United States
Department of
Agriculture

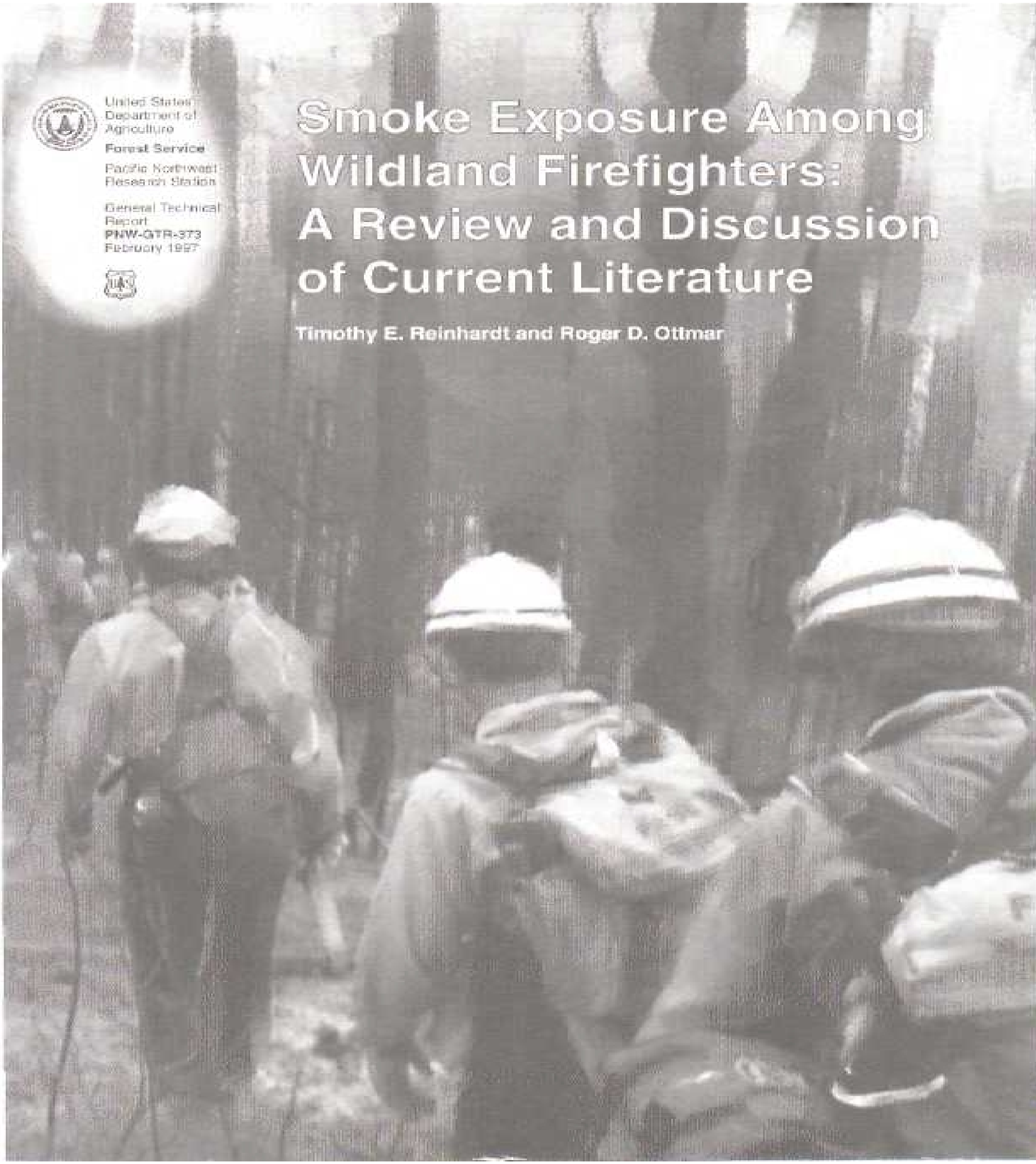
Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-373
February 1997

Smoke Exposure Among Wildland Firefighters: A Review and Discussion of Current Literature

Timothy E. Reinhardt and Roger D. Ottmar



Authors

TIMOTHY E. REINHARDT is a senior industrial hygienist, Radian Corporation, 11711 SE Eighth Street, Suite 200, Bellevue, WA 98005-3543; and ROGER D. OTTMAR is a research forester, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 4048 Roosevelt Way, Seattle, WA 98105. Fulfills cooperative agreement PNW 91-0031 between the USDA Forest Service, Pacific Northwest Research Station, and Radian Corporation

Abstract

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

This paper reviews and summarizes literature about smoke exposure and the resulting adverse health effects among wildland firefighters Many studies have been done on this problem between 1973 and 1995 Overall the data indicate that smoke exposure at wildfires and prescribed fires is usually no more than an inconvenience, but on occasion it approaches or exceeds legal and recommended occupational exposure limits Management action is necessary to bring all smoke exposures into compliance with occupational safety regulations

Keywords Fire, smoke, human health, occupational exposure, safety smoke exposure

Summary

Overexposure to carbon monoxide and respiratory irritants is likely among firefighters when direct control of fire is required and smoke production is intense Such overexposures are mostly brief events, but sometimes poor atmospheric dispersion or rigorous work schedules cause hours or even days of unhealthful working conditions Increased respiratory health problems have been measured in wildland firefighters Small but statistically significant declines in lung function have been observed in a number of wildland firefighters, across both workshifts and seasons More data are needed to determine whether these losses are reversible

Smoke exposure data are limited in geographic scope and representativeness and focus mostly on large Western U S wildfires or prescribed fires in the Pacific Northwest Data-collection efforts have been ill prepared for the mobility and responsiveness needed to capture smoke exposure during initial attack, as a result most studies have obtained many duplicative measurements of smoke exposure during the latter stages of fire suppression when smoke exposure is considered low Exceptions to this have identified a limited but significant problem Smoke exposure is likely to be the highest during initial attack, during direct attack of fires in high winds, and in large-fire situations that suffer from poor atmospheric dispersion

Recommendations are made to develop smoke exposure management plans Health surveillance is recommended to accompany exposure management Collection of additional exposure data is recommended, but only for high-exposure situations and in regions that have not been well represented in the data collected so far The following items summarize the conclusions of this review

- There is a smoke exposure problem among wildland firefighters in the United States, but it is a manageable problem, requiring control during about 5 percent of the workshifts studied
- The hazards in smoke seem to be limited to respiratory irritants and carbon monoxide, but these can reach unhealthful levels at both prescribed fires and wildfires Other potential health hazards include crystalline silica, which is a poorly characterized but potentially significant hazard during fire operations in dusty conditions, and exposure to benzene among firefighters exposed to gasoline fumes

- Acute smoke exposure is a more prevalent problem than the average exposure during a work shift Acute exposures are common, but shift-average exposures frequently comply with exposure limits because the brief periods of overexposure are compensated by lengthy low-exposure periods within workshifts

- Small declines in lung function have been detected among firefighters, with statistically significant losses shown across both workshifts and fire seasons, it is unknown whether the cross-seasonal losses are reversible, but limited evidence suggests that they are

- Ambient windspeed is a key factor controlling smoke exposure potential, with smoke exposure proportional to windspeed at both prescribed fires and wildfires Prescribed burning at either extreme of the fuel moisture prescription also may be associated with increased smoke exposure among firefighters

- The work task of an individual at a prescribed fire strongly influences smoke exposure Those workers holding the fireline (maintaining fire within firelines) and conducting direct attacks usually have greater smoke exposure than workers igniting prescribed fires or mopping up Similar trends are indicated at wildfires

- High smoke exposures should be expected when firehnes must be maintained in spite of smoke exposure, such as at wildland-urban interface fires or during prescribed burning adjacent to poorly defensible resources Overexposure to smoke also may be associated with direct attacks when fires are small or slow moving or when mechanized equipment allows attack at the head of a fire Smoke exposure also may be high when heavy ground fuels support smoldering combustion

- Smoke exposure management should be implemented for all regions of the United States, because overexposure to smoke likely is not limited to one geographic region or fuel type Insufficient data have been collected to show any regional or fuel-specific differences that may exist at either prescribed fires or wildfires

- To develop an accurate risk assessment of the consequences of smoke exposure, demographic data need to be collected to assess firefighter career smoke exposures

- Further health effect evaluations should include newly hired firefighters to determine whether first-season lung function decline is greater than the small seasonal losses documented among experienced firefighters

- Strategists for smoke exposure management may wish to consider the physiological effects of carbon monoxide exposure among smokers already subject to impaired blood oxygen transport, and whether those individuals are at greater risk of adverse consequences from job-related smoke exposure

- Further collection of smoke exposure data should be an integral component of smoke exposure management plans By routinely measuring smoke exposure with real-time instrumentation, the recognition, documentation, and avoidance of acute overexposures are more likely to occur Safety and health managers should meet with the appropriate occupational safety regulatory agencies (such as the Occupational Safety and Health Administration) and propose the routine use of electronic carbon monoxide dosimetry as a cost-effective alternative to comprehensive smoke exposure monitoring among firefighters

- Research-level data collection is indicated only for regions such as the Southwest, Southeast, and Northeast where data are sparse, and then only to determine whether smoke exposure management is warranted for those areas Data collection is recommended for high-exposure situations, such as initial attack, wildland-urban interface fires, backfiring, and burnout operations, to improve the strength of inter-pollutant correlations for routine monitoring When a firecamp is established in smoky inversion conditions, ambient air quality monitoring should be conducted Finally, analysis of the crystalline silica content of stored particulate samples is recommended based on limited data showing a potential health hazard

- Enough evidence has been gathered to begin developing and implementing strategies for smoke exposure management Management plans that address the possibilities of overexposure as indicated by the existing data are not likely to require changes in strategy as a result of further monitoring, only in the scope of application

Contents

Introduction

Smoke exposure among wildland firefighters is a concern of few outside the fire management community Only recently has it attracted attention from occupational health specialists Within the fire management community, interest in smoke exposure has steadily increased, but few have any knowledge about the scope of the problem beyond their own first-hand experience This review is aimed at those who have some experience with wildland fire

Objectives

This review summarizes current knowledge of smoke exposure among firefighters, identifies significant gaps in knowledge, and recommends strategy to fill those gaps for agencies considering management of smoke exposure risks Resources include published and unpublished data about firefighter smoke exposure, the occurrence of wildfires and prescribed fires in the United States, and the strategies and tactics of fire management Anecdotal knowledge from experienced firefighting professionals was helpful in summarizing current developments in the field In many cases, the lack of objective data about smoke exposure in various fuel types and fire situations makes "expert knowledge" the only available source of reference Other than seeking further corroboration, no evaluation was made of any bias that may exist in the expert knowledge

History

Smoke exposure has been a recognized issue since about 1910, the beginning of fire management in the United States, because smoke has always been recognized as an irritant to firefighters Witness the implementation of bandannas, which have been commonplace among firefighters since 1910 Although occupational safety was a rudimentary concern back then, the workplace laws, and science have evolved dramatically since Current concern with smoke exposure dates from the early 1970s, when a few investigations into fatigue and injury among firefighters hinted at smoke exposure as a contributing factor

The interest in the topic waxes and wanes with the severity of fire seasons and the results of each new study Studies have been done by various groups, especially at wildfires, with the scope of these studies mostly limited to a few components of smoke and a few days of sampling Lack of grounding in industrial hygiene theory and practice has hampered some studies The largest study to date (in terms of samples collected) was done in the mid-1970s by the USDA Forest Service (Jackson and Tietz 1979) In spite of results that found significant overexposure to carbon monoxide (CO, the primary known hazard in smoke at the time) details about factors controlling the exposures were not collected, and the data were not collected so that acute health effects could be examined, which may be the most important aspect of smoke exposure Other studies have had the industrial hygiene capability but insufficient understanding of the wildland fire workplace, how variable it was, what factors coincide to result in overexposure to smoke, and what it would take logistically to adequately characterize smoke exposure Many studies have suffered from the vagaries of fire well-laid plans for research were useless when weather and fire did not cooperate to produce the anticipated phenomena of smoke exposure

A comprehensive approach to assessing smoke exposure and the resulting adverse health effects among firefighters was developed at a meeting of wildland fire agencies, physicians, industrial hygienists, and safety experts in January 1989 (Ward and others 1989) in San Diego. Unfortunately, the multiple goals of the participants resulted in an unwieldy proposal to Congress for a multimillion dollar assortment of projects, in spite of heroic efforts to pare down unnecessary work and focus on what was really necessary. Congress did not fund the proposed project, and the participants have not revisited the issue with any coordination

The National Wildfire Coordinating Group (NWCG) has been the only interagency focus for concern about smoke exposure and firefighter health in the last decade. Supported by a small amount of funding, NWCG has brought together interested agencies, coordinated research needs, funded a few small projects, and maintained a central brokerage of information about the health hazards of smoke, it produces a widely read newsletter[1] that summarizes recent results in smoke exposure, health effects research, and exposure management.

Overview

Wildland firefighters are workers Where they do their jobs, in the forest or on rangeland of America, is a workplace. Occupational safety regulations in the United States apply to all workers in all workplaces to ensure that no one will be exposed to unsafe or unhealthful working conditions. There is no exemption from these laws for emergency workers, or workers employed by a particular employer It is each employer's responsibility to see that their employees' working conditions are safe.

There is a smoke exposure problem among wildland firefighters in the United States, but it appears to be manageable. Industrial hygiene measurements of firefighter exposure to respiratory irritants and carbon monoxide (CO) at prescribed fires document incidents exceeding OSHA (Occupational Safety and Health Administration) permissible exposure limits (Reinhardt and others 1994), and evidence points to similar overexposures at wildfires. Firefighters occasionally report illness from exposure to smoke—both acute, adverse health effects and chronic illness that they (or others) attribute to smoke exposure. Anecdotal reports of overexposure to smoke are common at both wildfires and prescribed fires. Most experienced firefighters can attest to incidents in which they or others suffered from exposure to smoke. Although acute effects are well known, links between smoke exposure and morbidity or mortality are equivocal at the present time.

Anecdotal reports are insufficient to develop policy in the United States. Managers here need what is perceived as more solid information to allocate resources effectively. There are a wide variety of potential management strategies to select from; however, to spend limited resources on an ineffective shotgun solution to an ephemeral problem is no wiser than ignoring the problem If personal protective equipment is chosen unwisely, the cure may be worse than the disease, especially to firefighters who already carry a heavy load of equipment, work at the upper limits of endurance, and are subjected to extremes of heat and cold while they work to control a physical phenomenon that can kill without warning.

[1] The Newsletter, 'Health Hazards of Smoke, is available from the USDA Forest Service, Northern Region, Equipment Development Center, Fort Missoula Bldg 1, Missoula, MT 59501

Attempts to quantify smoke exposure invariably conclude that it is a limited problem, insignificant most of the time but possibly harmful some of the time, every report reviewed here concludes that smoke exposure deserves further analysis This conclusion frustrates managers looking for solutions rather than more studies, but follows from the extremely transient nature of the phenomenon At any given wildfire or prescribed fire attended by firefighters, it is almost axiomat c that someone will enjoy fresh air while another is exposed to varying degrees of smoke Industrial hygienists find it difficult to deploy their equipment on the right firefighter at the right time and place to measure one of those transient smoke exposure episodes that firefighters talk about "You should have been here yesterday" is a phrase too often heard

To begin to grapple with the smoke exposure problem is to first realize that firefighters are a diverse lot, differing in age, physical health, lifestyle attitude, and work habits This variability influences their susceptibility to adverse health effects from smoke exposure. No less significant in determining the boundaries of the smoke exposure problem are the great variety of smoke exposures possible within the diversity of the wildland fire milieu

Health Hazards in Smoke

The principal known inhalation hazards among wildland firefighters have been summarized in detail (Reinhardt and others 1994) The identity of these hazards seem to differ little between prescribed fires and wildfires, although certain activities, fuels, and situations may elevate exposure to one or more components Briefly, the chief inhalation hazards are CO, aldehydes, and respirable particulate matter (PM3 5) and total particulate matter (TPM), either of which may contain crystalline silica Crystalline silica is not considered a *smoke* exposure hazard per se because it is not created as a combustion product, however, as an inhalation hazard common to many dusty environments, crystalline silica must be included in any general discussion of smoke exposure hazards among firefighters unless smoke is the sole source of the particulate matter And, conversely, crystalline silica can be a hazard in the absence of smoke Of the aldehydes, formaldehyde (HCHO) and acrolein have been studied the most, but many other low-to middle-molecular weight aldehydes also are present in smoke. Benzene is a potential hazard, depending on work activity and the hazard evaluation guideline selected Other chemicals in smoke seem less likely to pose a significant health hazard, but the list could expand or contract as our knowledge of toxicology and smoke exposure improves (Dost 1991)

Occupational Exposure Standards

Several evaluation guidelines exist for occupational inhalation exposures The Occupational Safety and Health Administration sets legal permissible exposure limits (PELs) for all Federal employees in the United States, and for all private industry employees not under the jurisdiction of a state agency to which OSHA has delegated authority for enforcement of occupational safety programs. Twenty-three states presently operate designated state agencies, such as the California Occupational Safety and Health Administration (CAL-OSHA), and have legal jurisdiction over state and private industry workers. The National Institute for Occupational Safety and Health (NIOSH) advises OSHA on health hazards in the workplace and establishes recommended exposure limits (RELs). The American Conference of Governmental Industrial Hygienists (ACGIH) recommends threshold limit values (TLVs) for worker safety

Each organization expresses the exposure limits for airborne pollutants via three basic time-categories These categories of exposure limits are

- Time weighted average (TWA), an average concentration for a normal 8-hour day in a 40-hour workweek, to which nearly all workers may be exposed for a working lifetime without adverse effect
- Short-term exposure limit (STEL), a maximum concentration to which workers can be continuously exposed for up to 15 minutes without adverse effect
- Ceiling (C) a concentration that should not be exceeded even instantaneously

A 'skin" notation for a particular chemical indicates that dermal absorption is an important route of exposure that should be considered in management strategies Table 1 summarizes present exposure limits for these inhalation hazards from regulatory agencies and the most current (or proposed) guidelines from occupational health organizations

At a minimum, *all* worker exposures in the United States must comply with either the PELs or the applicable state limits For evaluation guidelines that more accurately reflect current knowledge of health hazards, ACGIH and NIOSH recommendations are appropriate

Prescribed Fire

Broadly speaking, a prescribed fire is a wildland fire that achieves vegetation management goals of the responsible agency Prescribed fire has traditionally been most widely applied to activity fuels (fuels altered by silvicultural activities), including timber harvest residues and thinning residues Underbuming in tree plantations to reduce wildfire hazard and maintain pine species is a major application of prescribed fire in Southern States Piling biomass residues and burning under favorable conditions is a common practice in many parts of the country In the last 15 years, prescribed fire in natural fuels has been recognized as an important tool to maintain fire-adapted ecosystems threatened by fire-intolerant species unnaturally favored by decades of vigorous fire suppression Proposals for restoration forestry in the inland Western United States depend on large increases in thinning, selective harvesting, and burning (Mutch and others 1993)

Because prescribed fire includes such a great variety of fire situations, making generalizations about smoke exposure is difficult Exposure potential may be expected to differ among different prescribed fire applications Prescribed fires in activity fuels have different characteristics than prescribed fires in natural fuels Prescribed fire ignitions may be scheduled or unscheduled, but scheduled ignitions predominate

Common to prescribed fire in general—and particularly to scheduled ignitions—is the assumption of responsibility by the on-site fire manager (fire boss) to maintain control over the prescribed fire This responsibility for control raises the likelihood of high smoke exposure should the fire test the boundaries of control The conventional wisdom is that a brief control effort conducted in intense smoke often can prevent a large resource loss, even among fire managers concerned about smoke exposure, this "pay a little now or a lot later" maxim justifies smoke exposure that may be harmful

Table 1—Occupational exposure limits for inhalation hazards

Standard	Acrolein	Benzene	CO	HCHO	Particulate matter	Crystalline silica
	Parts per million				*Mg/m[3]*	
OSHA Permissible exposure limits	0 1 TWA[a]	1 0 TWA 5 0 STEL-C[b]	50 TWA	0 75 TWA 2 0 STEL[c]	Respirable 5 TWA Total 15 TWA	Respirable $\frac{10\ mg/m^3}{\%\ SiO^2 + 2}$ Total $\frac{30\ mg/m^3}{\%\ SiO^2 + 2}$
NIOSH Recommended exposure limit	1 TWA 3 STEL	1 TWA 1 0 STEL-C	35 TWA 200 STEL	016 TWA 1 STEL C		
ACGIH Threshold limit value	1 TWA 3 STEL	10 0 TWA[d] (skin)	25 TWA	3 TWA C	Respirable 3 TWA	Respirable 0 05-0 1 quartz
CAL-OSHA	1 TWA 3STEL	1 0 5 0 STEL-C	35 TWA 200 STEL-C	75 TWA 2 0 STEL	Respirable 5 TWA	

[a] TWA = time weighted average
[b] STEL-C = short-term exposure limit ceiling
[c] STEL = short-term exposure limit
[d] American Conference of Governmental Hygenists 1996

A general breakdown of work activities may be made for prescribed fires First, some sort of incendiary technique is used to ignite the biomass within the area (unit) designated for burning. Drip torches, fusees, Aluma-gel balls, helitorches, flamethrowers, drip torches mounted on all-terrain vehicles, and aerial incendiary devices (Ping-Pong balls) are all employed in specific situations.[2] Ignitions by aerial and all-terrain vehicle can burn more acreage per day than hand ignitions, and may be necessary to achieve residue consumption targets when fuel moisture is high, however, the greater rates of heat release associated with aerial ignitions can cause control problems from unexpected fire behavior. A specific pattern of ignition is selected for each prescribed fire, depending on the local conditions and objectives of the burn

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

When the unit is ignited, some personnel are usually assigned to "hold" the perimeter of the unit where fire is expected to challenge control preparations—usually the downwind and uphill firelines The fuel adjacent to these lines often is ignited first in a low-intensity fire to provide a burned buffer strip before main ignition of the unit The 'holders' may be assigned to one location for some time, moved from one critical section to another, or just patrol the edges of the burn When spot fires erupt outside the firehnes or the prescribed fire crosses the fireline in a "slopover," the holders conduct direct attack, "hotspotting" (seeking out and controlling the spread of the hottest portions of the fire) the unwanted fire with direct control efforts that culminate in mop up (extinguishing smoldering fuels after the flaming phase of a fire)

For many prescribed fires, escape potential or smoke management restrictions warrant mop up of the unit after the main fire has dwindled into the smoldering phase Mop up involves digging up and turning smoldering duff and large-diameter fuels, scraping off embers, and extinguishing residual fire with dirt or water

In all regions of the United States, prescribed burning at the wildland-urban interface is increasingly common Concern about fire and smoke impacts on properties adjacent to the burn unit limits the margin for error Additional personnel often must be used to maintain burn perimeters near private property When a fireline must be held in spite of adverse conditions, firefighters can be exposed to significant amounts of smoke

Prescribed Fire Literature

There is very little literature about smoke exposure at prescribed fires Only six studies were found as of June 1995, which resulted in the following papers Jackson and Tietz (1979), Reinhardt (1989, 1991), McMahon and Bush (1992), Materna and others (1992a), Reinhardt and others (1994), and Betchley and others (1995) These resources provide the basic data about smoke exposure at prescribed burns In some cases, more thorough discussions of the methods and results were found in the unpublished project reports These data provide a reasonable base from which to evaluate smoke exposure at prescribed fires

Jackson and Tietz (1979)—The first attempt at exposure assessment at broadcast prescribed burns was documented in a 1979 project record by Jackson and Tietz This study examined only CO exposure but included both wildfires and prescribed fires Exposure sampling at nine prescribed fires in 1975 and 1976 relied on measurements of CO in end-exhaled breath (alveolar air) to calculate carboxyhemoglobin (COHb) levels from Ringold's equation (Ringold and others 1962) Samples were collected in the morning before firefighters went to the fireline and again within an hour of leaving the fireline Time worked at the fireline differed but was usually more than 8 hours Only data from nonsmokers were used because COHb levels in smokers were a large source of variation in the results Quality assurance data were not reported Measurements at seven prescribed fires in 1975 found that 12 of 233 firefighters (5 percent) had COHb levels 5 percent, which implies that they suffered overexposure to CO (the CO standard was intended to prevent COHb levels above 5 percent) In 1976, two prescribed fires were monitored At the first burn, 12 firefighters were monitored, and none had a COHb level >5 percent At the second burn, 15 of 20 (75 percent) of the firefighters had COHb levels >5 percent The first burn in 1976 was in light, discontinuous fuels and low windspeeds (<5 m p h), and the second burn was in heavy fuel loading and winds of 5 to 10 miles per hour The high COHb levels at the second burn were attributed to heavy smoke exposure during a 1 5-hour direct attack of a slopover on the uphill side of the fire

The monitoring strategy could have biased the results of this study to underestimate smoke exposure in certain circumstances This is because the biological half-life of CO is around 4 hours If smoke exposure is at a maximum early in the workday, COHb from peak CO exposures early in the shift could be mostly eliminated from the body by the t,me COHb is measured at the end of the shift

McMahon and Bush (1992)—In 1988, smoke exposure was monitored at 14 prescribed fires in Georgia by McMahon and Bush (1992) This study was primarily concerned with assessing potential exposure to herbicide residues from prescribed burns on sites treated with herbicides under "brown and burn programs Personal and area monitors were used to sample for the herbicides imazapyr triclopyr, hexazinone, and picloram Coincidental with the herbicide monitoring was personal-exposure sampling for PM3 5 and CO by using filter and cyclone assemblies and passive diffusion tube dosimeters, respectively The PM3 5 monitoring was done at a higher sample flow rate (4 0 rather than 1 7 liters per minute) to enhance detection limits Some monitoring for herbicides and total particulate matter was conducted using area monitors

Spike recovery data (addition of a known amount of analyte to a sample to evaluate accuracy of a chemical analysis) are reported for herbades and detection limits are reported for all methods used Data for particulate matter sampling indicated good precision between the area method and the personal PM3 5 method, but a 12-percent lower collection efficiency was observed for the cyclones operated at 4 liters per minute versus the standard flow rate No herbicide residues were detected in 140 smoke samples, despite sensitivities below 4 micrograms per cubic meter and spike recoveries in the 66 to 105 percent range Breathing zone samples of PM3 5 ranged between 0 2 and 3 7 mg/m^3 (median 1 3 mg/m^3) Sample durations ranged between 1 2 and 6 3 hours, depending on the acreage burned imedian 2 8 hours) About half of the CO samples were above detection limits and were quantified as ranging between 6 and 30 parts per million (ppm)/hour, with the nighest value averaged over 1 7 hours Thus the highest concentration was calculated to be about 50 ppm The CO and PM3 5 concentrations are in agreement with those measured by other researchers at low- to moderate-exposure prescribed burns (see discussion below) In view of the lower collection efficiency of the PM3 5 method used, the PM3 5 concen trations may be biased slightly on the low side

This study also reported good correlations between PM3 5 and CO, with r^2 ranging between 0 74 and 0 81 (McMahon and Bush 1992) The slope coefficients agree with those reported by Reinhardt and others (1994) McMahon and Bush (1992) concluded that the OSHA PEL TWA exposure limits for CO and PM3 5 are not likely to be exceeded, but a 200-ppm ceiling limit for CO could be exreeded as workers occasionally move through areas of thick smoke

Reinhardt (1989)—The pilot study by the USDA Forest Service, Pacific Northwest Research Station (PNW), primarily examined smoke exposure among USDA Forest Service firefighters at broadcast burns of timber harvest residues (slash burns) in the Pacific Northwest (Reinhardt 1989) Three days of smoke exposure also were measured in northern California—at one prescribed fire in grass and during mop up at two wildfires Some of the results from this study were published in 1991 (Reinhardt 1991), but the final analysis of the data was completed in the 1989 report Firefighter exposure to CO, carbon dioxide (CO2), benzene, acrolein HCHO, and PM3 5 was measured concurrently Worst-case exposures were largeted in this study, where sampling was done on whichever firefighters were in the smoke rather than monitoring specific firefighters regardless of conditions during the day Shift-average exposures were not calculated in this study Peak exposure data from intense smoke exposure episodes are comparable with other studies (Materna and others 1992a, McMahon and Bush 1992, Reinhardt and others 1994), because each study used nonrandom sampling for peak exposure measurements This exploratory project lacked a thorough quality assurance program, thus the data must be considered provisional although much of the pilot study data are probably accurate because the same instruments or methods were used in the 1994 project (Reinhardt and others 1994) which did have a suitable quality assurance design

Benzene exposure was found to be the highest among those lighting prescribed fires, although few data were reported "Direct attack" (hotspotting) was identified as a high-exposure work activity for all pollutants The mean CO concentration during direct attack was 33 ppm, and the mean HCHO concentration was 0 37 ppm The study concluded that "lighting" was a low-exposure activity, averaging 4 ppm CO and 0 07 ppm HCHO "Holding line" was identified as a high-exposure work activity, averaging 31 ppm CO and 0 46 ppm HCHO in this study Mop up exposures were relatively high in this study, averaging 31 ppm CO and 0 17 ppm HCHO The high mean smoke exposures observed for the "holding line" and "mop up" samples could be an artifact of the nonrandom sampling—mostly limited to significant smoke exposure in this pilot study

The acrolein data from the pilot study are probably not accurate exposure measurements This is because inadequate chromatographic performance could have allowed a coeluting acetone peak to cause a positive bias in the acrolein measurement The acrolein measurements did not benefit from the recent method improvement whereby total acrolein recovery is obtained by summing chromatographic results for acrolein and the x-acrolein breakdown product (Reinhardt and others 1994)

These chromatography problems did not affect the formaldehyde data, however The concentration of the calibration standard for HCHO in the pilot study was independently verified by the USDA Forest Service Intermountain Research Station, which provided at least one quality assurance check of the calibration for HCHO Peak levels of exposure to HCHO in the pilot study commonly ranged between 1 0 and 2 0 ppm over sampling periods lasting 30 minutes or more The greatest HCHO exposure measured was 3 2 ppm for 26 minutes Although the bulk of the HCHO data in the pilot study agreed with data representing moderate smoke exposure in the 1994 project, the peak HCHO exposures were substantially higher than those measured in the 1994 project (Reinhardt and others 1994) Possible exposure differences between the two projects are discussed below The highest of these peak concentrations exceeded OSHA STEL limits for HCHO exposure, thereby reinforcing the principle that smoke exposure management will have to address short-term exposures to respiratory irritants to ensure compliance with OSHA exposure limits

Some justification for the accuracy of the HCHO data is found in the CO data from the pilot study, which also were higher than the 1994 results (Reinhardt and others 1994), about 20 percent of the CO samples were above 100 ppm, and they ranged up to 218 ppm The pilot study used the same techniques and similar calibration procedures as the better documented 1994 study Further evidence of the accuracy of the 1989 HCHO data were the similar slope and intercept coefficients for the regressions between concurrent HCHO and CO samples in both studies. The peak CO exposures exceeded the former OSHA ceiling limit of 200 ppm, thereby providing evidence that peak exposure to smoke can exceed exposure limits designed to prevent acute, adverse health effects

Benzene sampling was not well executed in the 1989 study As a result, few exposure data were successfully obtained, and some of those were fraught with reagent contamination and sample breakthrough problems. This clouds interpretation of these results, which were about an order of magnitude higher than those found in the 1994 study (Reinhardt and others 1994).

The pilot study found high exposure to respirable particulate matter among firefighters Many data were missing in the study because of sampling difficulties, but over 30 percent of the PM3.5 data were above 5 mg/m^3 and ranged up to 20 mg/m^3 The slope of the regression between concurrent PM3.5 and CO samples also agreed with the similar regression measured in 1994 (Reinhardt 1989), which suggests the PM3 5 data were accurate.

Ambient windspeed was considered a key factor controlling smoke exposure potential-smoke exposure was greater at higher windspeeds. The study also identified fuel moisture (or relative humidity) as a possible factor contributing to high smoke exposure. The study found that smoke exposure increased proportionately to fuel moisture content of the 10-hour timelag fuels (those with a diameter between 1/4 and 1 inch). A possible explanation for this observation was that at higher fuel moistures, flaming combustion was poor and a strong convection column was not developed, which allowed any ambient wind to overcome the column and push smoke into firefighters stationed downwind of the fire.

The 1989 study had one additional observation worth noting, although it could be coincidental' The dominant fuel species at the unit was associated with differences in smoke exposure. Hemlock-dominated (*Tsuga* sp.) sites had a greater exposure to CO (and especially HCHO) than any of the other sites, which included Douglas-fir (*Pseudotsuga menziesn* (Mirb.) Franco), ponderosa pine *(Pmus ponderosa* Dougl ex Laws.), a single prescribed burn in grass, and two wildfires in northern California chaparral and oak (*Quercus* sp.)-grass savannah (Reinhardt 1989).

The dearth of quality control information makes it difficult to evaluate method-induced bias in the pilot study measurements, but subjectively high smoke exposures were commonly observed at those burns. The 1989 study had some unique aspects that may have contributed to the high smoke exposures measured First, some of the burns with high smoke exposure had relatively thick duff depths Smoldering consumption of duff is an inherently inefficient process, with high emission factors for CO and particulate matter (Ward and Hardy 1986) Second, some of the higher exposure burns were ignited when conditions were marginal, and subsequent winds caused significant control problems. Windspeed data were obtained from the local fire managers in the 1989 pilot study, those data showed a strong correlation with the measured smoke exposure, as they did in the 1994 project The range of windspeeds was about five times greater in the pilot study, but those were instantaneous or hourly average readings, and the 1994 data were fire averages Although the data are not directly comparable, the higher smoke exposures in the pilot study could be caused by burning in greater ambient windspeeds Third, there is presently a much-diminished timber harvest level in the Pacific Northwest For locations with concomitant reductions in burning acreage, this may allow fire managers to be more selective and obtain ideal burning conditions that reduce the potential for smoke exposure Finally, attitudes about smoke exposure seem to have changed since the 1989 pilot study, at least in the Pacific Northwest Even as recently as 1988, there were many fire personnel who believed that smoke was rarely, if ever, hazardous In 1995, the belief that *too much smoke exposure is bad* is more widespread, there are fewer fire personnel who do not consider smoke exposure to be a potential problem in this region

Materna and others 1992a—This report summarizes observations of smoke exposure and lung function by the California Department of Health Services among firefighters at wildfires and prescribed fires in California Separate investigations were performed in 1987, 1988, and 1989 Details of the sampling and interpretation of results are found in individual project reports, such as that for the 1989 season (Harrison and others 1992) The 1987 and 1988 sampling occurred only at wildfires and is discussed in "Wildfire Suppression" in this review, as are the results of the 1989 lung function testing

The 1989 sampling included 3 days of smoke exposure monitoring at broadcast prescribed fires in the Mendocino National Forest, California The exposure monitoring consisted of breathing zone measurements of CO, PM3 5, respirable crystalline silica, and selected aldehydes over sample periods of various lengths Standard NIOSH methods were used Quality assurance data are not reported About 4 hours of each 8-hour workday were spent at the small (<6 acres) broadcast prescribed fires of logging slash, with one unit hand-ignited per day with drip torches On the third day, the firefighters conducted mop up of the previous burns

Smoke exposure monitoring at the prescribed burns indicated that all average exposures across workshifts were within the OSHA PELs The authors point out that exposure during the partial-workshift sampling periods was observed to exceed the PELs on several occasions, they felt it reasonable to assume that firefighters could perform similar tasks for periods up to and beyond 8 hours Mean CO exposure during the prescribed fires averaged 17 7 ppm at one fire, and 9 2 ppm at the second fire, where a stronger convection column pulled smoke away from the firelines The highest CO exposure of the entire study was observed at a prescribed burn—38 ppm averaged over 2 5 hours (this exceeded the 35 ppm OSHA PEL in effect at the time)

Most PM3 5 exposures were below the OSHA PEL Respirable particulate exposure averaged 1 15 mg/m^3 at the prescribed fires, with one exposure of 5 1 mg/m during mop up at a prescribed burn During the first burn, PM3 5 exposure averaged 1 50 mg/m3, but at the second burn the PM3 5 exposure was lower—0 81 mg/m^3 Crystalline silica was detected in 5 of 21 PM3 5 samples analyzed (range 1 to 8 percent silica) Four of these detectable silica samples were collected during mop up at prescribed fires or wildfires, and the fifth was obtained during the flaming phase of a prescribed burn

Aldehyde levels generally were low Mean and peak aldehyde exposures were not reported separately for the prescribed fires Determination of low-level aldehyde exposures in this study was limited by the sensitivity of the measurement method used, this was especially so for short-duration peak samples Some of the samples were very close to the limit of quantification, the authors consider those results to be semiquantitative The mean HCHO concentration from 30 samples at wildfires—and presumably, prescribed fires—was 0 13 ppm The two highest HCHO exposures were over 0 33 ppm for 3- to 4-hour-duration samples (it is not known if these were obtained at prescribed fires) Furfural was detected in 25 of the samples, with a mean concentration of 0 028 ppm and a maximum of 0 058 ppm This is well below the OSHA PEL of 5 ppm and the ACGIH TLV of 2 ppm Acetaldehyde was detected in 24 of the samples, exposure averaged 0 044 ppm with a maximum of 0 08 ppm This is far below the OSHA PEL of 200 ppm, and the ACGIH ceiling TLV of 25 ppm Acrolein was detected in a few samples, but analytical problems (chromatographic resolution) precluded accurate quantification The authors estimate that the highest acrolein exposure was no greater than 0 02 ppm

The average exposure levels for CO, PM3 5, and HCHO are in good agreement with measurements from prescribed fires in the Pacific Northwest (Reinhardt and others 1994) However, the highest concentration samples obtained in this study are about one-fifth of the peak concentrations measured in the 1994 Pacific Northwest study Thus the range of smoke exposures measured is less than in the Pacific Northwest This may be a real difference, but is more likely to be a result of the differences in sampling protocol (sampling in the 1994 Pacific Northwest study differed because it specifically targeted peak exposure events)

The results of the study by Materna and others (1992a) indicate that strong plume development during the prescribed burn could result in lower mean exposure to CO and PM3 5 than when a strong plume does not develop This agrees with the conclusions of the 1989 pilot study (Reinhardt 1989) The authors also found that exposure to PM3 5 (but not CO or HCHO) was higher during mop up (at two wildfires and one prescribed fire) than during 2 days of prescribed burning when the flaming phase dominated This contrasts somewhat with the results of the 1994 study by Reinhardt and others, which found that PM3 5 exposure was intermediate during mop up compared with tasks earlier in a prescribed fire The different conclusions may be due to small sample size in this study, or because this study compared overall exposure between the days, while the conclusions in the Pacific Northwest study were based on exposure differences between work activities

Interpollutant correlations were tested between CO and PM3 5 and between CO and HCHO These correlations are important because if consistency in the equations were demonstrated nationwide, fire managers could minimize routine monitoring and rely instead on strong correlations to infer exposure to many components of smoke by measurements of one or two The CO vs PM3 5 correlation was moderately strong, with an r^2 of 0 6 The CO vs HCHO correlation was less strong, with an r^2 of 0 45 The regression equations were not provided for comparison with the 1994 Pacific Northwest results The correlation coefficient for CO vs PM3 5 is comparable to that in the Pacific Northwest study The correlation coefficient for CO vs HCHO is much lower than that in the Pacific Northwest study (Reinhardt and others 1994) This may be a result of the difference in HCHO detection limits between the aldehyde analysis methods in the two studies, rather than a poorer relation between the compounds A lower detection limit results in less variability in HCHO measurements, especially at lower concentrations This lower variability in turn reduces the variation in the correlation, thereby giving a better r^2 A poorer relation between pollutants is also possible when other pollutant sources impact the firefighters, as would occur in urbanized settings

Reinhardt and others (1994)—The 1994 cooperative study by PNW and Radian Corporation monitored exposure to smoke among firefighters at prescribed burns (Reinhardt and others 1994) Sampling used only personal breathing zone measurements to assess smoke exposure Pollutants concurrently measured included acrolein and HCHO with EPA method TO-11 (U S Environmental Protection Agency 1984), benzene with NIOSH method 1501 (National Institute for Occupational Safety and Health 1989), CO and CO2 with Intersociety Committee method 128 (Lodge 1989), and PM3 5 with NIOSH method 0600 (National Institute for Occupational Safety and Health 1989) Firefighters were selected for sampling by random draw, and detailed observation of them was done throughout their workday to discern differences in exposure among various work activities as well as compute TWA exposures A comprehensive quality assurance program was integrated into the study, a key component absent or undocumented in other projects

Quality assurance data collected during the project indicated that the overall accuracy of the exposure measurements (measured by percentage of recovery) was good for CO and CO2 (100±8 and 3 percent, respectively) and acceptable for benzene (100±26 percent) and for measurements of HCHO and acrolein (100±30 and 36 percent, respectively) Overall precision estimates (measured by relative standard deviation of field replicates) ranged between 14 percent for CO2 and 25 to 35 percent for benzene, acrolein, CO, and respirable particulate, and up to 45 percent for HCHO

Exposure data were collected from 221 firefighters during 39 prescribed fires Workshifts averaged 11 hours, and about 7 hours were spent on-site during the burns The study concluded that average exposure to smoke per workshift exceeded PELs for respiratory irritants and CO for 1 to 5 percent of the firefighters The estimate of overexposure increased to 10 percent when the more restrictive ACGIH TLVs were used as evaluation criteria The 1994 project found that smoke exposure was higher during the burns, but the unexposed time setting up the bums and traveling between the duty station and the unit brought many shift-average exposures within workshift exposure limits Table 2 shows the mean and maximum TWA exposures found in this study

The workshift overexposures to smoke were mostly caused by intense smoke exposure during line holding, line supervision, and direct attack activities, when peak exposures could exceed recommended STELs Smoke exposure was lowest for the fire lighters and burn boss and during mop up Table 3 shows the differences in mean smoke exposure among various work activities

Table 2—Time-weighted average exposures by pollutant, Pacific Northwest, 1994

Pollutant	Duration[a]	Mean	Maximum
Acrolein (ppm)	Shift	0 009	0 06
	Fire	0015	0 098
Benzene (ppm)	Shift	0016	0 058
	Fire	0 028	0 086
Carbon dioxide (ppm)	Shift	450	740
	Fire	519	860
Carbon monoxide (ppm)	Shift	4 1	38
	Fire	69	57
Formaldehyde (ppm)	Shift	0 047	0 39
	Fire	0 075	0 60
Respirable particulate (mg/m3)	Shift	0 63	69
	Fire	1 00	105
Respiratory irritants (no units)	Shift	04	34
	Fire	06	5 1

[a] Shift = entire workday fire = portion of workday on firelme

Table 3—Mean smoke exposure by work activity and pollutant, Pacific Northwest, 1994

Pollutant	Burn boss	Lighting	Holding	Holding boss	Sawyer	Direct attack	Mop up
Acrolein (ppm)	0 031	0 005	0018	0 030	0010	0 062	0012
Benzene (ppm)	0 021	0 045	0 021	0 026	0 091	0 041	0 020
Carbon dioxide (ppm)	508	510	565	577	700	762	499
Carbon monoxide (ppm)	59	37	11 6	132	142	33 2	92
Formaldehyde (ppm)	0 077	0 038	0 127	0119	0 346	0 464	0 091
Respirable particulate (mg/m^3)	1 32	0 75	1 56	1 81	2 93	4 04	0 75

Table 4 shows the mean and maximum smoke exposure during samples identified as "peak" exposure samples Peak exposure data may be compared with STELs and ceiling limits so long as the biasing effect of sample duration is considered (in variable atmospheres, sample concentrations tend to decrease with increasing sample duration) Peak exposure samples were typically about 20 minutes in duration Thus the peak smoke exposures approached and may have exceeded 15-minute STELs for aldehydes and the ceiling limit for CO Electronic carbon monoxide dosimeter results for CO showed that instantaneous peak smoke exposures often were higher than levels in these integrated samples

Smoke exposure was proportional to ambient windspeed for the direct-attack work activity The report concluded that overexposures often occurred during direct attack, which is in agreement with Jackson and Tietz (1979) The study found strong correlations among the pollutants in smoke It suggested that large-scale monitoring for smoke exposure within the Pacific Northwest Region could rely on CO measurements and these interpollutant correlations to minimize the sampling burden A significant detriment to this concept is the potential for overexposure to TPM from nonsmoke sources, such as entrained dust Crystalline silica and TPM were not monitored, although filters from the project are archived, should crystalline silica analysis be of interest in the future[3] Benzene exposure was found to be within PELs, but could exceed RELs, especially among personnel handling gasoline or operating gas-powered equipment at the fires

The 1994 Pacific Northwest study identified fuel moisture (also indicated by relative humidity) as a possible determinant of smoke exposure The 1994 study had more data at lower fuel moistures than the 1989 pilot study, and a parabolic trend appeared in the exposure data, smoke exposure appeared to be higher at either extreme of the prescribed burning range (low and high fuel moistures), but low in the midrange (Reinhardt and others 1994) This still supported the 1989 explanation of poor column development at high fuel moisture, and the added evidence of high exposure at low fuel moistures is explained by the common occurrence of control problems at fires in low fuel moistures Fire control problems are less likely if ambient windspeeds are low or the layout of the topography and resources at risk is conducive to control Additional data analysis could better quantify these relations

The authors recommended that the Pacific Northwest Region develop and implement a comprehensive risk management strategy to identify workers at risk from smoke exposure, conduct medical surveillance of worker health, and maintain all smoke exposures below occupational exposure limits

[3] Material archived at the USDA Forest Service Pacific Northwest Research Station Forestry Sciences Laboratory 4043 Roosevelt Way NE Seattle WA 98105 6497

Table 4—Peak smoke exposure, by pollutant, Pacific Northwest, 1994

Pollutant	Mean	Maximum
Acrolein (ppm)	0 071	0 129
Benzene (ppm)	0 064	0 277
Carbon monoxide (ppm)	54 3	179 4
Formaldehyde (ppm)	0 468	1 456
Respirable participate (mg/m^3)	7 00	37 11

Betchley and others (1995)—This study by the University of Washington s Department of Environmental Health examined changes in lui g function and prevalence of adverse respiratory symptoms in a group of Pacific Northwest firefighters in 1992 and 1993, on behalf of the USDA Forest Service (Betchley ind others 1995) The study had both cross-season and cross-shift results, as we'i ^ some annual data The cross-shift results are especially significant because tH population underwent smoke exposure assessment during these workshifts as part * the Pacific Northwest prescribed fire study in 1994 (Reinhardt and others 1994 The cross-seasonal and annual results also are discussed here, although the pxposure of the population to wildfires must be noted as a contributing factor to smo><e induced health effects The study measured forced vital capacity (FVC), 1-second jtced expiratory volume (FEVi), mean forced expiratory flow during the middle naif of the FVC (FEF25 75) and the prevalence of respiratory symptoms in 76 firefighters across their workshifts in 1992 and 1993, data were collected before, during ana after each workshift Personal smoking history was considered in the data analysis i he respiratory symptoms were evaluated by self-administered questionnaires Smokf exposure measurements were concurrently taken by PNW scientists Correlation of the smoke exposure measurements with the respiratory symptoms and lung function i3 the subject of a separate paper (Betchley and others 1995)

The cross-shift results showed small but statistically s gnificant mean individual declines in FVC, FEV1, and FEF25 75 between preshift and the midshift and postshift tests Respiratory symptoms of sore throat and chest tightness increased significantly during the same periods The authors note that these uross-shift losses of lung function were correlated with the smoke exposures mp-*sured by PNW scientists (Betchley 1994) Clearly, these results demonstrate a i nk between occupational smoke exposure and acute loss of lung function and Averse respiratory symptoms Although a small loss of lung function might not be considered a severe adverse effect by some, others might consider any job-related impairment of off-duty abilities to be unacceptable, no matter how temporary the effe^s

The cross-seasonal comparisons examined the occurrence of respiratory symptoms and pulmonary function performance among 53 firefighters across the 1992 fire season The results showed mean individual declines in FVC, FEV_1, and FEF25 75 although FVC decrements were not significant across the season In spite of these functional declines no significant changes in respiratory symptoms were detected across the fire season The cross-seasonal pulmonary function declines were consistent with those noted in other studies among wildland firefighters, which are discussed below in "Wildfire Suppression "

These firefighters worked an average of nine prescribed burns (range 1 to 25 burns) and six wildfires (range 0 to 24) during the season studied The postseason testing occurred an average of 2 5 months after the last smoke exposure of the season, which prompted the authors to note that postseason recovery was not as rapid as they expected Ten firefighters were followed at the beginning of the next fire season, about 6 months after the end of the 1992 fire season At that time, all but one individual had recovered to the baseline 1992 pulmonary function levels The authors recommend a longitudinal study to determine whether acute decrements in lung function cause long-term chronic effects as has been noted for urban firefighters (Sparrow and others 1982)

Prescribed Fire Summary and Data Needs

Prescribed burns in activity fuels are likely to cause occasional overexposure to smoke among firefighters, especially over short periods The known health hazards in smoke are CO and respiratory irritants Crystalline silica may be a hazard, but this can be assessed inexpensively by chemical analysis of existing filter samples obtained from firefighters

The long-term effects of smoke exposure on health and pulmonary function are not known Demographic data are needed to assess how firefighting careers may be expected to progress in the future, as cumulative career exposure determines the additional lifetime risk of many chronic adverse health impacts A smoke exposure management program incorporating demographic assessment with medical monitoring could not only track the performance of smoke exposure management strategies but also assess long-term health implications and help to identify individuals at increased risk of adverse health effects

Overexposure to smoke is likely at prescribed fires in regions of the country other than the Pacific Northwest, although the percentage of overexposures may differ by fuel type, burn procedures, and region Brief exposures to high concentrations of smoke are possible in any type of prescribed burning, mostly in the control of small escapes, while overexposure to smoke during an entire workshift may be a less prevalent problem Further comprehensive characterization of smoke exposure during broadcast burns of activity fuels is not recommended in the Pacific Northwest To date, the limited data from exposure monitoring in the rest of the United States are consistent with data from the Pacific Northwest Smoke exposure management strategies should be extended nationwide, or data should be collected to show why prescribed burns in certain fuel types and regions have no potential for overexposure to smoke

Slash Burning

Prescribed burns of timber harvest residues are widespread in regions where timber production is important In recent years, burning prescriptions have evolved from nearly complete consumption of biomass on a site to lighter burns that reduce fine fuels and minimize consumption of large-diameter fuels Great skill is sometimes needed to successfully meet burning prescriptions Depending on unit size, topography, adjacent resources at risk, and fuel moisture burning crews may range between 2 and 30 workers In early spring conditions one or two people can ignite a unit and be assured that humidity recovery will extinguish the fire overnight Conversely, in summer or early fall a similar site might require 15 people to hold firelmes, and mop up of the unit might continue for a week

Smoke exposure during slash burns has been amply covered in the Pacific Northwest by Jackson and Tietz (1979), Reinhardt (1989, 1994) and the University of Washington lung function study (Betchley and others 1995) The studies reach similar conclusions and are not contradictory in their exposure measurement results Together, the results of these studies define a limited but consistent smoke exposure problem during broadcast burning in Pacific Northwest timber harvest residues Smoke exposure at these burns ranges from inconsequential to substantial, depending mainly on ambient wind, fuel moisture, and fire behavior

The 1994 Pacific Northwest project results gave numerical estimates of the probability of a given exposure (Reinhardt 1994). About 90 to 95 percent of the time, the smoke exposure will be minor and well within recommended exposure limits Site and weather factors come together in the wrong combination, however, about 5-10 percent of the time, when firefighters can experience significant smoke exposure, as demonstrated by the COHb measurements in Jackson and Tietz (1979) and the exposure data of Reinhardt (1989) and Reinhardt and others (1994) . All three reports associate high smoke exposures with holding the line downwind from the unit and direct attack of slopovers that escape the prescription Reinhardt and others (1994) and Jackson and Tietz (1979) rely on a large number of samples to document the relatively infrequent (< 10 percent) occurrence of overexposure to smoke at prescribed burns; smaller data collection efforts are likely to miss such events These reports show that smoke exposure (especially over brief periods) can exceed exposure limits for respiratory irritants (acrolein, formaldehyde other aldehydes, and PM3 5), and CO. The Pacific Northwest pilot study (Reinhardt 1989) adds valuable worst case exposure data for CO and HCHO and provides additional estimates of the upper end of the exposure range Measurements of the worst smoke exposures may not yet be in hand, because many experienced firefighters have attested to exposures that subjectively exceeded the highest exposure events that we have sampled in the Pacific Northwest projects. This should not be surprising, because the Reinhardt (1989) project showed that even an observer with a modest amount of experience can visually estimate worsening smoke exposure, and capturing brief, high-intensity smoke exposures has proven to be a very elusive task for researchers

Most individuals will experience eye and respiratory tract irritation in situations with high smoke exposure Some may have more severe reactions than others, depending on their predisposition to the effects of inhaled irritants The University of Washington study has demonstrated small cross-shift and cross-seasonal declines in pulmonary function among prescribed fire personnel (Reinhardt and others 1994) Such declines are forecast from exposure to respiratory irritants The cross-shift declines were associated with prescribed burning, but the cross-seasonal declines have not been ascribed solely to prescribed burning The health implications of these declines remains to be proven Certainly they could be considered an adverse health effect, but most people might not notice small (1-2 percent) declines in pulmonary function On the other hand, college students who are top athletes in aerobic sports might not agree that a percentage or two loss in a pulmonary function index is insignificant Limited annual test data of Betchley and others (1995) suggest that the observed declines are reversible given enough time

Time is an important issue in evaluating health impacts and establishing risk-based occupational exposure limits The demographic makeup of various agencies may differ and should be considered when evaluating career health risks from occupa tional exposure Some believe that the size of the wildland fire workforce has peaked in some agencies, and career fire personnel thus will not be able to work "on the ground' for only 5 or 10 years before moving to a smoke-free administrative job, as may have been the rule in the past (Linane 1995)

- Demographic data need to be gathered to assess how firefighting careers develop and how that might define the smoke exposure history amassed during a working lifetime

Although the significance of the adverse effects may be debated, the exposure data and observations of adverse health effects provide evidence that CO and respiratory irritant exposure exceed healthful levels and a smoke exposure management program is warranted, at least for prescribed fires of timber harvest residues Several unanswered questions remain in the available data

- Are lung function losses among firefighters in their first season of firefighting greater than losses in subsequent seasons?
- Are cross-seasonal losses cumulative, or do firefighters in the Pacific Northwest regain their pulmonary function during the off-season, as indicated by limited data?
- Are some personnel especially sensitive to the respiratory effects of smoke exposure, and can screening identify these people?
- Is crystalline silica present in the dust that firefighters inhale at prescribed fires?

The first three questions could be inexpensively answered through long-term pulmonary function and respiratory health data collection, which could be an integral part of the medical monitoring recommended for the Pacific Northwest by Reinhardt and others (1994) A well-designed medical monitoring plan could provide data to answer the questions without incurring the costs of separate studies If adequate respiratory protection is an accepted component of a risk management strategy, then further pulmonary function studies per se may not be worth pursuing On the other hand, much of the data collection for medical monitoring should be an integral part of risk management, thereby allowing objective evaluation of the effectiveness of strategies to reduce respiratory health impacts

The fourth question is important because excessive crystalline silica exposure in other industries has been associated with nonreversible fibrogenic changes in lung tissue that impair pulmonary function If the dust firefighters breathe contains significant crystalline silica (the likely source would be entrained soil dust), respiratory protection might be warranted in some circumstances regardless of the presence of smoke There are no data on this issue for the Pacific Northwpst Materna and others (1992a) have demonstrated a potential problem in northern California This question could be inexpensively answered by crystalline silica analysis of a cross-section of the filters already collected and stored by the Pacific Northwest 1994 project (see footnote 3)

The highest CO exposures found at these burns can be expected to increase COHb beyond the 5-percent threshold that OSHA intended to meet with the former 35-ppm CO exposure standard The Jackson and Tietz (1979) measurements demonstrated this at prescribed slash burns, even after adjusting their results downward by 1 percent to correct for a possible bias from their algonthm for converting alveolar CO to COHb (see Brotherhood and others [1990] in Wildfire Suppression" section, below) The results of COHb measurements in smokers at wildfires should be of concern to those responsible for crew management Smokers can have 5 to 10 percent COHb from cigarettes, inviting impaired judgment when fire-generated CO adds another 5 to10 percent COHb Administrative controls to minimize CO overexposure at prescribed fires should be developed and implemented in the Pacific Northwest Region without further study

Whether exposure control strategies should be extended to other regions and agencies is a difficult question The cost of compliance with exposure limits is significant, but so are the costs of further industrial hygiene surveys to evaluate the need Local funding for either is unlikely without upper management commitment Managerial attitudes about firefighter smoke exposure differ Some managers are content to avoid the issue, some are convinced the problem is severe and the liability is unacceptable, some consider smoke exposure to be part of the job, and some adhere to the maxim that there is no smoke exposure in their rpgion In some areas, there may be very little prescribed burning of timber harvest residues Such regions may find the cost of compliance negligible Regardless of the area of the country, prescribed burns in timber harvest residues are likely to have sufficient fuel loadings to produce smoke densities comparable to the prescribed fire data from the Pacific Northwest Region, and because prescribed burns will occasionally go awry, firefighters will be exposed to smoke during control efforts

The data from the Jackson and Tietz (1979) report fcr example are dated because of improvements in prescribed fire techniques and practice, but in the absence of more recent measurements, one could assume that smoke exposure at slash burns in the Northern Region of the Forest Service is similar to that in the Pacific Northwest Region This conclusion follows because the percentage of overexposures to CO in the Jackson and Teitz study (about 5 percent) is the same as in the Pacific Northwest Region Discussion with some prescribed fire experts in the Northern Region characterize the smoke exposure problem as limited to steep terrain where "holding" is required on the uphill side (Thomas 1994) More than one expert in the Rocky Mountains notes that irritation from smoke is especially bad in prescribed burns of high-altitude spruce and subalpine fir, smoke at one prescribed fire in 1994 caused emergency hospitahzations among the line-holding crew (Hvizdak 1994) In such incapacitating exposures, unusual emissions from burning specific fuels may be less of a factor than the intensity of the smoke exposure, as similar incidents occur in other regions (Betchley 1993)

The exposure data from Materna and others (1992a) include two small prescribed slash burns in northern California The mean pollutant exposures noted at these burns are similar to the data from Pacific Northwest Region, even though the data set is small The highest exposures they measured are consistent with average peak values from the Pacific Northwest In addition to the other pollutants, 5 of 21 PM3 5 samples from this project had detectible levels of crystalline silica, and at least one was from a prescribed burn Although the authors did not document noncompliance with PELs over entire workshifts, they did measure partial-shift exposures above occupational exposure limits If the frequency of high-exposure events in California is similar to the Northern and Pacific Northwest Regions, we would not expect data from only two prescribed fires to capture high-exposure events, which occur with 5 percent frequency Thus the limited data for prescribed fire smoke exposure in California are consistent with those from the Pacific Northwest Region Some experts in California consider smoke exposure there to be similar to the results from the Pacific Northwest it is not a problem until the prescribed fire goes awry, then direct attack may take place in significant smoke (Stutler 1994)

In terms of annual acreage burned in prescribed fire, the Southeast leads other regions of the United States In spite of the volume of burning, there are few data to conclude whether smoke exposure is a problem there Private industry and state forestry agencies conduct more prescribed burning in the South than Federal agencies do The smoke exposure data of McMahon and Bush (1992) in southeastern broadcast burns are consistent with those from the Pacific Northwest The authors concluded that only the former OSHA ceiling exposure limit for CO (200 ppm) was likely to be exceeded on those burns Their conclusion that TWA exposures were unlikely to violate CO PELs is in accordance with observations in Pacific Northwest Region, where less than 5 percent of CO exposures exceeded PELs and only 10 percent exceeded more stringent recommended exposure limits (Reinhardt 1994) McMahon and Bush did not consider additive effects on the same target organ from exposure to more than one pollutant—the principal reason that the exposure limit for "respiratory irritants" was reached before the TWA PEL for CO in measurements within the Pacific Northwest Region

McMahon and Bush (1992) and other observers note that smoke exposure seems highest while firelines are being held and whenever direct attack of small slopovers or spot fires is needed, an event occurring "approximately every couple of burns" (Rounsaville 1994) As these are usually wind-driven events and the firefighters conducting direct attack would probably be in smoke from the unit being burned, short-term exposures are likely to be the main problem requiring management These events may be more frequent during growing season burns, when winds are more erratic (Wade 1995) Finally, the prescribed burning season in the South is essentially year round Should firefighters experience decreases in lung function, they may not have sufficient unexposed time in a year to return to the functional baseline, as some suggest occurs in populations where smoke exposure is more seasonal

In the Southwest, no data exist with which to assess smoke exposure One expert in the Southwestern Region of the Forest Service concludes that there probably is not much difference between the Southwest and the Pacific Northwest in terms of smoke exposure at prescribed burns (Russell 1995)

- Because data from other regions either do not exist or are consistent with data from the Pacific Northwest, exposure management should be extended to those regions, or sufficient exposure measurements should be made to document the compliance of their exposures during broadcast prescribed burning of timber harvest residues

Broadcast Underburning

Prescribed burning in surface fuels and the understory beneath a canopy of trees is broadly termed "underburning " Variations of this practice result in specific names for the general technique, such as hazard reduction burning, vegetation management burning, and growing season burning It occurs widely especially in southern pine plantations, and in pine and mixed-conifer stands thro ughout the South, Southwest and interior West Proposals to apply restoration forestry in the inland Western United States involve tenfold increases in thinning, selective harvesting, and burning (Mutch and others 1993)

In the Southern Region of the Forest Service, 540,000 acres of Federal land are treated annually by underburning (Rounsaville 1994) State and private forestry acreages in the Southeast are about an order of magnitude larger (Wade 1995) In most of that Region, prescribed burning occurs in every month, reflecting a recent trend toward more growing-season burning where burns traditionally were limited to fall and winter months Growing-season burns now constitute oetween 15 and 50 percent of the acreage burned in the Southeast, depending on the organization and location (Wade 1995) Firehne personnel there are mostly permanent employees, a factor to consider when estimating cumulative smoke exposure over a career and compared with Regions more reliant on seasonal workers One observer estimated that a firefighter at a district having a good prescribed burning p'ogram averages 40 to 50 days per year of prescribed fire, plus 30 days of wildfire suppression on the home district plus another 20 days at wildfires in other Regions (Kubiak 1995) Underburning is practiced to a lesser extent in the Great Lakes region comprising less than 10 percent of all prescribed burning in the Eastern Region of the Forest Service, for example (Martin 1994)

One characteristic of underburning is that relatively low intensities often are prescribed to avoid scorch damage to the overstory Such fires do not develop strong convection columns, in contrast to broadcast fire techniques that generate higher fire intensities to pull heat and smoke away from firehnes (Reinhardt 1989). As much as 40 percent of the smoke emitted in a low-intensity fire is not entrained in the convection column but is dispersed locally (Lavadas 1995) This local smoke may not contribute to smoke exposure among fire lighters if they can stay ipwind of the fire, as is usually the case. Holding efforts are often less extensive because the lower intensity fires have less potential to cross firehnes (Hvizdak 1994) Many experts observe that smoke exposure during underburning is normally highest for holding crews during initial firing of the firehnes, when they might patrol in the smoke for an hour or so (Rounsaville 1994), after which the smoke exposure is insignificant No measurements are available to evaluate this, but the assertion of relatively low smoke exposure may be accurate, especially for burns employing low-intensity backfire (planned ignition of fuel ahead of a wildfire; one that burns into the prevailing wind) and flank fire ignition patterns Others note that some jurisdictions have wildlife habitat trees to protect within the burn unit, which requires close work in the smoke until the tree is secure (Kubiak 1995) Ignition of prescribed fires from helicopters in the Southeast also may be associated with limited smoke exposure if the aerial ignition is applied to larger burns surrounded by secure firebreaks and roads, or the burns are unattended on the ground

In parts of the Southeast, mop up and the associated smoke exposure may not occur, especially where thin duff layers provide little available fuel and high humidity recovery extinguishes burned areas overnight (Wade 1995) In units with a lot of stumps, mop up may cause increased smoke exposures because of the many point sources within the burned block The need for mop up may differ among organizations; some experts perceive Federal land managers to be the most concerned with mop up to minimize the impacts of residual smoke

Review of the literature shows very few measurements of smoke exposure among firehne personnel conducting underburning in "activity fuels " Conspicuously absent are exposure measurements during underburns in the South, Southwest, and Southeastern United States McMahon and Bush (1992) did not include underburning The Reinhardt and others report (1994) contains exposure monitoring results from two days of underburning in ponderosa pine stands in the interior of southeastern Oregon Those burns (Dry Lake #1 and Dry Lake #2/Hogleg) were under relatively moist prescriptions Smoke exposure during those two days of burning was generally low, although the sampling data were incomplete The worker most heavily exposed to smoke during the two days was estimated to average 16 ppm CO and a combined respiratory irritant index of 0 7 (based on OSHA limits) over 7 5 hours Interestingly, this person spent most of the time operating an all-terrain vehicle with a mobile drip torch Smoke exposure among the other personnel at the site averaged about one-third of this maximum, although sampling missed one key episode of direct attack on a stopover where smoke exposure was probably higher This slopover was caused by an unexpected wind shift that pushed fire outside the unit and required direct attack

Similar small spot fires or slopovers occur frequently in underburns, perhaps every few burns for a typical burning crew, according to one estimate of prescribed burning in the South (Rounsaville 1994) Although topographical relief may be less in some regions, which makes fire control easier, wind shifts can cause control problems anywhere Given the anecdotal reports of the frequency of small slopovers and spot fires, and observations of smoke exposure during the initial burning out of the lines, the exposure problem in underburning activities is most likely compliance with short-term exposure limits rather than average exposure during the workshift The volume of prescribed underburning in the South, coupled with the lack of smoke exposure measurements, shows the need to obtain such measurements

- Data are needed to assess whether smoke exposures during underburning are significantly different from broadcast burning in clearcut units, to determine whether the practice can be categorically excluded from smoke exposure management

Other Activity Fuels

Smoke exposure during certain types of prescribed fire in activity fuels may differ from exposure situations reported in the literature Exposure assessment is warranted for any prescribed burning with potential for excessive smoke exposure, if the existing data are not considered representative

Chemically treated fuels ("brown and burn") are typically brush and young hardwood species treated with herbicides months before prescribed burning occurs As mentioned previously, measurements designed to assess the exposure to herbicide residues were unable to detect herbicides in the smoke from such burns (McMahon and Bush 1992) The production of other unusual combustion products has not been evaluated If smoke exposure from brown and burn programs is of interest, an initial step would be to review literature about toxic emissions from combustion of herbicides and herbicide decomposition products With detailed knowledge of the potential hazards and estimated concentrations in emissions the need for further exposure sampling could be addressed

Piling biomass residues by hand, tractor, or grapple and burning the piles at a later date is commonplace in many parts of the country This practice may increase because of the desire to limit total emissions to the atmosphere from residue burning Exposure measurements have not been made during pile burning but we can draw on our own observations and the opinion of experts who conclude that exposure during pile burning is unlikely to approach levels of concern because the convective plume of the pile carries most of the smoke away from the firefighter (Russell 1995)

Natural Fuels

Prescribed fires in natural fuels are either scheduled and ignited by natural resource managers or result from lightning strikes The diversity of fuels and purposes of prescribed fire warrant examination of the exposure potential associated with each Prescribed natural fire (PNF) is lightning-caused fire aimed at accomplishing natural processes within ecosystems Many agencies have increased or plan increases in PNF within their jurisdictions, especially in wilderness and park areas Under the umbrella of forest health, agencies in many regions of the United States also are planning for a dramatic increase of scheduled ignitions in natural fuels Where PNF programs are implemented, teams of fire behavior monitors may be assigned to check fire progress through visual estimation of parameters such as flame length, rate of spread, and so forth During first-hand inspection of the fire, these people can be briefly exposed to significant amounts of smoke as they maneuver around the fire to check its progress, but the exposure is usually minor (Kiefer 1995)

Chaparral—Chaparral poses a critical fire management problem in California and parts of the Southwest Chamise *(Ceanothus* sp) chaparral is an example of a fire-adapted species where decades of fire suppression have resulted in aged stands with a high proportion of dead fuels To reduce wildfire hazards in such fuels (especially as the wildland-urban interface encroaches), fire is used to reduce fuel loading Sometimes the fuels are crushed or otherwise treated before burning The flammability of the fuelbeds can produce fires characterized by high fireline intensities and a high rate of spread, especially in stands over 25 years old

The high proportion of extractable oils in the leaves of some chaparral species raises a question about whether the smoke is particularly unhealthy Data addressing unusual irritants or toxic compounds in the emissions from chaparral are not available Where unusual pollutants are suspected, better emission characterization in a laboratory-scale setting might be the most efficient way to determine the hazard potential Once the combustion products are identified exposure measurements can determine whether the pollutants reach hazardous levels in the breathing zones of firefighters

No data are known that evaluate smoke exposures during prescribed burns in chaparral Emission monitoring over prescribed fires in southern California chaparral showed that CO emission factors were only about half of those in logging slash (Ward and Hardy 1989) Because CO correlates so well with other products of incomplete combustion, it may be that exposure to CO and respiratory irritants are similarly reduced in chaparral burns Some smoke exposure occurs during hand-lighting of chaparral burns, but the most smoke exposure is likely among holding crews (Smith 1995) Exposure during mop up is considered minimal in all but the oldest chaparral stands because of the lack of residual fuel Either additional exposure assessment is needed to prove there is negligible smoke exposure during chaparral burning, or exposure management strategies should be developed based on exposure measurements in other fuel types

Southern hardwoods—Prescribed burning in the "rough" is done as restoration burning or maintenance burning throughout the South and Southeast Hardwood species and brush that flourish in the absence of fire are controlled by prescribed burning, but smoke exposure potential may differ by organization conducting the burn Firefighters working for Federal agencies may have more smoke exposure than state or private fire personnel because the Federal agencies may exert more effort in mopping up burns to comply with smoke management goals (Wade 1995) Where roads and natural barriers can be used as firelines, holding exposures may be brief, but some land managers must contend with an encroaching urban interface or, conversely, minimal-impact goals for wildlife areas, both of which can result in nonideal firelines that require holding and patrolling (Seamon 1995) In these situations, smoke exposure may be significant

Grasslands and sagebrush—Prescribed burning to maintain grasslands is common throughout the United States and actually dominates prescribed burning in many regions Grassland burning is characterized by high fireline intensities and rate of spread This discourages firefighters from remaining in close proximity downwind from the flaming front Smoke exposure is likely among fireline holders only at the beginning of the burn when fuels adjacent to control lines are burned (Romey 1994) When fuel moistures are conducive to prescribed burning, the high flammabihty of grasses and forbs results in relatively complete combustion and thus lower emissions of CO and other products of incomplete combustion Prolonged exposure to smoke during grass burns is unlikely, because there is virtually no smoldering after passage of the flaming front

Prescribed burning in sagebrush (*Artemesia* sp) is done primarily to replace the sagebrush with grasses and forbs for wildlife habitat Similar to chaparral and grasses, sagebrush burns are very rapid with a strong flaming phase Smoldering combustion is short lived, and smoke exposure is probable among lighting and holding personnel only during ignition of fuel adjacent to downwind firelines (Linane 1995) The smoke from sagebrush fires is very irritating (Linane 1994), and it may possess irritants or special health hazards, but detailed characterization of trace emissions in the smoke has not been done Emission sampling over full-scale prescribed burns of sagebrush found that emission factors for CO and respirable particulate matter during the flaming phase of combustion were significantly higher than all other Western United States fueltypes measured (Hardy and Teesdale 1991)

In some areas of the Western United States, historical fire suppression has allowed the encroachment of western juniper *(Juniperus occidentalis* Hook) into rangeland Prescribed fire is effective at controlling juniper felled to provide ladder fuels Smoke exposure during juniper burns is most likely during holding operations

Stand replacement burning—Burning to improve large-game habitat and restore fire-adapted ecosystems in the Rocky Mountains is often accomplished in lodgepole pine (*Pmus contorta* Dougl ex Laws) and spruce (*Picea* sp) at high elevations and in oak brush stands after spring greening has occurred These fires are typically prescribed as stand-replacement burns to remove decadent, overstocked forests (Oberheu 1995) Most units are ignited by hand with drip torches The high fuel moisture of green vegetation would be expected to result in a high proportion of CO and other products of incomplete combustion The prescription often targets an active crown fire behavior, and natural barriers are relied on to contain the fire as opposed to firefighters, who would be ineffective against such a fire Also, mop up usually is not done because of the remote locations burned These two factors combine to limit smoke exposure among the fire lighters to occasional wind-driven events (Chonka 1995)

Taiga—Prescribed fire in Alaska is done chiefly to improve wildlife habitat on public lands throughout the State and, to a lesser extent, for wildfire hazard reduction, especially near inhabited areas where fire suppression historically has occurred (Van Der Linden 1995) In absolute terms, the annual acreage burned in Alaska is small Prescribed fires often are large landscape-scale, stand-replacement burns, which allows the use of natural barriers and minimizes the need for firehne holding Fuels include mostly black spruce (P *manana* (Mill) B S P) and feathermoss associations (Viereck and others 1992) of the taiga Smoldering combustion is strong in the feathermoss layer, but mop up rarely occurs When adjacent resources require protection from the prescribed fire, firefighters engaged in holding firehnes and direct attack can be expected to encounter significant smoke Such situations can occur when prescribed fire is applied to create a fire barrier at an urban interface (Ricker 1995)

Wetlands—In the Southeast United States, prescribed burning is sometimes required in marshy areas called "pocosin," which have a very deep organic layer The fuels are analogous to peat bogs in the Great Lakes region When sufficiently dry, the organic layer can support vigorous smoldering combustion, often burning deep below the ground surface The smoke is very acrid and causes severe irritation of the eyes and upper respiratory system (Kubiak 1995)

Wildfire Suppression

Wildfires and fire suppression tactics differ across the United States owing to regional and local differences in fuel type and arrangement, weather, suppression resources, and agency goals Topographical relief and the resources at risk in a particular fire contribute to decisions about the appropriate management strategy to suppress the fire Weather, as it affects actual and predicted fire behavior, is perhaps the most important and unstable variable controlling suppression options

Wildfire suppression tactics begin with an initial assessment of the situation, followed by attack of the fire by the first resources at the scene perhaps supplemented by late-arriving suppression forces The strategy may be one of either direct or indirect attack, but the goals are to contain and extinguish the fire Containment is achieved by natural or artificial barriers to prevent further spread of the fire Roads, natural barriers, firelines, and backfires may be used for containment Extinguishing the fire is achieved by removing heat, oxygen, and fuel.

Wildfire Literature

Smoke exposure at wildfires has been more widely studied than smoke exposure at prescribed fires. The publications detailed below have examined smoke exposure among wildland firefighters

Jackson and Tietz (1979)—The 1979 report by Jackson and Tietz broke important new ground by examining the question of smoke exposure among wildland firefighters The study examined CO exposure at both wildfires and prescribed fires Results are discussed here from sampling at 11 wildfires from 1974 to 1976. An earlier publication summarized results from the first two wildfires in the project (Tietz 1975) Methods and their limitations were discussed above in "Prescribed Fire "

In Tietz (1975), both smokers and nonsmokers were included in the data Observations at the Outlaw Fire in Idaho concluded that 86 percent of 30 firefighters exceeded 5 percent COHb at either the beginning or end, or both, of their shift, and that a nightly atmospheric inversion may have been the cause of these results The Outlaw Fire burned in cedar (*Thuja* sp), larch (*Lanx* sp), and fir (*Abies* sp.) fuels At the Deadline Fire in Idaho, 21 percent of 293 firefighters exceeded 5 percent COHb. The Deadline Fire burned in ponderosa pine, lodgepole pine, and cottonwood (*Populus* sp.).

The Jackson and Tietz (1979) data from wildfires consisted of 1,396 pairs of observations of COHb at 11 wildfires. Of these, 132 (9.4 percent) of the postworkshift levels were above 5 percent COHb, generally accepted as the lower limit for acute health effects The percentage of firefighters exceeding this 5-percent COHb limit ranged between 0 and 100 percent of those measured, depending on the wildfire. Firefighters were implementing a direct attack fire plan at all wildfires The researchers observed that initial attack posed the greatest CO hazard among the firefighters, with 87 percent of the firefighters assigned to initial attack exceeding the 5-percent COHb standard (one of these initial attack incidents was a prescribed burn with a slopover). The initial attack crews had the highest COHb levels, ranging up to 8 percent.

Some narrative descriptions of the monitoring are provided for the 1976 field season. Although observation of work activities was not rigorous in this project, some clues as to the cause of high COHb levels may be obtained from the narratives At the Ingalls Creek Fire in Washington, 7.6 percent of 300 observations over 4 days exceeded 5 percent COHb at the end of a shift No description of work activities was made Fuels were subalpine conifers with grasses, a thin litter layer, and little duff Winds were between 5 and 10 m p h

At the Spring Canyon Fire in Utah, 1 of 34 firefighters (3 percent) exceeded 5 percent COHb The fire was under control by the time sampling commenced, therefore mop up may have been the only major work activity still occurring. Fuels consisted of sagebrush and grass. Winds ranged between 10 and 15 m.p.h., a possible cause of the single high smoke exposure.

The Roy Lake Fire in Minnesota involved mixed jack pine (*Pmus banksiana* Lamb), spruce (*Picea* sp.), and aspen (*Populus tremuloides* Michx.) with heavy litter and a thick duff layer. Winds averaged 10 m.p.h with gusts to 22 m p h Of the 380 COHb observations, 55 (14.5 percent) exceeded 5 percent COHb, with almost all occurring before the fire was controlled The authors note that high CO exposure was directly associated with proximity to the head of the fire

At the Jeannot Creek Fire, Idaho, in mixed conifers and grasses, winds ranged between 10 and 20 m p h and the fire was contained before monitoring began Even so, 10 of 202 firefighters exceeded 5 percent COHb evidently owing to smoke from heavy fuels smoldering within the fire perimeter

At the Walsh Ditch Fire in Michigan, 269 observations were made The TWA exposure limit was exceeded in 10 (3 7 percent) of those observations Winds ranged between 5 and 10 m p h The fire, burning in peat grass, and hardwoods, apparently was approaching containment by the time sampling began

The Dunham Creek Fire in Montana resulted in 100 percent of 14 smokejumpers exceeding the 5-percent COHb standard after their initial attack on the fire Winds ranged between 10 and 15 m p h , and the fire was burning in larch and spruce logging slash Line digging and mop up were the work tasks in "medium to heavy smoke "

The D Road Fire, Montana, was in lodgepole pine and spruce logging slash, with gusty winds ranging between 15 and 30 m p h Of 69 measurements, 12 (17 3 percent) exceeded 5 percent COHb These were all associated with the initial attack crew on the first day of the fire

Clearly, firefighters in the initial attack experienced CO exposures high enough to produce elevated COHb levels Of the fires in 1976 for which narratives are available, a trend seems to associate higher smoke exposures with higher windspeeds when medium to heavy fuels are present Smoke exposure also seems to decline as a fire progresses from initial attack to mop up More conclusions might be possible with a thorough review of the raw project data

Griggs and others (1983)—This report evaluates CO exposure during suppression of a brush and peat ground fire in North Carolina (Griggs and others 1983) Data were collected by the University of North Carolina School of Medicine and the U S Environmental Protection Agency, Environmental Monitoring Systems Laboratory, during 1 day of firefighting The sampling occurred after the fire had been contained, 2 days after high smoke exposures had resulted in hospitalization of several firefighters for smoke inhalation Blood COHb was determined directly by gas chromatography of blood samples from firefighters who had been either upwind or downwind of the fire Sampling occurred in late morning and was repeated 2 hours later Some area samples of ambient CO or grab samples of breathing zone CO also were obtained No quality assurance data are reported Ambient winds were around 6 m p h Smoke exposure on the downwind side of the fire was described as "moderately heavy" Firefighters were operating pumps and other equipment to drown the ground fire Their exertion levels were described as no more than moderate

Ambient CO levels averaged 75 ppm on the downwind side of the fire, with a peak level of 200 ppm Upwind concentrations of CO were less than 10 ppm The authors report that CO concentrations at another peat ground fire reached 500 ppm Late-morning blood COHb levels ranged between 6 and 13 percent in smokers downwind of the fire and between 4 and 5 percent in nonsmokers Repeat measurements from the same individuals 2 hours later showed that smokers' COHb declined to between 5 and 6 percent and nonsmokers' COHb increased during the same period to between 6 and 7 percent Thus both smokers and nonsmokers achieved an equilibrium COHb level consistent with the average ambient CO concentration, according to the authors Upwind nonsmokers had COHb levels in the 1- to 5-percent range One smoker operating a tractor in dense smoke on the upwind side had a COHb level of

9 percent Because the sampling occurred late in the fire when smoke intensities were lower, the authors concluded that intensive work on the firehne 2 days earlier could have resulted in higher COHb levels when the firefighters had required hospitahzation

Sutton and others (1988)—This draft report discusses an emergency response to evaluate smoke exposure among firefighters at the Klamath National Forest, northern California, during the 1987 Happy Camp fire complex (Sutton and others 1988) Some of the information in this document is summarized in a later article covering several years of work (Materna and others 1992a). Ambient CO was measured at four locations in the area by using active-type colonmetnc detector tubes. Seven fire crews were administered health evaluation questionnaires and tested for blood COHb by measurement of CO in end-exhaled breath. The COHb was calculated from exhaled air by using the Haldane equation (Stewart and others 1976) The CO analyzer used was calibrated only after the sampling, which may have affected the accuracy of the results Quality assurance data were not reported Total particulate matter exposure samples were collected from five firefighters with NIOSH method 0500 One 20-person crew was sampled during night shift line construction for benzene exposure by using passive sorbent badges. Firefighters were nonrandomly selected for monitoring based on their proximity to the fire, recent assignment to the firehne, and accessibility for sampling.

Results of ambient CO sampling ranged between 4 and 10 ppm in fire camp and at a remote drop point. The authors note that ambient CO monitoring by Siskiyou County Air Pollution Control District 2 days earlier had measured a maximum hourly average of 54 ppm CO in the fire camp, although the levels had decreased to about 11 to 12 ppm on the days of the study as a result of decreased atmospheric stability. Ambient CO sampling on the firehne ranged from 22 ppm on the fireline and 25 ppm near a chainsaw, up to 200 ppm near a water pump.

Questionnaires given to the firefighters showed a high prevalence of headaches (59 percent), cough (66 percent), shortness of breath (38 percent), hghtheadedness (32 percent), and wheezing (31 percent), among other adverse symptoms. Blood COHb was not reported in the draft report, but exhaled CO concentrations were reported to range between 9.1 and 53.2 ppm, with mean values between 13.0 and 25 7 ppm for subgroups of fire personnel. Smokers had higher COHb levels than nonsmokers. Results of benzene exposure sampling from a crew working line construction on the night shift were mostly below detection limits (0.07 ppm), with one at 0.08 ppm and one unusually high sample at 0.5 ppm. No explanation was given for the high sample result

Dust sampling was conducted for 1 day, with sample durations between 4 and 180 minutes. One 180-minute sample from a security checkpoint at Happy Camp found a TPM exposure of 1.8 mg/m^3. Ambient monitoring by the Siskiyou County Air Pollution Control District 3 days before had found a maximum 24-hour average of 4.6 mg/m^3 in Happy Camp, and 9 days in which the concentration ranged between 1 0 and 3 0 mg/m^3 The U.S. Environmental Protection Agency's national ambient air quality 24-hour standard for total suspended particulates (TSP) was 0.26 mg/m^3 (TSP is essentially equivalent to TPM). On the days of this study, the 24-hour TSP levels were 0 455 and 0.578 mg/m^3. A 17-minute sample and a 180-minute sample from a remote drop point had similar results of 3.6 and 4.4 mg/m^3, respectively. Short-term TPM sampling of two firefighters from a type I crew gave results of 7.3 and 17 5 mg/m^3 on the fire line

The authors concluded that firefighters may have been exposed to sufficient ambient CO to exceed 5 percent COHb levels, with associated performance impacts that could be hazardous to the firefighters and their coworkers Engine and pump operators were considered likely to have high levels of COHb Ambient CO exposure had declined from levels measured just a few days before thus the COHb levels might have been even higher earlier in the fire Hours of physical exertion and cigarette smoking were shown to be independently associated with exhaled CO, and smoking firefighters were likely to have greater COHb concentrations than were nonsmokers The high prevalence of respiratory symptoms were associated with dust exposure, which could exceed recommended standards Benzene exposure was minimal, based on the limited sampling

Among their recommendations, the authors suggested further industrial hygiene monitoring of CO and particulate matter in various fire and weather combinations Cross-shift pulmonary function testing also was recommended Disposable dust masks were recommended to reduce dust exposure, as was in house industrial hygiene capability and a medical surveillance program

Reinhardt (1989)—Included in this preliminary evaluation of smoke exposure among firefighters at prescribed burns (described earlier in this review) were 2 days of smoke exposure sampling at northern California wildfires, one during nighttime mop up in oak and grass rangeland and the other during mop up in chamise chaparral and pine (Reinhardt 1989) California Department of Forestry and Fire Protection (CDF) and USDA Forest Service firefighters were nonrandomly selected to characterize the range of smoke exposures Sample durations ranged between 15 and 200 minutes Mean CO exposure was about 22 ppm in chaparral and about 17 ppm in the oak and grass Mean HCHO exposure was about 0 1 ppm in chaparral and 0 02 ppm in the oak and grass The nighttime sampling was under inversion conditions, and smoldering heavy fuels, duff, and litter were the primary smoke sources No conclusions can be drawn from this limited sampling other than the potential for exposure to significant levels of CO and moderate levels of HCHO

Brotherhood and others (1990)—This study from the Australian National Institute of Occupational Health and Safety assessed CO exposure among bushfire fighters during experimental fires in dry eucalyptus (*Eucalyptus* sp) forests in Australia (Brotherhood and others 1990) Carboxyhemoglobin levels in 24 male firefighters (15 smokers and 9 nonsmokers) were studied from measurements of CO in end-exhaled breath The method of Smith (1977) was used to relate these alveolar CO levels to predicted COHb concentrations Quality assurance data were not reported Firefighters were observed as they participated in direct attack of experimental fires and constructing firelines with hand tools and chamsaws Fifteen direct-attack exercises were conducted with fires, the average duration of each was 86 minutes (range 37 to 187 minutes) Blood COHb also was determined from firefighters during 11 simulated direct attacks where no fire was present Two other work activities were evaluated on separate occasions backfiring, where firefighters held line and mopped up for 7 5 hours, and bulldozer line construction, where the firefighters using wildland fire engines held line and mopped up behind the bulldozer for about 2 hours In addition to data from the experimental fires, blood COHb was assessed in 12 nonsmoking scientific observers at the scene who followed the firefighters

The study found that smokers averaged 3.4 percent COHb before the experimental fires, and nonsmokers averaged 0.7 percent COHb. During the direct attack experiments, COHb increased in both groups at about 0.68 percent COHb per hour in the firefighters, and 0.32 percent per hour in the observers, who exerted less effort during the experiments. COHb was measured in firefighters within 40 minutes of completion of work and found to average 4.4 percent in the smokers and 2 percent in the nonsmoking firefighters. The maximum COHb observed in the direct attacks was 8 6 percent in the smokers and 4 7 percent in the nonsmokers.

During the backfiring operation, COHb increased by 1.4 percent in the first 1.25 hours before lunch and another 1.5 percent in the 6.25 hours after lunch. Final COHb concentrations were 7 percent (maximum 8.4 percent) in the smokers and 3.2 percent (maximum 5 6 percent) in the nonsmokers. During the bulldozer line construction, COHb increased by 1.5 percent in both groups, with final levels of 5.4 percent in the smokers and 3.2 percent in the nonsmokers. During nonfire exercises, the COHb of all participants decreased.

The authors calculated the environmental CO exposure of the participants based on the alveolar CO via the Cobum-Forster-Kane (CFK) equation (Coburn and others 1965). The mean CO exposure attributed to the fires during the direct attack exercises was estimated to be 13.5 ppm (range: 3 to 40 ppm). This was about equal to the CO exposure attributed to cigarette use among the smokers (who thus nearly doubled their CO exposure). During the backfiring operation, CO exposure averaged 26 ppm among the nonsmokers (maximum- 38 ppm) and CO exposure averaged 30 ppm (maximum: 50 ppm) during the bulldozer line construction. In the simulated direct attacks without fire, environmental CO was estimated to be 3 ppm (range. 1 to 6 ppm) for the nonsmokers.

Because the measurements were obtained over relatively short durations, the authors estimated the COHb levels that would result after 8 hours of exposure by using the CO levels estimated from the CFK equation and alveolar CO measurements (assuming a reduced work rate); results were COHb levels averaging 5 percent (maximum: 11 percent) in smokers and 3 percent (maximum: 7 percent) in nonsmokers. They further estimated that COHb would exceed 5 percent in fewer than 7 percent of the fires. They concluded that CO exposure among nonsmokers was generally low during direct attack of Australian bushfires.

They compared their results with those of Jackson and Tietz (1979) and estimated that the latter's use of the Rmgold equation (Ringold and others 1962) to relate alveolar CO to COHb would result in a bias of +1 percent in estimated COHb. On that basis, they stated that the percentage of exposures exceeding 4 percent COHb (rather than 5 percent) would be comparable The authors conclude that COHb levels below 10 percent would have negligible health or work capacity effects in healthy adults, and most CO exposures among Australian firefighters therefore would not be likely to cause adverse health effects.

Letts and others (1991)—This work was conducted by NIOSH on behalf of the National Park Service in 1990 to evaluate cross-seasonal changes in lung function and respiratory health (Letts and others 1991) Six type I crews from the National Park Service and the Forest Service stationed in southern California underwent preseason and postseason pulmonary function tests and completed respiratory symptom questionnaires. Spirometric measurements of FVC, FEV_1, and FEF25-75 were obtained from each firefighter and the ratio of FEV_1 to FVC was computed In all, 78 of 105 fire fighters completed both the preseason and postseason testing. Fifteen weeks of fire season elapsed between the two testing dates Some bias in the results is possible because the firefighters unavailable for postseason testing were younger and less experienced than those completing the testing, and the younger firefighters originally had slightly greater baseline FVC and FEV_1

Each crew foreman subjectively estimated the smoke intensity for each day of firefighting during the fire season, and a weighted index of smoke exposure was calculated for the season by multiplying the number of hours of firefighting by the smoke intensity for each fire. The crews were then divided into three exposure categories (low, medium, and high)

Health symptoms either declined or changed slightly across the fire season Among the firefighters who developed respiratory symptoms by the end of the season, only throat irritation was associated with smoke exposure (with little statistical significance) Lung function changed slightly across the fire season averages were -0 5 percent for FEV_1, +0.2 percent in FVC, -2 3 percent for $FEF_{25\ 75}$ and -0 5 percent in FEV_1/FVC These changes were not statistically significant, although the decline in FEF25 75 was nearly so (p=0.08). Changes in lung function of asthmatics were no different from the rest of the firefighters When compared by exposure category, all lung function indices decreased the most in the high-exposure category, but only the decrease in FEF_{25-75} approached dose-response linearity (p=0.08), with changes of +0 5 percent, -1.9 percent, and -4 7 percent for the low-, medium- and high-exposure groups, respectively The authors note that declines in FEF_{25-75} indicate constriction of peripheral airways (small bronchi and bronchioles), where chronic airflow-constricting diseases originate

The firefighters considered the 1990 fire season to be unrepresentative, with fewer hours on the firehne than usual. Thus the results could underestimate respiratory changes associated with a more active fire season Also, the effects of firefighting on previously unexposed workers could not be detected because these were experienced firefighters with many years of service (and possibly, respiratory capacity loss) prior to the "baseline" test. Finally, the exposure category classification may be inaccurate because smoke concentrations differ widely in a given day at a fire, thus the total hours per day should not be equally weighted by a single recollection of smoke intensity. The authors concluded that changes in lung function may have occurred across the fire season and that studies should be conducted to examine cumulative effects of firefighting A comprehensive respiratory surveillance program for firefighters was suggested, as was respiratory protection and exposure monitoring

Rothman and others (1991)—This study from the Johns Hopkins School of Hygiene and Public Health evaluated cross-seasonal changes in pulmonary function and respiratory symptoms in CDF firefighters from northern California during the 1988 wildfire season (Rothman and others 1991) The study was restricted to nonsmoking (for 6 months) firefighters Spirometric measurements of FEV_1 and FVC and a work practices-respiratory symptoms questionnaire were obtained from each firefighter Baseline data were collected in July after the fire season had begun, postseason data were collected 8 weeks later Prebaseline firefighting activities were reconstructed from California Department of Forestry fire station logs Daily firefighting hours during the study period were self-reported by the firefighters

Fifty-two of 69 firefighters (75 percent) completed both the preseason and postseason questionnaires and 50 also completed the spirometric measurements The 17 firefighters unavailable for postseason testing were not absent because of pulmonary complaints, other demographic information on this group was not significantly different from those completing the study On average, 18 hours of firefighting had occurred in the month before the baseline measurements, and firefighters worked an average of 98 hours at fires during the last month of the study

The authors found a significant increase in eye and nose irritation, cough, phlegm and wheezing across the study period Spearman rank-order correlations were observed between health symptoms and hours of firefighting late in the study Eye irritation (p=0 001) and wheezing (p=0 07) were associated with firefighting activity during the last 2 weeks of the study, and nose irritation (p=0 08) was associated with firefighting activity in the last week of the study

Baseline spirometry was not associated with the number of previous firefighting seasons Across the study period, changes in FEV_1, FVC, and FEV_1/FVC were -1 2 and 0 3 percent, and -0 006, respectively FEV_1 was associated with hours of firefighting in the final week (p=0 006), this association with weekly hours of firefighting weakened with elapsed time before the postseason testing Similar trends were found in the association between FVC and hours of firefighting in the study period, with hours in the final week showing the strongest association with decline in FVC (p=0 02) Changes in FEV_1/FVC were not associated with the firefighting hours Because of the variability in hours of firefighting in the last week (range 0 to 125 hours), the firefighters were divided into groups of none, low, and high firefighting activity The FEV_1 and FVC declines showed significant correlation with the exposure category for the final week

The authors concluded that small but significant declines were seen in FEV_1 and FVC, and that these were associated with firefighting activity in the final week of the study They questioned the accuracy of the self-reported hours of firefighting as an indicator of smoke exposure, because of the lack of objectivity and the widely different levels of smoke exposure at wildfires The possible reversibility of acute respiratory impacts was raised, because the study design was not intended to demonstrate whether the pulmonary function declines were the result of exposure over the season or over the last 2 weeks of the study They recommended comprehensive assessment of the health and safety hazards of wildland firefighting They suggested that respiratory irritant protection be made available and crew rotation be more frequent

Reh and Deitchman (1992)—This NIOSH project assessed smoke exposure among firefighters at Yellowstone National Park in August 1988 on behalf of the National Park Service (Reh and Deitchman 1992). The study sampled smoke exposure among 22 firefighters on 3 separate days at the Shoshone, Clover Mist, and North Fork fires Firefighters at the Shoshone fire were engaged in mop up during their workshift. At the other two fires, fireline construction was the major task

Breathing zone samples of CO, CO_2, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) were collected from the firefighters. Area samples for those compounds and TPM, volatile organic compounds, aldehydes, and polycyclic aromatic hydrocarbons (PAHs) also were collected. The CO, CO_2, SO_2 and NO_2 sampling was accomplished with colonmetric passive diffusion tubes. Total particulate matter was sampled with NIOSH method 0500. Volatile organic compounds were sampled with NIOSH methods 1003, 1500, and 1503. Aldehydes were monitored with NIOSH method 2539 Sampling for PAHs was done with NIOSH method 5515 *No* quality assurance data were reported

Volunteers were solicited from the crews being monitored for smoke exposure for a medical evaluation of exposure to CO and irritants The medical evaluation consisted of a preshift and postshift symptom questionnaire and measurements of heart rate, breathing rate, blood oxygen saturation, and blood COHb. Blood oxygen was measured on-site with a transcutaneous blood oximeter, and COHb was measured by blood sample and off-site COHb analysis.

All dosimeter data for the Clover Mist fire were invalidated because the crew worked a 24-hour shift that exceeded the time limits of the dosimeter tubes. Only dosimeter data for CO were available for the Shoshone fire. Personal monitoring results for the North Fork fire showed that CO ranged between 3.6 and 7.8 ppm (TWA) during mop up, and between 1.9 and 3.9 ppm during 1 day of fireline construction Carbon dioxide TWAs were all 1,000 ppm, and SO2 measurements ranged between nondetectable and 1.2 ppm. Measurements of NO2 were all below the detection limit of 0.2 ppm. The authors characterized the atmospheric conditions as "light smoke" for the period under study.

Area sampling lasted between 3.5 and 11 hours and found CO levels of 1.6 to 6.2 ppm in fire camps, up to 23.3 ppm on the fireline at the Shoshone fire, 4.6 ppm at the Clover Mist fire, and 11.5 ppm at the North Fork fire. Area samples of CO_2 ranged between 700 and 750 ppm on the fireline, and up to 1000 ppm in fire camps. Samples of SO2 showed 1.0 ppm in fire camp, and up to 1 9 ppm on the fireline at the Clover Mist fire. Area results for NO2 were below detection limits. Most area sampling results for TPM ranged between 0.1 and 1 2 $mg/m^3$and two samples were higher: a 5-hour sample at the Clover Mist fire was 15 9 mg/m^3, and a 4-hour sample at the North Fork fire was 47.6 mg/m^3. The fire camp samples were all between 0 1 and 0.6 mg/m^3. Four aldehyde samples detected only HCHO at average levels between 0.02 and 0.03 ppm. The results of area sampling for volatile organic compounds were all low, below 0.03 ppm for benzene ana 0 05 ppm for furfural. Area samples of PAHs over the same periods detected only gaseous-phase naphthalene (maximum of 3.53 mg/m^3, fluorene (maximum of 1 04 mg/m^3), and acenaphthene (maximum of 1.53 mg/m^3).

A slight increase in eye, nose, and throat irritation was noted from the preshift and postshift symptom surveys A statistically significant increase ($p=0\ 04$) was found in the number of firefighters reporting decreased alertness Blood oxygen saturation showed no significant changes between measurements The highest COHb level (4 7 percent) was in a smoker prior to the workshift Levels of COHb decreased an insignificant amount in the crew performing mop up at the Shoshone fire, decreased significantly ($p=0\ 005$) in the crew performing line construction at the North Fork fire, and increased significantly ($p=0\ 001$) for the crew constructing a fireline at the Clover Mist fire The crew at the Clover Mist fire worked a 24-hour shift and had their post-shift COHb measurements collected in the morning hours

The authors concluded that the exposures on the days sampled were mostly below applicable exposure limits and did not pose a hazard to the workers Most of the area samples also were below the evaluation criteria, although the authors noted that the fire camp levels of CO were similar to those measured at the fireline, and thus the fire camps could not be considered adequate CO-free zones The dosimeter tube results for SO_2 mostly exceeded 50 percent of the exposure limit criteria, an observation attributed to geothermally derived sulfur in local soils Subsequent discussions with NIOSH raised doubts about the accuracy of these and later SO_2 measurements by NIOSH because the dosimeter technology may be positively biased by other constituents in smoke (Kelly 1994) Of the area samples, two TPM samples exceeded occupational exposure limits

The authors mentioned that the "nuisance dust" classification was probably not appropriate for the TPM, because the TPM was likely to be composed of toxic chemicals The authors proposed modified exposure limits for CO using the CFK equation to account for the high altitude, heavy work rate, and long shift length that the firefighters experienced They also proposed modified exposure limits for NO_2, PAHs, aldehydes, and volatile organic compounds using the OSHA time-adjustment model to adjust exposure limits The authors concluded that the exposures measured could not be generalized to all firefighters because smoke exposure could be higher in different circumstances They recommended further study in smokier conditions and evaluation of the smoke exposure potential of different work activities, such as direct attack, holding line, and burnout operations Chemical characterization of the TPM is recommended for future industrial hygiene sampling

They concluded that the observed medical symptoms could be associated with smoke exposure and that the lack of significant increases could be due to previous fireline exposures among the crews before the baseline measurements Further, they mentioned that two of the crews had a 1- to 2-hour hike through low-exposure areas before the postshift measurements, which could result in an underestimate of COHb levels because of CO elimination from the body

Administrative controls were recommended to reduce workshift lengths and the number of consecutive days on the fireline and to site base camps in smoke-free areas Bandannas were not recommended, but single-use dust and mist filter respirators with exhalation valves were recommended for interim respiratory protection, in conjunction with a comprehensive respiratory protection program in accordance with OSHA requirements

Harrison and others (1992)—This project report summarizes work in 1989 by the California Department of Health Services on behalf of CDF and the Forest Service (Harrison and others 1992) The study obtained cross seasonal pulmonary function and smoke exposure measurements among firefighters during 3 days of prescribed fires and 2 workshifts at a wildfire in northern California The general protocols of the smoke exposure monitoring are described in this review (see Materna and others (1992a),' below) At the Layman fire (in the Plumas National Forest) smoke exposure monitoring captured two 12-hour workshifts The first workshift involved CDF fire fighters performing engine-supported mop up of smoldering areas at the fire during the day shift Subsequently, exposure monitoring was done on a Forest Service hotshot crew during mop up in inversion conditions on the night shift

Because some of the exposure monitoring results are not differentiated by wildfire or prescribed fire the general conclusions discussed in the Prescribed Fire section of this review may apply to the wildfire monitoring results as well Of the results specific to the Layman fire, between-day comparisons were made by assessing differences between mop up during the day and during the evening inversion Mean HCHO exposure was not found to differ significantly (p=0 1) among shifts but CO and respirable particulate exposures were significantly different The mean CO concentration was 9 3 ppm during the day shift and 17 1 ppm during the evening shift The mean PM3 5 concentration was 0 62 mg/m^3 during the day shift and 1 83 mg/m^3 during the evening shift In view of correlations observed among CO PM3 5 and HCHO at prescribed fires (Reinhardt and others 1994) and remote wildfires (Reinhardt and others 1995b), the nonsignificant difference of the HCHO levels between the two shifts may be a result of low-concentration samples and variation in analytical values caused by the high detection limit of the NIOSH method used

Sixty-three firefighters from CDF and the Forest Service were tested before and after the 1989 fire season for pulmonary function (FVC FEV_1 and $FEF_{25\ 75}$) as well as methacholine challenge testing to determine their nonspecific airway responsiveness (how much their airways constricted in response to increasing doses of methachohne) This protocol was intended to assess susceptibility of individuals to adverse pulmonary effects from exposure to respiratory irritants The firefighters had exposure to smoke at many wildfires during the fire season (averaging 58 days of exposure)

Only results for Forest Service hotshot crews were reported in Harrison and others (1992) These data also are published in a journal article (Liu and others 1992) The preseason and postseason pulmonary function testing found small but significant declines in FVC, FEV_1, and $FEF_{25\ 75}$ The postseason testing was within a week of the last fire The methachohne challenge testing showed a significant association between the log of the dose-response slope (how responsive the airways were to the methachohne) and an individual's history of allergies Further a history of asthma was associated with airway responsiveness, but the association was not statistically significant All firefighters had a significant increase in the mean dose-response slope across the fire season their airways constricted more readily when exposed to methachohne at the end of the fire season than at the beginning Individuals with adverse health symptoms in the lower respiratory tract had a significantly greater dose-response slope increase than the other firefighters as did those with a history of asthma (although their difference was not significantly greater than the other firefighters)

Materna and others (1992b)—This summary publication describes exposure monitoring by the California Department of Health Services from 1987 to 1989 (Materna and others 1992b) Most details of the monitoring are discussed in the Wildfire Supression section of this review and in the previously reviewed reports by Sutton and others (1988) and Harrison and others (1992) Information from Materna and others (1992b) not already mentioned include the results from monitoring for PAHs in TPM These PAH results were obtained with NIOSH method 5506 at a wildfire in the Lassen National Forest, northern California, in 1988

Twenty samples were obtained in the 1988 sampling, the mean sample duration was 345 minutes Twelve specific PAHs were identified in the samples, all at low levels (<1 mg/m^3) The sum of the PAHs was far below both the OSHA PEL of 200 mg/m^3 and the ACGIH TLV of 50 mg/m^3 The authors concluded that PAHs, although carcinogenic were found only at very low levels in smoke samples

Among their general findings over the 3 years of study was the observation that exposure data were inadequate to evaluate the hazards of firefighting, thus they recommended that more data should be collected, especially for potential carcinogens and crystalline silica Short-term sampling was recommended to assess acute smoke exposures They recommended medical surveillance for the workers to detect adverse health effects They suggested that the OSHA PELs might not be sufficient to protect workers' health, because of the extended workshifts and fire camp exposures, arduous work and high altitudes Also, the inert particulate standards were considered inadequate to protect against the irritant and carcinogenic substances adsorbed on smoke particulate Interim exposure management recommendations included frequent crew rotations, shift limitations, and development of respiratory protection specifically for wildland firefighters Feasibility studies were suggested for interim respiratory protection Training firefighters in the health hazards of smoke also was recommended

Kelly (1992a)—Smoke exposure data were collected on 3 days in July 1991 at the Thompson Creek fire in the Gallatin National Forest by NIOSH on behalf of the National Park Service (Kelly 1992a) Personal exposure sampling was conducted among two type I hotshot crews for CO, SO_2, PM3 5, crystalline silica, and aldehydes Passive colorimetnc diffusion tubes were used for CO and SO_2 Aldehydes were measured with NIOSH method 2539, and PM3 5 was measured with NIOSH method 0600, followed by crystalline silica analysis with NIOSH method 7500 Half of all PM3 5 samples collected were analyzed for crystalline silica In addition, two area samples were collected in fire camp on July 19 to evaluate off-shift exposures to PM3 5 and crystalline silica during a visible inversion Quality assurance data were not reported Twenty firefighters were monitored each day by using nearly full-workshift sample periods

On the first day, firefighters were engaged in structure protection away from the fire, smoke exposure was very low Almost half an inch of rain fell during the evening, thus reducing the fire danger On the second and third days, the firefighters constructed fireline and did some direct attack of spot fires Carbon monoxide exposure averaged 1 6, 6 9, and 6 2 ppm over the 3 days (range up to 17 ppm) Sulfur dioxide exposure ranged between 0 6 and 3 0 ppm Aldehyde concentrations were low, ranging from nondetectable up to 0 08 ppm HCHO, 0 06 ppm acetaldehyde, and 0 01 ppm furfural Trace amounts of acrolein were observed Respirable particulate exposure averaged 0 37 mg/m and the highest PM3 5 exposure was 4 3 mg/m^3 Two PM3 5 samples had detectable amounts of crystalline silica One was low concentration but the other had a quartz content of 0 35 mg/m^3 Fire camp sampling found the PM3 5 and crystalline silica concentration to be low, and only trace amounts of aldehydes were detected

The authors concluded that exposure to CO and aldehydes was low but that one firefighter was overexposed to crystalline silica and several exceeded exposure limits for SO_2 The direct attack monitored in this project was neither prolonged nor particularly smoky The authors recommended that smoky events be measured only through the establishment of a long-term routine monitoring program which is best accomplished by the agencies employing the firefighters

Materna and others (1992a)—This study, from the California Department of Health Services, examined the feasibility of three different methods of assessing CO exposure among a type I handcrew of firefighters at the Finley Lake fire in northern California during 1990 (Materna and others 1992a) Colonmetnc passive diffusion tubes, electrochemical sensor dataloggers, and exhaled alveolar air testing were evaluated In addition, CO exposures by work activity were to be compared through self-reporting of work activity by the firefighters in pocket logbooks Finally a questionnaire was used to determine firefighter attitudes and knowledge about adverse health effects of CO exposure Alveolar monitoring was related to COHb concentration through the equation used by Brotherhood and others (1990) Postshift COHb mea surements were made within an hour of departing the fireline No quality assurance data were reported

Three evening workshifts were monitored in August 1990 Twenty-five firefighters from one crew cooperated in the study Monitoring excluded travel time to limit sampling data to fireline exposure only Based on logbook entries work activities included line construction, back firing, and line holding on the first two evenings Mop up was the primary activity during the third workshift

Exposure monitoring with diffusion tubes found a mean CO exposure of 8 2 ppm (range 2 to 16 ppm) Electrochemical dataloggers had similar results, with a mean of 7 8 ppm Two of the 12 firefighters wearing the dataloggers had peak CO exposures of 212 and 339 ppm These exposures were associated with mop up activities Fifteen-minute peak exposure samples for CO were all 50 ppm or less, with the exception of 150 ppm for one firefighter The CO levels measured by the diffusion tubes and dataloggers showed moderate agreement, with an r^2 of 0 56 over all shifts, and 0 87 for just the first two shifts The diffusion tube readings were consistently higher than the datalogger results for the third shift

Measurements of CO in alveolar air demonstrated small but statistically significant increases in COHb across the workshifts The preshift COHb levels were high for a nonsmoking group, averaging 1 7 percent COHb One firefighter's COHb level increased to 3 6 percent across the workshift, which is at the limit of the Biological Exposure Index recently adopted by ACGIH The authors noted that this firefighter's TWA exposure was measured at 16 ppm, well below the 25 ppm TLV Two other firefighters had postshift alveolar air measurements coiresponding to more than 3 percent COHb The diffusion tube results showed only fair agreement with the cross-shift change in alveolar CO, the r^2 for the 51 pairs of measurements was 0 37

Only 8 of 25 activity logbooks were returned to the researchers, thus the planned comparison of exposure versus activity could not be done The firefighters' responses to the CO exposure questionnaire demonstrated a high level of interest in the hazards of CO exposure and a desire to monitor their own exposure Most of the firefighters correctly identified one or more symptoms of CO exposure, but many incorrectly associated additional health effects to CO poisoning A high percentage of the firefighters reported that they experienced adverse health effects while working at fires The firefighters associated direct attack, heavy smoke conditions, and mop up tasks with high CO exposure

The authors concluded that the CO exposures measured were low in comparison to other monitoring The prevalence of peak CO exposures above 200 ppm (17 percent of 12 samples) caused the authors to recommend further evaluation of short-term CO exposures The three methods of CO exposure monitoring had advantages and disadvantages The diffusion tubes were simple and inexpensive, moderately accurate, and useful for acquiring large amounts of data A significant drawback was the lack of response to peak exposures or warning to users about high CO hazard situations The electrochemical dataloggers were very useful for detailed data collection and associating CO exposure with work activities and situations The dataloggers required more skills to calibrate and retrieve data but were simple to use in the field The dataloggers drifted in their measurement of zero CO The high initial cost and periodic maintenance requirements were disadvantages of the dataloggers The technique of analyzing the last portion of an exhaled breath was relatively easy to perform but had high initial costs and periodic maintenance requirements The advantage of biological monitoring was cited, because the method assesses the delivered dose regardless of individual differences in CO uptake and elimination Assessing CO exposure by preshift and postshift COHb measurements may miss detecting overexposure to CO early in the workshift, because COHb from such an exposure may be eliminated by the time the postshift measurement is made

The authors recommended that postshift alveolar air measurements be taken at the fireline rather than in fire camp The choice of CO monitoring method was left open the answer depends on the purpose of sampling, budget, size of project, accuracy needed, and field personnel capabilities Additional exposure monitoring was recom mended and should be aimed at associating CO exposure levels with specific work activities and conditions Dataloggers were suggested for this Direct observation, rather than self-reported logbooks, was recommended for obtaining work activity data Development of practical smoke exposure controls is recommended for high exposure situations Training is recommended for all wildland firefighters, to communicate the hazards and symptoms of overexposure to smoke and ways to reduce health risks Equipment for CO monitoring is recommended for large fire camps to assess camp exposure and screen suspected cases of CO poisoning Passive diffusion tubes are recommended for widespread data collection Medical surveillance programs also are recommended for wildland firefighters

Kelly (1992b)—This study by NIOSH took place at the Gauley Mountain fire in West Virginia during November 1991 on behalf of the National Park Service (Kelly 1992b) Two days of smoke exposure monitoring were accomplished by using the same methods described above (Kelly 1992a), with the addition of benzene soluble PAHs measured with NIOSH methods 5023 and 5515, and volatile organic compounds (benzene, toluene, xylenes, and trimethylbenzene) measured with NIOSH methods 1003, 1500, and 1503 No quality assurance data are reported Full-workshift sampling was employed and was supplemented by ambient air measurements at a visitors' center

Twenty firefighters from a type I hotshot crew were monitored for 2 days On the first day, firefighters conducted a back-firing operation and held line on a road below the backfire—smoke exposure was described as very low On the second day indirect attack was done, followed by the setting of back fires from another dirt road Smoke exposure was low for most of the shift and moderate for less than 1 hour during the back-firing operation Average exposure to CO was 4 ppm (range up to 9 ppm) Average exposure to SO_2 was 2 ppm (range up to 9 ppm) Over half of the SO_2 samples were above the NIOSH recommended exposure limit of 2 ppm Formaldehyde exposure ranged up to 0 1 ppm (average 0 07 ppm) The maximum furfural exposure was 0 03 ppm Acetaldehyde and acrolein exposures were below 0 06 and 0 02 ppm, respectively Volatile organic compounds were not detected, in spite of a 9 parts per billion detection limit for benzene Exposure to PM3 5 averaged 0 49 mg/m^3, with a high of 1 5 mg/m^3 Crystalline silica was not detected Vapor-phase PAHs were not detected, but particulate-phase PAHs were found at very low levels Area samples showed very low concentrations for measurable pollutants

Recommendations included administrative controls that did not rely on subjective estimates of smoke exposure to reduce SO_2 exposure because the smoke intensity did not relate to the measured SO_2 levels Routine monitoring of smoke exposure was recommended Longitudinal studies of the smoke exposure of individual firefighters over the entire fire season were recommended Smoke exposure assessment at prescribed burns also was recommended, because the pianned nature of the burns facilitates logistical preparations and the data might prove comparable to wildfire results

Reh and others (1994)—This study by NIOSH was conducted in August 1990 at the Arch Rock fire in Yosemite National Park of behalf of the National Park Service (Reh and others 1994) Two days of smoke exposure data collection were accomplished among three fire crews (two type I and one type II) Exposure data were supplemented by a medical survey among one of the type I crews and the type II crew The breathing zone concentrations of CO, SO_2, and NO_2 were determined by colorimetric passive diffusion tubes The diffusion tube sampling was supplemented by less extensive use of active sampling methods Sampling of PM3 5 exposure was done with NIOSH method 0600 Volatile organic compounds were measured with NIOSH methods 1003, 1500, and 1503 Aldehydes were monitored with NIOSH method 2539 Samples of gaseous and particulate PAHs were obtaired and then analyzed with NIOSH method 5515 Air samples for hydrochloric hydrofluoric, sulfunc, hydrobromic, nitric, and phosphoric acids were collected by using NIOSH method 7903 No quality assurance data were reported

The medical survey consisted of preshift and postshift spirometnc measurements of lung function (FEV_1 FVC and $FEF_{25\ 75}$) measurements of CO in alveolar air, and a health symptom questionnaire The COHb levels were calculated from the alveolar air measurements by using Ringold s method (Ringold and others 1962) Each firefighter also was asked to estimate on a scale of 1 to 4, the smoke intensity during the workshift

The two type I crews (the Pike and Plumas hotshots) conducted a burnout operation on August 15 with the Pike crew lighting and holding the burnout in moderate smoke and the Plumas crew holding a flank and mopping up in light smoke Sampling was not done during the 2-hour hike to and from the fireline Among the Pike hotshots, CO exposure averaged 18 3 ppm (range 6 1 to 24 2 ppm) and SO_2 averaged 1 4 ppm (range 1 1 to 2 4 ppm) Among the Plumas crew, CO averaged 3 9 ppm (range 1 2 to 9 4 ppm) and SO_2 averaged 1 4 ppm (range 0 2 to 2 9 ppm) Sampling did not detect NO_2 exposure in either crew Sampling for PAHs detected low levels of gas-phase acenaphthene (up to 1 0 µg/m^3), anthracene (up to 26 5 µg/m^3), and naphthalene (up to 35 9 ug/m^3), and particuiate-bound acenaphthene (up to 1 7 µg/m^3) anthracene (up to 1 2 µg/m^3), benzo(b)fluoranthene (up to 1 7 µg/m^3), and fluoranthene (up to 9 3 µg/m^3) Aldehyde monitoring found low-level exposures to acetaldehyde (up to 0 04 ppm), acrolein (up to 0 01 ppm), HCHO (up to 0 07 ppm), and furfural (up to 0 008 ppm) Sampling for acid gases found low levels of hydrochloric acid (up to 0 04 mg/m^3), sulfunc acid (up to 0 09 mg/m^3), and hydrofluoric acid (up to 0 15 mg/m^3) Respirable particulate matter exposure was higher among the Pike crew (1 3 to 1 7 mg/m^3) than the Plumas crew (0 6 to 1 1 mg/m^3) Exposure to volatile organic compounds was very low, with a maximum of 0 03 ppm for benzene

Twenty-one of 25 firefighters agreed to participate in the medical evaluation Preshift COHb levels averaged 1 3 percent, postshift levels averaged 2 7 percent, with nonsmokers slightly higher than smokers The type I crew had a slightly higher postshift COHb level (average 2 9 percent) in comparison with the type II crew (average 2 4 percent) No correlations were observed between the measured CO exposures and the postshift COHb levels Lung function was found to decline across the workshift averaging -0 7 percent in FVC, -1 2 percent in FEV_1, -0 4 percent in $FEF_{25\ 75}$, and -1 4 percent in the ratio, FEV_1/FVC The declines in pulmonary function were larger among the type I crewmembers and achieved statistical significance (p=0 05) the declines among the type II crewmembers were not significant The cross-shift declines were not correlated with self-reported smoke exposure Health symptoms increased slightly across the workshift, with nose irritation showing the greatest increase of the symptoms noted

Bandannas used by the firefighters were examined under an electron microscope Measurements showed the pore size of the bandannas exceeded 100 micrometers Thus they afford no protection against particulate matter having health significance, let alone gas-phase pollutants

The authors concluded from their breathing-zone CO measurements that 30 percent of the Pike hotshots exceeded an adjusted CO exposure limit of 21 ppm (based on the CFK equation), and that the Plumas crew's exposure was within this limit Adjusted exposure limits were recommended for several components of smoke (using the OSHA approach) They also found that the COHb evels increased across the workshift, but that all were below 5 percent COHb The delay in postshift sample collection and the length of the shift relative to the half-life of CO were noted as possible sources of bias in the results

The cross-shift declines in pulmonary function were small but significant For both the type I and type II crews, FEVi losses were statistical significant Cross-shift losses in FVC and FEVi/FVC were significant in one or the other of the two crews The medical significance of these acute losses was not clear because none of the mean changes exceeded 3 percent The authors report that other researchers do not consider declines in FEVi to be significant until they exceed 8 percent They considered the small number of participants to be a factor limiting 01) association between self-reported smoke exposure and pulmonary function losses, and (2) the inability to demonstrate significant changes in adverse health symptoms The self-reported smoke exposure also was considered to be a crude measure of exposure and possibly was biased among those working a nighttime shift because of restricted visibility then

The authors recommended additional smoke exposure assessment to examine other work activities and high-exposure situations Both TWA and peak exposures were recommended for evaluation Collection of medical and epidemiological data was rec ommended in concert with exposure assessments to establish dose-response relations The authors recommended banning bandannas to prevent any misconceptions that they contribute to respiratory protection Disposable dust-mist respirators were recommended, in conjunction with an approved OSHA respiratory protection program Because the CO monitoring indicated exceedence of an adjusted CO exposure limit, administrative controls were recommended to reduce CO exposure Among the suggestions were reduced workshift duration, reducing the number of consecutive days on the firehne, and locating fire camps in nonsmoky areas Routine CO and SO2 monitoring by the agencies was recommended, and a respiratory health surveillance program also was suggested

Betchley and others (1995)—The methods, study p pulation, and results of this study (Betchley and others 1995) are described in detail above in the "Prescribed Fire" section The authors found a small but statistically significant cross-season decline in the firefighters' mean pulmonary function indices This decline was reversed and lung function returned to baseline levels by the start of the following season The cross-season results and recommendations apply to wildfire suppression as well, because the firefighters had worked an average of six wildfires (range up to 24) during the fire season

Reinhardt and others (1995a)—Smoke exposure among wildland firefighters in Redding, California, was measured by the USDA Forest Service, Pacific Northwest Research Station, and Radian Corporation on behalt ot the California Department of Forestry and Fire Protection (Reinhardt and others 1995a) Firefighters from one fire station were monitored during 11 days of initial attack responses in 1993 and 1994 to provide a preliminary evaluation of smoke exposure during initial attack activities at vegetation fires, determine whether smoke exposure exceeded occupational health standards, and identify key factors that cause high smoke exposure levels The study examined how smoke exposure differed among various work activities at wildfires and tested correlations between smoke exposure and fire behavior determinants The study also tested correlations among different pollutants in smoke to evaluate the feasibility of estimating exposure to many pollutants from measurements of a single pollutant

Sampling used only personal breathing zone measurements to assess smoke exposure Pollutants measured included acrolein and HCHO with EPA method TO-11, benzene with NIOSH method 1501, CO and CO_2 with Intersociety Committee Method 128, and $PM_{3.5}$ with NIOSH method 0600 Electronic carbon monoxide dosimeters (dataloggers) also were evaluated for accuracy and ease of use Peak and workshift exposures were evaluated The authors considered the combined impact of respiratory irritants according to the OSHA model, calculating an equivalent respiratory irritant exposure index based on the exposure to acrolein, HCHO and $PM_{3.5}$ (U S Department of Labor 1994b)

Quality assurance data collected during the project indicated that the overall accuracy of the exposure measurements (measured by percentage of recovery) was good for CO and CO_2 (100±8 and 3 percent, respectively), acceptable for benzene (100+23 percent), and relatively poor for some measurements of HCHO and acrolein (100±35 and 56 percent, respectively) Overall precision estimates (measured by relative standard deviation of field replicates) ranged from 14 percent for CO_2, to 24 to 33 percent for benzene, acrolein, CO, and respirable particulates, and up to 43 percent for HCHO

The study calculated TWA exposures for 37 firefighters Smoke exposure was well below occupational exposure limits at these vegetation fires, which burned mostly in grass and oak savannah and some chaparral Individual fires were of short duration, with a median time at the fire of about 4 hours On the other hand, the workshifts (defined for exposure estimating purposes as the time from breakfast to the end of active work during the day) averaged about 14 hours Table 5 shows the mean and maximum TWA exposures averaged on the fireline and over the workshift

Brief occurrences of intense smoke exposure were common at the fires, but the highest of these were within permissible short-term exposure limits set by occupational health agencies Mean and maximum peak exposures based on nominal 15-minute samples are shown in table 6

At difficult fires, overexposure to respiratory irritants and CO was considered possible, based on interviews with experienced firefighters and the authors' observation of missed sampling opportunities Smoke exposure during direct attack activities was significantly higher than during mop up Table 7 shows the mean exposure by work activity when firefighters were in or near smoke

Smoke exposure during all work activities except mop up increased linearly with ambient (20-foot) windspeed between 5 and 15 m p h Electronic CO dosimeters were considered practical devices for routine smoke exposure monitoring, although a quality assurance program was indicated for their use to ensure valid data Insufficient data were available about the correlations among pollutants to eliminate the need for comprehensive smoke exposure monitoring

Table 5—Time-weighted average exposures at small wildfires in northern California

Pollutant	Duration[13]	Mean	Maximum
Acrolein (ppm)	Shift	0 002	0.006
	Fire	0.010	0.037
Benzene (ppm)	Shift	0 003	0.009
	Fire	0.017	0.052
Carbon dioxide (ppm)	Shift	394	710
	Fire	508	920
Carbon monoxide (ppm)	Shift	1 9	13
	Fire	7 0	27
Formaldehyde (ppm)	Shift	0 009	0.035
	Fire	0 039	0.09
Respirable particulate (mg/m3)	Shift	0 24	0.9
	Fire	1 07	2.3
Respiratory irritants (no units)	Shift	0 08	0.25
	Fire	0 43	1.05

[a] Shift = entire workday; fire = portion of workday on fireline.

Table 6—Peak smoke exposures at small wildfires in northern California

Pollutant	Mean	Maximum
Acrolein (ppm)	0.018	0.066
Benzene (ppm)	0.035	0.082
Carbon dioxide (ppm)	642	1265
Carbon monoxide (ppm)	14.3	42.2
Formaldehyde (ppm)	0.117	0.339
Respirable particulate (mg/m^3)	2.08	6.88

Table 7—Mean smoke exposure at small wildfires in northern California, by pollutant and work activity

Pollutant	Initial attack	Engine	Mobile attack	Mop up
Acrolein (ppm)	0018	0015	n d	0010
Benzene (ppm)	0 032	0 032	0 036	0015
Carbon dioxide (ppm)	652	546	483	539
Carbon monoxide (ppm)	120	8 8	12 4	8 8
Formaldehyde (ppm)	0 098	0 073	0 051	0 036
Respirable particulate (mg/m^3)	1 82	1 91	2 49	1 10

n d = no data

A smoke exposure management program was recommended The recommendations included establishing a baseline for smoke exposure at wildfires and prescribed fires throughout California With such data, the true smoke exposure management needs would be better defined, thereby allowing the development of efficient risk management strategies

Reinhardt and others (1995b)—Smoke exposure among wildland firefighters was measured at five wildfires in the northwestern United States by the USDA Forest Service Pacific Northwest Research Station, and Radian Corporation on behalf of the National Wildfire Coordinating Group (Reinhardt and others 1995b) The same pollutants and methods outlined in Reinhardt and others (1995a) were used in this project Objectives of the project were to develop a preliminary assessment of smoke exposure at wildfires identify key factors controlling smoke exposure among firefighters, and evaluate correlations among pollutants to assess the feasibility of estimating exposure to many pollutants in smoke by measuring only one Electronic carbon monoxide dosimeters also were evaluated for accuracy and ease of use

Quality assurance data collected during the project indicated that the overall accuracy of the exposure measurements (measured by percentage of recovery) was good for CO and CO_2 (100±8 and 3 percent, respectively), acceptable for benzene (100±23 percent), and relatively poor for some measurements of HCHO and acrolein (100+35 and 56 percent, respectively) Overall precision estimates (measured by relative standard deviation of field replicates) ranged from 14 percent for CO_2 to 24 to 33 percent for benzene, acrolein CO, and respirable particulate, to 43 percent for HCHO

Twelve days of data collection were accomplished at five wildfires between 1992 and 1994, average smoke exposures per workshift were calculated for 66 firefighters Workshifts averaged 13 hours, and time on the fireline averaged over 9 hours Smoke exposure was found to be below PELs at these fires, but in some instances it exceeded ACGIH and NIOSH recommendations The authors considered higher exposures to be likely to occur, based on interviews with experienced firefighters and their own observation of missed sampling opportunities Respiratory irritants were the key health hazard at these fires, although the highest CO exposures measured could cause adverse health impacts among persons suscept b!e to CO poisoning including pregnant women and persons with cardiovascular disease Benzene was not a health hazard among most firefighters but persons working withgasoline containing equip ment experienced higher benzene exposure Table 8 shows the average and maximum of the TWA exposures among the firefighters

Only three peak exposure samples were obtained in the study These peak expo sures were below OSHA short-term exposure limits but they could exceed more stringent exposure limits recommended by ACGIH and NIOSH to protect workers engaged in hard labor Maximum peak exposures based on nominal 18 minute samples are shown in table 9

Smoke exposure was highest during strong inversion conditions and when firehnes were maintained on the downwind edge of burnouts Smoke exposures were higher during direct attack of spot fires and lower during mop up but insufficient data were obtained to evaluate the significance of the exposure differences among work activi ties Atmospheric inversions and ambient windspeed Were considered to be important variables controlling smoke exposure, but fire-weather gata were not sufficiently representative of local conditions to evaluate the influence of weather

Pollutants were well correlated in smoke, but more high concentration data were needed to make the correlations useful for predictive purposes This is because there were so few high-concentration observations that the error bands around the resulting regressions were especially wide at the higher concentrations where health effects might be expected, thereby making the estimated exp sures imprecise Electronic carbon monoxide dosimeters were practical devices for roLtine smoke exposure monitoring, but a strong quality assurance program was considered necessary to ensure valid results The authors recommend a smoke exposure management program that combines existing safety programs with continued exposure assessment, exposure management, and risk assessment work

Wildfire Summary and Data Needs

Overexposure to CO has been documented during initial attack and in the course of direct attack activities Respiratory irritants are likely to exceed PELs when CO exposure is high Exposure to smoke at project fires is expected to decline after initial attack to lower levels during the mop up phase Most measurements of smoke exposure at wildfires have been biased by the inability of researchers to quickly sample smoke exposure early in the course of a fire At one fire high levels of CO and TPM were measured in fire camp and were consistent with other measurements on firehnes High smoke exposure can occur anywhere at a fire during inversion conditions Smoke exposure at fire camps in inversion conditions should be further assessed Exposure to crystalline silica is poorly characterized, but significant exposures are possible during line construction, mop up, and travel through dusty areas when soils have a crystalline silica component Archived smoke exposure samples should be analyzed for crystalline silica to better characterize this hazard without the cost of field efforts

Table 8—Time-weighted average exposures to smoke, Pacific Northwest, 1992-94

Pollutant	Duration[a]	Mean	Maximum
Acrolein (ppm)	Shift	0 003	0012
	Fire	0 004	0015
Benzene (ppm)	Shift	0016	0 26
	Fire	0 020	0 36
Carbon dioxide (ppm)	Shift	439	590
	Fire	469	670
Carbon monoxide (ppm)	Shift	4 1	32
	Fire	54	38
Formaldehyde (ppm)	Shift	0 023	0 079
	Fire	0 029	0 086
Respirable particulate (mg/m3)	Shift	0 69	23
	Fire	0 90	28
Respiratory irritants (no units)	Shift	0 24	0 79
	Fire	0 31	0 97

Shift = entire workday fire = portion of workday on fireline

Table 9—Peak smoke exposures at large wildfires in the Pacific Northwest

Pollutant	Maximum
Acrolein (ppm)	0 072
Benzene (ppm)	0 058
Carbon dioxide (ppm)	998
Carbon monoxide (ppm)	106
Formaldehyde (ppm)	0 282
Respirable particulate (mg/m^3)	5 5

Among work activities, initial attack by handcrews, engine crews, and mechanized equipment teams are a high priority for smoke exposure assessment because they appear most likely to receive high smoke and dust exposures, yet few measurements exist Differences in exposure potential among fuel types and regions are indicated because of differences in suppression strategies and residence times of fire in the fuels Direct-attack fireline construction is a specific activity having moderately high potential for smoke exposure, but one for which few exposure measurements have been made Holding during backfiring and burnout operations is another work activity with few measurements but potentially high smoke exposure potential Mop-up exposures are likely a concern only in soils with a crystalline silica component or when residence times of fire are long, such as in regions with heavy ground fuels or thick duff layers

Fires in the wildland-urban interface are considered to put the firefighter at great risk of overexposure to smoke because of the need for structure protection, but no exposure measurements have been done when fire was threatening structures Measurements of smoke exposure should be done during structure protection and fire suppression at interface fires Finally, regional differences in smoke exposure are likely the highest exposures are probably where heavy fuel loading and thick duff layers predominate, such as Pacific coastal forests, peat bogs in the Great Lakes region and pocosm fuels in the Southeast

Initial Attack

The first firefighters on the scene of a wildfire are responsible for assessing the incident—evaluating life, property, and resources at risk from the fire, the size and rate of spread of the fire; and the likelihood of successful control with the suppression resources at hand The strategy and tactics chosen for initial attack often play a major role in determining the ultimate size of the fire Because over 95 percent of all wildland fires are kept to small size and are extinguished within the first burning period, initial-attack actions are overwhelmingly effective Initial attack forces are guided by the goals of working safely and effectively and achieving control over the fire with a minimum of suppression costs relative to the resource value at stake Given these goals, it is reasonable to assume that initial-attack firefighters will exert maximum effort to contain and extinguish the fire as rapidly as possible This commitment to the task at hand, while laudable, may cause firefighters to expose themselves to significant smoke during initial attack

At level 5 and level 4 fires, where few firefighters are at the incident, a wide variety of scenarios are possible Some scenarios have a much higher probability of excessive smoke exposure than others Common examples are provided from experience and the literature (Pyne 1984)

Hand crews—An example of a typical incident begins when lightning starts a fire in a heavily timbered area The local agency dispatches two smokechasers to locate and, if possible, extinguish the fire. They visually locate the fire and determine that laying a hose from the nearest road is impractical These firefighters must hike in to the site, perhaps a burning snag with one-quarter acre of ground fire beneath After sizing it up, they decide to attempt control themselves, perhaps with backup from a few more firefighters

Firefighters likely would start by "hotspotting" the perimeter where the fire was most likely to grow beyond their control capabilities This direct attack activity probably has the highest risk of brief overexposure to smoke The hotspot might be approached from downhill, upwind, or the blackened area If so, smoke exposure should remain within recommended ceiling exposure limits But other times, effective direct attack requires the firefighters to closely flank the fire or approach from the uphill or upwind side (a safe strategy in this small-fire scenario) This could take an hour or more if several hotspots are threatening The firefighters' physical effort will probably peak as they get into the worst smoke, thus intensifying their uptake of pollutants. The firefighters might be able to step out of the smoke to get fresh air, but this often is delayed by excitement and the desire to get the job done Smoke exposure may exceed ceiling limits and STELs in these situations, especially as the firefighters "pinch off" the head of the fire or if winds are erratic.

After controlling the immediate threats, the firefighters might turn attention to dropping a burning snag. An area is prepared and the tree is felled. The firefighters quickly move into direct attack to prevent the fire from spreading, with concomitant potential to exceed STELs and ceiling limits. Once the perimeter is established and mop up begins, it is less probable that any STEL or ceiling exposure limit will be exceeded, but the cumulative dose of many hours of low-level exposure during mop up combined with the initial direct attack dose could result in exceeding a TWA, even if the initial attack exposure was within ceiling and STEL limits.

Such direct attack of small fires may provide the greatest opportunity for overexposure to smoke among firefighters. Local district personnel commonly encounter this type of fire Smokejumpers and hehtack (helicopter-delivered) and heli-rappel (delivered by rapelling from a helicopter) crews are other firefighting forces that will experience similar scenarios Support of hand crews with aerial water and retardant drops can temporarily quell the fire and allow direct attack of the head of the fire. From a safety and efficiency perspective, such support can make the difference between effective suppression versus pulling back and calling for reinforcements. Aerial drops do not always completely extinguish the fire; the firefighters may be able to finish the direct attack but might do so while directly downwind of strongly smoldering hotspots

One study reports exposure measurements for handcrews during initial attack, but only CO exposure was assessed in Western U S fuels Jackson and Tietz (1979) concluded that the highest COHb levels in nonsmoking firefighters are associated with initial attack, and these often exceed 5 percent.

Engine-supported attack—Wildland engines (ground tankers) carrying a few firefighters also may experience heavy smoke exposure during their initial attack operations Typically, the engines will approach from an anchor point at the rear of the fire and move along the flanks using either fixed hoselay or mobile attack, depending on fuels and terrain. As long as the wind is consistent, the firefighters can stay upwind of the highly concentrated smoke from the flaming and first smoldering phase of combustion If winds are erratic, they may be exposed to significant amounts of smoke, but probably for only short periods With small or slow-moving fires, direct control of flaming areas can put the firefighters in the thick of the smoke, especially when attacking the head of the fire. Although smoke exposure probably will be brief, the smoke easily can be concentrated enough to exceed STELs and ceiling limits, and the firefighter's attention will be focused on the blaze rather than health hazards of smoke

Thus STEL and ceiling exposure limits rather that TWA limits are most likely to be violated during initial attack If slow-burning heavy fuels or smoldering ground fuels in the fire perimeter are upwind from the firefighters, these sources contribute to the total dose received by the firefighters, and this can continue into mop up If smoke exposure approaches STELs during the initial attack, the additional smoke from smoldering areas can result in violation of TWA exposure limits, even though mop up exposures are less likely to be hazardous

Only one study reports smoke exposure for crews during initial attack by ground tankers Reinhardt and others (1995a) found that smoke exposure among engine crews in grass and chaparral fires was low They noted that the conditions were representative of most fires in that fuel type but did not include the range reported by experienced firefighters No engine-supported initial-attack measurements are reported in any other fuel types or regions of the United States

Tractor-plow attack—In most of the South and Southeast and parts of the Great Lakes region, mechanized approaches (bulldozers or a tanker- or tractor-plow) are employed for initial attack to contain the fire Depending on fire behavior, the attack may begin at the head or flank of the fire the head is attacked if the rate of spread is slow The smoke exposure potential any time personnel are downwind of the fire will be governed by proximity to the fire, windspeed, and drection, and the pollutant source strength Equipment operators may receive the most smoke exposure at such fires (Grimes 1994) Because plows or dozers are relatively slow moving, operators may experience significant smoke exposure when flanking or pinching off the head of the fire because they cannot get out of the smoke Short-term exposure limits and ceiling limits are the most likely criteria to be exceeded Where a firefighter follows behind the plow and burns out (ignites the unburned fuel), hand crews may be used to hold the plow line during the burnout If winds are sufficient, these firefighters could experience excessive smoke exposure even though spot fires were not a problem If fine fuels are dry enough, spot fires during the burnout will necessitate direct control efforts, which are likely to have high (though short-lived) smoke exposures

Equipment operators may be exposed to high levels ci dust and crystalline silica in addition to smoke from the fire Hand crews supporting equipment operators also may receive high exposures during burnout operations and while attacking hot spots Only one measurement of smoke exposure among mechanized equipment operators during initial attack is reported in the literature Gnggs and others (1983) found that one bulldozer operator (also a smoker) had a blood COHb level of 9 percent at a peat fire in North Carolina

- Few exposure measurements exist among handcrews engine crews, or mechanized forces during initial attack, although data indicate that these situations cause the highest COHb levels among firefighters Most wldfires are contained as level 4 and 5 fires Data need to be collected at such fires in various fuel types to adequately assess smoke exposure during initial attack

Project Fires

Project fires have attracted the most attention among those concerned about smoke exposure The level 3 through 1 fires involve more acreage, thus fire behavior can be more extreme through involvement of more fuel, and high rates of heat release can generate strong winds Firestorms and crown fires have less potential for direct smoke exposure among firefighters, though, because the crews will be pulling back from such events The smoke exposure problem at large fires is inherent to specific tasks and situations, some of which are similar to level 4 or 5 fires and prescribed fires

Line construction—Fireline construction may be direct or indirect Direct line construction (hot line) has a much greater chance of significant smoke exposure than indirect line construction if the fire is actively burning in the area, direct line construction after the smoldering phase is nearly over has little potential for smoke exposure, as does indirect line construction Those involved in burnout of an indirect parallel line following line completion might experience significant smoke exposure Direct line construction adjacent to slow-moving fires is more likely to produce significant smoke exposure if the entrapment risk is low, because firefighters can confidently work closer to the fire than they would if the fire had a potentially fast rate of spread Type I crews are most likely to encounter such a hot-line scenario at a project fire Type II and III crews are not expected to be placed in such situations

For any crew, the main hazard during line construction in dry soils is expected to be exposure to entrained dust The dust may be composed of large-diameter particles that do not penetrate the lower respiratory tract, but occupational exposure is regulated nonetheless Many areas of the country have significant levels of crystalline silica in local soils The presence of crystalline silica in dust lowers the exposure limit considerably

- Direct-attack fireline construction has a high probability of exposure to smoke, dust and possibly, crystalline silica Some of the greatest smoke exposures at large wildfires have been measured during direct-attack activities Additional exposure measurements are needed during direct attack to expand the variety of fuel types and fire situations and add respiratory irritants to the CO database

Burnout operations—Burnout operations are similar to prescribed fires in planning and execution Removing unbumed fuel from the path of the fire during a burnout operation can result in two groups of exposure hazard among the fire lighters using hand ignition, and among the fireline holders, when holding is required Aerial ignition removes the potential for smoke exposure among fire lighters Fire lighters are often type I crews or experienced type II crews, holders are likely to be type II or III crews

The fire lighters may experience elevated exposure to smoke, especially when winds are light or variable This is because wind shifts can make it difficult to stay upwind of the smoke They also may be exposed to benzene if they use drip torches containing gasoline, but this exposure has not been demonstrated to exceed PELs Based on sampling from a few wildfires and many prescribed fires, fire lighters usually do not have significant smoke exposure Anecdotal reports of irritation from fusee smoke are difficult to evaluate without more data and perhaps specialized sampling

Holders will experience smoke exposure levels ranging between none and high, depending on the situation Low-exposure situations are foreseen when winds are favorable for the burning operation or topography prevents smoke from reaching the holders High smoke exposure potential occurs when winds are unfavorable or shifting, or when topography or adjacent resources at risk force the holders to maintain a fireline that the smoke is likely to reach They may be more likely to receive high smoke exposure if they have a safe escape zone nearby, because they can manage the backfire with a degree of impunity Functionally, holding line adjacent to a burnout is equivalent to holding during a prescribed fire If wind or topography direct smoke across the fireline into the holders, they easily can have smoke exposures exceeding recommended exposure limits

The highest smoke exposures measured in the study by Reinhardt and others (1995b) were found among a holding crew during a burnout operation Among the smoke exposures measured in Australia by Brotherhood and others (1990), back-firing operations produced higher smoke exposures than did direct attack line con struction Smoke exposures were low during one backfire where the firefighters were downhill from the area burned (Kelly 1992b) but moderate for a brief period during a second backfire Smoke exposure was highest among a crew lighting and holding fireline during an exposure assessment (Reh and others 1994) but low in another crew holding a different flank of the same backfire

- Further exposure assessment is needed among personnel lighting and holding firehnes during backfires and burnout operations Exposure measurements indicate that these are high-exposure situations, but few measurements exist

Mop up—Type II and III crews are most often assigned to mop up The predominance of such crews in the workforce means that more firefighters are involved in mop up than other activities This task is functionally equivalent to mop up at prescribed fires Exposure to significant levels of TPM is more plausible than exposure to PM3 5 because mop up involves soil and ash disturbances that generate dust Other respiratory irritants and CO can be present at significant levels, especially so when there are heavy fuels or duff smoldering in the vicinity Crystalline silica is another hazard of mop up that is poorly characterized Exposure during mop up may be a matter of individual work habits, as different firefighters show variations in vigor of effort and proximity to the source

Some authors found CO exposure during mop up to be low in Western wildfires (Jackson and Tietz 1979) Other measurements corroborate this (Reh and Deitchman 1992) In a peat fire situation, the smoldering organic layer caused relatively high CO exposures among those working downwind from the fire (Gnggs and others 1983) Another study found that mop up during a night shift in inversion conditions had moderate PM3 5 and CO exposure (Harrison and others 1992), but the elevated exposures may have been caused by the inversion rather than the task One study found that two peak CO exposures above 200 ppm were associated with mop up tasks (Materna 1992a) Smoke exposure during mop up was low at small fires in northern California grass and chaparral (Reinhardt and others 1995a) and relatively low at large Western U S wildfires (Reinhardt and others 1995b) Crystalline snica has been identified in PM3 5 samples obtained during mop up by two studies (Kelly 1992a, Materna and others 1992a)

- Mopping up in areas of heavy fuel loading may be associated with moderate smoke exposure, and a few measurements have quantified crystalline silica exposure in certain regions of the country Mop up exposure should be further assessed at fires with heavy fuel loading and areas with thick duff layers Existing PM3 5 sample filters should be analyzed for crystalline silica and if those results are significant, additional measurements should be made in different areas of the country

Transportation—In many project fires, base camps are located an hour or more (by vehicle) from the fireline along unpaved roads Although inversion conditions can add smoke exposure to this transportation time, dust exposure is the most likely problem, especially so in the dry conditions conducive to large-fire development Crystalline silica is a potential hazard from some soils Road dust can be controlled by watering Although measurements are lacking, observations have been made of significant exposures to road dust (Reinhardt 1995) Vehicular exhaust is unlikely to be a significant source of pollutant exposure, unless firefighters must wait next to idling vehicles The common task of hiking into the fire along trails and firelines and through blackened areas is likely to also produce exposure to significant levels of TPM, especially among large crews Most wildfire smoke exposure assessments have specifically avoided sampling during transit and, in some cases during hiking to and from the fireline

- Further exposure assessment at large wildfires should specifically sample exposure to total and respirable particulates during transportation to and from the fireline

Fire camp—Fire camp locations are diverse, but some conditions can create high smoke exposure in the camp Camp locations are primarily chosen for logistical convenience Proximity to the fire is important to minimize travel time, but this proximity can cause smoke from the fire to be a problem in camp At large fires, residual smoke from the fires often impacts the fire camp Down-valley winds at night can transport smoke into the camp Diurnal inversions are common, occasionally they can keep smoke trapped in valley bottoms for weeks on end, as observed in the Happy Camp area of California in 1987 (Sutton and others 1988) Even a typical nightly inversion can exacerbate the respiratory health of firefighters by exposing them to additional smoke when they should be recovering from exposure during the previous workshift Dust-control practices, such as watering high-traffic areas, can minimize the impacts of vehicular traffic on roads and near camps In the absence of such efforts, TPM exposure from entrained dust can contribute to the inhalation hazards in fire camps Exposure to ambient CO can exacerbate fatigue among firefighters seeking rest in camp Incident command staff often work extended hours planning strategy and managing the fire Although low-level CO exposure should not significantly affect personnel in a fire camp, exposure to moderate levels of CO over extended time could contribute to errors in judgment

Two reports of fire camp smoke exposure are found in the literature. Sampling at the Happy Camp complex in California measured moderately high dust levels in the fire camp, and ambient air quality monitoring found dust levels very close to the PEL on days when inversion conditions existed (Sutton and others 1988) Hourly CO levels in fire camp were documented at levels above the PEL by the same study. Most fire camps will not reach such levels, but other measurements also have found CO and TPM at low to moderate levels in fire camps (Reh and others 1992)

- Additional measurements of CO and respiratory irritants should be obtained in fire camps when inversion conditions exist

Interface Fires

The future of wildland firefighting will be affected by encroachment of human development into locations poorly defensible from wildland fires. Protection of buildings with a water supply from an engine or standpipe places the wildland firefighter in a difficult situation Often, the proximity of the structure to the wildland fuels and topographical limitations are such that ideal firehnes are not possible. In the course of protecting property from advancing fire, the wildland firefighter may experience significant smoke exposure (Romey 1994) If a good escape zone is nearby such as a road, the firefighter may not be in physical danger, but relative safety may encourage firefighters to hold firehnes around structures even though smoke exposure is high Firefighting within structural interiors is not considered here, as virtually all firefighting agencies trained in structural firefighting use self-contained breathing apparatus (SCBA) to protect against smoke exposure hazards

Only one study has collected exposure measurements specifically during structure protection (Kelly 1992a). He found very little smoke exposure because the firefighters were away ftom the fire This may be the case more often than not but when the fire finally does arrive, smoke exposure is reported by many to be bad because of the need to protect property (Stutler 1994) The smoke exposure assessment for initial attacks in northern California (Remhardt and others 1995a) found relatively low smoke exposures, but these were small fires in grass and light chaparral fuels and did not involve structure protection Other parts of the country experiencing urbanization of wildlands, such as the Great Lakes States, the Southeast, and the Southwest, may have heavier fuels with correspondingly longer flame residence times in the fuel beds

- Smoke exposure should specifically be assessed at urban interface fires Because only limited data are available, more representative data need to be collected given the widespread consensus that these situations can have the worst smoke exposures.

Regional or Specific Fuel Type Issues

Many of the considerations mentioned earlier in the 'Wildfire Suppression" section apply to wildfires as well Here, we summarize the important points from the "Wildfire Suppression" section and considerations that derive from common suppression tactics in those fuels

Wildfires in forested areas will have a broad spectrum of smoke exposure controlled by the residence time of the fire in the fuel, the proximity of the firefighters adjacent to and downwind of the fire, and atmospheric stability and winds Heavier fuels and thick duff layers dry enough to support combustion will be associated with the highest smoke exposures Sparse surface fuels and thin duff and litter layers are associated with lower smoke exposures

The flammabihty of Southern brushy areas (rough) and Southwestern chaparral during wildfire season limits smoke exposure when it limits the proximity of the firefighters When such fires are attacked from the rear, and firefighters advance along the flanks, smoke exposure should be low (Wachtel 1995) Brief peak exposures are likely the only concern. Frontal assaults or hotspotting would have more significant exposures, but STEL compliance would remain the primary concern Burning out of firehnes and backfiring operations also could cause smoke exposure problems Residence times are brief in brushy fuels, thus smoke exposure during mop up is probably minor, with the possible exception of exposure to TPM and crystalline silica

Grassland fires have potential smoke exposure among tractor-plow and dozer operators, and those doing line burnout and back-firing operations when spot fires are a concern Flame residence times are so brief that mop-up exposure is probably inconsequential

In the interior of Alaska, effective direct attack of wildfires in black spruce-feathermoss fuels is often done by swatting the flames with branches or large flaps (similar to mudflaps from vehicle tires, attached to a handle, also conifer boughs) Brief but intense smoke exposure may occur during initial attack when this technique is used (Boatner 1995) Exposure measurements are needed to assess peak exposures during initial attack When mop up is required in these fuels, smoke exposure can be extensive (Wilcock 1995)

Peat bog fires and fires in the Southeast pocosin fuels may be among the worst smoke exposure situations, because the smoldering ground fires could have high emission factors for products of incomplete combustion (like CO and respiratory irritants) Wildfires in Florida and southern Georgia swamplands may burn in a similar manner (Wetzel 1995) The early COHb study in North Carolina (Gnggs and others 1983) found significant levels of smoke during mop up of a peat fire The flaming phase is brief, similar to other brushy fuels, but because the smoldering phase can last for weeks or more, mop up can entail extended periods of smoke exposure (Walden 1995)

- Smoke exposure should be assessed at wildfires in regions with heavy fuel loading and thick duff layers, such as Pacific Northwest coastal forests, peat bogs in the Great Lakes region, Alaska taiga, and pocosin fuels in the Southeast

Conclusion and RGCOmmGndations

Smoke exposure among firefighters has been recognized as a potential problem since the early 1970s Several organizations have made efforts to assess smoke exposure during the last 20 years, with various degrees of success Overall coordination of these studies has been lacking in the past, and the unfamilianty of occupational health researchers with the wildland fire workplace and lack of industrial hygiene expertise among agency fire management personnel have, in some cases, resulted in fragmented, exploratory studies Most of these studies have concluded that they should be followed with extensive further studies, because it is so difficult to measure such a variable phenomenon as smoke exposure during firefighting This review has attempted to adequately summarize the findings of the various projects and accurately assess further data needs

Based on exposure monitoring and discussion with fire management experts, exposure to smoke (and dust) among firefighters does not appear to be a problem 90 to 99 percent of the time This is because the tactics of wildfire suppression and prescribed burning have evolved to maximize safety and efficiency and to take advantage of control opportunities afforded by the environment Nonetheless, in a small percentage of cases, overexposure can occur among firefighters and has been demonstrated for some components of smoke and dust The long-term health significance of overexposure to smoke is uncertain, but small, statistically significant increases in respiratory symptoms and declines in lung function have been found among firefighters, at least for several weeks or months Whatever the long-term health risks, overexposure to CO or respiratory irritants as defined by OSHA or the appropriate state agency is not acceptable and should be managed further

Based on review of the literature and discussions with fire experts, factors contributing to high smoke exposure include

- A necessity to control the fire with little regard to the inconvenience" of smoke exposure, examples include prescribed burns and wildfires in the wildland-urban interface
- The ability to work closely to the fire, as when mechanized equipment provides good support or when fires are small or rate of spread of the fire is slow and firefighters can conduct direct attack with little fear of entrapment
- The occurrence of strong smoldering combustion because of a high organic content of the soil or a heavy ground fuel load, long fire residence time in the fuelbed causes extended exposure to smoke among suppression and control forces
- Erratic or strong winds, during initial or direct attack of wildfires and while holding fireline during burnout operations or prescribed fires
- Poor positioning of firefighters to avoid smoke because of the terrain or adjacent resources at risk from the fire
- Atmospheric inversion conditions trapping smoke from large fires in topographically confined spaces.

When one or more of these factors are present, overexposure to smoke will occur Because of the variability of the fire environment, it is difficult to say how bad the overexposure will be or among how many firefighters, but the overall percentage of overexposed firefighters is expected to be low The recommendations for data collection in the "Wildfire Suppression" and "Wildfire Summary and Data Needs" sections are aimed at further assessing exposure in such worst case situations where monitoring has not occurred.

Enough evidence has been gathered to begin to develop and implement smoke exposure management strategies Management plans addressing the possibilities of over-exposure indicated by the existing data are not likely to require changes in strategy as a result of further monitoring, only in the scope of application Agencies interested in employee health and safety and minimizing liability should press ahead with such plans and not be frustrated with suggestions for further monitoring Indeed, they should get used to the concept of routine monitoring and incorporate it (hopefully with a reduced scope of indicator pollutants) into their exposure management strategies As OSHA progresses from standards developed in the late 1960s and early 1970s to comprehensive standards for pollutants, the need for exposure assessment will not abate, as exemplified by the standard for formaldehyde which requires comprehensive initial monitoring of employees to"

> develop a representative sampling strategy and measure sufficient exposures within each job classification for each workshift to correctly characterize and not underestimate the exposure of any employee
>
> U S Department of Labor (1994a)

Given our discussions with fire experts and reviews of exposure monitoring data, we believe the additional monitoring recommended should satisfy such requirements Requirements for initial monitoring are supplemented by periodic monitoring (that is, every 6 months) as well as monitoring whenever complaints of symptoms associated with overexposure are received

Because smoke exposure seems to be a problem in only a small percentage of readily identifiable workshifts, management strategies may have a variety of options to reduce all exposures to acceptable levels without compromising the effectiveness of fire management efforts or unreasonably expending limited budgetary resources

Units of Measure

When you know.	Multiply by.	To find.
Meters (m)	3 281	Feet
Cubic meter (m^3)	35 32	Cubic feet
Miles (mi)	1 609344	Kilometers
Liters (1)	0.908	Quarts
Milligrams (mg)	0.000035274	Ounces
Micrograms (µg)	0 000003527	Ounces
Feet (ft)	0.3048	Meters
Inches (in)	2 54	Centimeters
Acres	0.40	Hectares

References

American Conference of Governmental Hygenists. 1995-96. Threshold limit values (TVLs) for chemical substances and physical agents and biological exposures indices (BEIs). Cincinnati, OH

Betchley, C. 1993. Personal communication. November. Seattle, WA: Department of Environmental Health, University of Washington.

Betchley, C. 1994. Personal communication. December 3. Seattle, WA. Department of Environmental Health, University of Washington.

Betchley, C; Koenig, J.Q.; van Belle, G. [and others]. 1995. Pulmonary function and respiratory symptoms in forest firefighters. Unpublished report. On file with. University of Washington, Departments of Environmental Health and Epidemiology, Mailstop SC-34, Seattle, WA 98195.

Boatner, T. 1995. Personal communication. May 3. Fairbanks, AK: U.S. Department of the Interior, Bureau of Land Management, Alaska Fire Service, Smokejumper Branch, chief.

Brotherhood, J.R.; Budd, G.M.; Jeffery, S.E. [and others]. 1990. Fire fighters' exposure to carbon monoxide during Australian bushfires American Industrial Hygiene Association Journal. 51(4): 234-240.

Chonka, J. 1995. Personal communication. April 25 Gunnison, CO: U.S. Department of Agriculture, Forest Service, Grand Mesa-Uncompaghre-Gunnison National Forest, Gunnison Ranger District, fire management officer.

Coburn, R.F.; Forster, R.E.; Kane, P.B. 1965. Considerations of the physiological variables that determine the blood carboxyhemoglobin concentration in man Journal of Clinical Investigation 44(11) 1899-1910

Dost, F.N. 1991. Acute toxicology of components of vegetation smoke In Reviews of environmental contamination and toxicology New York NY Springer-Verlag Inc 2-46 Chapter 19

Griggs, T.R.; Mage, D.; Simpson, R.J., Jr.; Haak, E 1983. Carbon monoxide exposure associated with fighting a peat ground fire Fire Management Notes 44(1) 6-8

Grimes, L. 1994. Personal communication December 15 Atlanta, GA U S Department of Agriculture, Forest Service Southern Region, regional fire training specialist

Hardy, C.C.; Teesdale, D.R. 1991. Smoke emissions from prescribed fires in western juniper and big basin sagebrush of central Oregon Seattle, WA U S Department of Agriculture, Forest Service, Pacific Northwest Research Station, final report, [contract no unknown]

Harrison, R.; Materna, B.; Liu, D.; Balmes, J. 1992 Respiratory effects of smoke exposure in wildland firefighters methachohne challenge testing and exposure monitoring Berkeley, CA California Occupational Health Program, California Department of Health Services

Hvizdak, R. 1994. Personal communication December Eureka, MT U S Department of Agriculture, Forest Service, Kootenai National Forest, Rexford Ranger District

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

Kelly, J. 1992a. Health hazard evaluation report U S Department of the Interior National Park Service, Gallatin National Forest, Montana Cincinnati, OH U S Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, HETA 91-312-2185

Kelly, J. 1992b. Health hazard evaluation report, U S Department of the Interior, National Park Service, New River Gorge National River West Virginia Cincinnati, OH U S Department of Health and Human Services Public Health Service, Centers for Disease Control, National Institute for Occupational Health and Safety HETA 92-045-2260

Kelly, J. 1994. Personal communication May Cincinnati OH National Institute for Occupational Safety and Health, industrial hygienist

Kiefer, M.B. 1995. Personal communication, April 27 Three Rivers, CA U S Department of the Interior, National Park Service Sequoia-Kings Canyon National Park, ecologist

Kubiak, P. 1995. Personal communication April 27 Tallahassee, FL U S Department of Agriculture, Forest Service, Appalachicola National Forest, Appalachicola Ranger District, fire management officer

Lavdas, L.G. 1995. Personal communication March 13 Macon, GA U S Department of Agriculture, Forest Service, Southern Forest Fire Laboratory

Letts, D.; Fidler, AT.; Deitchman, S.; Reh, CM. 1991. Health hazard evaluation report, U S Department of the Interior, National Park Service, southern California Cincinnati OH U S Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health HETA 91-152-2140

Linane, M. 1995. Personal communication April 25 Los Frelos, CA U S Department of Agriculture, Forest Service, Los Padres National Forest, crew superintendent

Liu, D.; Tager, I.B; Balmes, J.R.; Harrison, R.J. 1992. The effect of smoke inhalation on lung function and airway responsiveness in wildland fire fighters American Review of Respiratory Disease 146 1469-1473

Lodge, James P. 1989. Methods of air sampling and analysis 3d ed Chelsea, MI Lewis Publishers, Inc 296-302

Martin, P. 1994. Personal communication December 16 Park Falls, WI U S Department of Agriculture, Forest Service, Eastern Region

Materna, B.; Koshland, C; Harrison, R. 1992a. Carbon monoxide exposure in wildland firefighting a comparison of monitoring methods Berkeley, CA California Occupational Health Program, California Department of Health Services

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

McMahon, C.K.; Bush, P.B. 1992. Forest worker exposure to airborne herbicide residues in smoke from prescribed fires in the southern United States American Industrial Hygiene Association Journal 53(4) 265-272

Mutch, R.W.; Arno, S.F.; Brown, J.K. [and others]. 1993. Forest health in the Blue Mountains a management strategy for fire-adapted ecosystems Gen Tech Rep PNW-GTR-310 Portland, OR US Department of Agriculture Forest Service, Pacific Northwest Research Station

National Institute for Occupational Safety and Health. 1989. Manual of analytical methods, third edition Cincinnati OH U S Department of Health and Human Services, Centers for Disease Control, NIOSH 0600-1 to 0600-6, 1501-1 to 1501-7

Oberheu, R. 1995. Personal communication April 25 Delta, CO U S Department of Agriculture, Forest Service, Grand Mesa-Uncompaghre-Gunnison National Forest, fire management officer

Pyne, S.J. 1984. Introduction to wildland fire fire management in the United States New York John Wiley & Sons 379

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

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

Reinhardt, T.E. 1989. Firefighter smoke exposure at prescribed burns a study and action recommendation Unpublished report On file with U S Department of Agriculture, Forest Service, Pacific Northwest Research Station, Fire and Air Resource Management Project, 4043 Roosevelt Way NE Seattle, WA 98105-6497

Reinhardt, T.E. 1991. Monitoring firefighter exposure to air toxins at prescribed burns of forest and range biomass Res Pap PNW RP-441 Portland, OR U S Department of Agriculture, Forest Service, Pacific Northwest Research Station

Reinhardt, T.E.; Black, J.; Ottmar, R. 1995a. Smoke exposure at northern California vegetation fires Unpublished report On file with U S Department of Agriculture, Forest Service, Pacific Northwest Research Station, Fire and Air Resource Management Project, 4043 Roosevelt Way NE Seattle WA 98105-6497

Reinhardt, T.E.; Black, J.; Ottmar, R. 1995b. Smoke exposure at Northwest wild-fires Unpublished report On file with U S Department of Agriculture Forest Service, Pacific Northwest Research Station, Fire and Air Resource Management Project, 4043 Roosevelt Way NE, Seattle, WA 98105 6497

Reinhardt, T.E.; Hanneman, A.; Ottmar, R. 1994. Smoke exposure at prescribed burns Unpublished report On file with U S Department of Agriculture, Forest Service, Pacific Northwest Research Station, Fire and Air Resource Management Project, 4043 Roosevelt Way NE, Seattle, WA 98105-6497

Ricker, D. 1995. Personal communication April 25 Anchorage, AK State of Alaska Division of Forestry, aviation manager

Ringold, A.; Goldsmith, J.R.; Helwig, H.L. [and others]. 1962. Estimating recent carbon monoxide exposures a rapid method Archives of Environmental Health 5 308-318

Romey, M. 1994. Personal communication December 16 [City unknown], MI U S Department of Agriculture, Forest Service, Huron-Manistee National Forest

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

Rounsaville, M. 1994. Personal communication December Atlanta, GA U S Department of Agriculture, Forest Service, Southern Region regional prescribed fire specialist

Russell, W. 1995. Personal communication January 18 Phoenix, AZ U S Department of Agriculture, Southwestern Region, Aviation and Fire Management

Seamon, P. 1995. Personal communication March 22 Tallahassee, FL The Nature Conservancy, fire manager

Smith, J. 1995. Personal communication April 25 Camino CA California Department of Forestry and Fire Protection, Amador-El Dorado Ranger Unit, vegetation management program officer

Smith, N.J. **1977.** End-expired air technique for determining occupational carbon monoxide exposure Journal of Occupational Medicine 19(11) 766-769

Sparrow, D.; Bosse, R; Rosner, B; Weiss, ST. 1982. The effect of occupational exposure on pulmonary function American Review of Respiratory Disease 125 319-322

Stewart, R.D.; Stewart, R.S.; Stamm, R.; Seelen, R.P. 1976. Rapid estimation of carboxyhemoglobin level in fire fighters Journal of the American Medical Association 235(4) January 26, 1976

Stutler, J. 1994. Personal communication December 21 Bishop, CA Inyo National Forest, fire management officer

Sutton, P.; Castorina, J.; Harrison, R.; Ford, D.P. 1988. Carbon monoxide exposure in wildland fire fighters Berkeley, CA Occupational Health Surveillance and Evaluation Program, Epidemiologic Studies and Surveillance Section California Department of Health Services

Thomas, D. 1994. Personal communication December Superior, MT U S Department of Agriculture, Forest Service, Superior Ranger District

Tietz, J.G. 1975. Firefighters' exposure to carbon monoxide on the Deadline and Outlaw fires ED&T 2424 - Rep 7551-2219 Missoula, MT U S Department of Agriculture, Forest Service, Equipment Development Center, Smoke Inhalation Hazards

U.S. Department of Labor, Occupational Safety and Health Administration. 1994a. Code of Federal regulations, title 29, part 1910 1000(d)(2)(i) Washington, DC 7

U.S. Department of Labor, Occupational Safety and Health Administration. 1994b. Code of Federal regulations, title 29, Part 1910 1048(d)(2)(i) Washington, DC

U.S. Environmental Protection Agency, Research and Development. 1984. Compendium of methods for the determination of toxic organic compounds in ambient air EPA-600/4-84-041 Research Triangle Park, NC Environmental Monitoring Systems Laboratory TO11-1 toTO11-38

Van Der Linden, L. 1995. Personal communication April 17 Fairbanks, AK U S Department of the Interior, Fish and Wildlife Service, State fire coordinator

Viereck, L.A.; Dyrness, C.T.; Batten, A.R.; Wenzlick, K.J. 1992. The Alaska vegetation classification Gen Tech Rep PNW-GTR-286 Portland, OR U S Department of Agriculture, Forest Service, Pacific Northwest Research Station 278 p

Wachtel, D. 1995. Personal communication May 1 Morgan Hill, CA California Department of Forestry and Fire Protection, Santa Clara Ranger Unit, vegetation management program officer

Wade, D. 1995. Personal communication, March 13-14 Macon, GA U S Department of Agriculture, Forest Service, Southern Forest Fire Laboratory

Walden, D. 1995. Personal communication April 28 Raleigh, NC North Carolina Division of Forest Resources, deputy director

Ward, D.E.; Hardy, C.C. 1986. Advances in the characterization and control of emissions from prescribed broadcast fires of coniferous species logging slash on clearcut units Unpublished report On file with U S Department of Agriculture, Forest Service Pacific Northwest Research Station 4043 Roosevelt Way NE, Seattle, WA 98105-6497

Ward, D.E.; Hardy, C.C. 1989. Emissions from prescribed burning of chaparral In Proceedings, 82d annual meeting, Air and Waste Management Association. 1989 June 25-30, Anaheim, CA Pap 89-25 5 Pittsburgh PA Air and Waste Management Association

Ward, D.E.; Rothman, N.; Stickland, P. 1989. The effects of fire smoke on firefighters a comprehensive study plan Proceedings of a meeting [dates unknown] [San Diego, CA] [Place of publication unknown] U S Department of Agriculture, Forest Service, Intermountain Research Station

Wetzel, F. 1995 Personal communication May 3 Folkston GA U S Department of the Interior, Fish and Wildlife Service, Okeefenokee National Wildlife Refuge, assistant fire management officer

Wilcock, L. 1995. Personal communication May 3 Anchorage, AK U S Department of the Interior, Fish and Wildlife Service, Matanuska Susitna National Wildlife Refuge, fire management officer

* U S GOVERNMENT PRINTING OFFICE 1997 - 589-353 / 63008 REGION NO 10

Reinhardt, Timothy E , Ottmar, Roger D 1997 Smoke ex[illegible] among wildland firefighters a review and discussion of current literature [illegible] Tech Rep PNW GTR 373 Portland OR U S Department of Agric[illegible] Forest Service Pacific Northwest Research Station 61 p

This paper reviews and summarizes literature about smoke [illegible]re and the resulting adverse health effects among wildland firefighters Many stu[illegible] [illegible]ave been done on this problem between 1973 and 1995 Overall the data indi[illegible] [illegible]at smoke exposure at wildfires and prescribed fires is usually no more than an [illegible]enience but on occasion it approaches or exceeds legal and recommended [illegible]ational exposure limits Management action is necessary to bring all smoke [illegible]res into compliance with occupational safety regulations

Keywords Fire smoke human health occupational expos[illegible] [illegible]y smoke exposure

Pacific Northwest Research Station
333 S W First Avenue
P O Box 3890
Portland, Oregon 97208-3890