIOSH 0600	2.272	0.284

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

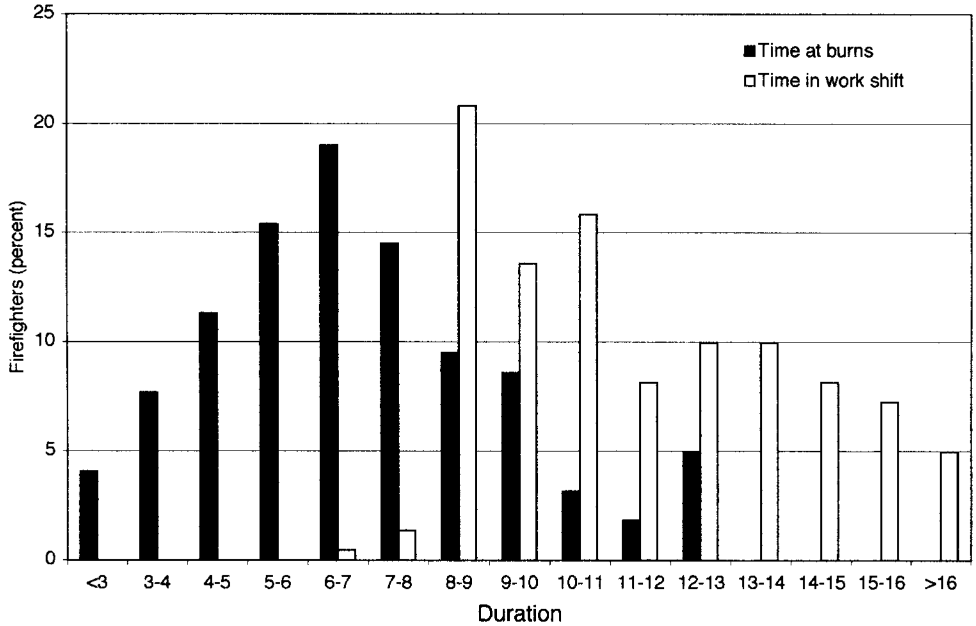

Figure 3— Amount of time spent daily in work shift and at prescribed burns for monitored firefighters.

Method detection limits were calculated for each pollutant by using the procedures specified by the EPA (1984). These are summarized in table 6. Sample concentrations that are less than four times the associated method detection limits are expected to show greater variability than those above this value. For this reason, field replicates with values less than four times the method detection limit were excluded from the overall precision calculations summarized in table 5.

Two laboratory systems audits, one field sampling audit, and three analyses of performance evaluation (PE) samples were performed during the course of the project, as required in the quality assurance project plan. The audit results indicated that, overall, the sampling procedures and analytical methods were producing data of sufficient quality for project use; however, several problems were noted that required corrective action. Only one problem noted during a laboratory audit affected data (acrolein), and the associated data produced at that time were invalidated. Two sets of PE results for acrolein and formaldehyde indicated a low bias of 50 percent and 65 percent, respectively, but corrective actions taken to identify the source, along with method spike and certified standard analysis, were inconclusive. The third set of PE results for these pollutants, prepared by a different vendor, were acceptable. Either the PE sample preparation or true value calculation may have been erroneous for the first two sets, but project data for formaldehyde and acrolein are considered potentially biased low by a factor of two and three, respectively.

Shift- and Burn-Average Exposure Assessment

A total of 221 shift- and burn-duration TWA exposures were calculated for the firefighters. Because of uncertainty in estimating the smoke exposure during unsampled periods, 21 of these were eliminated from the data. Of the remaining 200 TWAs, the work shifts averaged 11.5 hours in duration with 7 hours of work onsite during the

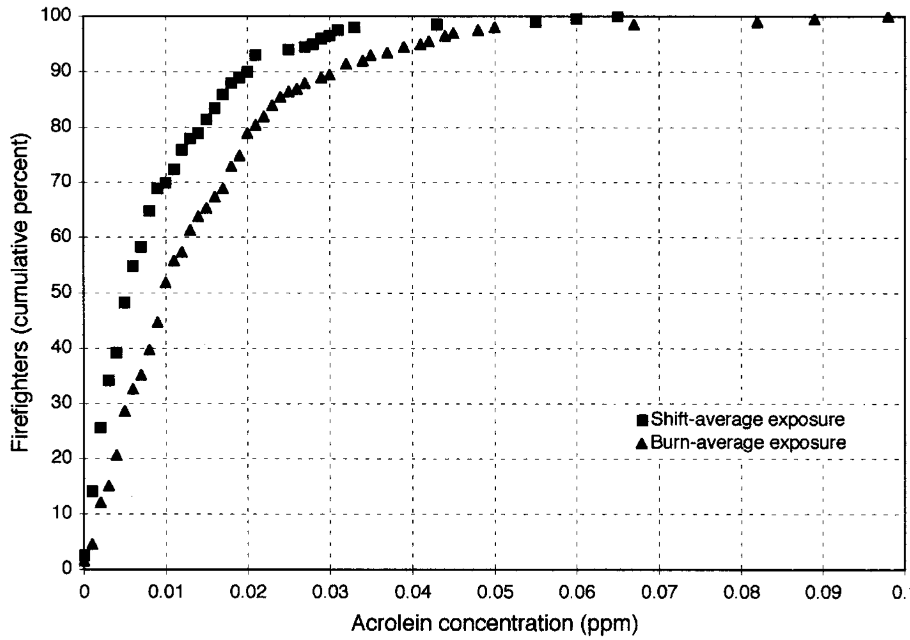

Figure 4—Distribution of shift- and fireline-average acrolein exposure among firefighters at prescribed burns. The x-axis is the acrolein exposure and the y-axis is the percentage of firefighters at or below that concentration.

prescribed burns. Figure 3 shows a histogram of the hours in the work shift and time spent on the fireline for firefighters sampled at prescribed burns.

Exposure to acrolein during a work shift averaged 0.009 ppm for the firefighters in this study, with the firefighter having the highest exposure averaging 0.06 ppm during the work shift. During the time on the fireline, their exposure to acrolein averaged 0.015 ppm, ranging up to 0.098 ppm. For comparison, the current PEL and TLV for acrolein are both 0.1 ppm. Figure 4 shows the cumulative frequency distribution of acrolein exposure among firefighters at prescribed burns.

Firefighters had an average benzene exposure of 0.016 ppm during their work shift and 0.028 ppm while they were on the fireline. The firefighters with the highest exposure had average exposures of 0.058 and 0.088 ppm during the work shift and on the fireline, respectively. The current PEL for benzene is 1.0 ppm, and ACGIH recommends a TLV of 0.5 ppm. Figure 5 shows the cumulative frequency distribution of benzene exposure among the firefighters at prescribed burns in this study.

The average level of CO_2 in the breathing zone was 450 ppm during the firefighters' work shifts and 519 ppm while at the fire. Much of this CO_2 could be normal metabolic waste in exhaled breath. For comparison, the current PEL and TLV for CO_2 are both 5,000 ppm. Figure 6 shows the cumulative frequency distribution of CO_2 levels among the firefighters at prescribed burns.

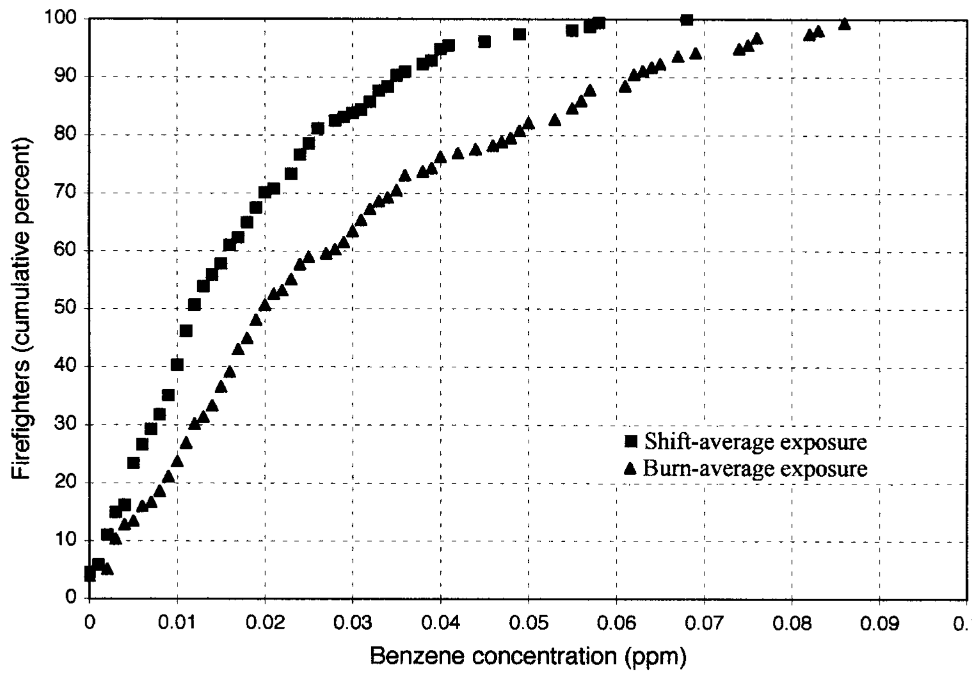

Figure 5—Distribution of shift- and fireline-average benzene exposure among firefighters at prescribed burns. The x-axis is the benzene exposure and the y-axis is the percentage of firefighters at or below that concentration.

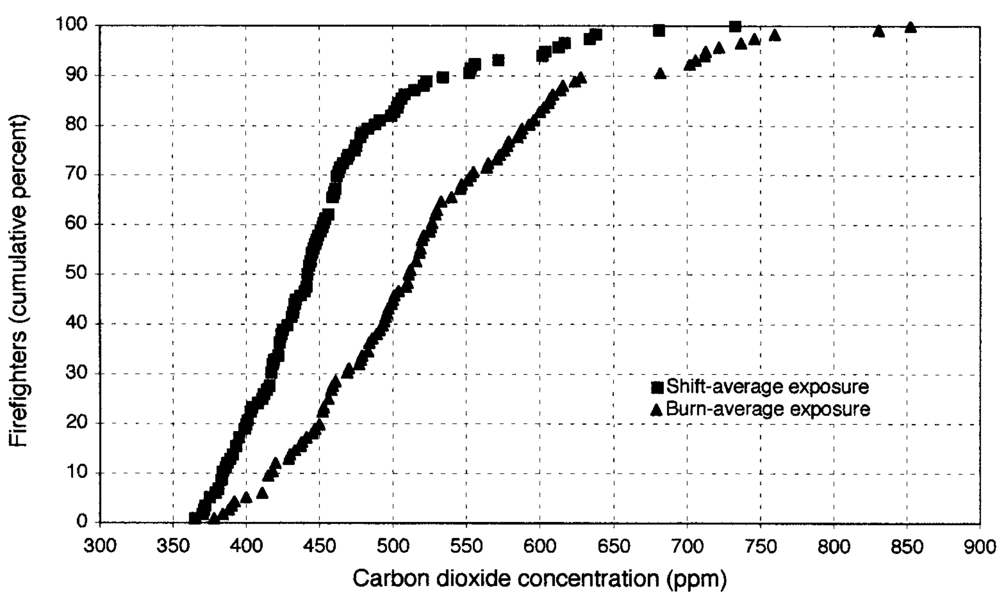

Figure 6—Distribution of shift- and fireline-average CO_2 exposure among firefighters at prescribed burns. The x-axis is the CO_2 exposure and the y-axis is the percentage of firefighters at or below that concentration.

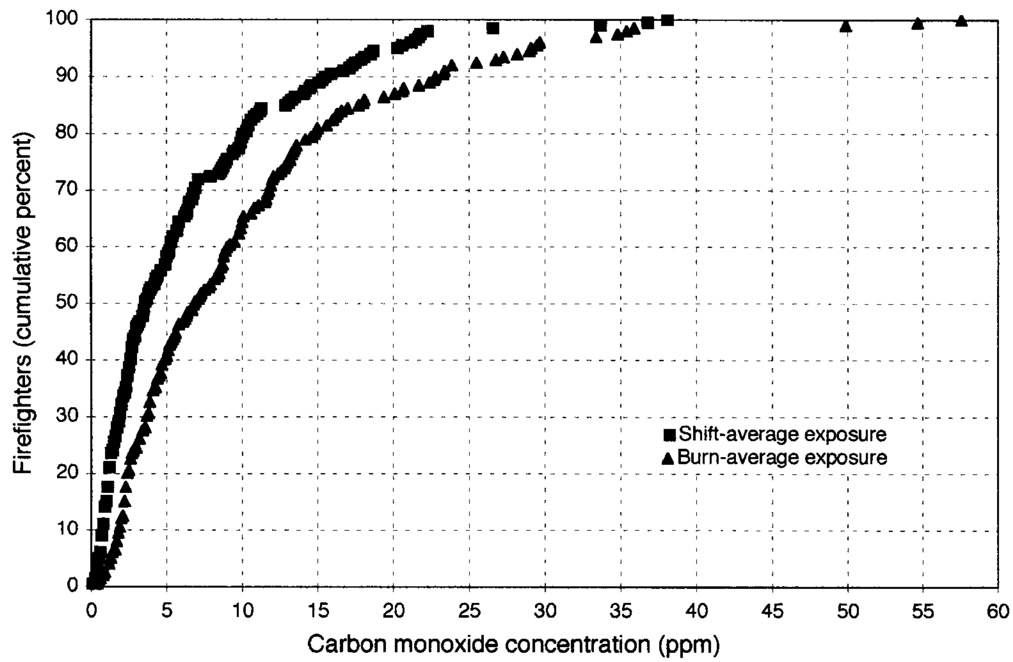

Figure 7—Distribution of shift- and fireline-average CO exposure among firefighters at prescribed burns. The x-axis is the CO exposure and the y-axis is the percentage of firefighters at or below that concentration.

Exposure to CO averaged 4.1 ppm over the firefighters' work shifts and 6.9 ppm while they were at the burn. The highest shift-average exposure to CO was 38 ppm, and the highest fireline-average CO exposure was 58 ppm. For comparison, the current PEL and TLV for CO are 50 and 25 ppm, respectively. Figure 7 presents the cumulative frequency distribution of CO exposure among the firefighters working at prescribed burns.

Exposure to formaldehyde among firefighters averaged 0.047 ppm during their work shifts and 0.075 ppm during the burns. The highest formaldehyde exposure averaged 0.39 ppm over the work shift and 0.6 ppm during the prescribed burn. The current formaldehyde PEL and TLV for comparison are 0.75 ppm and 0.3 ppm. Figure 8 shows the cumulative frequency distribution of the formaldehyde exposure among those working at prescribed burns.

Respirable particulate matter exposure among firefighters averaged 0.63 mg/m^3 over the work shift and 1 mg/m^3 while at the burns, with corresponding maximum exposures that averaged 6.9 mg/m^3 over a work shift and 10.5 mg/m^3 during the burn. For comparison, the present PM3.5 PEL is 5 mg/m^3 and the TLV is 3 mg/m^3. Figure 9 shows the cumulative frequency distribution of the PM3.5 exposure among firefighters involved in prescribed burning.

The exposure to respiratory irritants (acrolein, formaldehyde, and PM3.5) was evaluated in accordance with the simple additive model in equation (1). With the recommended ACGIH TLVs as divisors in the equation, the resulting irritant exposure index (E_m) averaged 0.4 over the work shift and 0.7 during the burns. The firefighters with

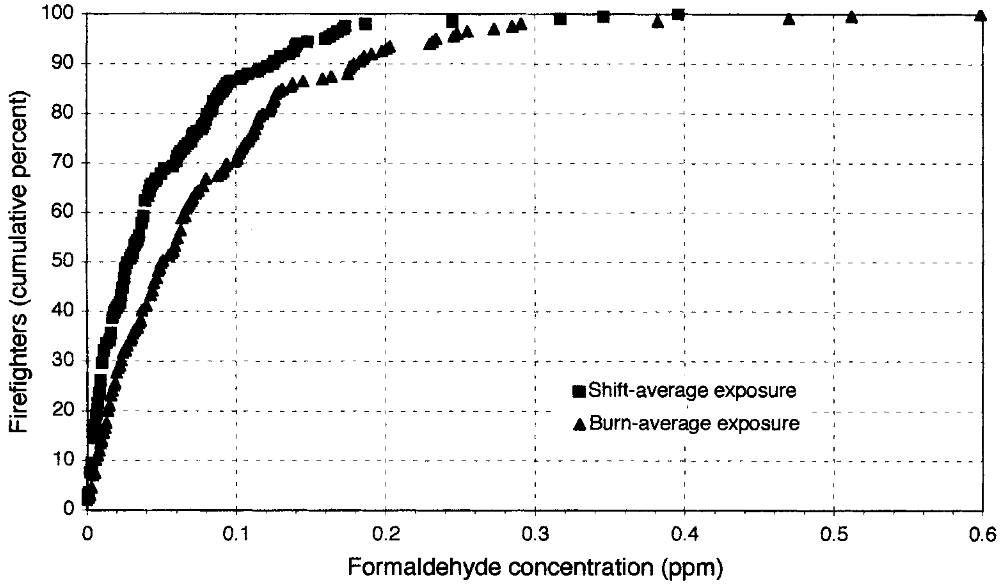

Figure 8—Distribution of shift- and fireline-average formaldehyde exposure among firefighters at prescribed burns. The x-axis is the formaldehyde exposure and the y-axis is the percentage of firefighters at or below that concentration.

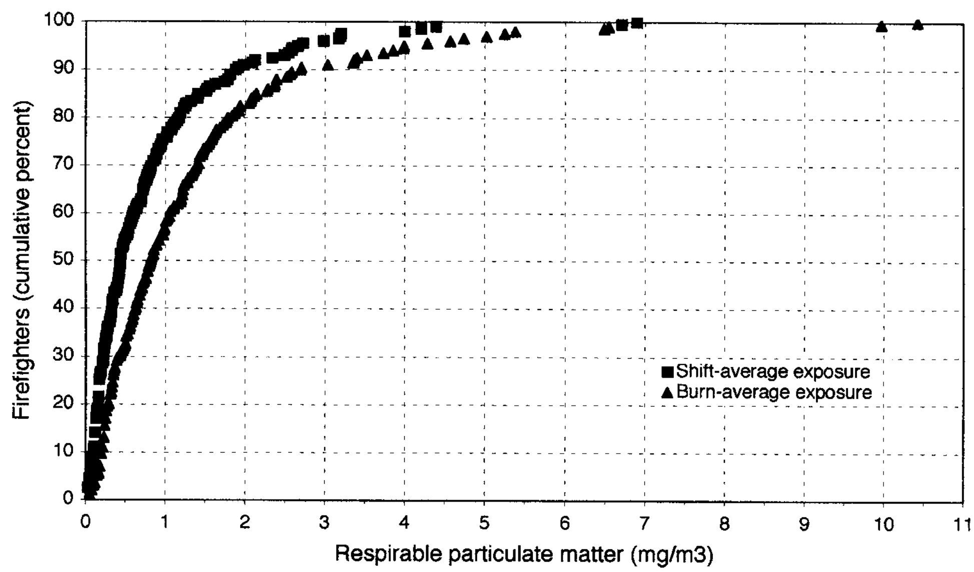

Figure 9—Distribution of shift- and fireline-average respirable particulate matter exposure among firefighters at prescribed burns. The x-axis is the respirable particulate exposure and the y-axis is the percentage of firefighters at or below that concentration.

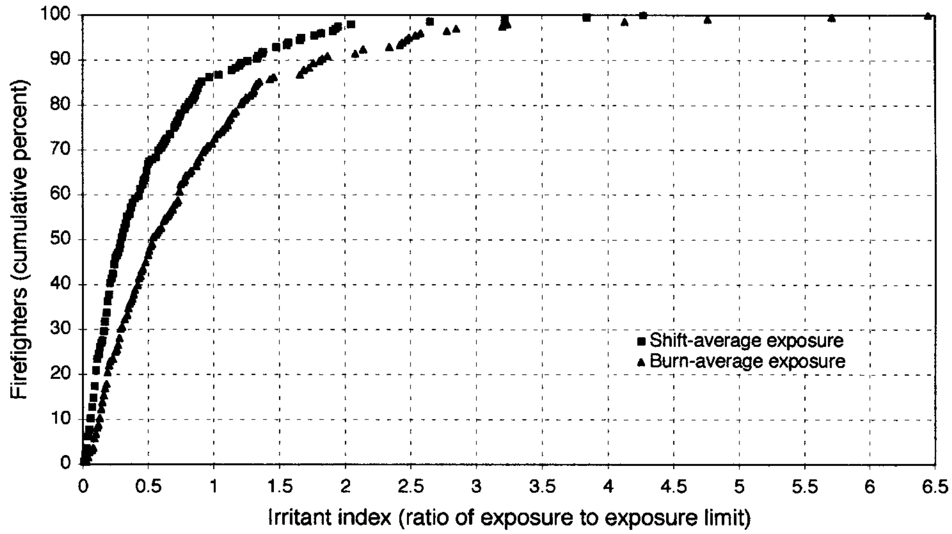

Figure 10—Distribution of shift- and fireline-average respiratory irritant exposure among firefighters at prescribed burns. The x-axis is the respiratory irritant exposure and the y-axis is the percentage of firefighters at or below that concentration.

the highest exposures had shift-average and burn-average E_m values of 4.3 and 6.5, respectively (fig. 10). Using the OSHA PELs as the divisors in equation (1) results in a shift-average E_m of 0.3 (maximum shift-average E_m of 2.6) and a burn-average E_m of 0.4 (maximum burn-average E_m of 3.9). To evaluate the significance of these values, compare them with the TLV and PEL E_m of 1: An E_m of 0.4 based on TLVs describes a combined irritant exposure that was 40 percent of the recommended exposure limit, and an E_m of 2.6 based on PELs describes an exposure that is 2.6 times the PEL.

Peak Exposure Assessment

The study collected 18 peak-smoke exposure sample sets from situations where the firefighters endured intense smoke exposure. The total respiratory irritant exposure could not be determined accurately because most of the peak exposure samples had no valid data for one or more of the irritants. Table 7 summarizes the peak smoke exposure data. The current ACGIH TLVs are included in table 7 for comparison with the peak exposure data.

Exposure Determinants

Work activity—Table 8 summarizes the smoke exposure sample data for each major work activity identified in the project. For each pollutant, the number of samples and the geometric mean are listed by work activity. The mean exposures represent conditions when smoke was at least occasionally present. Actual means by work activity may be somewhat lower because the data do not represent the unsampled periods (when smoke was usually absent).

Site-specific variables—Table 9 lists the burn-average windspeed, site-average fuel moisture for the 10-hour timelag fuels (those between 1/4 and 1 inch in diameter), fuel and duff loading, and the total acreage of each prescribed burn in the study.

Figure 11 summarizes the combination of burn-specific variables that were considered possible determinants of the potential smoke exposure at each fire. The burn-average

Table 7—Peak smoke exposure summary

Parameter	PM3.5	CO	Formaldehyde	Acrolein	Benzene	Duration
	Mg/m^3	*- - - - - - - -Parts per million- - - - - - - - - - - -*				*Minutes*
Maximum	37.11	179	1.456	0.129	0.277	32
Mean	7	54.3	.468	.071	.064	20
Minimum	<2.27	9.0	<.033	.054	<.028	10
Threshold limit value	9	200[a]	.3[a]	.1[a]	5	
	- - - - - - - - - - - - Number of Samples - - - - - - - - - - - -					
No. of samples	12	16	15	5	14	18

[a] Ceiling limit.

Table 8—Mean pollutant concentration by work activity

Work activity	Geometric mean sample data: Carbon monoxide		Carbon dioxide		Respirable particulate		Benzene		Formaldehyde		Acrolein	
	ppm	*N*[a]	*ppm*	*N*	*Mg/m^3*	*N*	*ppm*	*N*	*ppm*	*N*	*ppm*	*N*
Burn boss	5.9	14	508	14	1.32	17	0.021	16	0.077	17	0.031	9
Lighting	3.7	110	510	110	.75	105	.045	98	.038	100	.005	31
Holding	11.6	75	565	74	1.56	82	.021	85	.127	96	.018	33
Holding supervisor	13.2	22	577	22	1.81	17	.026	19	.119	21	.030	11
Attack	33.2	16	762	16	4.04	10	.041	15	.464	12	.062	1
Mop-up	9.2	57	499	57	.75	49	.020	62	.091	56	.012	29
Sawyer	14.2	6	700	6	2.93	6	.091	3	.346	3	.010	1
Engine	10.2	5	597	5	1.37	5	.039	5	.098	6	.000	1
Attack/lighting	15.1	3	566	3	1.17	2	.109	4	.197	4	.031	4
Attack/mop-up	23.9	5	664	5	2.46	6	.033	5	.136	6	.073	1
Attack/holding	15.4	14	569	14	2.20	10	.032	13	.170	12	.022	1
Lighting/holding	8.0	13	544	13	1.62	14	.047	14	.083	17	.012	7
Holding/mop-up	15.9	17	563	17	1.99	15	.044	10	.138	18	.025	11

[a] N = number of samples.

Table 9—Site-specific variables for prescribed burns

Burn number	Average windspeed	Fine fuel moisture[a]	Woody fuel loading	Duff loading	Burn area
	Miles per hour	*Percent*	- - - - - *Tons/acre*	- - - - -	*Acres*
1	1.5	12.1	60	28.5	20
2	.4	11	52.8	18.7	44
3	NA	12	42	9.4	32
4	1.5	10.1	54.2	9.4	41
5	.4	17.9	52	18.7	16
6	1.3	11	41.3	18.8	13
7	1.4	9.5	17.4	14	NA
8	1	11.6	8.5	16.1	NA
9	.6	16.5	45.4	41.6	93
10	1	8.6	25.6	36	37
12	1.9	16.4	13.2	7.3	28
13	2.1	9.3	15.2	4.9	48
14	0	10.1	23.4	4.8	35
15	3.8	9	34.1	3.5	12
16	2.2	12.4	39	0	NA
17	1.6	9.3	64.6	4.8	21
18	3	10.7	51.5	18.7	10
19	1.2	8.6	26.4	0	16
25	.2	12	32	16	26
26	1	13	16.2	12.3	20
27	1.3	11.3	28	6.1	26
28	0	15.3	87.9	77.8	77
29	2.6	17.6	22.7	0	61
30	1.4	11	22.8	6.1	NA
31	2.9	10.7	33.3	25.4	30
32	1.6	16	46.3	8.5	25
33	1	16.5	38.4	7.8	37
34	1.3	10.5	16	3.6	29
35	2.7	10	22	3.6	25
36	3.1	8.9	44	18.7	82
37	1.2	10	55.8	28.1	33
38	.3	11.6	70	28.5	38
39	.1	11	17.5	9.4	49
40	2.7	9	40.4	9.4	NA
41	.6	16.2	62.1	20.9	27
42	.2	14.3	51.4	20.6	50
51	3.1	18	62.5	21.7	25
52	1.6	19	63.9	21.1	14

NA = site data not available.

[a] Moisture content of 10-hour timelag fuels.

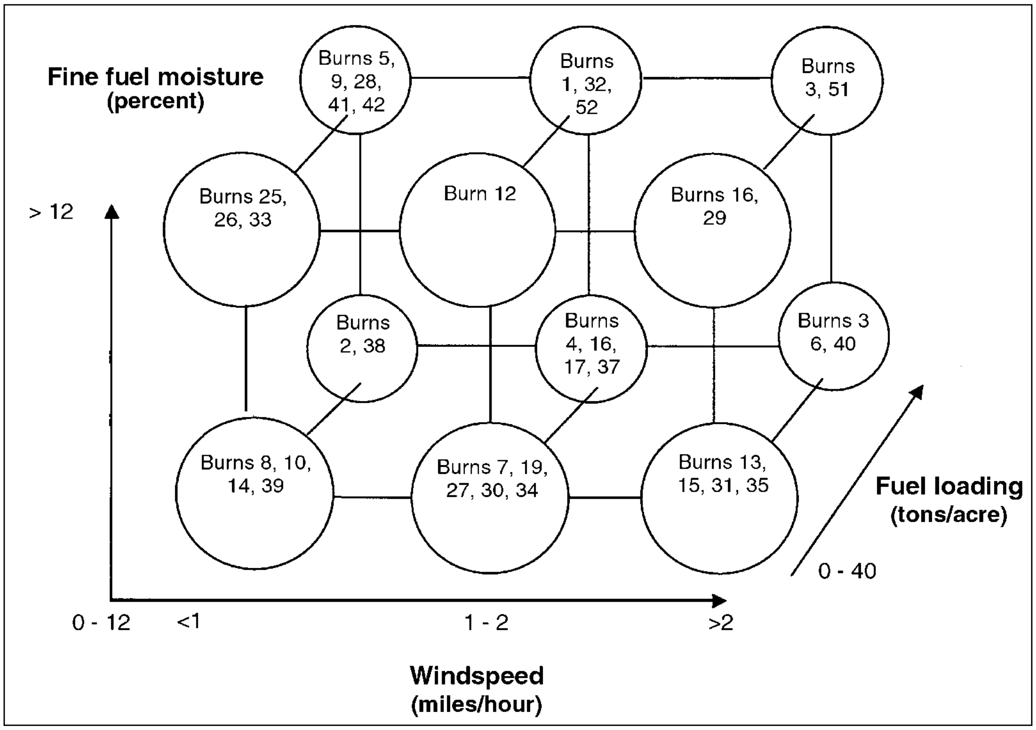

Figure 11—Combination of environmental variables at each burn including 10-hour fuel moisture (0-12 and greater than 12 percent), wind speed (less than 1, 1-2, and greater than 1 mile per hour), and fuel loading (0-40 and greater than 40 tons per acre). Each burn was selected to fit into the three-dimensional matrix.

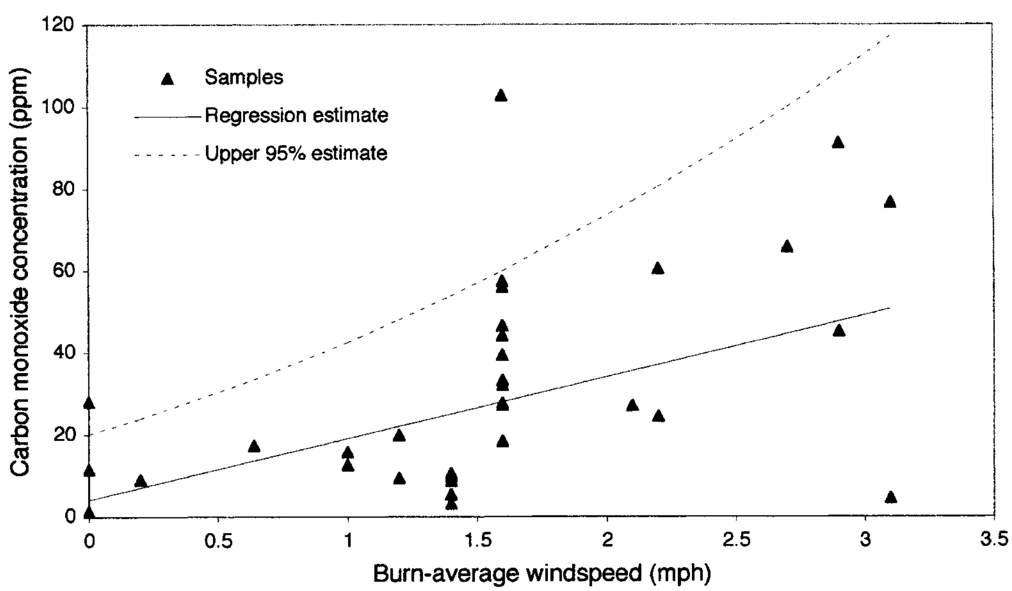

Figure 12—Carbon monoxide exposure of firefighters involved in direct attack tasks compared to average wind speed for the prescribed burn displaying sample concentrations, linear regression fit to the samples, and the upper bounds on the regression estimate. Ninety-five percent of the firefighters' carbon monoxide exposure is estimated to be below the dotted line.

windspeed and fuel loading data obtained in the study were much less variable than had been expected.

Some trends in smoke exposure versus the burn-specific environmental variables were indicated. Smoke exposure levels were slightly higher during direct attack tasks at burns with a high fuel loading, and smoke exposure levels appeared to be higher during burns conducted at the high and low ends of the fuel moisture range. Only burn-average windspeed was significantly correlated to smoke exposure, however, and only for the attack tasks (attack, attack-hold and attack/mop-up). The correlation is shown in figure 12.

A linear regression was developed between the burn-average windspeed and the CO exposure among firefighters during direct attack tasks. Equation (6) provides this regression (which had an r^2 of 0.46):

$$[CO] = 15 \times U_s\ (\pm 3) + 4\ (\pm 4) \quad , \tag{6}$$

where

[CO] = the carbon monoxide exposure during direct attack activities (in ppm), and

U_S = the site-specific average windspeed (in miles/hour).

Dosimeter Performance Evaluation

The dosimeter tubes and the dataloggers were reasonably accurate. Table 10 summarizes linear regression statistics comparing the burn-average CO exposure collected from firefighters at prescribed burns by using reference method 128 and CO measured from two brands of dosimeter tubes and a CO datalogger.

Two key difficulties arose with the dosimeter tubes. The first was the necessity to store them at temperatures below 25 °C until use; this is difficult to achieve in field programs. The second difficulty was observing the faint color change in the tubes that indicated CO exposure. This was especially hard to see on the Sensidyne tubes in low ambient light conditions. The interpretation error in reading the scale caused the dosimeter tube results to be rather imprecise (indicated by the low r^2 values in table 10), especially at low to moderate CO exposures.

Our CO exposure estimates (from the method 128 data and observer field notes) were 7 to 25 percent higher than the corresponding datalogger or dosimeter results, as shown by slope values below 1 in table 10. Error in estimating exposures for the unsampled periods in the TWAs could have caused this discrepancy. To evaluate this, we compared the datalogger results versus those from method 128 on a sample basis, eliminating any bias caused by inaccurate CO exposure estimates for unsampled periods. A similar comparison planned for the dosimeter tube results was not possible because most data from the dosimeter tubes were below the detection limit of the tubes for such short periods. The sample comparison of the datalogger versus method 128 was done by linear regression. This period-specific comparison revealed that the datalogger results were very precise but biased low by about 20 percent (the r^2 for the regression of the datalogger results versus the corresponding 36 samples using method 128 was 0.99, but the slope was only 0.8). Investigation of the QC data obtained in the field by the datalogger confirmed that the dataloggers were biased.

Table 10—Summary of statistics from linear regressions comparing carbon monoxide results from dosimeters or dataloggers with the time-weighted average calculated from the reference method data

Type of monitor	Number of samples	r^2	Slope
Draeger passive dosimeter tube	19	0.57	0.87
Sensidyne passive dosimeter tube	19	.71	.93
Draeger 190 datalogger	17	.96	.75

The datalogger calibrations were checked before and after use by exposing the sensor to a calibration gas with a known CO concentration of 51 ppm. The results of 19 calibration checks of the dataloggers in the field with this second-standard CO mixture averaged 86 percent of the theoretical value. None of the indicated values was higher than 93 percent, and the lowest indicated response was only 77 percent of the theoretical amount. Together, the results indicated that the dataloggers underestimated true CO exposure when used days to weeks after their monthly calibration according to manufacturer's instructions (the dataloggers were within 1 percent of the theoretical concentration immediately after calibration). Subsequent studies have shown that this bias can be assessed and prevented with more frequent calibration and a QA program that includes tracking calibration accuracy at the beginning and end of each day of data collection. In spite of the bias problem, the dataloggers provided more detailed information about CO exposure than did the other measurement methods. Figure 13 shows an example of the CO exposure data obtained from a firefighter at a prescribed burn.

Pollutant Correlations

Each sample showed strong correlations among the pollutants. Linear regression was used for pairwise comparisons among the pollutants in a given sample. Figure 14 shows an example of the correlation data obtained, in this case between concentrations of CO and formaldehyde. The confidence bands enveloping the regression show the 95-percent interval for the predicted mean formaldehyde concentration at a given level of CO. Figure 15 shows the same data over a narrower range (omitting the single CO observation at 179 ppm) and plots the 95-percent confidence interval of a predicted formaldehyde sample concentration from a given level of CO. The wider confidence bands indicate the additional variability from sample to sample, whereas figure 14 shows only the variability in estimating the mean formaldehyde concentration from a given sample of CO. Table 11 summarizes the statistics from the regression analyses. The relatively high correlation coefficients (r^2) demonstrate the precision with which one can estimate exposure to one of these pollutants from measurements of another. Data for regressions including benzene excluded samples from work activities where exposure to gasoline was likely, such as chainsaw operation, vehicle or pump operation, or lighting with a drip torch.

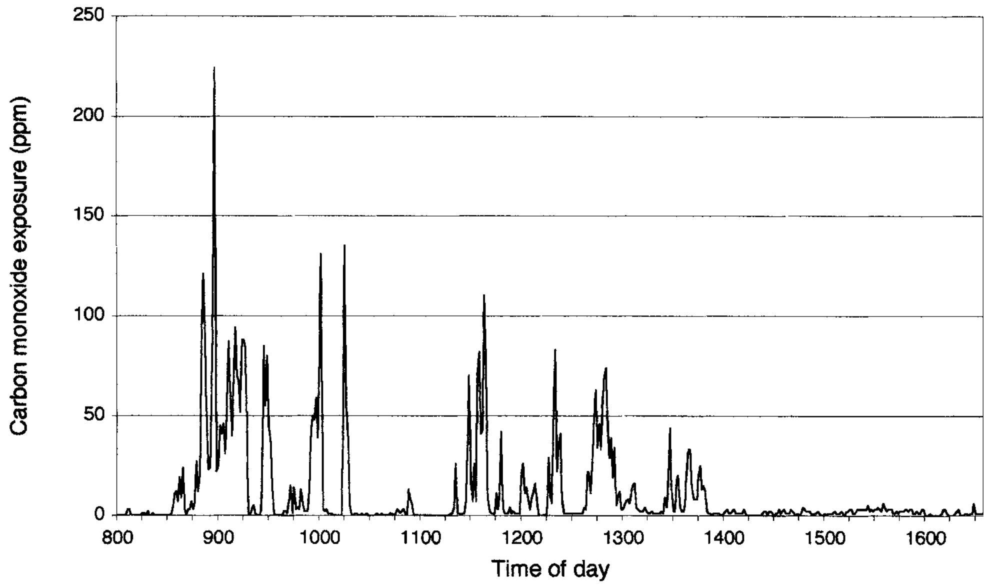

Figure 13—Datalogger record of a firefighter's exposure to carbon monoxide during a prescribed burn.

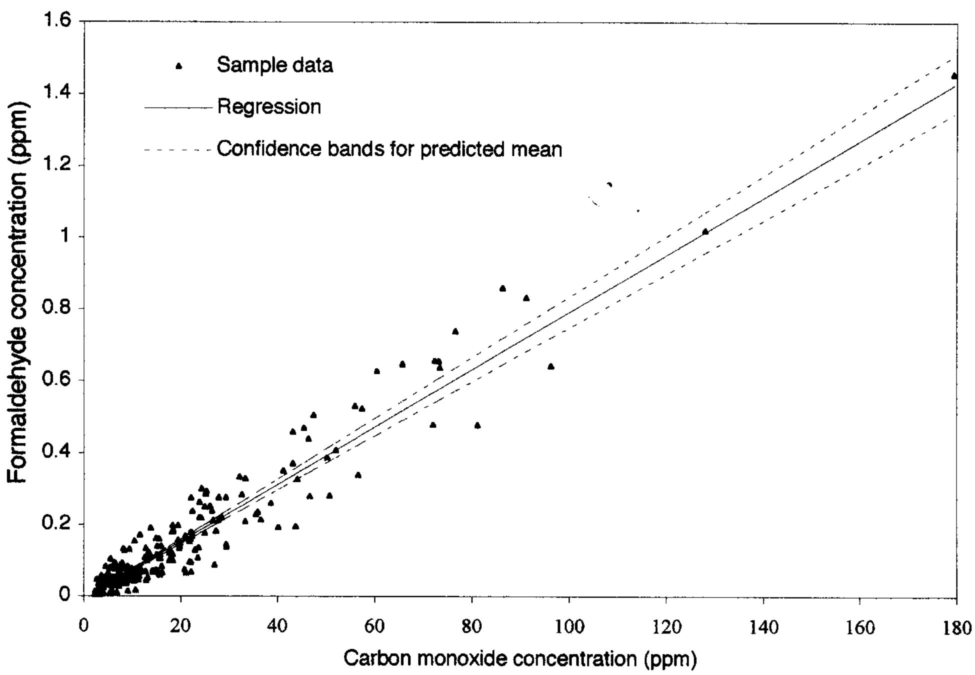

Figure 14—Correlation between formaldehyde and CO in smoke samples. The 95-percent confidence bands are for the predicted mean exposure to formaldehyde.

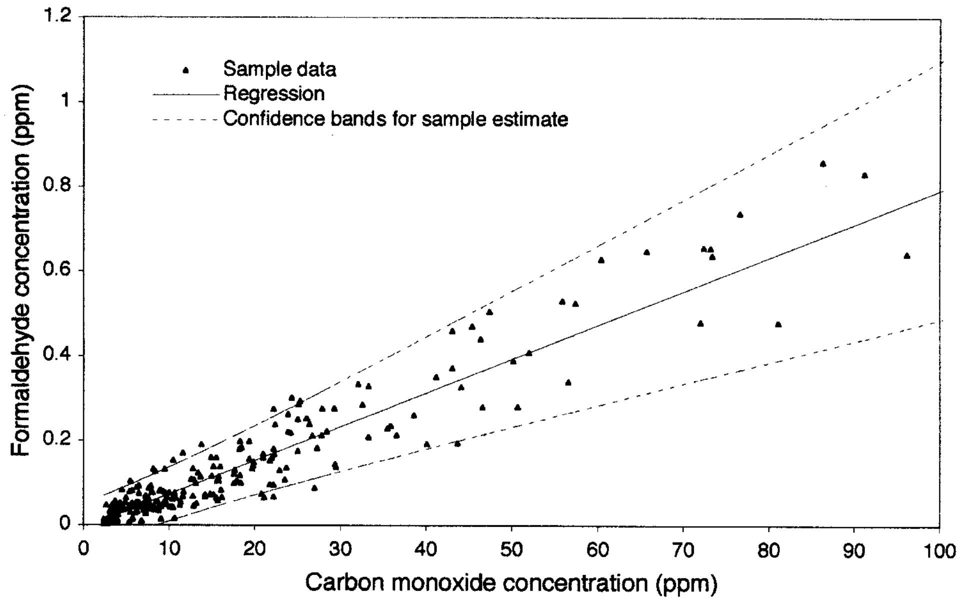

Figure 15—Correlation between formaldehyde and CO in smoke samples. The 95-percent confidence bands are for all samples and include variability among samples.

Table 11—Summary statistics of correlations between pollutants in smoke samples at prescribed burns

			Regression coefficients (y=ax+b)[a]	
Pollutant pairs (x,y)	Samples	r^2	a (±standard error[b])	b (±standard error)
Carbon monoxide, acrolein	87	0.63	$9.48x10^{-4}$ ($\pm 8x10^{-5}$)	$4x10^{-3}$ ($\pm 1x10^{-3}$)
Carbon monoxide, benzene	125	.74	$1.01x10^{-3}$ ($\pm 5x10^{-5}$)	$6x10^{-3}$ ($\pm 2x10^{-3}$)
Carbon monoxide, formaldehyde	240	.82	$7.99x10^{-3}$ ($\pm 2x10^{-4}$)	$-6x10^{-3}$ ($\pm 3x10^{-3}$)
Carbon monoxide, respirable particulate	162	.73	$1.14x10^{-1}$ ($\pm 5x10^{-3}$)	$-3x10^{-2}$ ($\pm 4x10^{-2}$)
Formaldehyde, respirable particulate	154	.82	$1.43x10^{1}$ ($\pm 5x10^{-1}$)	$2x10^{-2}$ ($\pm 4x10^{-2}$)
Respirable particulate, acrolein	74	.62	$7.49x10^{-3}$ ($\pm 7x10^{-4}$)	$6x10^{-3}$ ($\pm 1x10^{-3}$)
Formaldehyde, acrolein	127	.86	$1.71x10^{-1}$ ($\pm 6x10^{-3}$)	$2x10^{-3}$ ($\pm 4x10^{-4}$)
Formaldehyde, benzene	159	.78	$1.20x10^{-1}$ ($\pm 5x10^{-3}$)	$8x10^{-3}$ ($\pm 1x10^{-3}$)
Respirable particulate, benzene	110	.71	$8.3x10^{-3}$ ($\pm 5x10^{-4}$)	$1x10^{-2}$ ($\pm 2x10^{-3}$)

[a] Regression units are in ppm for all pollutants except respirable particulate, which is in mg/m^3.
[b] Standard errors of regression coefficients at 95-percent confidence level.

The interpollutant regressions for the respiratory irritants (formaldehyde, acrolein and respirable particulate) are especially significant because large-scale smoke monitoring programs may rely on them to cost-effectively estimate irritant exposure based on CO datalogger results. The correlation of formaldehyde and CO was shown in figures 14 and 15. Figure 16 shows the regression derived between acrolein and CO. There is considerable variability in the acrolein concentration at CO levels above 40 ppm (the 95-percent confidence interval around the predicted mean acrolein concentration is shown for each level of CO). Figure 17 shows the correlation between respirable particulate and CO. Significant variability is present for PM3.5 concentrations at CO levels above 60 ppm. The width of the 95-percent confidence intervals for predicting the PM3.5 concentration of a sample at a given CO value (shown in fig. 16) is the direct result of this variability.

Discussion

Data Quality

The overall accuracy and precision of the smoke exposure measurements are similar to the initial data quality objectives. The results for the aldehydes were more variable and less accurate than anticipated but adequate for the project goals. The most significant finding was that the aldehyde measurement results may be biased low by a factor of two to three, as indicated by some performance evaluation audit samples. Thus it is possible that a somewhat larger percentage of the firefighters' exposures may have exceeded an OSHA irritant PEL and the ACGIH irritant TLV. Such a result would not change our conclusions. In addition, the actual concentrations for each pollutant may vary by up to ±30 percent of the value reported, and any individual observation could differ by up to 45 percent (refer to table 5 to evaluate these parameters by pollutant).

Because our sampling strategy did not include every moment that the firefighters were in smoke, error was introduced to the TWA exposure estimates. The magnitude of this error was evaluated by our comparison of the CO results from the dataloggers with those from method 128 by period and overall TWA. This comparison indicated that the overall TWA estimates based on the method 128 data may overestimate the actual exposure by up to 5 to 10 percent, depending on how much unsampled CO exposure there was in the firefighter's shift. We believe that this potential overestimate was due to our conservatism in applying the codes in table 2 to estimate CO exposure during the unsampled periods in the day. We believe that this bias would apply to the other pollutants as well, because the same codes were used for all pollutants.

Average Exposure Assessment

It is suggested that managers of prescribed burns be concerned about two parameters for their firefighters: exposure to CO and exposure to respiratory irritants (formaldehyde, acrolein, and PM3.5). The results in figures 7 and 10 indicate that smoke exposure at prescribed burns can exceed both legal and recommended limits for these two parameters. Conversely, benzene exposure was not shown to be a major concern. Overall, we found that firefighters do not face significant levels of smoke most of the time; however, during the occasional overexposure, management action needs to be considered.

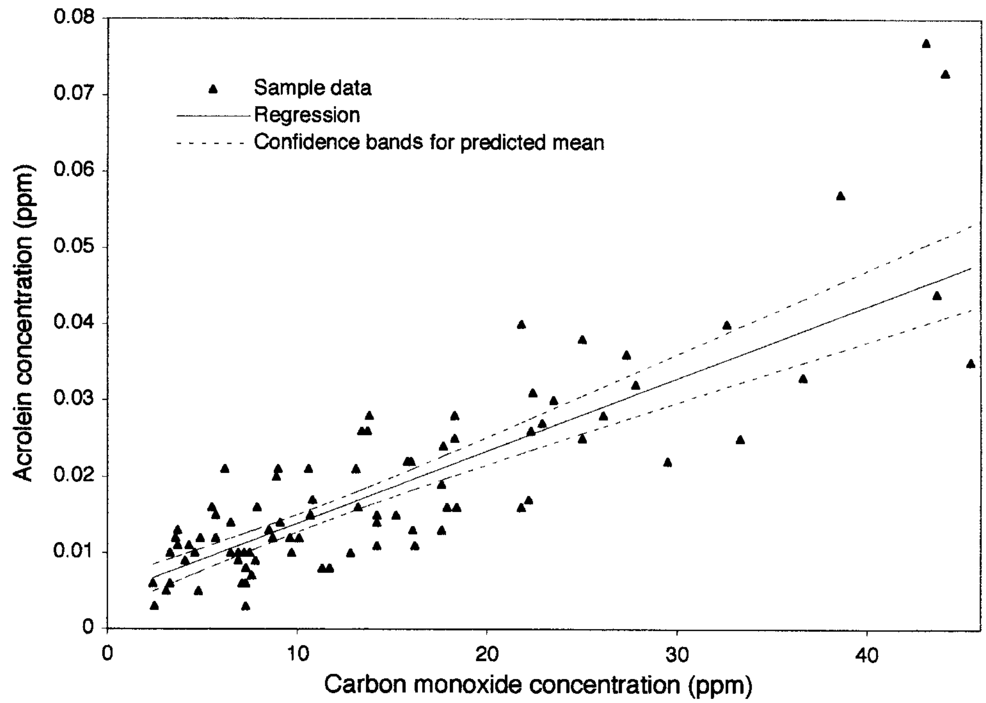

Figure 16—Correlation between acrolein and CO in smoke samples. The 95-percent confidence bands are for the predicted mean exposure to acrolein.

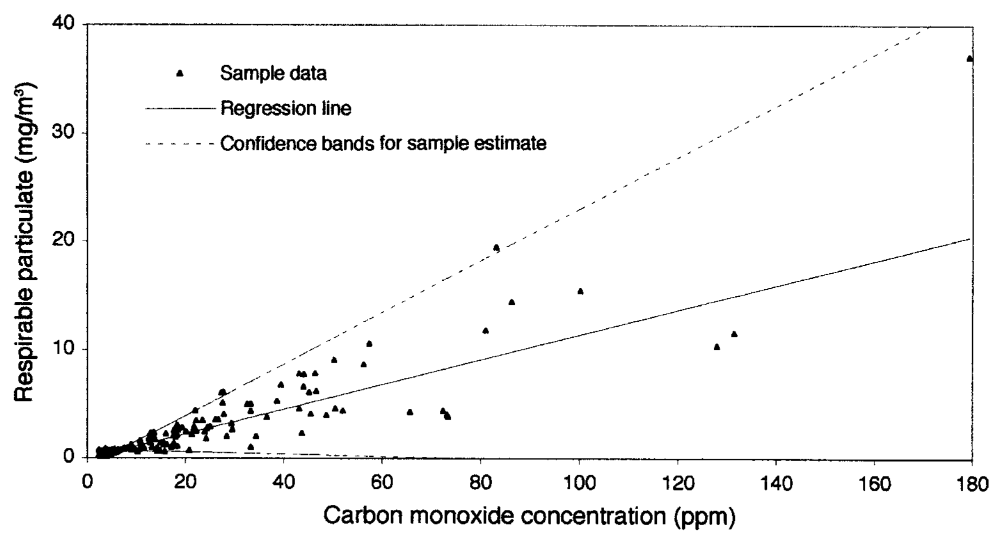

Figure 17—Correlation between respirable particulate and CO in smoke samples. The 95-percent confidence bands are for all samples and include variability among samples.

Benzene—In no case did benzene exposure approach the recommended TLV, let alone the PEL, as shown in figure 5. Even if the exposure limits were adjusted downward for the long-duration work, the observed benzene exposures were well below current regulatory standards. We suggest that no further management actions are needed at this time to limit benzene exposure. It is suggested, however, that information be made available to firefighters that benzene is present in many of the gasoline products they handle and that exposure to gasoline and its vapors should be minimized.

Carbon monoxide—Evaluation of firefighters' exposure to CO requires information on the duration of the work shift. Although the work shifts averaged 11.5 hours, only 7 hours on average were spent on the firelines. For exposures of less than 8 hours, the recommended CO standard of 25 ppm is adequate to protect the average worker's health. Roughly 25 percent of the firefighters worked more than 8 hours on the fireline while at the prescribed burns, however, and they spent up to 12 hours or more at the burns. For those workers, an adjustment to the CO standard was done by using the reduction factor computed in equation (2). Computing this adjusted standard results in a recommended exposure limit as low as 16.6 ppm CO for workers at the burns for 12 hours. From figure 7, one can see that about 8 percent of the firefighters had average CO exposures exceeding 25 ppm CO during the burns, and about 2 percent exceeded 25 ppm for the entire work shift. These percentages increase as the adjusted TLV is lowered to 16.6 ppm for the longest duration prescribed burns. We concluded that shift-average CO exposure is a problem deserving better management at prescribed burns and therefore suggest the use of TLVs as evaluation criteria.

For those who wish to rely on the current CO PEL as the criterion, two firefighters exceeded 50 ppm CO during their time on the fireline, and another was a fraction of a ppm below 50, although none exceeded 50 ppm for the entire work shift. The OSHA reduction factor for the average 11.5-hour work shift would drop the PEL to 34.7 ppm, however; a limit that would be exceeded by about 1 percent of the firefighters during the average work shift. For the 16-hour work shifts, the PEL would be lowered to 25 ppm, a level exceeded by about 2 percent of the firefighters. Thus, the CO exposures remain problematic from the PEL-based viewpoint as well.

The immediate consequences of these overexposures to CO are likely to include reduced work capacity and ability to concentrate on detailed tasks, increased fatigue, headache, and nausea. The long-term health implications are not clear, based on present epidemiological studies. Whether one relies on the TLVs or the PELs, it is suggested that CO exposure be reduced among firefighters at prescribed burns. This is especially so for at-risk workers, such as those in poor health, suffering from angina or heart conditions, and during pregnancy. Smokers are at risk of adverse effects from work-related CO exposure because they already receive CO from cigarette smoking (smoking incurs blood CO levels in the range of 5 to 10 percent COHb, and adverse effects occur at around 5 percent COHb). Current respiratory protection devices (short of self-contained breathing apparatus) offer no protection against the effects of CO.

Respiratory irritants—Exposure to respiratory irritants is the most prevalent industrial hygiene problem at prescribed burns. As shown in figure 10, about 14 percent of the firefighters had shift-average irritant exposures that exceeded the recommended exposure limit for E_m, and 30 percent exceeded the limit while at the burns (these percentages are greater than those in the original study report because the ACGIH has lowered the recommended exposure limit for PM3.5). The highest exposures were four to six times the recommended irritant exposure limit. From a PEL compliance viewpoint (using the PELs rather than the recommended TLVs as the divisors in equation [1]), the percentage of overexposures is less dramatic but still a serious problem, as 5 percent of the firefighters exceeded their work shift PELs for respiratory irritants, and 13 percent exceeded the PELs while at the burns. The highest shift- and burn-average irritant exposures were, respectively, 2.6 and 3.9 times the PELs. At the levels we measured, firefighters will have significant eye, nose, and respiratory irritation. Short-term consequences include mucosal discharges (runny nose and tearing of the eyes), irritant discomfort ranging from a mild to untenable stinging sensation, and small temporary decreases in lung function. Longer term effects are possible, especially among chronically exposed individuals, but insufficient studies have been undertaken to assess such effects.

Our quality assurance program for the project indicated a possibility that the formaldehyde and acrolein data may underestimate the actual aldehyde exposure by as much as a factor of two and three, respectively. Thus, the total irritant exposures may be even greater. In that case, the percentage of respiratory irritant overexposures would increase, but this would not alter our conclusion that the exposure to respiratory irritants exceeds acceptable limits in some portion of the workers and can be controlled.

There are many lightweight respirators that can protect the respiratory system from fine particles and the nuisance levels of aldehydes that we have measured. These would need to be used only in medium- to heavy-smoke situations, which are readily apparent to most firefighters. Carbon monoxide exposure could be a greater hazard to firefighters working in full-face respirators. This is because the respirator would prevent irritant exposure, leading to a false comfort in thick smoke because only the irritants are removed, not CO. Selecting a half-mask respirator to protect the lungs from respiratory irritants may be a better interim strategy, because eye irritation could help signal to a firefighter that a dangerous smoke situation exists and high levels of CO could cause harm. Ultimately, a wildland firefighter respirator is needed that can remove irritants and CO and possesses a service-life indicator when the CO adsorbent expires.

Peak Exposure Assessment

Firefighters typically worked in significantly smoky conditions less than 5 percent of the time at prescribed burns. This estimate is based on the number of peak exposures we observed and were logistically able to sample, divided by the total number of samples we obtained. We missed other peak sample opportunities, but also did not sample during much of the nonexposed time. Exposure data for each work activity show that the peak exposure situations most often occurred during tasks aimed at keeping the fire within the unit boundaries, such as holding line, conducting direct attack on spot-fires, and supervising line-holding operations.

Figure 18—Firefighter lighting a prescribed fire in eastern Oregon.

During the smokiest conditions on the firelines, the peak exposures to CO and formaldehyde (and other respiratory irritants) can exceed legal and recommended short-term exposure limits. We obtained few measurements of all the respiratory irritants simultaneously during these peak exposure events, but by adding up the separately calculated means in table 7, the combined irritant exposure during these peak samples would have averaged about 2.6 times the recommended E_m. We can say that the average formaldehyde level during peak exposure situations exceeded legal and recommended limits, and the peak exposures can last a relatively long time; the maximum peak sample for formaldehyde and CO in table 7 is an average value over 18 minutes. The averaging process of integrated sample collection masks brief fluctuations in pollutant concentrations, so it is likely that the CO level exceeded the recommended 200-ppm ceiling during much of the sample. Figure 13 demonstrates this variability of CO exposure during a firefighter's work at a prescribed burn. The short-term health consequences of the higher peak exposures can include eye, nose, and respiratory irritation, fatigue, inability to concentrate on complex tasks, headache, dizziness, and nausea.

Exposure Determinants

Work activity—Work activity is a parameter that defines smoke exposure at prescribed burns (table 8). The firefighters lighting the burns with drip torches had the lowest exposure to all pollutants in smoke except benzene (fig. 18). The lighters ignite the unit in a pattern that places them upwind (or downhill) of previously ignited fuels, thus they can usually avoid significant smoke exposure. The moderate benzene exposure they received was most likely because of benzene vapors from the gasoline used in the drip torches. This is consistent with the relatively higher benzene exposure measured among sawyers and those who were lighting until called to other tasks, such as holding the firelines and attacking small spot-fires.

Considering all the pollutants, smoke exposure levels were uncomfortably high for those holding fireline during smoky episodes (fig. 19). In such events, exposure to respiratory irritants and CO is significant when comparing data from tables 7 and 8 with the United States occupational exposure limits (table 1). Holding line when there is no smoke is easy unless one has to patrol a steep section of fireline, but exposure to irritants and CO rapidly becomes a problem when the fire challenges a section of fireline and smoke blows into the line holder's position. If a worker can step out of the smoke, the problem can be controlled, but we often observed that topography or commitment to maintaining the fire within the unit boundaries prevented workers from avoiding excessive smoke exposure. The smoke exposure among holding supervisors was usually worse than for the holders, because the supervisors spent their time leading line-holding efforts along threatened sections of fireline.

Smoke exposure was the worst when the fire crossed firelines and threatened protected resources. Firefighters working at direct attack efforts incurred smoke exposure that was more than double that during other tasks. Although typically lasting less than 30 minutes, these attack events very likely exceeded recommended ceiling exposure limits and STELs for CO and respiratory irritants. The sawyers' relatively high exposure to smoke occurred because they often worked in support of attack efforts or mop-up and had to cut up smoldering logs or drop burning snags.

Smoke exposure during mop-up ranged between low and moderate. We observed that total dust exposure (including nonrespirable particles) may be relatively high during mop-up because the workers often generated clouds of ash and soil dust while excavating and extinguishing smoldering ground fuels. Unfortunately, we did not measure total dust exposure. However, we invalidated over one-third of the respirable particulate samples from the mop-up activity because so many airborne nonrespirable dust particles passed through the sampling devices onto the filters.

In summary, smoke exposure differed among work activities. Smoke exposure management could have the most efficient results by controlling the peak smoke exposures that occur during line holding and attacking escaped fire. Techniques of doing this include:

- Preplanning of units to avoid placing firelines in indefensible locations (such as midway up a steep slope).

- Pretreating of critical areas outside the firelines with water (via sprinkler systems) or foam to prevent the need to place personnel in those areas.

- Viewing minor "slopovers" as an acceptable consequence of prescribed burning, and controlling the escaped fire when conditions abate and there is less potential for intense smoke exposure among firefighting personnel.

Figure 19—Firefighter in the smoke while maintaining fireline at a prescribed fire.

- When smoke exposure must be endured to accomplish objectives, equipping and training firefighters with respiratory protection against irritants, so long as realtime CO monitors are used to alert them to evacuate to fresh air when the CO exposure becomes hazardous.

Windspeed–Our data showed that as average winds increase, fire managers should expect unhealthy smoke exposure among the firefighters who are required to work adjacent to the downwind fireline. Many prescribed burns rely on moderately strong winds to carry the fire and accomplish burn objectives. For these burns, increasing wind has little relation to smoke exposure, because the fire managers have planned for the wind's effect on fire behavior. For most burns, however, increasing or shifting ambient winds are one of the main causes of containment problems during the prescribed burning. The wind's effect on fire behavior is so strong that a minor directional shift or unanticipated wind speed increase can cause a well-behaved burn to become problematic. As the smoke plume from a burn is bent downwind, smoke and embers are carried within it. Where ignitable fuels are outside the unit, firefighters are deployed to hold the fireline and extinguish spot-fires. When the fire wins this battle, holding becomes a more active attack process, during which the ambient wind may continue to carry smoke into the firefighters and increase smoke exposure. During tasks such as mop-up or lighting, and for holding that is not downwind of the fire, the firefighters can avoid the smoke by staying upwind. This is why the correlation between ambient windspeed and smoke exposure was significant only during work tasks that involved attack of the fire.

Our measurement of average windspeed for the duration of the burn at one convenient location near the unit was, in hindsight, an insensitive measure of the local winds. We took that approach because fire managers typically make the same measurement, and a correlation could help them predict the smoke levels based on data they already gather themselves. From that standpoint, the regression in equation (6) provides a useful field estimator of the potential for smoke exposure (see fig. 12). Those fire managers who check winds before and during a burn may use the regression as a rough estimator of smoke exposure, if they are using a burn-average windspeed as the input variable. Ideally, the best resolution of the interaction between ambient wind and smoke exposure would be gained by measuring average windspeed during each exposure sample at a spot nearer to the firefighter, and identifying that position as being upwind or downwind of the burn. We expect the resulting data then would have a slope that differs from the burn-average data we collected.

Other site-specific variables—Smoke exposure did not show a clear trend versus the remaining site-specific variables (fuel moisture and fuel loading). It may be that further data analysis using sophisticated techniques could better identify underlying trends. Data plots of smoke exposure versus site variables suggested a slightly higher smoke exposure at higher fuel loading, but the limited range of fuel loading and lack of replication at the upper end of the range did not warrant an indepth analysis. One trend that did appear promising indicated higher smoke exposure at either extreme of the range of fuel moistures observed for the fine fuels (that is, less than 9 percent or greater than 16 percent moisture content). A plausible hypothesis is that burns in low-moisture fuels have intense fire behavior and spot fires ignite easily in the dry fuels, whereas burns in high-moisture fuels do not develop strong columns to draw the smoke away from the firelines, thus a relatively low ambient windspeed can carry a great deal of smoke into firefighters if they must work the downwind firelines.

Dosimeter Performance Evaluation

Dosimeters and dataloggers provide convenient and low-cost methods of measuring CO exposure, but the dataloggers we used underestimated the actual exposure when calibrated only monthly per the manufacturer’s recommendation. The relatively good agreement of the dosimeter tubes and method 128 data for CO confirmed that the tubes are useful for shift-average CO exposure measurements. They also have an advantage in low cost and simplicity.

The strength of the dataloggers (and other electronic dosimeters) is the realtime feedback provided. The user can glance at the readout and determine the instantaneous CO concentration and the accumulated TWA since the shift began. These features take the guesswork out of decisions to pull back firefighters during smoky situations. The user will find that the dataloggers are simple to operate as well.

The computer data provided by the dataloggers is a very good source of information for fire managers and health and safety staff (fig. 12). Each graph of CO exposure versus time can be saved for a permanent record of exposure, and when annotated with activities or condition changes, the graphs can be instructive tools to train firefighters in recognizing and preventing smoke exposure. The ability of the instruments to reliably sample very brief but harmful CO exposures is an important feature. We found that peak exposure samples were difficult to sample with our backpack samplers but were easy to capture with the dataloggers.

The Draeger 190 dataloggers were reasonably sturdy, but other manufacturers offer competitive electronic dosimeters and dataloggers, some of which seem to be more rugged and better able to cope with water or dust exposure. We experienced sensor failure with the model 190 when stray water from fire hoses contacted the sensor. The everpresent dust in the field also forced daily changing of the dust filter to obtain good results.

Our experience showed that the recommended monthly calibration interval is inadequate. Immediately after calibration, the dataloggers passed a calibration check with a second-source CO standard, but after several days or weeks, the dataloggers gave low readings of the same gas, even if they had not been used in the interim. We suggest that users of dataloggers or electronic dosimeters develop a calibration and QA protocol to address such problems by routinely checking the response of the instruments to a second-source calibration standard before and after use each day. The second-source standard helps to ensure that any errors in calibration (such as a leak or incorrect data entry) with the primary calibration gas will be caught before the instrument is used. Maintenance and recalibration are necessary when the instrument response exceeds acceptable limits.

Pollutant Correlations

We found that the levels of all the pollutants measured were highly correlated to each other in any given smoke sample. Note the linearity of the relation in figure 14 over a wide concentration range. As indicated by the r^2 values in table 11, these correlations are sufficiently strong that one can use a measurement of any of the pollutants as a surrogate to estimate exposure to the rest via a linear regression. This provides a way to cost-effectively estimate exposure to respiratory irritants and benzene from measurements of CO. The limitations on the estimates are given by the range of the regressions (the graph axes) and the width of the confidence intervals around the sample concentrations predicted by the regressions (shown in figs. 14 and 16). When the regressions are used to predict exposure to unsampled pollutants, it is suggested the user does not exceed the range of the regression and consider the width of the confidence interval to evaluate the significance of the estimated concentration. In addition, these regressions are specific to prescribed burning in the Pacific Northwest; they may differ in other fuel types and regions and under combustion conditions that differ from the prescribed burns where the data were obtained.

Recall that the data comprising the regressions for benzene were limited to samples from tasks where gasoline was not handled or used. Work activities such as chainsaw operation and refueling, swamping (assisting the sawyer), lighting with or refueling drip torches, and tending a gas-powered pump or engine most likely would add benzene exposure that cannot be predicted from these regressions, because they are valid only for smoke from prescribed burns.

In practical use, the regressions are suited to predict total pollutant exposure at a given level of CO. The CO measurement could be obtained from an electronic dosimeter or datalogger. An example illustrates the process, which can be converted into a nomogram or programmed into an electronic calculator to facilitate field use.

Assume that the TWA CO exposure of a firefighter for an 8-hour day is 15 ppm. Using the appropriate four regression equations from table 11, the corresponding pollutant exposures are:

Pollutant	**TWA exposure regression result**	**Recommended TWA exposure limit**
Formaldehyde (HCHO)	0.11 ppm	0.3 ppm
Respirable particulate (PM3.5)	1.68 mg/m^3	3 mg/m^3
Acrolein (C_3H_4O)	0.02 ppm	0.1 ppm
Benzene	0.02 ppm	0.5 ppm

In this example, benzene exposure is not an issue. The combined irritant exposure to formaldehyde, PM3.5, and acrolein is an issue, however, and is assessed by putting the regression results into equation (1) as follows:

$$E_m = \frac{[HCHO]}{0.3} + \frac{[PM3.5]}{3} + \frac{[C_3H_4O]}{0.1} \quad , \quad \text{or}$$

$$E_m = \frac{[0.11]}{0.3} + \frac{[1.68]}{3} + \frac{[0.02]}{0.1} = 1.13 \quad .$$

Even though the firefighter was not overexposed to CO for an 8-hour day, it is suggested that the exposure to respiratory irritants be reduced because the combined irritant exposure exceeds 1.0. A lightweight half-mask respirator for fine particles could achieve irritant control, provided that an advanced training program in respirator use be implemented. In addition, CO exposure will need to be monitored closely when a respirator is used because the respirator affords relief from respiratory tract irritation but does nothing to reduce CO exposure.

These straightforward calculations extend the capabilities of a routine smoke monitoring program based on measurements by CO dataloggers. The instruments directly indicate the CO data, and through the interpollutant regressions they also give a good indication of the potential exposure to respiratory irritants and benzene. Using this approach alleviates the need to monitor each pollutant separately. The correlations give a more complete picture of smoke exposure, thus providing managers with the information necessary to judge whether respiratory protection is needed to control irritant exposure or whether the CO hazard would still be high enough that crew retreat into clean air is the best strategy.

Management Implications

If the goal of managers is to minimize the exposure of firefighters to unhealthful levels of smoke that exceed legal and recommended limits, then managers could implement the following steps:

- Finish ongoing health risk assessment efforts to evaluate long-term consequences of smoke exposure among personnel involved with prescribed burning.

- Develop a smoke exposure management program aimed at reducing smoke exposure to acceptable limits, and assign long-term responsibility for the program to a team comprised of fire managers, workers, and health and safety experts.

- Improve training on the hazards of smoke exposure within the context of existing firefighter training coursework.

- Acquire electronic CO dataloggers within each region conducting a large-scale prescribed burning program. Develop a sound protocol with adequate QA to routinely collect CO exposure data on a wide scale and alert firefighters to the hazards of peak smoke exposures.

- Use the interpollutant correlations to estimate exposure to respiratory irritants from CO measurements in the Pacific Northwest.

- Develop a health surveillance program to identify individuals especially at risk of adverse health effects from smoke exposure, and track the health of workers who are chronically exposed to smoke.

- The smoke exposure management team could change prescribed burning practices to reduce the need for holding and attack in smoky conditions by (1) better laying out of new units to take advantage of natural barriers, (2) better line preparation and prewetting of fuels along strategic sections of fireline, (3) burning under higher fuel moisture conditions to reduce the need for line holding and mop-up, (4) limiting burning when winds are forecast to increase if adjacent resources are at risk, and (5) accepting minor slopovers and waiting until conditions abate before constructing additional fireline.

- Implement training and fit-testing for an OSHA-compliant respirator program, and equip core resource groups of firefighters with half- or full-face respirators and electronic CO dosimeters to protect them from respiratory irritants and CO when they must work in smoky conditions.

Few further research needs exist, and management can begin to control peak exposures and those situations where firefighters must endure smoke during holding and direct attack. Exposure control efforts begun now will not likely require wholesale changes due to further research discoveries. Here are the remaining research and development issues, as we see them:

- How does smoke exposure during prescribed burning in other areas of the country compare with the Pacific Northwest? By properly planning the data collection protocol for the CO dataloggers to ensure that all monitors provide data with known quality, we can acquire comparable data in each region to cost-effectively answer this question.

- How applicable are the interpollutant correlations in other areas of the country? Are the aldehyde data accurate or do they underestimate the actual exposure? These questions could be answered by limited comprehensive data collection on exposure to the irritants and CO in other regions of the country. Expanding these correlations is the key to reducing the long-term cost of routine monitoring.

- Have we identified all the main hazards in smoke? We may find that a more complete evaluation of the chemical composition of smoke identifies additional irritants, such as other aldehydes and formic acid, that comprise a significant proportion of the fine particles. If so, these other irritants can be factored into the total irritant exposure equation. This analysis could be done cost-effectively in a laboratory setting rather than requiring extensive new fieldwork.

- Is total particulate exposure a concern? Unfortunately, entrained dust will not likely be correlated with the respirable particulate or the other components of smoke. Limited monitoring in dusty-smoky situations could answer this question, however. The results would have a bearing on the extent of respirator use recommended by the smoke exposure management team.

- Does the particulate matter that firefighters encounter at prescribed burns contain significant crystalline silica, as other researchers have found (Harrison and others 1992)? If so, the exposure limits to be achieved could be lowered further. This possibility can be evaluated by analyzing the archived particulate filters obtained by PNW for their crystalline silica content. The relatively low-cost analysis could be achieved without incurring the cost of additional field effort.

- Development efforts could be initiated to design and receive OSHA approval to use a wildland firefighting respirator that removes fine particles, aldehydes, and CO, is rugged and lightweight, does not restrict breathing ability, and has an end-of-service indicator for CO capacity.

Since this project began, awareness of the hazards of smoke exposure has risen significantly. We believe that the increased awareness and recent moves to increase the scope of prescribed burning in the United States create a climate whereby agencies conducting prescribed burning can rapidly achieve results from a smoke exposure management effort. The results and management implications of this study can form the baseline from which to move forward, if sufficient resources are dedicated to solving the problems of smoke exposure.

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
BLM	Bureau of Land Management
C	Ceiling
C_3H_4O	Acrolein
CAL-OSHA	California Occupational Safety and Health Administration
CDF	California Department of Forestry and Fire Protection
CFK	Coburn-Forster-Kane equation
CO	Carbon monoxide
COHb	Carboxyhemoglobin
CO_2	Carbon dioxide
E_m	Equivalent exposure (irritant) index
EPA	Environmental Protection Agency
FEV_1	Forced expiratory volume of the lung in one second
FEF_{25-75}	Forced expiratory flow of the lung in the midrange of exhalation
FVC	Forced vital capacity of the lung
HCHO	Formaldehyde
mg/m^3	Milligrams per cubic meter
µm	Micrometer
NIOSH	National Institute for Occupational Safety and Health
NPS	National Park Service
OSHA	Occupational Safety and Health Administration
PE	Performance evaluation
PEL	Permissible exposure limit
PM3.5	Respirable particulate
PNW	Pacific Northwest Research Station
ppm	Parts per million
QA	Quality assurance
QC	Quality control
r^2	Coefficient of determination
REL	Recommended exposure limit
STEL	Short-term exposure limit
TLV	Threshold limit value
TWA	Time-weighted average

Acknowledgments

Outstanding personal contributions to this research were made by Aimee Backlund, Todd Barker, Christine Betchley, Jenelle Black, Ray Borgen, Todd Burke, Dave Cambensy, Tanya Copeland, Stacey Drury, Dave Frewing, Michael Hallett, Ken Harris, Brian High, Cheryl Luschei, Doug Milligan, and Charles Sauvageau.

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