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Wildland Firefighter Smoke Exposure Study

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WILDLAND FIREFIGHTER SMOKE EXPOSURE STUDY

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I. INTRODUCTION

This report addresses exposure to smoke from wildland and prescribed fires encountered by wildland firefighters. Smoke from vegetation as well as off-gasses from equipment such as chain saws, pumps, and drip torches are accounted for. Section II provides an overview of industrial hygiene science and techniques. Section III is a discussion and literature review of the components in wildland smoke, and section IV identifies the health concerns associated with smoke inhalation and a review of the current literature on exposure to inhalation irritants. Section V covers research that has been done on wildland firefighter smoke exposure. Section VI is an overview of the Wildland Firefighter Smoke Exposure Study, a project I have managed since 2009. This final section describes the objectives, methods, data collection, and analysis of the study. In its entirety, this report can be used to identify locations, times, and firefighter activities that have a high probability of causing high exposures as well as to identify management actions that can mitigate these exposures.

Wildland firefighters work in a dynamic environment and are often faced with a variety of hazards from fire to fire and shift to shift. One of the most common, but often overlooked, hazards is exposure to potentially harmful levels of contaminants in wildland smoke. This may also be one of the least understood risks of wildland firefighting (Reisen et al., 2009). With a growing body of information regarding the potential health effects of vegetative smoke to respiratory and cardiovascular systems, it became apparent to United States Forest Service (USFS) fire management officials that more research needed to be done. The USFS realized the need for current, valid data to accurately assess the exposure wildland firefighters and personnel at fire camps experience during their work shift.

Unlike municipal firefighters, wildland firefighters do not wear respiratory protection equipment such as a self-contained breathing apparatus (SCBA). Without SCBA, wildland firefighters are subject to exposure from a variety of inhalation irritants ranging from carbon monoxide, aldehydes, particulate matter, crystalline silica, and polycyclic aromatic hydrocarbons. Some of the compounds in wildland fire smoke are known or suspected carcinogens. Health effects include short-term conditions such as headaches, fatigue, and nausea, while long-term health effects may include an increased risk of cardio-vascular disease. In order to assess the long-term risks associated with wildland firefighting, a comprehensive study of exposure was necessary. By identifying the conditions and activities that lead to high exposure, firefighters and fire managers can be better prepared to reduce these exposures.

This study focused on wildland firefighters engaged in the suppression of wildland fires and working on prescribed fires primarily on federally-managed lands (forests and rangelands) throughout the United States. Study subjects included any firefighter employed by the following federal land management agencies: US Forest Service, National Park Service, Fish and Wildlife Service, Bureau of Indian Affairs, and the Bureau of Land Management, as well as employees contracted by these federal agencies. Firefighters employed by various states are also included in the study, as well as those engaged in initial attack and project fires. Study subjects also included fire support personnel who work at incident command posts (ICPs) and spike camps. Fire suppression and management of prescribed fires involves many different activities. In order to successfully account for differences in exposure among firefighters, these activities were monitored and recorded during the data collection phase.

Background

In December of 2008, I attended a Fire Equipment Working Team meeting in Boise, Idaho as a technical advisor. I am a Fire and Fuels Project Leader for the USFS Technology and Development Program. The Fire Equipment Working Team (now called the Equipment Technology Committee) is a chartered committee under the National Wildfire Coordinating Group (NWCG). The committee was discussing the health and safety of wildland firefighters, and smoke exposure was identified as a primary issue of concern. The committee chair, who was also the USFS Branch Chief for Fire Equipment and Chemicals, determined that the Forest Service needed a better understanding of the exposure levels agency firefighters were experiencing in order to understand the level of risk and how to manage this risk successfully. As a result of that determination, I was tasked with undertaking a project to quantify exposure for all wildland firefighters across the United States. At the request of the NWCG Safety and Health Committee, the study was expanded to include all employees working on wildland fires, specifically those in support positions (NWCG Tasking Memo TM-2008-04).

Following the December 2008 meeting, I undertook a literature review of wildland smoke exposure and industrial hygiene monitoring. The results of that effort became the Wildland Firefighter Smoke Exposure Study, the subject of this report.

Vegetative Smoke Concerns

Vegetative smoke contains numerous inhalation irritants with the potential to cause short- and long-term health hazards to wildland firefighters in the normal course of their duties (Reinhardt, 1991; Reinhardt & Ottmar, 1997, 2004). Although there have been previous studies of wildland smoke exposure, many suffer from some form of limitation: limited in scope; number of firefighters, length of study, geographic area, and challenges inherent in conducting research in the fire environment. Other wildland firefighter exposure studies have provided valuable knowledge to our understanding of exposure in the wildland fire environment, which will be discussed in Section 4, the literature review section of this report.

There are numerous studies on human exposure to urban pollution, smokers, and populations that use wood and/or coal as a primary heating or cooking fuel, which can shed light on the effects of smoke exposure. However, due to differences in the type and amount of exposure wildland firefighter’s face, these studies cannot be used to accurately determine the consequences of exposure to wildland firefighters (Leonard et al., 2007; Gaughan et al., 2008). Previous NWCG-sponsored smoke exposure studies indicate that employees were overexposed approximately 5% of the time at wildfires and 10% of the time at prescribed fires (Reinhardt et al., 2000). The Wildland Firefighter Smoke Exposure Study was designed to build upon the knowledge gained by the work of Reinhardt and Ottmar (2000). The National Institute for Occupational Safety and Health has done several studies that indicate a concern for both wildland firefighters and support personnel working at ICPs. However, there has not been a study that encompasses the wide geographic area where wildland firefighters work, nor has a study covered sufficient subjects that would allow federal agencies to accurately determine exposures for the various duties, environments, and other variables associated with wildland firefighting.

Human Dimensions

The primary objective of this study is to accurately quantify the exposure wildland firefighters face on any given fire and develop recommendations to reduce exposure and provide a safer work environment. By measuring the exposure to these individuals, annual and career exposures can be determined. From this, the risk to short-term and long-term health consequences can be assessed.

The human dimensions aspects of this paper address the potential health risks faced by wildland firefighters from smoke inhalation. Fire management decisions can adversely affect one group in an effort to minimize exposure to another. They will also include a discussion of risk management and risk transfer such as asking who decides where the risk of wildland firefighting will reside.

Ecology

Forest health is often dependent on fire. In many western and intermountain forests in the US, the fire return interval can range from less than 15 years to 30 years. The exclusion of fire from many federal lands has been, in part, responsible for unhealthy forests, i.e., heavy accumulation of fuels, dense stands of timber, and less fine fuels that can carry low intensity fires. In addition to contributing to these problems, fire exclusion policies place wildland firefighters at risk of exposure.

The ecology aspects of this paper relate to management of prescribed natural fires. This section addresses the consequences of fire suppression versus resource benefit fires and the tradeoff between firefighter exposure and ecosystem health.

Law and Policy

Federal agencies and non-governmental organizations establish safety and health laws and recommendations. Recommendations by industrial hygiene organizations are often more strict than federal laws and guidelines. Whether these recommendations should guide wildland firefighter exposure limits rather than federal laws is covered in this section. Finally, the establishment of recommended occupational exposure limits for wildland firefighters is also addressed.

The law and policy section discusses relevant laws and regulations regarding employee safety and health as they relate to exposure. This includes federal laws and regulations established by the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) as well as guidelines established by the American Conference of Governmental Industrial Hygienists (ACGIH). Occupational Exposure Limits (OELs) and the terms used to identify various exposure limits are also described.

Economics

The economics section addresses the information available on the health-related cost of smoke exposure to wildland firefighters.

II. PRIMER ON INDUSTRIAL HYGIENE

The Wildland Firefighter Smoke Exposure Study is an exposure assessment, essentially an industrial hygiene (IH) study. In order to understand the issues and methods discussed throughout this report, a basic understanding of industrial hygiene will be required. This section provides an introduction and overview of the art and science of industrial hygiene and the accepted practices that need to be followed when conducting these assessments. It also provides a summary of terms and methods used to determine risks associated with employee health in the workplace. Finally, there is a discussion on the various regulatory bodies that together work to set occupational exposure limits. The information in this section also serves to measure the quality and effectiveness of the design and implementation of the Wildland Firefighter Smoke Exposure Study.

“Industrial hygiene is defined as the science and art of anticipating, recognizing, evaluating, and controlling health hazards in the workplace” (Bullock et al., 2006). This includes identification, characterization, and assessment of exposures. Bullock et al. (2006) insist that a quality IH program must “be thorough, systematic, well-documented, and efficient.” In addition to assessing and managing health risks to workers, industrial hygiene programs must be prepared to manage other risks such as regulatory and legal risks.

In assessing exposures, consideration must be given to the fact that there are many chemicals that do not have existing occupational exposure levels (OELs), and for many that do, the current limits may change as new information becomes available. Historically, as limits are changed, they are revised lower. Oftentimes OELs are developed on incomplete knowledge, and new research can affect future changes.

Exposure assessment can be used to prioritize and manage worker health, build exposure histories, and confirm that the employer is meeting regulatory mandates. A well-documented assessment can provide guidance for employer training, medical surveillance programs, and requirements for personal protective equipment. Understanding all the risks faced by employees will provide the information necessary to identify the highest risks and provide guidance on how to best protect employees by prioritizing and controlling these risks.

In order to manage risk we must determine the health risk associated with exposure to toxins, displayed by this equation: Health Risk = (Exposure) X (Toxicity). Exposure and toxicity are the two most relevant components of industrial hygiene and for the Wildland Firefighter Smoke Exposure Study. The goal of this study is to understand the risk and provide guidance to the USFS to manage the danger. Good risk management is dependent on a good risk assessment which in turn is dependent on the exposure assessment.

Rather than focusing on a compliance-based approach to industrial hygiene, Bullock et al. (2006) state the focus should be on a broad range of risk evaluations and an assessment of the risks they pose. Employers need to understand all the risks, present and future, in order to efficiently manage all these exposures.

An exposure assessment strategy consists of 7 steps:

1. Define the goals of the assessment and create a written exposure assessment plan.
2. Basic characterization: gather information to characterize the workplace, work force, and environmental agents.
3. Assess exposures: this includes creating similar exposure groups (SEGs).
4. Additional information gathering: prioritized exposure monitoring or collection of more information on health effects, make judgments based on exposure profiles of SEGs and use these to prioritize control, and collect more information on uncertain exposures.
5. Health hazard control: implement control strategies for unacceptable exposures.
6. Reassessment: perform reevaluation of exposures and determine if routine monitoring is required to verify that acceptable exposures are maintained.
7. Communication and documentation: communicate findings and maintenance of data.

The exposure assessment strategy must be made under the supervision of a certified industrial hygienist.

During the data collection phase of the assessment, you must ensure the data are accurate and precise by having standard methods, trained monitoring personnel, a quality assurance/quality control plan, and independent review of the data. Important quality control indicators include field replicates which indicate the precision of the exposure measurements, field blanks and calibration checks which provide a measure of accuracy of the exposure measurements, and review of data quality by an objective expert.

The characterization of the workplace requires an understanding of the chemical, physical, and biological agents in the work environment. Additional necessary information includes the health effects associated with exposure to these agents, OELs for each agent, how the workforce is organized, and significant sources of exposure.

In order to efficiently and effectively characterize employees who may have different exposures due to varying work shifts, duties, and exposure to different toxins, it is beneficial to place workers in similar exposure groups (SEGs). By quantifying the exposure to a sample of each group, you can characterize the exposure to the entire group. An SEG is “a group of workers having the same general exposure profile for an agent because of the similarity and frequency of the task(s) they perform, the similarity of the materials and processes with which they work, and the similarity of the way they perform the task(s)” (Bullock et al., 2006). SEGs can be determined by observation or qualitatively. They can be classified by the task (and frequency in which the task is performed) workers perform and expected exposure to a toxin. Creating SEGs by sampling requires more effort and resources but can be more accurate and statistically valid. SEGs allow the agency to classify employee exposure risk. Once confirmed, SEGs can be classified as to the level of risk for each, and mitigation can be prioritized for the highest risk groups.

Regulatory Organizations

Occupational Safety and Health Administration

Wildland firefighters are covered by the regulations set forth by the Occupational Safety and Health Administration (OSHA) as are all workers, regardless of who they work for, where they work, or the type of work performed. There are no exemptions from these regulations because they are federal employees or work in emergency situations.

OSHA was established after the Occupational Safety and Health Act of 1970. All employers are legally required by this Act to meet the levels specified by an OSHA standard. Federal employees are covered by OSHA standards under executive order 12196 (Feb. 26, 1980, 45 FR 12769, 3 CFR, 1980), Occupational Safety and Health Programs for Federal Employees of 1980. According to Executive Order 12196 , the head of each agency shall: “Furnish to employees places and conditions of employment that are free from recognized hazards that are causing or are likely to cause death or serious physical harm.” OSHA sets Permissible Exposure Limits (PELs) for all federal employees and private employees not covered by a state agency. These OELs are legally binding and enforced by the federal government.

OSHA is also able to cite employers under the general duty clause (Section 5(a)(1) of the U.S. Occupational Safety and Health Act of 1970. The general duty clause requires employers to provide a workplace that is reasonably free from recognized hazards. Where no PEL or other OEL exists for a substance, many employers develop their own exposure limit.

The original PELs established by OSHA in 1970 were adopted from the ACGIH Threshold Limit Values (TLVs®) from 1968 and the standards of the American National Standards Institute. In 1989 OSHA revised the PELS for 428 chemicals to be current with the 1989 TLVs established by the ACGIH. These were to be legally binding PELS; however, various groups challenged OSHA in court and eventually these updated PELs were all overturned and reverted back to the original PELs of 1970.

National Institute for Occupational Safety and Health

The National Institute for Occupational Safety and Health (NIOSH) provides guidance to OSHA on health hazards and establishes Recommended Exposure Limits (RELs). NIOSH recommended standards are based on concerns relating to the prevention of occupational disease. Although NIOSH standards are often based on more recent science than OSHA PELs, they have no legal authority. NIOSH often follows the guidance set by ACGIH.

American Conference of Governmental Industrial Hygienists

The American Conference of Governmental Industrial Hygienists (ACGIH) standards are also recommended standards and have no legal authority. ACGIHs occupational exposure limits are called Threshold Limit Values (TLVs®). ACGIH publishes revised TLVs® yearly; consequently, these are the most current OELs available and are based on the latest scientific research. In most cases the TLVs® are more restrictive than OSHA PELs.

Environmental Protection Agency

The Environmental Protection Agency (EPA) also establishes exposure limits called the National Ambient Air Quality Standards (NAAQS). The NAAQS are established under Title 40 U.S Code of Federal Regulations Part 50 and cover a limited number of pollutants called "criteria" pollutants. These standards are designed to protect the health of all citizens including those at higher risk or sensitivity such as children, asthmatics, and the elderly. Consequently, EPA guidelines are typically much lower than those established for the workplace. The exception to this is for carcinogens which do not have toxicity thresholds because they pose a potential risk regardless of the exposure. Exposure to carcinogens is evaluated by assessing the level of cancer risk posed by the exposure and compared to "acceptable risks" which are established by the EPA or other agencies.

Occupational Exposure Limits

OSHA, NIOSH, ACGIH, and some states set exposure limits for airborne pollutants for various time frames (see Table 1). OELs are based on an exposure level (dose) and time. Dose is the amount of irritant going to a target organ; the dose is dependent on the level and duration of exposure as well as the rates of uptake and elimination by the body. Dose and time must always be considered together. The time is an average time for the exposure and can be set at any amount, but it is dependent on the toxicity of the agent. Primary OELs are set for eight hours, 15 minutes (STEL short-term exposure limit), and instantaneous (ceiling limit).

Time weighted average (TWA) is commonly set for a "normal" 8-10 hour work day and a 40-hour work week. It is an average concentration across the daily and weekly work shift that should not be exceeded and will provide a safe work environment for a career length exposure. These are used for slow-acting and/or toxins that can accumulate in the body over time.

Short-term exposure limit (STEL) is a 15-minute TWA exposure that should not be exceeded at any time during the work day. These are typically set for quick-acting toxins. These are established by ACGIH and some states.

Ceiling (C) limits, established by OSHA, is an exposure that should never be exceeded, even instantaneously. Ceiling limits are appropriate for very fast-acting agents, particularly if there could be irreversible health effects.

Immediately Dangerous to Life and Health (IDLH) limits, established by NIOSH, were originally developed to ensure that a worker could escape without injury or irreversible health effects from the exposure. Although the IDLH was based on a 30-minute exposure, they are not intended to imply workers should stay in that environment for 30 minutes but should in fact leave immediately. This is used for fast-acting toxins.

Organizations can also set internal OELs or develop working OELs. These are informal limits that can be used if existing OELs are not sufficient or are not available for a specific toxin. They can be set and used when there is uncertainty with the existing OELs or there is insufficient data on the irritant.

Some toxins can pose both acute and chronic issues, so both the dose rate and cumulative doses are relevant. Therefore, both short-term and long-term OELs are required.

Table 1. Carbon Monoxide OELs

Parameter	Relevant Occupational Exposure Limit (OEL) (ppm CO)
Maximum 1-minute CO exposure	NIOSH IDLH[1]: 1200
Maximum 5-minute CO exposure	State STEL[2]: 200
Maximum 8-hour CO exposure	OSHA PEL[3]: 50
	State PEL: 35
	ACGIH TLV®[4]: 25

1. National Institute for Occupational Safety & Health (NIOSH) 1-minute average level immediately dangerous to life and health (IDLH).
2. Washington State 5-minute average short-term exposure limit (STEL).
3. U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) 8-hour average permissible exposure limit (PEL).
4. American Conference of Governmental Industrial Hygienists (ACGIH) 8-hour average Threshold Limit Value® (TLV®).

Special Considerations for OELs

OELs are established for traditional work schedules and environments, therefore they may not provide the expected level of safety for workers in nontraditional jobs. As mentioned previously, they are based on an 8-hour work day/40-hour work week and sedentary work. Finally, these OELs do not account for exposure to multiple toxins simultaneously. The exposure duration and irritant uptake assumptions used to develop OEL criteria may not be appropriate for wildland firefighters; therefore, in order to accurately assess wildland firefighter exposure, these differences must be accounted for. Wildland firefighters work extended shifts with variable exposures, extremely strenuous work, and exposure to multiple toxins during these exposures. Adjustments must be made to the occupational exposure criteria to account for work schedules, exertion, and concurrent exposures that create a synergistic or additive health risk. These adjustments are required to maintain the peak dose below the level that workers would experience in a "standard" workplace.

There are several ways to account for the differences and assure acceptable safety standards are met.

One method used by OSHA is an adjusted exposure limit, which takes into account work shifts longer than 8 hours. For carbon monoxide, the adjusted CO exposure limit is calculated with this equation:

$$\text{CO Exposure Limit} = \text{PEL} \times \frac{8}{\text{Duration}} \qquad \text{Equation 1}$$

Duration is the actual shift time.

An alternate method is to use the highest 8-hour exposure with the existing standard while also including the exposure for the remainder of the work shift.

Additive effects of irritants occur when contaminants have the same target organ or the same mechanism of action, so the total effect on the body equals the sum of effects from each substance (Reisen, 2009). When workers are exposed to multiple irritants, the combined effect of these irritants must be considered. ACGIH and OSHA recommend using a combined equivalent irritation exposure index (E_m). This can be calculated as:

$$E_m = \frac{\text{conc. [C3H4O]}}{\text{limit [C3H4O]}} + \frac{\text{conc. [HCHO]}}{\text{limit [HCHO]}} + \frac{\text{conc. [PM3.5] (1)}}{\text{limit [PM3.5]}} \qquad \text{Equation 2}$$

E_m = the equivalent exposure irritant index (unitless);
conc. = the measured concentration of the irritant;
limit = the selected exposure limit of the irritant; i.e., the PEL or TLV;
[C3H4O] = acrolein (parts per million [ppm]);
[HCHO] = formaldehyde (ppm); and
[PM3.5] = respirable particulate (mg/m3).

Reinhardt et al. (2000) used acrolein, formaldehyde, and PM3.5 in the preceding example because they all cause irritation of the same organs and are the most likely to be present in and cause irritation from wildland smoke. The equivalent exposure (E_m) must be below 1 for the workplace to be considered in compliance or safe.

Coburn-Forster-Kane Equation (CFK)

The Coburn-Forster-Kane equation can be used to predict carboxyhemoglobin (COHb) levels in the blood resulting from CO exposure. NIOSH used the Coburn-Forster-Kane equation to develop the REL for CO of 35 ppm, as an 8-hour TWA. The equation takes into account numerous variables such as duration of exposure, work activity level (breathing rate), diffusion rates in the lungs, blood volume, and barometric pressure (altitude).

NIOSH set the REL based on an 8-hour work shift, sedentary work activity, dry barometric pressure in the lungs, and the partial pressure of oxygen in the capillaries. The last two variables are affected by altitude, and NIOSH used sea-level for their standard. Although several of the variables in the equation are constants due to physiological processes, some of them can be changed to better describe the work environment for wildland firefighters. These are length of shift, level of work activity, and altitude. When exposure occurs at elevations above 5000-ft., NIOSH recommends lowering the REL to compensate for the loss in the oxygen-carrying capacity of the blood. Two other variables are also used to compensate for different work conditions: DL, which is the CO diffusion rate through the lungs and VA, which is the ventilation rate.

Both DL and VA have values for sedentary, light, and heavy work activity levels. When calculating a safe REL for wildland firefighters, NIOSH recommends using the heavy work level in the CFK equation for DL and VA to ensure an exposure level that would result in a COHb level of 5%. COHb levels of 5% or less pose no significant harmful effects.

When managing exposure there are several methods available to employers and employees. NIOSH recommends the traditional hierarchy of controls approach to eliminate or minimize workplace hazards. In order of preference, they are:

1. Substitution or elimination of the hazard.

2. Engineering controls such as exhaust ventilation or process enclosure.
3. Administrative controls such as limiting exposure duration, training, work practice changes, and medical surveillance
4. Personal protective equipment (McCleery et al., 2011).

III. WILDLAND FIRE SMOKE

Components of Wildland Fire Smoke

Where there is smoke, there is fire – or in our case, where there is fire, there is smoke. It is common knowledge, of course, that fires produce smoke although the components within smoke are complex and often misunderstood. Smoke is the most obvious product of wildland fires and results from the incomplete combustion of forest fuels, i.e., carbon-based compounds, both organic and inorganic. As the smoke interacts with the atmosphere, intermediate chemicals are also formed (USDA FS, 1989).

As a wildland fire progresses through its burning phases, different compounds/chemicals are released (Reisen et al., 2009). In the initial stage, as the fuel heats up, liquid in the vegetation volatilizes and several volatile organic compounds (VOCs) are released. As decomposition of the fuel occurs, volatile gases are released such as carbon monoxide (CO), carbon dioxide (CO_2), and oxygenated-VOCs (OVOCs). OVOCs include methanol, acetic acid, acetone, and furan. Smoldering, or glowing combustion, is the next phase which leads to flaming combustion. The flaming phase releases gas-phase emissions, primarily oxidized compounds such as CO_2, nitrous oxides (NO_x), sulfur dioxide (SO_2), hydrogen chloride (HC_l), and aerosols.   Burling et al. (2010) identified the following compounds associated with flaming combustion: CO_2, NO, NO_2, HC_l (hydrogen chloride), SO_2 (sulfur dioxide), and HONO (nitrous acid). The fire then reverts to the smoldering phase/incomplete combustion which releases CO, methane (CH_4), ammonia (NH_3), and sulfur dioxide ($S0_2$). In addition to these, Burling et al. (2010) also found propene (C_3H_6), and furan (C_4H_4O) in the smoldering phase. As a wildland fire moves across the landscape, all these phases may occur simultaneously. However, some fuels such as grasses and other fine fuels will be dominated by the flaming phase (Barboni et al., 2010; Burling et al., 2010; Bytnerowicz et al., 2009). Barboni et al. identified 79 compounds in smoke produced from prescribed fires on the island of Corsica (France). These fires were in typical Mediterranean vegetation which is similar to that found in many areas of southern California. These compounds include volatile organic compounds, aldehydes, and polycyclic aromatic hydrocarbons.

There are several irritants and toxins in wildland smoke that are of particular concern to wildland firefighters due to their potential health consequences. Polynuclear aromatic hydrocarbons (PAH) are contained within the fine particulate matter. PAHs include many organic compounds which consist of two or more fused aromatic rings. They are a byproduct of the combustion of organic matter such as wood (USDOI, 1992). These PAH particles attach to the particulate matter created from the combustion of fuel (Ward, 1998). Aldehydes, most notably formaldehyde, are also produced from the incomplete combustion of burning biomass (Ward, 1998). Reinhardt and Ottmar (2004) also identified several compounds of particular concern in wildland fire smoke including CO, benzene, acrolein, formaldehyde and, of course, particulate matter.

Other chemicals released from the burning of forest and grassland fuels include ammonia (NH_3), nitric oxide (NO), nitrogen dioxide (NO_2), and semi-volatile and volatile organics including naphthalene and toluene.

The visible portion of smoke is composed of particulate matter (PM). There are two primary classes of particulates: fine particles with a mean aerodynamic diameter of less than 0.3 micrometers and coarse particulates which have a mean aerodynamic diameter greater than 10 micrometers.

As products of combustion react in the atmosphere, intermediate chemicals are formed. The majority of these intermediate chemicals are free radicals (USDA FS, 1989). Nitrous oxide gas (HONO) also present in the smoke becomes a source of hydroxyl (OH) radicals (Burling et al., 2010). Free radicals are also produced during the combustion of biomass. Although many of the free radicals may dissipate quickly after leaving the flaming zone, some may persist for up to 20 minutes. Free radicals absorbed by the body can cause harmful reactions, sulfur dioxide (SO_2) forms sulfuric acid in the presence of water vapor.

Not all phases of combustion are equal in their production of chemical compounds. An emission factor (EF) is the mass of pollutant produced per mass of fuel consumed. Smoldering combustion can produce several times the amount of mass of pollutants compared to a fire in which the majority of the fuel is consumed in the flaming phase (Bytnerowicz et al., 2009). The smoldering phase of combustion produces higher levels since this phase is a lower temperature and there is incomplete combustion of the fuel. Smoldering combustion produces more CO, NH_3, and particulates than flaming phase (Bytnerowicz et al., 2009; Ward, 1998). Smoldering fires also produce more methyl chloride, methyl bromide, methyl iodide, and VOCs (Ward, 1998).

Fuel types can influence the primary type of combustion, i.e., peat, rotten logs, and deep duff will tend to smolder whereas dry, light fuels will tend to be consumed in the flaming stage and, therefore, less particulates and CO will be released.

In 2009 Reinhardt constructed a list of the known chemicals in wildland fire smoke for the Smoke Exposure Task Group (see Table 2).

Although not a result of the burning of biomass, crystalline silica (SiO_2) poses a health concern to wildland firefighters. SiO_2 is a basic component of soil, and quartz is the most common form (OSHA, 2002). There are several forms of crystalline silica but the most common are quartz, cristobalite, and tridymite. Exposure to SiO_2 occurs when it is present in the soil and firefighter activity makes it airborne when traveling on dusty roads, hiking on trails or through burned areas, and especially during mop-up. Sometimes crystalline silica is referred to as quartz because it is the most common form of SiO_2 (USDOI, 1992).

Why Does it Matter?

"Distraction is a very very real problem for firefighters. Fatigue and carbon monoxide do not help with the decision making process either." Paul Gleason

Paul Gleason is well known in the wildland firefighting community. He dedicated his career to wildland firefighting and placing the safety of his crew and all firefighters above all else. He may be remembered best for bringing the term LCES into wildland fire management: Lookouts, Communication, Escape Routes, and Safety Zones. The preceding quote by Paul is at the heart of this report. Now that we have seen what is contained within wildland smoke, this section will discuss the known and suspected health outcomes associated with wildland smoke inhalation. Although Gleason correctly identifies CO as a hazard to wildland firefighters, we have seen that there are many other irritants and toxins contained within this smoke.

Table 2. Known chemicals in vegetative smoke (Reinhardt, 2009)

Chemical Class	**Chemical**	**Chemical Class**	**Chemical**
Particulate Matter	Total PM	**VOCs**	
	PM4	Aldehydes	Formaldehyde
	Crystalline silica		Acrolein
			Furfural
Semivolatiles			Acetaldehyde
PAHs	acenaphthene		
	acridine	Aromatics	Benzene
	anthracene		Naphthalene
	benz(a)anthracene		
	benzo(a)pyrene	**Gases**	Carbon monoxide
	benzo(b)fluoranthene		Carbon dioxide
	benzo(ghi)perylene		Sulfur dioxide
	benzo(k)fluoranthene		Nitrogen dioxide
	Chrysene		Nitric oxide
	Dibenz(a,h)anthracene		Ammonia
	Fluoranthene		Hydrogen cyanide
	Indeno(1,2,3-cd)pyrene		
	Phenanthrene		
	Pyrene		
	Retene		
Methoxylated Phenols	Levoglucosan		
Carboxylic acids	Formic acid		

Carbon Monoxide and Other Gases

Carbon monoxide is harmful to humans because it reduces the amount of oxygen available to the body. As CO is inhaled, it displaces O_2 in the red blood cells as it combines with the red blood cells and forms carboxyhemoglobin (COHb). COHb reduces the ability of the blood to carry oxygen and causes hypoxia. In an effort to compensate for this deficiency, the body increases the heart rate and blood flow to certain areas of the body, especially the heart and brain. COHb has a half-life of about 5 hours, and the CO will leave the body through exhalation when the person is breathing clean air (OSHA, 2002).

Symptoms of CO poisoning include headaches, dizziness, nausea, and drowsiness. Prolonged, high exposure can cause confusion and loss of consciousness. These symptoms can be more acute for people with heart or lung disease, smokers, and at high altitude. Coma and/or death may occur if high exposure continues (OSHA, 2002).

Sulfur dioxide causes severe irritation of the eyes, skin, upper respiratory track, and mucous membranes, and it can also cause bronchoconstriction. SO_2 forms sulfuric acid in the presence of water vapor. SO_2 has been shown to damage the airways of humans, and long-term exposure reduces lung volume and its ability for gaseous diffusion (Bytnerowicz, 2009).

Particulate Matter

Particulate matter is described by its mean aerodynamic diameter because the size of the particle determines how far it travels through the air as well as how far it will travel through the human respiratory system. The smaller the size, the deeper it will penetrate causing exposure and depositing both the particle and any compounds adhering to the particle in the respiratory tract (Bytnerowicz, 2009).

The particles can be inhaled into and throughout the respiratory tract. Gases and liquids present in the smoke adhere to the particles and thus can enter the airway, lungs, and bloodstream. The fine particles are a major concern as they can be inhaled into the deeper recesses of the lungs, the alveolar region. These particles carry absorbed and condensed toxicants into the lungs (USDA, 1989).

Respirable particulate matter (RPM) are particulates with a mean aerodynamic diameter of 10 micrometers or less. Particulate inhalation can cause inflammation of the lungs, and short-term effects include cough, shortness of breath, and chest pain.

Aldehydes (VOCs)

Aldehyde compounds can cause immediate irritation of the eyes, nose, and throat, and inhalation can cause inflammation of the lungs. Short-term effects include cough, shortness of breath, and chest pain (Reinhardt, 1991; USDA, 1989). Some aldehydes may be carcinogens. The most abundant aldehyde in smoke is formaldehyde. When formaldehyde enters the body, it is converted to formic acid, which is also toxic. Another aldehyde present in smoke is acrolein, which is produced during the incomplete combustion of forest fuels. Acrolein is a cause of irritation and may increase the possibility of respiratory infections (Reinhardt 1991; USDA, 1989). Long-term effects can include chronic respiratory irritation and permanent loss of lung function if exposure occurs over many years (USDA, 1989).

PAHs

Vegetative smoke contains numerous chemicals known to be human carcinogens including polycyclic aromatic hydrocarbons and benzene. Benzene, when inhaled, can cause headaches, dizziness, nausea, confusion, and respiratory tract irritation. Although the human body can often recover and repair damage caused by irritants, prolonged exposure from extended work shifts and poorly ventilated fire camps can overwhelm the ability to repair damage to genes and DNA (USDA, 1989).

Gaseous compounds such as VOCs and PAHs that are attached to the particulate matter will penetrate the respiratory system and deposit both the particle and any compounds adhering to the particle in the respiratory tract (Bytnerowicz, 2009).

Crystalline Silica

Prolonged and excessive exposure to crystalline silica in mining dust can cause silicosis, which is a noncancerous lung disease that affects lung function. It is an extremely common mineral found in many areas of the world, and it is the second most common element in the earth’s crust. Crystalline silica is classified as a human carcinogen (OSHA, 2002). Crystalline silica present in the dirt/dust can be hazardous even if smoke is not in the air.

Intermediate Chemicals

As the smoke interacts with the atmosphere, intermediate chemicals are formed, the majority of which are usually in the form of carbon, hydrogen, and oxygen free radicals (Leonard et al., 2007).

The formation of free radicals as an intermediate reaction has been found in wildland smoke studies (Leonard, 2007; Leonard et al., 2000). These free radicals have been shown to cause a variety of health problems including bronchopulmonary carcinogenesis, fibrogenesis, pulmonary injury, respiratory distress, chronic obstructive pulmonary disease (COPD), and inflammation (Leonard, 2007). The authors' conclude that the chemicals generated by secondary reactions can cause increased H_2O_2 (hydrogen peroxide), OH (hydroxyl radical), and lipid peroxidation. The most reactive particles were in the ultrafine class which can enter the deepest recesses of the lungs. They further state that this can cause "acute lung injury." Leonard et al. (2000**)** also conclude that wood smoke causes DNA damage and lipid peroxidation resulting from the OH radical. This occurs in the presence of H_2O_2, which is formed as part of the respiratory burst in the lungs. The white blood cells response to a harmful organism in the airways; a respiratory burst, also called oxidative stress is designed to destroy the invading organism. During this process the organism undergoes oxidation and is destroyed. However the respiratory bust is indiscriminate and may cause damage to neighboring cells. Oxidative stress has been shown to contribute to a number of diseases, particularly cardiac diseases, as these neighboring cells are oxidized.

IV. REVIEW OF THE LITERATURE

This section reviews many of the studies that have been undertaken to assess exposure to wildland firefighters. Before undertaking any research on fires, researchers must first make arrangements with agency officials and fire management staff to assure appropriate access will be granted. Conducting research in the fire environment presents numerous challenges; foremost among these are the dangers inherent in the wildland fire setting. Environmental conditions also present challenges to both the researchers and the equipment necessary to measure exposure: extreme temperatures, and extremes in relative humidity, dust, ash, and wind. Other challenges are also present: observing the fire at the right time, rapidly changing fire conditions, and often long travel times. Once researchers arrive at the fire, they must be prepared to work long days and be willing to hike or drive long distances.

Materna et al. (1992) measured CO, particulates, PAHs, crystalline silica, aldehydes, and benzene during ten shifts on wildfires and prescribed fires in California from 1986 to 1989. Crews were conducting mop-up operations on 8 of these days, and there was no direct fireline construction.

They found that exposure to respirable particulates was significantly higher on days with smoldering fire than with flaming fire. Of the 46 personal breathing zone samples for CO, one exceeded the NIOSH REL of 35 ppm. Three of the 22 samples (14%) for total particulate exceeded the OSHA PEL.

Due to the small sample size, the authors state that further exposure monitoring is needed, and their study is not representative of the "full range of exposures fire fighters may encounter." Materna et al. (1992) go on to say,

> *"In part, because of the rigors of performing industrial hygiene measurements under fire fighting conditions, data are limited and could not be considered representative of the full range of exposure fire fighters may encounter; workers are not easy to follow and observe so must find other means to document work activities."*

Recommendations:

- Additional monitoring should also include crystalline silica
- Identify job tasks and fire conditions that contribute to higher exposures
- "Medical surveillance of wildland fire fighters and further epidemiologic research will be needed to correlate the extent of hazardous exposures in wildland fire fighters with potential adverse health effects."

- Reduce exposure by limiting shift length, and rotate crews out of heavy smoke areas
- Train firefighters in potential health effects from smoke exposure.

Materna et al. (1992) identify several reasons to develop PELs specifically for wildland firefighters: high altitudes, high temperatures, heavy physical work, and extended shifts may intensify the effects of irritants, particularly CO. These factors may mean OSHA PELs are not adequate to protect wildland firefighters.

They recognize that the other contaminants contained in the particulates are an issue. “Synergism between different chemicals, even if they are present at what is typically considered safe levels individually, may result in an overall adverse health impact” (Materna et al., 1992).

Rothman et al. (1993) undertook a study of California Department of Forestry firefighters from fire stations along the foothills of the Sierra Nevada Mountains in northern California. This study was designed to test whether exposure to PAHs contributed to the formation of white blood cell PAH-DNA adducts. If PAHs bind to DNA, they may form DNA adducts which may be an early step in causing cancer. A DNA adduct is a piece of DNA covalently bonded to a (cancer-causing) chemical. This process could be the start of a cancerous cell. Initial measurements were made early in the fire season, and secondary measures were made two months later. Laboratory analysis was done to test this hypothesis, and Rothman et al. found no difference in the PAH-DNA adduct level among any of the 47 firefighters studied. The authors state that their findings are unclear, and mortality and morbidity studies are necessary in order to determine if there are cancer concerns for wildland firefighters.

Leonard et al. (2000) conducted a study to determine if free radicals generated by wood smoke could cause cellular damage. In the presence of H_2O_2, which is formed as part of the respiratory burst, they found that wood smoke was responsible for causing DNA damage. The primary cause of this damage was attributed to the OH radical generated from materials in the wildfire smoke.

Leonard et al. (2007) undertook a study using data gathered on the 2004 Boundary Fire in Alaska. Air samples were taken for five days near the fire line, with an average sampling time of 3.5 hours. Particulates were divided into three size classes: fine (0.42-2.4 µm), ultrafine (0.042-0.24 µm), and coarse (4.2-24 µm). Coarse particles typically become deposited in the nasal area, although some can enter the airways, fine particles are deposited in the upper airways but most enter the alveolar region of the lungs, and ultrafine particles enter the deeper pulmonary zones and alveoli.

By utilizing several testing methods, Leonard et al. (2007) found that the free radicals generated by secondary reactions can cause increased H_2O_2 (hydrogen peroxide), OH (hydroxyl radical), and lipid peroxidation. The most reactive particles were in the ultrafine class. They further state that this can cause “acute lung injury.”

Reisen and Brown (2009) measured exposure on 40 firefighters on 10 prescribed fires and 2 experimental fires in Australia between April and June 2005 and 2006. Measures of CO, respirable particulates (PM 3.5), aldehydes, and VOCs were made. Study subjects exceeded 1 for equivalent irritation exposure index (equation 2) for acrolein, formaldehyde, and PM 3.5 in 28% of the samples. The major VOCs in the bushfire smoke included benzene, toluene, xylenes, acetic acid, phenol, alkanes, alkane derivatives, and benzene derivatives. This study shows a good correlation between CO and respirable particulates (r2 = 0.86). Highest CO exposures occurred when firefighters were holding the burn or suppressing spot fires. Lowest exposures were for lighters. Reisen et al. state, “However, levels of pollutant exposures and whether these could cause health problems are yet to be determined.” Factors that affect how exposure can cause health problems include the concentration level within the breathing zone, duration of exposure, and exertion level.

Barboni et al. (2010) conducted a study to identify the components in wildland fire smoke. Personal breathing zone measurements were made on five separate sites. They identified 79 compounds in smoke produced from prescribed fires on the island of Corsica (France). These fires were in typical Mediterranean vegetation which is similar to that found in many areas of southern California. These compounds included volatile organic compounds, aldehydes, and polycyclic aromatic hydrocarbons.

None of the samples exceeded established OELs. Barboni et al. point out that factors such as wind speed and direction, temperature, fuel moisture, and fire intensity can influence the concentration levels of smoke.

NIOSH Health Hazard Evaluations

Since 1988 the National Institute for Occupational Safety and Health (NIOSH) has performed several Health Hazard Evaluations (HHE) on wildland firefighters. The Hazard Evaluations and Technical Assistance Branch of NIOSH conduct field investigations of possible health hazards in the workplace at the request of an employer or an authorized representative of employees. Findings and conclusions in HHEs are those of the authors and do not necessarily represent the views of NIOSH (McCleery et al., 2011).

This section will review seven HHEs done between 1988 and 2008. One report was requested by the Colorado Department of Public Health and Environment (CDPHE), five were requested by the National Park Service, and one was requested by the USFS. Six HHEs were personal breathing zone studies, and one was a medical survey.

The first NIOSH HHE (Reh et al., 1992) was done in 1988 at the request of the NPS due to concerns with firefighter exposure during the Yellowstone NP fires. The study was conducted on four different days in August, and personal breathing zone monitoring was done for CO, CO_2, SO_2, and nitrogen dioxide (NO_2). Area air sampling was done for these chemicals and for PAHs, VOCs, Total Particulate Matter (TPM), and aldehydes.

There were a total of 10 breathing zone samples that were usable in this study of 22 firefighters. Exposure levels for CO, CO_2, SO2, and NO_2 were all below the respective OSHA, NIOSH, and ACGIH exposure limits and were at levels that would not be expected to pose a hazard to the health of the workers. COHb levels showed no significant change across the shift and none were above the levels that would cause negative health effects. Two of the nine TPM samples were above the OSHA PEL.

The authors state that, due to the small sample size, these results cannot be used to make broad generalizations about firefighter exposure. They also state that post-shift COHb measurements should be taken soon after the exposure occurs. In this study, these measurements were made from 1-2 hours after the last exposure occurred.

Recommendations:

- Reduce work shift hours
- Reduce the number of consecutive days on a fire
- Provide clean air base camps
- Provide time for fighters to be in a no-exposure area to allow COHb to dissociate
- Undertake additional exposure assessments including other fire suppression activities
- Adjust the NIOSH REL for CO to account for work activity, length of work shift, and altitude.

As stated previously, the NIOSH REL of 35 ppm is designed to protect workers from health effects associated with COHb levels in excess of 5%. These authors used the Coburn-Forster-Kane (CFK) equation to calculate the maximum 8-hour exposure level that would result in a 5% COHb level. Using these values, they calculated that a 5% COHb would be reached with a CO exposure of 23 ppm at 5,000 ft. and 17 ppm at 10,000 ft.

The 1990 HHE conducted by Letts et al. (1991) was requested by the NPS. It was a medical survey of Interagency Hotshot (IHC) crewmembers designed to determine if there were cross-season changes in lung function and respiratory symptoms. Surveys and spirometry testing were conducted in June of 1990 to obtain a baseline, and follow-up surveys and testing were done in September 1990. Initial testing was done on 105 firefighters from 6 crews, and final testing was done on 78 crewmembers.

No direct smoke exposures were measured, but rather each crew supervisor completed a questionnaire for each fire rating the smoke on a scale of 1-5. Hours of exposure were determined by crew logs. Although the authors found small reductions in the measured values for lung function, "the NIOSH investigators conclude that there is limited evidence suggesting that forest fire fighting results in cross-season changes in lung function."

Recommendation:

- Agencies responsible for wildland fires should undertake respiratory surveillance programs to examine the long-term effects of forest firefighting on lung function.

The authors point out several limitations of their study, including:

- The study could not show chronic effects as it only covered one season
- They did not have a baseline from the subjects before they began their firefighting career
- Actual exposure may not be well correlated with the estimated exposure do to self-reporting methods.

This HHE (Kelly, 1992) was requested by the NPS to determine health effects from exposure to firefighters on the Thompson Creek Fire on the Gallatin NF in Montana. The study took place from July 20-22, 1991, and exposure measurements were taken on 20 crewmembers each day. Personal breathing zone samples were collected for CO, SO_2, aldehydes, respirable particulate matter (RPM), and crystalline silica.

Although the authors tried to target crews that would receive the highest CO exposure, measurements were all well below the OSHA PEL and NIOSH REL. TWA measurements for SO_2 were a concern for the researchers as three samples exceeded the OSHA PEL. Aldehydes levels were all well below OSHA and ACGIH criteria.

One sample showed a relatively high level of RPM, and this sample was also the highest measured crystalline silica. Since NIOSH personnel were not observing the firefighters, they could not account for this anomaly, especially since the other samples were either trace levels or non-detectable levels of silica.

The authors recommend that agencies responsible for fire suppression undertake routine exposure monitoring. Based on the data from this HHE, the authors calculated a CO REL of 21 ppm adjusted for 7,000 ft. elevation.

The HHE done by Reh et al. (1994) was requested by the NPS to evaluate firefighter exposure at the Arch Rock Fire in Yosemite NP. Sampling was carried out on August 15-16, 1990. Measurements of CO, SO_2, NO_2, RPM, VOCs, and PAHs were taken by personal breathing zone measurements on 21 firefighters. Total sample size was 20 firefighters over the two days with 12 hour shifts including travel. However, smaller sample sizes were used for several of the irritants: 9 for RPM and benzene, and 10 for VOCs and aldehydes.

Only one of the 40 SO_2 samples exceeded the NIOSH REL of 2 ppm. CO exposures were well below OSHA PELs and NIOSH RELs. Concentrations of aldehydes were below measurable quantities, and no SiO_2 or VOCs were detected. The remaining irritants measured were either well below all established limits or were non-detects. As in the previous study, one sample showed high SO_2, but this inconsistency with the remaining samples could not be accounted for.

Using the CFK equation, the authors calculated an exposure of 21 ppm for CO to maintain a 5% COHb level or lower.

Recommendations:

- Monitor firefighters for an entire season to determine short-term and long-term exposures
- Conduct routine exposure monitoring by agencies responsible for suppression
- Measure exposures at prescribed fires.

Kelly's (1992) HHE was requested by the NPS to evaluate exposure on the Gauley Mountain Fire on the New River Gorge National River in West Virginia. Data were collected November 3-4, 1991, and NIOSH measured CO, SO_2, aldehydes, VOCs, RPM, crystalline silica, and PAHs via personal breathing zone sampling. CO was well below NIOSH REL of 35 ppm.

No VOCs, PAHs, or SiO2 were detected, and concentrations of aldehydes were below the minimum quantifiable concentrations. Of the 40 SO_2 exposures, 23 were either at or above the NIOSH REL of 2 ppm.

NIOSH calculated an adjusted REL of 30 ppm for CO based on their CO measurements. They used the heavy work activity level for D_L and V_A and the corresponding barometric pressure values for 1000 ft. elevation.

Recommendations:

- Conduct routine exposure monitoring by the agency
- Monitor individual firefighters for the entire season to determine seasonal exposure.

The HHE done by McCammon et al. (2000) was requested by the Colorado Department of Public Health and Environment (CDPHE) in 1998. The purpose of the this HHE was to field-test the implementation of a wildland firefighter smoke exposure management and monitoring program which had been recommended to NWCG (Sharkey et al., 1997).The secondary goal was to collect smoke exposure data beyond the Pacific Northwest.

NIOSH provided smoke monitoring equipment for IHCs with the expectation that the crews would monitor their own exposures. Two firefighters from each crew received training on the use of the dosimeters, calibration, and data transfer. They were asked to record notes to correlate the data with the fire behavior, weather, crew activities, and etcetera. Although the authors claimed this is an efficient exposure data collection method, numerous issues arose that make the results inconclusive. Among the many issues that make the data suspect was inadequate note-taking by the firefighters. Of the four crews involved, exposure data collected by each crew was 0, 35,152, and 176 hours. The crew with 35 hours had no field notes; the crew with 176 hours had no data from four fires, while the crew with 152 hours had "sketchy" data from three days of firefighting. Minimal notes "made it difficult to establish that the monitors were always used when exposure was expected." In my experience, this would be expected as firefighters actively engaged in suppression must be focused on the mission to ensure their safety.

Quality assurance and quality control of the data were also problematic; issues arose when dates and times on the dosimeters did not match the field notes. Data were also lost when new files were downloaded and erased existing files on the computer. Important limitations to quality control and accountability also arose when the authors could not confirm that the dosimeters were calibrated or bump tested.

The HHE by McCleery et al. (2011) was requested by the USFS to measure exposure of incident base camp personnel on fires on the Klamath NF in northern California. Data were collected on August 13-14, 2008. Personal breathing zone samples of CO were collected on 19 individuals, and COHb was also measured. Area air samples in the camp were also taken. Total sample time was 30 hours.

Average work shift exposures were below OSHA PELs and other criteria as were area air samples (<6 ppm). Peak CO levels exceeded the NIOSH ceiling limit of 200 ppm for five of the 19, and four of the 19 exceeded 1000 ppm, short duration of less than one minute. However, these four measurements were suspect, and the authors suggest they could have been caused by radio frequency interference.

All COHb measurements were below 5%. Area air samples of CO were less than 3 ppm average.

Recommendations:

- Administrative controls
- Enforcement and monitoring of workplace
- Develop a base camp air monitoring program
- Develop CO and PM action levels to reduce exposure
- Limit extended shifts and frequency/duration of extended shifts.

Summary of NIOSH
Of the 6 HHEs that involved personal breathing zone measurements, a total of 11 shifts were covered for firefighters on the line and 1.5 shifts in a base camp. Approximate total personal breathing zone samples were 248. Several of the HHEs reported missing data and inconsistencies that could not be accounted for. Since the NIOSH investigators did not observe the firefighters but rather set the equipment up and then the crews left for the fireline, correlating exposures to conditions and accounting for anomalies was not possible.

Recommendations from the HHEs are consistent with the need for these agencies to undertake additional exposure assessments, expand exposure studies to increase sample size and geographic reach, examine long-term effects through studies, and adjust the CO PEL according to the CFK.

Respiratory Lung Function Studies

Several studies looked at lung function as an indicator of health effects from smoke inhalation. When individuals inhale particulates and other irritants, there is a marked physiological response in the upper and lower airways. These researchers used spirometry tests which are designed to measure how well the lungs and air passages move air in and out of the body. The measured values from spirometry are compared to expected values based on the individual's age, height, sex, and race. Lung function tests provide three different measures: 1) Forced vital capacity (FVC) which is the total amount of air an individual can force out of his/her lungs, 2) One-second forced expiratory volume (FEV_1) which is the amount of air an individual expels in the first second; this assesses the larger airways, and 3) Mean forced expiratory flow during the middle half of the FVC (FEF_{25-75}); this is the average air flow in the middle of the exhalation and can be used to indicate changes in the smaller, peripheral airways (Letts, 1991). Below average spirometry values indicate lung function is impaired.

Swiston et al. (2008) tested 52 firefighters from the British Columbia Forest Service from May through August in 2004 and 2005. Baseline measurements were taken pre-season. The authors used several biological markers to test whether firefighters exposed to smoke during fire suppression activity showed signs of respiratory inflammation. Based on the results of this study, firefighters exposed to smoke exhibited a "measurable inflammatory response in the lung(s)." The symptoms were associated with the upper and lower respiratory tracts. Inflammation of the lungs was measured by sputum samples taken before and after exposure, and lung function was measured pre- and post-firefighting by spirometry.

Rothman et al. (1991) measured the cross-seasonal changes in lung function on wildland firefighters in Northern California (*n*=52) by measuring forced expiratory volume in 1-second (FEV_1) and forced vital capacity (FVC) using spirometry. They found there was a small cross-seasonal change in pulmonary function. Actual study time was 8 weeks with most of the firefighting occurring during the last week of the study. The greatest changes were exhibited by firefighters with the most self-reported hours of firefighting in the last week. Firefighters with exposure to smoke early in the study, but not at the latter end, showed smaller changes in FEV_1 and FVC, which could indicate that the decline in pulmonary function is reversible.

Gaughan et al. (2008) looked for respiratory effects on 2 IHCs (*n*=58) using spirometry pre-season, post-fire, and post-season, and measuring inflammation in sputum. Their results showed a decrease in FEV_1 post-fire but indicated recovery by post-season. Results showed exposure was associated with upper and lower respiratory symptoms. Lower respiratory scores returned to pre-season levels at the post-season testing. However, upper respiratory improvement was minimal from pre-season to post-season. The study found that firefighters recovered from the short-term effects of exposure but speculate that wildland firefighters may be at increased risk of chronic lung and upper airway disease from career exposures.

Gaughan et al. (2008) state that research done on municipal firefighters which indicate negative consequences from exposure cannot be used for wildland firefighters because of differences in smoke composition, personal protective equipment, and longer duration exposures.

Reinhardt (1991) measured exposure to CO and aldehydes on four prescribed burns on the Wenatchee NF in central Washington in October 1988. All the samples (*n*=20) taken concurrently of CO and formaldehyde (HCHO) exhibited a good linear correlation between these two chemicals. Acrolein was also detected in the samples and is a concern because it is a very strong irritant. Firefighters complaining of irritation exhibited symptoms that were similar to those caused by acrolein. Although none of the measured exposures exceeded any established OELs, the highest exposures measured were during direct attack and mop-up of spot fires.

Reinhardt and Ottmar (19970 published a review of smoke exposure literature in 1997. At that time they stated "Smoke exposure data are limited in geographic scope and representativeness and focus mostly on large Western US wildfires or prescribed fires in the Pacific Northwest."

They identified numerous findings and data gaps.

Findings:

- Lack of high quality representative smoke exposure data
  - Data-collection efforts have been ill-prepared for the mobility and responsiveness needed to capture smoke exposure during initial attack
  - Most studies have obtained many duplicative measurements of smoke exposure during the latter stages of fire suppression when smoke exposure is considered low
  - "..capturing brief, high-intensity smoke exposures has proven to be a very elusive task for researcher."
  - Smoke exposures at wildfires have been biased due to the inability to quickly sample early in the course of a fire
  - Difficult to quantify exposure due to so many variables present
  - Some previous studies were hampered by lack of industrial hygiene expertise in agencies

- Major areas of concern:
  - Primary hazards are respiratory irritants and CO
  - Benzene for firefighters using pumps, engines, saws (gasoline exhaust)
  - Direct attack and holding were highest exposures
  - Highest exposures during smoldering combustion phase
  - Extent of problem requiring control during about 5% of work shift
  - Inversion conditions cause high exposures

Recommendations:
Most of the studies reviewed identified the need for more exposure data

- Holding during burnout operations
- High-exposure situations
- Geographical regions that have not been well represented
- Career exposure
- Crystalline silica
- Dust and TPM during transportation, especially hiking across the black and on dusty trails
- Additional fuel types
- Initial attack
- ICP, both dust and smoke

Reinhardt and Ottmar (2000) produced this seminal work on wildland firefighter exposure, and the effort spanned the years 1992 through 1995. Although the work was done only in the western United States, the findings have been both significant and influential in this field. One of the most significant results of this work was the finding that on wildland fires, exposure to acrolein, benzene, formaldehyde, and respirable particulate matter could be predicted from the measurement of CO. With this finding wildland firefighter exposure to these pollutants can be determined accurately by measuring the exposure to CO, thereby reducing some of the complexity of measuring wildland firefighter exposure. However, the authors realize that predicting exposure to respiratory irritants from CO may not be relevant in all geographic areas, but is valid "at least in the western United States".

Reinhardt and Ottmar measured exposures at 13 initial attack fires in California and at eight project fires in California, Idaho, Montana, and Washington totaling 30 days of data collection. Engine crews were monitored at the initial attack fires, with handcrews the primary subjects at the project fires.
About 3% of exposure at project fires exceeded the OSHA PEL for CO when adjusted downward for the length of the shift (14 hours).

Smoke exposure on initial attack fires was typically higher than project fires, but shift averages were higher at project fires due to the long periods of no exposure while crews were at their fire stations waiting for an initial attack assignment.

Their findings indicate that peak exposure in heavy smoke, although brief, is the primary factor causing most shift-average overexposures. The authors found that about 50% of the peak exposures exceeded the ACGIH STEL for the mixture of respiratory irritants: acrolein, formaldehyde, and respirable particulate matter. They used the equivalent irritant exposure index (E_m, page 8) to account for the combined effect of irritants in wildland smoke. Limiting over-exposures can reduce liability and could increase workforce productivity and health.

Recommendations:

- Use the ACGIH TLVs to better protect firefighters
- Measure crystalline silica exposure
- Broader-based sampling to define the distribution and upper bounds of smoke exposures
- Further sampling on project fires to account for the different tasks
- Management actions should be focused on short high exposures in order to bring down shift average exposures
- Training to assure an understanding of the short- and long-term health consequences of smoke exposure and the activities/conditions that create high exposure
- Monitoring program using dosimeters and randomly-selected crews for observations
- Holding can cause peak exposure limits to be exceeded, but their limited sampling could not measure this well.

Findings:

- Pollutant correlations – found significant correlations among pollutants they measured except for total suspended particulate. Correlations with CO are especially valuable now that high quality, reliable CO dosimeters are available. This allows us to use CO as a surrogate for total exposure to wildland smoke.
- Factors influencing smoke exposure:
    - Wind speed
    - Inversions
    - Fire behavior
    - Holding when downwind or uphill of the fire and during direct attack of spot fires
- When smoke is heavy, exposures exceeded STELs
- Repeated peak exposures or when combined with extended work in moderate smoke exposure can exceed recommended exposure limits for the shift
- Peak exposures typically exceeded STELs for CO and respiratory irritants during direct attack, initial attack, burnout operations, and holding
- Using Equation 2 (page 8), CO exposure must be below 21 ppm to keep the irritant exposures at a safe limit based on the ACGIH TLVs
- Smoke is not likely to cause a benzene health concern
- Up to 5% of shift-average CO exposures and the combined exposure to respiratory irritants exceeded ACGIH TLVs
- Up to 10% of firefighters exceeded the TLVs on the fireline
- When the OSHA PEL was adjusted for the increased shift length, the calculated PEL of 29 ppm was exceeded by about 3% of firefighters at wildland fires
- Half of the peak exposure samples exceeded the TLVs based on the E_m equation

- Based on the ACGIH TLVs, about 8% of firefighters exceeded the fireline TWA and 3% exceeded the shift TWA for respiratory irritants
- Using the CFK equation would place a lower limit for a long work shift; using this, about 10% of the CO exposures exceeded this adjusted exposure limit
- The authors suspect that since their data are skewed to the lower exposure, they did not measure the highest exposure so their results may underestimate exposures
- Particulate matter exposure is a concern during mop-up
- Exposure to benzene was higher for those workers running chainsaws, pump operators, engines, and drip torches.

Reinhardt et al. (2000) continued the reporting of their exposure monitoring from 1991-1994 with this paper focused on prescribed fires in the Pacific Northwest (Washington and Oregon only). On the prescribed fires reported, CO exposures exceeded OSHA PELS about 2% of the time, and respiratory irritant exposures exceeded OSHA PELs 5% of the time. When comparing exposures to ACGIH TLVs, 8% of firefighters exceeded CO and 14% exceeded the E_m for respiratory irritants. Reinhardt et al. again used acrolein, formaldehyde, and PM3.5 because they all cause irritation of the same organs and are the most likely to be present and cause irritation from smoke.

For this study, samples were only taken when firefighters were exposed to smoke, with the goal being to collect data under the worst conditions. Times without data were estimated by the observers. Some peak exposures were not measured due to equipment issues or because of the time it took to set up new sampling equipment. There were often long periods without samples as firefighters were assumed to be out of the smoke. The authors note that because their methods did not record the entire shift, or even the entire fireline time, their TWAs estimates may have errors introduced.

Recommendations:

- Smoke exposure training
- Monitor CO at RX burns using dosimeters
- Develop a health surveillance program
- Modify RX burn practices to reduce exposure through better planning and strategic water use
- Limit burning in high winds
- Allow minor escapes to burn until safer to contain
- Management focus on CO and respiratory irritants (formaldehyde, acrolein, and PM)
- Determine smoke exposure on prescribed burns in other parts of the country
- Determine if correlations with pollutants are comparable in other parts of the country
- Determine if particulate matter at prescribed fires contain crystalline silica in amounts of concern
- Future data collection for CO should be accomplished to test if results are comparable to their findings.

Findings:

- Mop-up exposure was low to moderate although they did not measure total dust exposure
- Only average wind speed was correlated with exposure for direct attack, mop-up, and holding
- Using Equation 2, they calculated a recommended exposure limit for CO of 16.6 ppm based on a 12-hour shift
- Using the OSHA PEL, 5% exceeded the shift and 13% exceeded the fireline exposure
- Results are specific to prescribed fires in the PNW
- Lighters had lowest exposure than all others except to benzene which was from the gas in the drip torches

- Holders had highest exposure, especially when wind direction changed or the fire challenged the line
- The greatest problem on RX burns is exposure to respiratory irritants
- Using E_m, they found that 14% of firefighters exceeded the recommended exposure, and 30 % exceeded the limit on the fireline.

Reinhardt and Ottmar (2004) reported additional findings from exposure monitoring from 1991 to 1995. The key finding reiterated is the strong correlation of CO to other irritants. Except for non-fire benzene and total particulate matter, the primary irritants exhibited a high correlation to CO. Benzene exposure was from powered equipment, and total particulate is generated from firefighters mopping up or otherwise disturbing the soil and ash. Exposure samples were from 84 wildland firefighters on suppression fires (30 days, 1992-1995) and 221 firefighters on prescribed fires (39 fires, 1991-1994).

Additional recommendations:

- Suggest more data to confirm this for wildland fires. Data are limited to PNW, especially need data for the southeast where there is peat soil and deep organic soils
- ICP data since this will affect recovery from CO exposure.

Booze et al. (2004) did a screening assessment commissioned by NWCG. The purpose of this assessment was to determine if exposure to wildland fire smoke posed a significant health risk to wildland firefighting hand crews. The authors selected the chemicals in vegetative smoke they thought to be the most likely to pose a health hazard. Where data were not available (specific chemical, hazard) they used conservative assumptions to assess the risk; therefore, the risk estimates presented are likely to be higher than those actually present.

Two expected exposures were used: upper range of exposures, calculated on the assumption of the maximum possible exposure, and the mean exposures, estimated by the average exposures which represent a more likely exposure estimate.

Booze et al. (2004) used the chronic reference dose established by the EPA, which is used to estimate the daily exposure to a human population that is likely to be without a risk of adverse health effects. If the dose of a chemical equals the reference dose, then the hazard of the chemical equals 1. In order to assess increased risk by a chemical/dose, the target health goal for the chemical is 1 or less. This is used for non-carcinogens because carcinogens do not have toxicity thresholds as they pose a potential risk regardless of the exposure. Exposure to carcinogens is evaluated by assessing the level of cancer risk posed by the exposure and compared to “acceptable risks” which are established by the EPA or other agencies.

Exposure estimates used for this assessment were based on data from the NIOSH HHE done in 1988 (Reh et al., 1992) and Reinhardt and Ottmar (2000). Estimates are based on the upper 95% confidence interval of the arithmetic mean. Number of days crews spend on prescribed fires was estimated based on data from two USFS Ranger Districts on the Okanogan NF in Washington. Number of days on wildland fires was estimated from five years of data obtained from the PNW Geographic Area Coordination Center. Mobilization time and travel time were not identified, so actual days on fires may be lower. Career length was determined by expert opinion.

Booze et al. (2004) compared the estimated exposures to the toxicity concentrations of the chemical to assess whether those concentrations posed a concern for human health. These estimated risks represent the upper-bound estimate of the probability of developing cancer over a lifetime. These were assessed for individual carcinogens, and then the estimate for each individual risk was added to determine the total estimated risk from the entire group of carcinogens. If the hazard quotient exceeds 1 for non-carcinogens, adverse health effects are possible.

Benzene and formaldehyde posed the highest cancer risk, with acrolein being the most prominent chemical contributing to the overall hazard. Particulates were the second most important contributor to this risk. Because these hazard indices were based on conservative assumptions, the authors consider them the upper bounds and state the actual risks may be much lower. Furthermore, they do not indicate an adverse outcome will result, but rather "the exposure exceeds what is considered a safe level". Except for acrolein and PM 3.5, all other chemicals had a hazard index less than 1.0.

Booze et al. (2004) state that this risk assessment should be replicated using a broader set of exposure data to better represent the larger population of wildland firefighters and their respective exposures. This should also include a better estimate of the number of days on fires/year and career length.

Sharkey et al. (1997) produced this publication as a result of the Health Hazards of Smoke Conference in San Diego, CA, held in April 1997. This conference was attended by agency employees from NWCG related agencies, specialists in occupational medicine, industrial hygiene, toxicology, and risk management. The conference reviewed the progress outlined in the original NWCG study plan developed in 1989 (USDA, 1989) and reached consensus on the elements of a risk management plan to reduce exposure.

Despite the mandate in Executive Order 12196 that the head of each agency shall "Furnish to employees places and conditions of employment that are free from recognized hazards that are causing or are likely to cause death or serious physical harm," participants recognized that, although it is impossible to ensure the complete safety of wildland firefighters in the fire environment, "management has the responsibility to ensure the health and safety of wildland firefighters."

Recommendations:

- Develop Occupational Exposure Limits for wildland firefighters
- Sponsor additional research
- Training
  - Include agency administrators and fire managers
  - Include smoke hazards in all appropriate fire training at all levels
  - Fire behavior analysts include smoke in messages and briefings
  - Emphasis on effects of smoke and how to avoid it
- Include smoke on ICS -215A
- Minimize mop-up; allow areas to burn out or use water
- Fire behavior forecasts should include smoke
- Locate camps in clean air areas
- Conduct lab and field tests to verify accuracy and precision of dosimeters
  - Test for ruggedness, fire environment variables, RFI, water, dust, temperature
- Respiratory protection should be considered only when all other options have failed
- Measure exposure in different geographic areas.

In *Managing Risk Management*, David Aldrich (Sharkey et al., 1997) states a risk management plan must include all risks faced by firefighters. Since smoke is just one of the hazards faced by wildland firefighters, a comprehensive risk management program is required to assure the health and safety of employees. The plan must be simple, easy to understand, and the solution cannot be worse than the problem: firefighters still need to get the job done. It must be fire service-wide as all firefighters are affected. Aldrich makes it clear that there must be a commitment from all personnel in the affected agencies from the top through field personnel. Employees must receive proper training and equipment and be empowered with knowledge and ability to take action and accomplish objectives.

Sharkey (Sharkey et al., 1997) identifies possible long-term concerns in *Health Effects of Exposure*, stating that long-term exposure, days to weeks, can lead to weakening of the immune system. Long-term exposure can weaken the body's ability to remove particulates from the respiratory tract by reducing ciliary action. Long-term exposure may cause or worsen health problems such as coronary artery disease, chronic obstructive pulmonary disease, and cancer. He notes that retrospective studies for mortality/morbidity of wildland firefighters have not been done, and this lack of information needs to be addressed.

In their *Exposure Monitoring* paper, Reinhardt and Ottmar (Sharkey et al., 1997) identify several reasons for additional smoke exposure monitoring: liability management, assessing progress towards goals, achieving regulatory compliance, and showing commitment to employee health. Monitoring objectives should be representative of all firefighters, be accurate and precise, simple with minimal training, inexpensive, and integrated into operations without being a burden. Focus should be on monitoring of CO and respiratory irritants, and then total particulate and crystalline silica. CO is the best indicator because it is always present in smoke. Additional data should be collected from other geographical areas to augment their data. If the correlations are good, then CO can be used to calculate the total respiratory irritant level in smoke across the US. Ensure data are accurate and precise by having standard methods, trained monitoring personnel, a QA plan, and an independent review of data.

In *Respiratory Protection*, Sharkey (Sharkey et al., 1997) addresses the use of respirators for wildland firefighters. Sharkey based his findings on studies done by the USFS Missoula Technology and Development Center (MTDC). MTDC studies, both in the lab and field, found that breathing resistance increases and work output decreases in proportion to the level of protection provided by a respirator. Air-purifying respirators (APRs) decrease work performance by increasing breathing resistance and heat stress due to the additional weight of the respirator. They significantly decrease both the maximum amount of work and prolonged work performance. When adding a cartridge for organic vapors and acid gas, the performance is decreased more. Adding protection for CO would add an even greater physiological cost through higher temperatures in the inhaled breath and increased breathing rate.

ICP Monitoring

McNamara et al. (2012) measured particulate matter in three incident base camps in 2009. In each camp particulate matter measurements were higher during the evening/nighttime hours. In addition to smoke from the wildland fire, sources of particulate matter in camps include dust from roads, vehicle emissions, and generator exhaust. Many wildland fire ICPs rely on diesel generators for power.

There were a total of nine sampling days, and none of the camps had any fire-induced smoke that was noticeable by sight or smell by the researchers. All camps relied solely on diesel generators for power. The highest sampling was at the La Brea Fire ICP where the sampling equipment was near a heavily used dirt road and several generators. Only the La Brea exceeded the 24-hour NAAQS established by the EPA. The EPA standards may be more appropriate for ICPs as personnel working in these areas are more representative of the general population. The authors speculate that this was due to the larger number of personnel at that ICP which led to more vehicle emissions and dust from roads as well as more generators, all of which will increase the PM 2.5 concentrations. Although not mentioned, the La Brea ICP was located in southern California, adjacent to the US101 freeway, which could have contributed to the PM load.

The findings from the study indicate that at least moderately elevated levels of PM 2.5 exist in ICPs during the night/evening hours. This particulate matter is most likely derived from anthropogenic sources so it can be mitigated through planning and management actions. Locations of roads and generators in relation to sleeping and working areas could reduce exposure levels to incident personnel.

In a paper titled *The Effects of Forest Fire Smoke on Firefighters,* prepared for the Congressional Committee on Appropriations for Title II – Related Agencies Department of Agriculture Forest Service and NWCG (USDA 1989), the executive summary reads, "The long-term health effects are not known and the relationship between the content of smoke and health related problems has not been identified."

The authors state that one cost of firefighting has not been quantified: "the effect of smoke exposure on firefighter health and productivity." This paper is a result of the congressional committee, which called numerous specialists and firefighters together to develop a study plan to determine the short- and long-term health effects of wildland firefighting. Among the questions this plan addressed was activities associated with wildland firefighting that may result in excessively high exposures, fuel and fire conditions that create dangerous concentrations of toxic materials, whether wildland firefighters experience unusually high levels of risk that require risk management, and what effective and practical measures can be taken to protect these employees.

Although many studies have been undertaken to determine the overall risks wildland firefighters face from smoke inhalation, a review of the literature confirms there are still gaps in our understanding of exposure and its consequences. Many researchers make the same comment as Reisen et al. (2009): "whether these could cause health problems are yet to be determined." Most of these researchers agree that more definitive exposure measurements are needed to more accurately identify areas of concern, and this research must account for the full range of exposures across the full range of geographic areas where wildland fires occur. A common thread throughout many of the studies discussed makes it clear that a larger more comprehensive exposure study would be required to address wildland firefighter exposure. For example, Reh et al. (1992) echo many researchers when they state their small sample size makes it impossible to make broad-based generalizations about firefighter exposure.

Monitoring of incident base camp personnel is even more limited.

Many of the studies present recommendations for reducing exposures. However, to date there has been no effort to monitor whether or not any wildland fire agencies have implemented these recommendations. Much of the focus on wildland firefighter safety in recent years has been a reaction to wildland firefighter fatalities. After the tragic events at the 30-Mile Fire and the Cramer Fire, new direction and training was developed in an effort to prevent similar tragedies. Unlike the burn-overs that occurred on these two fires, smoke inhalation is less dramatic, and the consequences are not so obvious even though they may be severe.

The Wildland Firefighter Smoke Exposure project is an attempt to address many of the shortcomings identified in the valuable work done in previous years.

V. ECONOMICS

There is precious little literature on the economic costs for health care for wildland firefighters due to smoke inhalation. Although studies are available to determine the health costs from pollution, these do not easily cross-walk to vegetative smoke exposure. Additionally, until it is clear what the consequences (short-term and long-term) actually are, it would be impossible to predict these costs. Once the findings from this present study are validated, it may be easier to determine the increased risk wildland firefighter’s face: increased morbidity/mortality and loss of work. At that time the associated health costs can be determined.

In their extensive literature search for studies on the health-related costs of wildfire smoke exposure, Kochi et al. (2010) found only six studies that examined this. All these studies focus on public exposure and health outcomes; therefore, they cannot be expected to predict the economic cost of health-related issues to firefighters. Since other studies of the economic cost of health-related problems are based on exposure to urban air pollution, these cannot be used either as exposure to wildfire smoke is not known to have the same effect as exposure to urban air pollution. Urban air pollution and wildfire smoke exposure may result in different health outcomes.

Within the USFS there is currently no precise way to identify health related outcomes to firefighters from smoke exposure. At established fire camps with Incident Management Teams (IMTs) there is a medical unit equipped to support firefighters. Although they often record each service they provide, there is not a method to determine if the medical visit was directly related to or caused by smoke exposure. For example, a firefighter may go to the medical unit with a complaint of a sore throat or cold/cough, but whether that was caused by smoke or a result of fatigue, hydration, diet, or was present before arrival at the fire is typically not known. In any event, unless the illness results in loss time at work there is no official tracking process.

Kochi et al. (2010) also reviewed epidemiology studies, comparing those done on urban air pollution and those done on wildfire smoke exposure. Again, these studies all examined the public health consequences using hospital admissions data as the key variable for admissions related to asthma, general respiratory symptoms, and cardiovascular symptoms. Comparing the two sets of studies, they found inconsistencies in the findings. Mortality and morbidity outcomes comparisons were difficult to make between the two study groups. The authors site several reasons for the possible differences: differences in the chemical makeup of urban pollution vs. wildfire smoke; dose response; wildfires may typically be higher exposure for short duration vs. long-term; lower exposure for urban air pollution; and it may be easier for the public to avoid at least some exposure from wildfire smoke episodes. Kochi et al. (2010) conclude that, “There is still significant uncertainty about the health effects of wildfire smoke.” They state that the available studies found “no significant health effect due to wildfire events, in contrast to what would be predicted based on conventional PM studies.” Clearly additional research in this area is warranted.

VI. RESEARCH

Wildland Firefighter Smoke Exposure Study

In December of 2008 I was given a task that seemed straightforward: determine the smoke exposure level wildland firefighters face. As with many of the projects I manage, once I began the initial research I quickly realized this would be a difficult task. Having been involved in wildland firefighting for over 20 years, I knew firefighters often encounter smoke, sometimes heavy and sometimes not much at all. What I did not realize was there are many constituents in smoke and that measuring smoke levels is a highly scientific undertaking.

Initially the goals of the wildland firefighter smoke exposure study were given to me verbally in very general terms, i.e., figure out the exposure. My first tasks were to understand what had been done in this field, how it was done, what remained to be done, and how best to accomplish this. After reviewing the literature on wildland smoke exposure, especially the papers by Reinhardt and Ottmar (1997; 2000; 2004), I realized their work would be a great foundation. Upon the recommendation of Timothy

Reinhardt and Roger Ottmar (personal communication), the decision was made to use carbon monoxide exposure on wildland firefighters as a surrogate for the other primary irritants in wildland smoke.

At the outset of this study I was told to describe the exposure to wildland firefighters across the US. To that end I identified the study area and study population as follows.

Study Area Location

The study area for this project was planned to encompass any area in the United States where wildland and prescribed fires may occur, but primarily on National Forest System lands (Figure 1). Since federal lands cover large portions of the US from Alaska to Florida, the Pacific Northwest to the Southwest and eastern seaboard, the study area elevation ranged from sea level to over 10,000 ft ASL and included forests, grasslands, sagebrush, chaparral and pinyon-juniper ecosystems.

Wildland fuels are classified according to the National Fire Danger Rating System into 13 different fuel models. The study was designed to collect data that would represent each of these fuel models. Fuel models 1-3 are grasses, 4-6 are shrubs, 7-10 are timber, and 11-13 are timber slash fuels.

Exposure data were collected on fires occurring primarily on federal lands being managed by agencies with wildland fire suppression responsibilities. Since most states rely on federal support for large fire management, fires occurring on state lands were also eligible for inclusion in the study. There are two types of fires that occur on wildlands. First are wildfires that are caused by lightning or human-caused, either intentionally (arson) or accidentally. The other type of fire, also human-caused, is prescribed fire. Prescribed fires are intentionally set by wildland firefighters as a tool to improve ecosystem health.

Phases of wildland fire management can be classified as initial attack, extended attack, and project fires. Initial attack is the first stage of a fire from discovery to the start of suppression activity through the first operational period, usually 24 hours. When crews cannot contain the fire within the first operational period, the fire moves into extended attack. When fires become large, complex, unlikely to be controlled within a few days, and additional resources are needed, they often become project fires. Project fires typically have an Incident Management Team (IMT) in place to provide logistical and operational support for the firefighters. Data were collected on initial attack and project fires. Exposure data were also collected on prescribed fires.

Wildland fires on federal lands can be managed under multiple strategies, from full suppression to monitoring the fire from aircraft and taking no suppression actions. Some National Forests and National Parks will take limited suppression actions on lightning-caused fires if the fire will provide positive benefits to the ecosystem and poses no immediate threat to life or property. National Forests must have Land Management Plans that identify areas where these fires are allowed to burn. These fires, called Prescribed Natural Fires in this report, are also included in the study.

Although federal agencies often have a range of options when managing wildland fires, states will always assume a full suppression strategy on all wildland fires.

Aspects of the Study Population

Although this research was funded by the USDA Forest Service, the study population includes any wildland firefighters actively engaged in suppression or prescribed fire efforts including federal, state, local, and contract employees. Because study subjects are federal employees or others working on federally-managed fires, participants were not required to give their consent when included in this study.

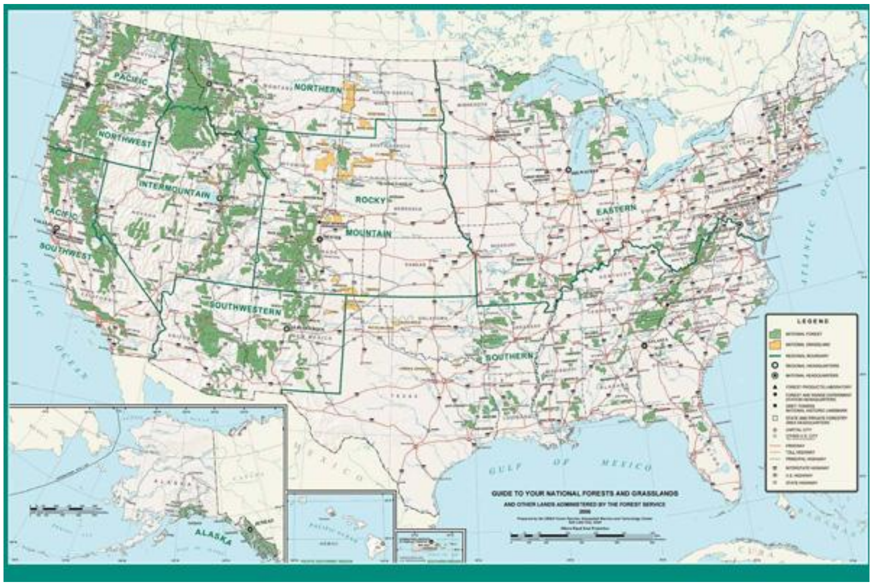

Figure 1. National Forests.

The study population includes firefighters working on handcrews and engines as well as dozer and tractor plow operators. Handcrews are organized into three types and typically consist of 20 persons: Type 1 (Interagency Hotshots), Type 2IA, and Type 2. Type 1 crews are the most experienced and highly trained and often receive the most challenging work assignments on wildland fires. All three crew types were included in the study. Engine crews may consist of 3-5 individuals, depending on the type and size of the engine. During the course of this study, data were collected on firefighters whose primary duty on suppression fires was to control or contain the fire. These are the individuals who construct handline along the fire perimeter, mop-up the fire edge, conduct burnout operations, and hold the fire along established firelines, roads, or natural barriers. In 2012 data collection was expanded to include higher-level fire management personnel. These are typically firefighters with more experience and training who lead crews, oversee divisions and engine strike teams (5 engines), or are members of an IMT.

On prescribed fires, exposures were measured on firefighters who were running drip torches to light the fire and those who were monitoring and holding the fire. Many of these are seasonal employees who work on fire crews during the summer and may attend college during the remainder of the year. Others are full- or part-time workers employed by various agencies. Most subjects are younger, ranging in age from 18-25 years, and include males and females. Therefore the study population is not characteristic of the general population in terms of age as most are young. The study population is also more physically fit and healthier than the general population. Employees who work on federally-managed fires are required to pass physical exertion tests each year to assure they are capable of performing work safely and successfully on wildland fires. The USFS has a medical standards program to ensure the health and fitness of USFS firefighters.

Throughout the course of this study, CO levels were measured in the personal breathing zone of firefighters. Measuring CO levels requires dosimeters, devices that are designed to measure CO concentrations over a period of time. Although there are numerous dosimeters on the market, they are primarily designed to be used in industrial settings and mining operations. None of the current dosimeters were designed to be used under the environmental conditions present in wildland fires. Therefore a thorough market search and evaluation was required to identify the best equipment for this study.

Equipment Evaluation
In order to accurately measure CO levels, a market search was conducted and subject matter experts were consulted (McCleary, NIOSH, personal communication, 2009; Ottmar, USFS, 2009; and Reinhardt, 2009) as well as numerous manufacturers' representatives. A matrix was developed to identify dosimeters that met the basic criteria needed for this study.

Eventually three different dosimeters were selected for field and lab evaluation: MSA Altair Pro Fire, Dräger PAC 5000, and Industrial Scientific GasBadge Pro. Each model was a single gas CO dosimeter. Dosimeters were purchased from each manufacturer and evaluated for:

- Accuracy
- Maintenance requirements
- Ease of use
- Battery life
- Calibration – ability to remain within acceptable range, ease of calibration
- Ability to function in the wildland fire environment: durability, withstand extreme heat and high/low relative humidity
- Radio frequency interference protection

In order to acquire CO exposure levels to meet the data analysis requirements, the dosimeters had to be able to record CO concentrations and allow for downloading of the data to a PC for analysis. For the purposes of this project, the dosimeters would have to be programmable to record CO levels at one-minute intervals. The MSA Altair Pro recorded a peak and average value each minute, while the Dräger PAC 5000 and the Industrial Scientific GasBadge Pro recorded only the peak reading for each minute. All the dosimeters recorded the date, time, and temperature for each minute.

These dosimeters use an electrochemical sensor to measure the CO concentration. These sensors must be tested daily to ensure they remain within the acceptable calibration range. To determine this, a gas of a known concentration of CO (certification traceable to the National Institute of Standards and Technology (NIST)) is passed across the sensor during a "function test." Since this test must be done each day, one requirement was the ease and amount of time needed to run this test. Another requirement was the ability of the dosimeters to remain within calibration limits for an extended period of time. When a dosimeter fails a function test, it must be calibrated. Calibration is similar to a function test, but the sensor is re-calibrated. At a minimum, the dosimeters were calibrated every 30 days during the course of this study.

Field testing the dosimeters revealed that both the Dräger and Industrial Scientific dosimeters failed the function tests after several shifts. Another shortcoming with these two models was damage to the water vapor/dust barrier that protected the sensor. On both the Dräger and Industrial Scientific dosimeters, this barrier is exposed to the elements and was often torn or partially removed while firefighters were wearing them. Dust and soot collected on the barrier, which appeared to be the cause of the dosimeters failing the function test. If a dosimeter fails a function test at the end of the shift, the data cannot be used. The water vapor/dust barrier on the MSA dosimeter is protected by a serrated plastic covering. There were no instances of the MSA failing a function test or damage to the water vapor/dust barrier. Daily function tests for the AltairPro were quick and easily performed under field conditions. Running the function tests for the Dräger and Industrial Scientific dosimeters was a much longer process that required resetting the alarm set points before and after running each test. This was a tedious process that also introduced the possibility that alarm set points and data recordation values could be set to the wrong values for the following day's work. Field evaluations also helped determine the ability of the dosimeters to withstand the environmental extremes that are often present in the fire environment such as extremes in temperature and relative humidity.

During the field evaluation it appeared that the different dosimeters were not all showing the same CO level under similar conditions. To evaluate this observation, the San Dimas Technology and Development Center (SDTDC) designed a small, clear, airtight chamber to view each device under controlled conditions. The dosimeters were calibrated prior to this test. Each dosimeter was placed in the chamber, and the chamber was purged of all other gases using a purified Nitrogen test gas or “zero” gas (NIST traceable). When a zero gas is detected, the dosimeters should all read “0” and the sensors are cleared (zeroed). After applying the zero gas, 100 ppm CO gas was introduced to the chamber. Values on the dosimeters were recorded and the process was repeated with the zero gas and the 100 ppm CO. Under this scenario, the MSA dosimeters were shown to be the most accurate, least variable, and had the least difference among each MSA as well as between the other dosimeters.

The MSA Altair Pro Fire dosimeter was selected and used for the duration of this study to measure CO concentrations.

Study Plan

Bullock et al. (2006) suggest that an industrial hygiene effort should be made under the supervision of a certified industrial hygienist. With that in mind, I wrote a statement of work, and the USFS entered into a contract with AMEC Geomatrix, Inc. (Seattle, WA) to obtain the services of Timothy Reinhardt. One component of this contract was to assist in the development of an exposure assessment plan.

The assessment plan was designed to address many of the recommendations from other studies so that this study would not suffer from some of the same shortcomings.

Before undertaking the actual assessment, field data collection protocols needed to be developed and logistics for the study had to be considered. The original field data protocols established for the project are listed below:

Field Data Collection Protocols. Protocols for data collection were designed to achieve the following:

- Corroborate and supplement findings of Reinhardt and Ottmar
- Expand data collection to geographic areas and fuel types that have not been analyzed
- Collect data under extreme environmental conditions, i.e., RH and temperature
- Collect CO levels and exposure at Incident Command Posts (begun in 2010).

In order to assess the exposures among wildland firefighters, metrics were established for how the data were to be collected and analyzed. Table 3 details this study plan.

Field protocols were developed to provide a rich data set that could be used to analyze exposure against a variety of variables, specifically those that were identified as lacking in previous studies. As a result, data collection forms were designed to gather numerous environmental variables and firefighter activities. Several different forms were used, but the primary one, Form 7 (see Appendix), was completed each hour to account for changes in the environment and crew activities (see the appendix for all field forms). The protocols were designed so that the data being collected could stand on its own and also be used to supplement and corroborate the data from the work of Reinhardt and Ottmar.

Incident Personnel Monitoring. As mentioned at the outset, this project was originally a task from the Fire Equipment Working Team. Prior to the 2010 fire season, I was contacted by the NWCG Risk

Table 3. Data Collection Metrics

Smoke Exposure Metric	Carbon Monoxide (CO)	Respirable Particulate Matter (PM4)*
1) Duration of workshift	Hours per day	Hours per day
2) Shift-average exposure	Shift-TWA CO (ppm)	Shift-TWA PM4 (mg/m^3)
3) Duration of exposed time in shift	Hours per day	Hours per day
4) Fireline-average exposure	Fireline-TWA CO (ppm)	Fireline-TWA PM4 (mg/m^3) (and respirable crystalline silica exposure for select samples, in mg/m^3)
5) Maximum 8-hour TWA exposure	Max 8-hr TWA CO (ppm)	Max 8-hr TWA PM4 (mg/m^3)
6) Maximum peak exposure (and other peaks - time and pattern)	5-minute max CO (ppm)	15-minute max PM4 (mg/m^3) - as opportunities occur
	1-minute max CO (ppm)	
7) Fire Camp Exposure (including off-shift exposure)	Daytime TWA CO (ppm)	Daytime TWA PM4 (mg/m^3)
	Nighttime TWA CO (ppm)	Nighttime TWA PM4 (mg/m^3)

*Started in 2010

Management Committee (RMC) as they had received a request to measure exposure to incident base camp personnel. The RMC issued a Tasking Memorandum (TM-2008-04) in May of 2008 that was added to this study for the 2010 fire season. This expanded the project to fully consider exposure to all incident personnel.

Smoke Exposure Task Group

In February 2010 the USFS convened a group of specialists to discuss the inhalation hazards of wildland smoke. This group, the Smoke Exposure Task Group, is chartered under the RMC. The meeting was attended by several risk management specialists for the USFS and BLM, and university researchers (U. of Georgia, U. of California, U. of California at Irvine, U. of Alberta,) specializing in epidemiology and inhalation hazards, Tim Reinhardt, Roger Ottmar, and myself.

At the conclusion of this meeting it was decided that the CO exposure work would continue, and I would also begin to collect particulate matter (PM4) and crystalline silica (SiO_2) data. PM 4 was added to the study to validate the findings of Reinhardt and Ottmar and to test if the CO/PM correlation would stand across various regions of the country. Crystalline silica has been identified as an irritant of concern but had not been measured sufficiently, so it was added to the study. Once again the project expanded considerably and required substantial effort in terms of acquiring additional equipment, developing protocols for the field and data management, and training for the field assessment crews.

With the addition of particulate matter and crystalline silica, it was necessary to undertake a search for the best equipment. Measuring PM and SiO_2 requires the use of personal industrial hygiene sampling equipment. Eventually the selected equipment included the Airchex XR 5000 industrial hygiene pump

(SKC, Fullerton, CA) attached to a BGI Triplex Cyclone (BGI Instruments, Waltham, MA), designed to have a 50% aerodynamic cutoff point of 4.0 *u*m. Standard operating procedures and field protocols were written for each piece of equipment.

Field Support Personnel

Due to the size of the sample population and the geographic scope of the study, it was evident that I would need support for the data collection. One of the shortcomings identified in previous studies was lack of trained field personnel. In many wildland firefighter smoke studies, researchers were not directly observing firefighters during the time measurements were being recorded. In order to address these two issues, detailers were hired to assist with this study. Each detailer was a current USFS employee with multiple years of firefighting experience. These individuals were required, at a minimum, to be red-carded as a single-resource boss meaning they were qualified and had experience supervising handcrews or engine modules. In practical terms it meant they had the ability to operate independently in the fire environment, and they understood the safety and communications requirements and the Incident Command System standard operating procedures. Each detailer received training on the use and maintenance of each piece of equipment, protocols, and study objectives. In addition to their initial training, I accompanied each detailer on several fires until they were competent in the entire data collection procedure and would continue to work with them throughout the entire fire season.

Field Coordination and Safety

Data collection in the wildland fire environment requires extensive pre-season planning. To assure success I worked with national incident commanders and the Interagency Hotshot Steering (IHC) Committee to identify areas of concern and discuss logistical needs for the project. I gave presentations to the Area Commanders/Incident Commanders Council and the IHC Steering Committee to explain the objectives of the study and the proposed process that would be used to select fires and gain access to the fires and selected crews. I also met with the National Interagency Coordination Center manager to establish dispatch protocols. The dispatch protocols were then distributed to each of the Geographic Area Coordination Centers. This preseason work facilitated the initiation of resource orders and expectations between the Incident Management Teams and the field data collection personnel.

The assessment personnel were fully equipped and self-sufficient. They followed all safety guidelines in the Incident Action Plan and Fireline Handbook. While on a fire only meals and other minor logistical support was needed from the IMT.

Field Procedures

In order to provide unbiased data, fires would be selected randomly and firefighter selection at each fire would also be as random as possible. By reviewing the National Situation Report and Incident Status Summaries (ICS 209) daily, I was able to identify fires with a high potential for data collection. When a candidate fire was selected, I would contact the Incident Commander or Fire Management Officer in charge and request permission to collect data on that incident. Upon receiving approval I would contact the geographic area coordination center with responsibility for the fire and request that resource orders be initiated for the assessment crews. In most cases the assessment crew consisted of two individuals, and in some instances there would be two crews at the same fire who would monitor different crews on the fire.

Once the assessment crew arrived, they would meet with the Incident Commander to receive an overview of the fire situation and explain the data collection process. Assessment crews also met with the Operations Section Chief and the Safety Officer to ensure they knew of our plans and to gain a better understanding of the fire situation and any safety concerns. Using the daily Incident Action Plan and in discussion with the Operations Section Chief, a division (a designated portion of the fire) was selected in which the assessment crew(s) would work. This selection was as random as possible but at times constrained by limitations placed on the observers by the incident management team.

During the 2009 fire season all travel was done via commercial airlines and rental vehicles. In 2010 an old helitender, an FS vehicle used by helicopter crews, was obtained for this study. This vehicle was converted to make a mobile office to provide a clean, dry work area for the assessment crew. The vehicle also provided a work space that was used for data transfer, calibration, and equipment storage.

A Day's Work

Pre-work. Work shifts typically begin at 6:00 AM on most wildland fires. However, in order to be prepared for the day's work, data collectors began their work earlier. In addition to the normal things required to prepare for a day on the fireline such as eating breakfast, getting lunches and water, and making sure handheld radios were ready, the assessment crew had several other things to attend to.

IH pumps had to be started at least one-half hour prior to calibration to ensure they were sufficiently warmed up. In order to organize all the necessary data and ensure data consistency, field forms were designed for different components of the fieldwork. While the pumps were warming up, Forms 1 and 3 (see Appendix) were initiated. Every component used in the pump setup was labeled, and this information was recorded on Form 4. A field blank filter was also used each day to test for ambient PM and SiO_2 and to evaluate the data accuracy of the sample filters. Filters were attached to the cyclone and then attached to the pump. Pumps were calibrated after the warm-up period, and pre-flow rates were recorded in Form 4. A BIOS Defender DryCal calibrator was used for pre-flow and post-flow measurements. Pre-printed labels were used to track each filter, and one label was placed on the filter, Form 4, and a plastic bag used to store each day's filters. The use of pre-printed labels reduced the possibility of transcription errors. Camera, GPS, dosimeters, Kestrels (electronic weather meter), and other equipment were readied. Once all the equipment was ready, the crew attended the morning operational briefing.

Operations Briefing. The operational briefing takes place prior to each shift where various individuals from the IMT speak to the assembled fire leadership. The assessment crew(s) attended the morning operational briefing, turned on the dosimeters, and began to enter data on Form 3. Immediately after the operational briefing there is a division breakout where the Division Supervisor relays the tactics and strategies for the day to his/her assigned resources. The assessment crew introduced themselves to the Division Supervisor and explained why they were there, the project goals and data collection methods, and answered any questions or concerns. Typically we asked for a crew to volunteer to wear the monitoring equipment, and three volunteers on the crew would be asked to wear a dosimeter for the shift. One firefighter would wear an IH pump in addition to the dosimeter. At this time the initial COHb reading also was taken from each firefighter wearing a dosimeter. COHb (carboxyhemoglobin) readings were taken with a Masimo RAD-57 handheld oximeter. When working with dozers, the pump(s) were placed directly on the dozer. From that point on we shadowed the crew throughout the entire shift.

Travel. Normally a crew drove from the briefing area to their assigned work area. Upon arrival at the work area, the particulate matter pump was activated and attached to the firefighter. Once the particulate pumps were activated, the fireline time began. Often the crew then hiked into the fire area to begin work. These travel times were recorded on Form 3.

Work Activity. In order to determine if different activities (see Fire Activity Codes in the Appendix) are related to exposure, everything the firefighters did had to be directly observed and recorded. For the purpose of this study, every possible job task on a fire was given a numerical code to be used for analysis purposes. Job tasks or activities included fireline construction, hiking, mop-up, holding, etcetera. Once the fire crew reached their designated work area, the assessment crew recorded the specific work activity and time each firefighter with a dosimeter was engaged in it on Form 7. This form allowed the observer to constantly record each activity the firefighter was involved in. Form 7 was completed hourly, except for the activity section which was constantly updated, and the weather section which was updated every 15 minutes. Therefore, minute-by-minute observations were recorded for later analysis and comparisons of CO exposure versus activity.

GPS track files recorded the movement of the crews and digital images were taken to record smoke levels. Using the time stamp on the image file and the time stamp on the CO dosimeter data, a photo series can be developed to use as a visual aid in determining CO levels. Throughout the shift, the assessment crew did not attempt to influence the crew's work practices. An electronic weather meter (Kestrel 4000) was used to determine relative humidity, temperature, wind speed, and barometric pressure. A clinometer was used to measure slope percent.

Once crews returned to their vehicles, the particulate pump would be removed from the crew member prior to his/her return to the incident command post. Post-flow measurements on the pump were taken immediately after leaving the fireline, whenever feasible. Dosimeters were also removed from the firefighters at this time. COHb and SpO_2 readings were taken as well. Recording these measurements immediately after the firefighters left the fireline assured more accurate measurements and followed NIOSH recommendations (Reh et al., 1992). These readings provided the CO, PM4, and SiO_2 exposure for the time the firefighter was on the fireline. Travel times were recorded as the crew returned to the Incident Command Post or spike camp. If the crew line spiked (spent the night in a safe location near the fireline), the assessment crew also remained on the line for the night. By remaining with the crew throughout the entire shift, accuracy of the data and accounting for any factors that may influence smoke exposure levels was ensured.

As stated in the study plan, replicates for the particulate matter were also collected by attaching two IH pumps to firefighters. This procedure ensured the precision of the data collection and field protocols. If replicate filters were not similar, it would indicate a problem with the equipment or field procedures.

Post-Shift. Once the fire crew had returned to their base, the assessment crew did their post-shift work. Each dosimeter was downloaded to a PC, and three separate files from each dosimeter were saved: the session file and the periodic file (saved in MS Excel format), and the .MSA file which is the native file format for the dosimeter. The periodic file contains the minute-by-minute exposure data. The session file contains information about the dosimeter including the last function test, date, time, and pass/fail, the calibration date, and any exposure events that exceeded the programmed alarm values. The SOPs included a naming and filing convention for dosimeter files. Then a function test was performed on the dosimeter, recorded on the appropriate form, and the unit was cleaned and made ready for the next day. If a dosimeter failed the bump test, the data from that unit was removed from the analysis data set. Dosimeters were then stored in a sealed case to allow the sensor to "rest" and ensure it was in an atmosphere free of CO.

Image files and GPS data were then downloaded to the computer. All electronic files − dosimeter data, images, and GPS data − were filed according to the data management plan. Once all the files were on the computer, they were copied to an external hard drive.

Post-flow measurements were made on the IH pump if they hadn't been taken earlier and recorded on Form 4. Pumps were then cleaned and placed on the charger to ensure a full charge for the following shift. Cyclones were cleaned by compressed air after each use. Field forms were checked for accuracy and to identify any deficiencies or missing information and then filed in a separate folder. Field notebooks were restocked for the next shift.

Incident Command Posts and Spike Camps. IH pumps and dosimeters were also set up in each ICP or spike camp the crews were working from. This equipment recorded exposure levels for 24 hours and provided exposure measurements for the incident camp personnel. These CO data were also appended to the data from the firefighter's dosimeters to provide a 24-hour exposure for them.

Data Management

All field data were returned to the office and handed over to the data manager. Data management and maintenance was guided by the direction in the study plan and a separate document written by Tim Reinhardt that detailed the spreadsheet strategy.

Electronic and Xerox copies were made of all the field data collection forms. Dosimeter data were copied to the FS server, an external hard drive, and the data manager's PC. The external hard drive was returned to the field kits.

Chain-of-evidence forms were completed and air volume calculated prior to sending the filters to RJ Lee Group for analysis. The air volume was used by RJ Lee Group to determine the level of PM4 and SiO2.

The data manager developed an Excel workbook in which all the field data were entered. A master spreadsheet was created for each day of observation. Each field form was replicated within the Excel Master Spreadsheet. As data were entered, relevant data were automatically pushed to the correct corresponding cell(s) in other sheets. For example, once the firefighter name was entered in the CO-PM Exposure Monitoring data sheet, it would be carried to the Exposure Summary Metrics page. CO data were imported into separate sheets for each firefighter and was used to calculate the values in the Exposure Summary Metrics page (see Appendix). Field data and CO, PM4, and SiO_2 data were placed on multiple pages within each master spreadsheet.

Various exposure values were calculated within this spreadsheet. Because CO data were collected on a minute-by-minute basis during operational shifts, it is possible to calculate several different occupational exposure metrics: 24 hr., shift, fireline, max 8 hr., max 5 min., and max 1 min. CO exposures were calculated for every firefighter who wore a dosimeter. The times that the 1-minute and 5-minute maximums were reached are expressed in the spreadsheet, as well as the activity the firefighter was engaged in at that time. Total particulate exposure was also calculated based on the analysis results from RJ Lee using the OSHA Silica PEL formula (29 CFR 1910.1000 table Z-3).

The 1- and 5-minute maximum environmental sheet (see Appendix) shows various conditions present for the maximum 1- and 5-minute exposures such as fuel model, fire behavior, wind speed and direction, firefighter position relative to fire, and wind and temperature.

Equipment. Exposure to CO was measured with electronic data logging dosimeters according to OSHA Method ID-209. CO was measured using Mine Safety Appliances (Altair Pro Fire) single gas CO dosimeters with an electrochemical CO sensor. Dosimeters were placed in the breathing zone of the firefighter and directly recorded 1-minute peak and average CO levels throughout the work shift. The dosimeters were function tested (Altair Automatic Quick Check Station) after each shift and calibrated at a minimum of every 30 days using 60 ppm NIST certified CO.

Respirable and fine particulate and crystalline silica were measured with an Air Check Model XR5000 personal sampling industrial hygiene pump (SKC, Fullerton, CA) using pre-weighed 37-mm diameter 5 µm pore size polyvinyl chloride filters in clear 3-piece polystyrene cassettes. The top to the filter assembly was removed in the field, and the main portion housing the filter was fitted on a BGI Triplex SCC 1.062 aluminum cyclone (BGI Incorporated, Waltham, MA) designed to have a 50% aerodynamic cutoff point of 4.0 *u*m. The pump was calibrated to within +/- 10% pre-flow before each shift to 1.05

ml/L. A BIOS Defender DryCal (Bios International, Butler, NJ) calibrator was used for pre-flow and post-flow measurements.

Carboxyhemoglobin (COHb) and blood oxygen saturation level (SpO2) readings were taken with a Masimo RAD - 57 handheld oximeter (Masimo Corp., Irvine, CA). These readings were taken three times daily: prior to the firefighter entering the fire area, mid-shift, and post-shift.

Filters were sent to RJ Lee Group Labs (Monroeville, PA) for analysis. A chain-of-custody form was completed prior to shipping the filters to RJ Lee Group. Analysis for respirable dust and crystalline-free silica dust on 5 *u*m PVC air filters was performed using gravimetry NIOSH 0600 and X-ray diffraction and NIOSH 7500 methods.

Kestrel 4000 (Nielsen-Kellerman, Boothwyn, PA) pocket weather meters were used to measure temperature, relative humidity, barometric pressure, and wind speed.

DeLorme PN 20 (Yarmouth, ME) GPS units were used to track the movement of crews.

Summary of Data Collection Procedures. The objective of this study was to assess firefighter and incident personnel exposure to CO, PM4, and SiO_2 throughout the US and to:

- Determine the variability and extent of exposures
- Identify factors that contribute to unsafe exposure levels
- Include peak exposure assessment to describe the highest smoke levels monitored, and
- Summarize important determinants of smoke exposure.

Data collection procedures and data analysis were designed to provide this information.
For all firefighters, CO, PM4, and SiO_2 samples were taken in the breathing zone. Incident support personnel exposures were taken by area samples. The extensive data set was designed to gather data that were representative of the many activities and varied exposures (low to high) experienced by wildland firefighters. Complete data numbers can be found in the appendix.

Dedicated trained personnel collected all the exposure data following sound IH procedures and established protocols. These personnel followed the monitored firefighters constantly whether driving, hiking, flying, and when staged in camps. Strict quality assurance standards were followed.

Equipment was kept in optimal condition, and extra equipment was available in the event of equipment failure. The BIOS DryCal calibrators were sent to the factory for re-calibration each year. IH pumps were also returned for service if they indicated any problems. Daily function tests on dosimeters and calibration procedures ensured accurate CO data. The use of NIST certified calibration and test gases and recording and signing daily test sheets were part of the daily standard operating procedures.

Field replicates were done by placing two pumps and filter assemblies on the same firefighter and/or dozer and comparing analysis of the two filters. Field replicates were also used at ICPs. This procedure provides the relative percent difference to test the precision of field measurements.

Field blanks and calibration checks also provided a measure of accuracy of the exposure measurements.

Quality Assurance/Quality Control. The highest level of quality assurance measures was taken and industrial hygiene standards were strictly followed. Adherence to these standards was assured by adhering to the following:

- Written study plan to guide data collection, data management, and analysis
- Dedicated and trained data collectors
- Daily review of data
- Independent review of data by a certified industrial hygienist
- Field replicates to determine precision of field data
- Field blanks were used daily
- NIOSH approved and industry standards for calibration and function tests were followed
- Chain-of-custody forms were used for sampling, replicate, and field blank filters
- Written protocols for data collection procedures and equipment.

Data Collection Summary
Data collection goals for the Wildland Firefighter Smoke Exposure Study were set to account for a variety of variables. To that end, the study was successful in meeting many of these objectives. Data were collected in all but one USFS Region, 17 different states, on project (suppression) fires, prescribed natural fires, prescribed fires, and during initial attack (see Table 4). Handcrews, engine crews, dozer operators, and overhead personnel exposures were measured, as were virtually every job task performed by wildland firefighters. The fireline activity form (see Appendix) lists each activity that was monitored. Over 30 different job tasks were identified including handline construction, sawyer, mop-up, and pump operator. Field assessment personnel used the field notes to record any activity that was not on the activity form.

Table 4. Data Collection Summary

Total For FY 2009, FY 2010, FY 2011, and FY 2012			
Total # of Days of Observations	**Total # of Crew Observations**	**Total # of Engine Observations**	**Total # of Dozer Observations**
200	160	40	20

Total # of Wildland Fires	Total # of Prescribed Fires	Total # of Diff. States	Total # of Shift Hours Observed
57	23	17	3289.97

Total # of Firefighters Observed	Total FF Log Hours	Total # of ICPs Observed	Total ICP Log Hours
667	7517.47	81	1554.88

Total Log Hours	Total # of Observations of Overhead Positions
9072.35	41

During the four-year study, 7,517 hours of CO measurements on firefighters and 1,554 hours of CO measurements at ICPs and spike camps were taken. There were a total of 179 PM4 and SiO_2 firefighter samples and 78 samples at ICPs and/or spike camps covering 1,554 hours. Complete data collection details are provided in the Appendix.

The average shift time for all firefighters was 12.97 hours. This shift time aligns well with the SETG recommended shift-length OEL. Average time on the fireline was 8.85 hours. The remaining shift time was taken up by travel, briefings, and preparing for various assignments.

Data Analysis

The analysis (Tables 7-10) presented in this paper has been done by Tim Reinhardt (CIH) to accurately assess exposures based on standard industrial hygiene methods. Specific variables and types of analysis were requested in order to obtain the values necessary for exploring and answering the objectives set forth in this study. Industrial hygiene specific statistics were done in R, using the package SAND (Frome et al., 2011), implementing the American Industrial Hygiene Association data analysis strategy (Bullock et al., 2006). This analysis includes data from 2009 through 2011. Data analysis for 2012 data has not yet been done in R. The statistical tables presented below summarize the AIHA-approved refinements to classical statistics for lognormal distributions, as appropriate for censored and noncensored data (censored values are those below method detection limits).

As stated previously, CO exposures were recorded on a minute-by-minute basis, which made it possible to calculate several different occupational exposure metrics (the Appendix contains examples of detailed and summary exposure results). By direct observation of fire behavior, environmental conditions, and the work activity being done by the firefighters, it is possible to determine which factors may cause or contribute to high exposures.

Data Analysis Assumptions

- Exposures were calculated by fire type: wildland, initial attack, prescribed, and prescribed natural fire
    - to determine the exposure characteristics associated with each fire management regime
    - to account for differences in shift averages impacted by the amount of time firefighters were actually engaged in fire suppression
- Shift TWAs included all the time firefighters were in paid status
- One-minute average CO concentration was used for analysis
- OSHA PEL formula (29 CFR 1910.1000 table Z-3) was used to calculate total particulate exposure.

Occupational Exposure Limits. In order to determine whether wildland firefighters may be exposed to harmful levels of CO, exposures are compared to existing OELs and the recommended NWCG 2012 Guidelines (SETG interim OELs) for wildland firefighters. Table 5 contains the relevant OELs used for this analysis.

Numerous statistics can be calculated in the R package for SAND. The statistics used in the analysis for the data presented in this paper can be found in Table 6. This table explains statistical options to estimate the point estimate and boundaries for the 95th percentile, and the percentage of firefighters whose work shifts exceed various OELs. All calculations are done with 95% confidence. Although each statistic can be calculated for each fire type the value of each type of statistic is dependent on the specific set of data being analyzed. Standard parametric methods are used when there is no (or minimal) censored data. With censored data such as these, nonparametric methods will obtain better results.

Table 5. Occupational Exposure Limits used for analysis

Exposure Duration	Occupational Exposure Limit	Source	Notes
1-minute maximum	1200 ppm CO	NIOSH IDLH	
5-minute maximum	200 ppm CO	NIOSH ceiling, state STELs	
8-hr maximum	50, 35 or 25 ppm CO	OSHA PEL, State PEL, or ACGIH TLV	
Fireline TWA (10 hr)	35 ppm or 25 ppm CO	NIOSH REL, ACGIH TLV	
Shift TWA (13 hr)	16 ppm CO	Interim NWCG 2012 OEL	
24-hour TWA	8 ppm CO	Interim NWCG 2012 OEL	
Fireline TWA (10 hr)	1.0 mg/m^3 PM4	Interim OEL	1/100 ischemic risk[a]
Shift TWA (14 hr)	0.7 mg/m^3 PM4	Interim OEL	1/100 ischemic risk
Fireline TWA (10 hr)	0.1 mg/m^3 PM4	Interim OEL	1/1000 ischemic risk
Shift TWA (14 hr)	0.07 mg/m^3 PM4	Interim OEL	1/1000 ischemic risk

[a]Ischemic risk is calculated risk of excess mortality from ischemic cardiovascular diseases assuming average of 69 firefighting days/year and retirement from significant smoke exposure by age 40 (Type II reasonable maximum). Data based on study by Doll et al., from SETG committee on smoke exposure occupational exposure limits.

Prescribed Fire Summary

Table 7 provides the results from the analysis for prescribed burns from 2009-2011 (n=83). The average shift duration on prescribed fires was 10:27 (hh:mm) with a maximum of 17:00 and minimum of 4:08. The average fireline duration was 6:03 with a maximum of 12:00 and minimum of 1:25. The prescribed fire data include no censored data. The statistically-estimated exposures are estimates based on the number of samples and the variability in the actual data. As with all industrial hygiene statistics, the key variables of interest are the upper confidence limits as these estimates provide the highest level of safety to employees.

The highest 1-minute exposure value provides the peak exposure level for each firefighter on every shift. This is a good value to compare against the IDLH standard and addresses the study goal of identifying the highest exposures on prescribed fires. The average highest (1-minute average) CO exposure at prescribed burns was 122 ppm, but this average could be as high as 149 ppm (95th percentile upper confidence limit). The 95th percentile confidence value means that we are 95% sure that 95 percent of the time the values will be below the 95th percentile upper confidence limit. The highest 1-minute CO exposure measured was 450 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 360 ppm, and we are 95% confident that fewer than 5% of these firefighters would have 1-minute exposures above 464 ppm. We estimate that 0.15% of the 1-minute exposures exceed the OEL of 1,200 ppm (IDLH) and are 95% confident that this percentage does not exceed 0.55%.

The average highest 5-minute CO exposure at prescribed burns was 72 ppm, and the average could be as high as 92 ppm (95th percentile upper confidence limit). The highest measured 5-minute exposure was 271 ppm and, based on the data, we estimate that 5% of the exposures were found to be higher than 92 ppm. We are 95% confident that fewer than 5% would have 5-minute exposures above 314 ppm. We estimate that 6.7% of the 5-minute exposures exceed the 5-minute OEL of 200 ppm and are confident that this percentage does not exceed 11%.

Table 6. Summary of IH statistics in R package SAND V1.5 (5/31/12)

Statistic	Description
EX	Arithmetic mean for lognormal distribution.
EX.LCL	Lower confidence limit (LCL) of arithmetic mean.
EX.UCL	Upper confidence limit (UCL) of arithmetic mean.
KM.mean	Kaplan-Meier (KM) estimate of arithmetic mean. A nonparametric method for censored data. Works for the lognormal distribution but doesn't require it. Gives the same result as Land's 1972 approximation recommendation #2 with noncensored data. *Equals "normal parametric statistics" for complete case.*
KM.LCL	LCL of KM arithmetic mean. *Equals "normal parametric t-statistics" for complete case.*
KM.UCL	UCL of KM arithmetic mean. *Equals "normal parametric t-statistics" for complete case.*
Xp.obs	Estimate of Xp (the p^{th} percentile, default = 95th) from PLE
Xp	Maximum likelihood estimate of Xp, the p^{th} percentile. *Use for censored data, normal, or lognormal distribution.*
Xp.LCL	Maximum likelihood estimate of the LCL for Xp. *Censored data, normal, or lognormal distribution.*
Xp.UCL	Maximum likelihood estimate of the UCL for Xp. *Censored data, normal, or lognormal distribution.*
Maximum	Largest observation
NonDet%	Percentage of censored data (non-detects)
n	Number of samples
f	The maximum likelihood estimate of the exceedence fraction (percentage that exceeds the limit L). *Use for large samples with censored data (having non-detects). Closest to lognormal parametric statistics results for complete cases.*
f.LCL	95^{th} percentile lower confidence limit on f. *Use for large samples with censored data (having non-detects). Closest to lognormal parametric statistics results for complete cases.*
f.UCL	95^{th} percentile upper confidence limit on f. *Use for large samples with censored data (having non-detects). Closest to lognormal parametric statistics results for complete cases.*
fnp	Nonparametric estimate of F that exceeds the limit L. *Conservative.*
fnp.LCL	Nonparametric estimate of UCL for F. *Conservative.*
fnp.UCL	Nonparametric estimate of LCL for F. *Conservative.*
L	Occupational or other exposure limit of interest

Table 7. Statistical summaries for prescribed burns (T. Reinhardt)

	Maximum Carbon Monoxide Exposure (in parts per million)							Maximum Fireline-Average Respirable Particulate Exposure (in milligrams per cubic meter)	
Statistic	**1-Minute Average**	**5-Minute Average**	**8-Hour Average**	**8-Hour Average**	**8-Hour Average**	**Shift Average**	**24-Hour Average**	**Respirable Particulate (Smoke)**	**Respirable crystalline silica**
Exposure Limit	**1200**	**200**	**50**	**35**	**25**	**16**	**8**	**1.0**	**0.1**
Exposure Limit Source	NIOSH IDLH	NIOSH Ceiling, State STEL	OSHA PEL	State PEL	State PEL, ACGIH TLV, NIOSH REL	NWCG 2012 Guideline	NWCG 2012 Guideline	NWCG Risk Management Committee	OSHA & State PEL
EX (mean)	122	72	10	10	10	6.5	3.5	0.81	0.02
EX.LCL	100	57	6.7	6.7	6.7	4.6	2.3	0.57	0.01
EX.UCL	149	92	15	15	15	9.2	5.2	1.1	0.05
KM.mean	119	68	9.4	9.4	9.4	6.3	3.2	0.84	0.02
KM.LCL	100	56	6.7	6.7	6.7	4.6	2.3	0.52	0.01
KM.UCL	139	80	12	12	12	8.0	4.1	1.2	0.04
Xp.obs (95^{th} %)	360	206	45	45	45	29	15	1.9	0.07
Xp (95^{th} %)	360	234	39	39	39	24	13	1.9	0.08
Xp.LCL	279	174	25	25	25	17	8.7	1.2	0.03
Xp.UCL	464	314	60	60	60	36	20	3.2	0.19
Maximum	450	271	62	62	62	41	22	2.9	0.14
n (# of obs)	83	83	83	83	83	83	83	15	15
Nondetect (%)	0	0	0	0	0	0	0	20	53
f (% > OEL)	0.15	6.7	3.5	5.8	8.8	9.0	9.5	26	2.9
f.LCL (%)	0.03	3.9	1.8	3.2	5.4	5.6	5.9	12	0.2
f.UCL (%)	0.55	11	6.5	10	14	14	14	44	17
fnp (% > OEL)	0	6.0	2.4	12	14	14	14	20	6.7
fnp.LCL (%)	0	2.4	0.4	6.7	8.6	8.6	8.6	5.7	0.34
fnp.UCL (%)	3.5	12	7.4	20	22	22	22	44	28

Eight-hour exposures were also calculated for each firefighter. A rolling eight-hour exposure was calculated and can be compared to 8-hour duration OELs. In cases where the firefighter was on the line for more than eight hours, the highest eight-hour exposure is used in the analysis. When the firefighter was on the line for less than eight hours, the eight-hour exposure is calculated by adding the appropriate amount of time at zero exposure to the time of the measured fireline exposure, so the calculation can be made on an eight-hour exposure. In these cases, observers confirmed that no exposure took place during the additional time in the eight hours. This is an example of a time-weighted average (TWA)[1].
Long-term exposures can be determined by calculating the maximum 8-hour exposure and the 24-hour TWA. The 8-hour exposure was compared to OSHA PEL, NIOSH REL, and ACGIH TLV. Both the 8-hour and 24-hour exposures can be used to determine both short-term and long-term health risks from smoke exposure. The 24-hour exposures are based on the NWCG 2012 guideline (SETG interim) OEL.

The average highest 8-hour TWA CO exposure at prescribed burns was 10 ppm, which is less than any of the OELs that could be adopted, but the average could be as high as 15 ppm (95th percentile upper confidence limit). The highest observed 8-hour TWA exposure was 62 ppm, which is above each 8-hour OEL. Based on the exposure data, we estimate 5% of the exposures were found to be higher than 45 ppm and are 95% confident that fewer than 5% of the firefighters would have 8-hour TWA exposures above 60 ppm. We estimate that exposures exceed the relevant 8-hour OEL for between 3.5% and 8.8% of the firefighters at prescribed burns, ranging from 3.5% of exposures exceeding the 50 ppm PEL to 8.8% exceeding the 25 ppm TLV®. We are confident that these percentages do not exceed 6.5% and 14%, respectively.

Shift exposures were also determined for each firefighter by using the total exposure during fireline operations and adding the total shift time to the calculations. The shift exposure is a TWA that includes exposure (or zero exposure) off the fireline. If the firefighters were in an inversion and were exposed, even though they were not on the fireline, this would be included in the shift average.

The average highest shift-average CO exposure at these prescribed burns was 6.5 ppm and could be as high as 9.2 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 41 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 29 ppm, and we are 95% confident that fewer than 5% would have shift average exposures above 36 ppm. We estimate that 9% of the shift exposures at prescribed burns exceed the recommended shift-average NWCG 2012 Guideline for CO of 16 ppm and are 95% confident that this percentage does not exceed 14%.

The average highest 24-hour-average CO exposure at prescribed burns was 3.5 ppm and could be as high as 5.2 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 22 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 15 ppm, and we are 95% confident that fewer than 5% would have 24-hour exposures above 20 ppm. We estimate that 9.5% of the 24-hour exposures exceed the recommended shift-average NWCG 2012 guideline for CO of 8 ppm at prescribed burns and are 95% confident that this percentage does not exceed

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[1] Time-weighted averages simply weight each exposure period in the day by the amount of time the exposure period lasted. When a TWA is calculated over two periods in a day, say time on the fireline and time away from it, more weight is given to the longer period – if they are equal length, they have equal weight. For example, the formula to calculate a two-period TWA for CO is: TWA (in PPM) = [(CO PPM for sample 1 x duration of sample 1) + (CO PPM for sample 2 x duration of sample 2) / (duration of sample 1 + duration of sample 2). The TWA can be any duration, such as over the entire workshift, but unless specified it is usually eight hours.

14%. CO data obtained from the CO dosimeter at the ICP or spike camp where the firefighters were stationed was used and appended to the dosimeter data that each firefighter wore to obtain the 24-hour exposure.

Respirable Particulate. The average highest exposure to respirable particulate was 0.84 mg/m^3 and could be as high as 1.2 mg/m^3 (95th percentile upper confidence limit). We estimate that 20% of exposures exceed the NWCG RMC recommended exposure of 1.0 mg/m3 and are 95% confident that this percentage does not exceed 44%.

Crystalline Silica. The average highest exposure to crystalline silica was 0.02 mg/m^3 but this could be as high as 0.04 mg/m^3 (95th percentile upper confidence limit). We estimate that 6.7% of exposures exceed the OSHA PEL of 0.1 mg/m3 and are 95% confident that this percentage does not exceed 28%.

Wildland Project Fire Summary

Table 8 provides the results from the analysis for wildland project fires from 2009-2011 (*n*=417). The average shift duration on these fires was 13:38 (hh:mm) with a maximum of 17:00 and minimum of 7:30. The average fireline duration was 9:57 with a maximum of 16:00 and minimum of 1:10. This data contains censored data. The statistically-estimated exposures are estimates based on the number of samples and the variability in the actual data.

The average highest 1-minute exposure value provides the peak exposure level for each firefighter on every shift. This is a good value to compare against the IDLH standard. The average highest (1-minute average) CO exposure at wildland project fires was 142 ppm, but this average could be as high as 164 ppm (95th percentile upper confidence limit). The 95^{th} percentile confidence value means that we are 95% sure that 95 percent of the time the values will be below the 95^{th} percentile upper confidence limit. The highest 1-minute CO exposure measured was 1500 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 255 ppm, and we are 95% confident that fewer than 5% would have 1-minute exposures above 609 ppm. We estimate that 1.1% of the 1-minute exposures are above the OEL of 1,200 ppm (IDLH) and are confident that this percentage does not exceed 1.7%.

The average highest 5-minute CO exposure at project fires was 81 ppm, and the average could be as high as 96 ppm (95th percentile upper confidence limit). The highest measured 5-minute exposure was 933 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 131 ppm and we are 95% confident that fewer than 5% of firefighters would have 5-minute exposures above 365 ppm. We estimate that 8.9% of the 5-minute exposures exceeded the 5-minute OEL of 200 ppm and are 95% confident that this percentage does not exceed 11%.

Eight-hour exposures were also calculated for each firefighter. A rolling eight-hour exposure was calculated and can be compared to 8-hour duration OELs. In cases where the firefighter was on the line for more than eight hours, the highest eight-hour exposure is used in our analysis. When the firefighter was on the line for less than eight hours, the eight-hour exposure is calculated by adding the appropriate amount of time at zero exposure to the time of the measured fireline exposure, so the calculation can be made on an eight-hour exposure. In these cases, observers confirmed that no exposure took place during the additional time in the eight hours.

The average highest 8-hour TWA CO exposure at these fires was 16 ppm, which is less than any of the OELs that could be adopted, but the average could be as high as 21 ppm (95th percentile upper confidence limit). The highest observed 8-hour TWA exposure was 108 ppm, which is above the PEL, REL, and TLV. Based on the exposure data, 5% of the 8-hour TWAs were found to be higher than 18 ppm, and we are 95% confident that fewer than 5% would have 8-hour TWAs above 72 ppm. We estimate that 5.6% to 10.7% of the 8-hour TWA exposures exceed the relevant 8-hour OELs at project

Table 8. Statistical summaries for project wildfires (T. Reinhardt)

	Maximum Carbon Monoxide Exposures (in parts per million)							Maximum Fireline-Average Respirable Particulate Exposures (in milligrams per cubic meter)	
Statistic	**1-Minute Average**	**5-Minute Average**	**8-Hour Average**	**8-Hour Average**	**8-Hour Average**	**Shift (13-hr) Average**	**24-Hour Average**	**Respirable Particulate (Smoke)**	**Respirable crystalline silica**
Exposure Limit	**1200**	**200**	**50**	**35**	**25**	**16**	**8**	**1.0**	**0.1**
Exposure Limit Source	NIOSH IDLH	NIOSH Ceiling, State STEL	OSHA PEL	State PEL	State PEL, ACGIH TLV, NIOSH REL	NWCG 2012 Guideline	NWCG 2012 Guideline	NWCG Risk Management Committee	OSHA & State PEL
EX (mean)	142	81	16	16	16	10	5.8	0.64	0.04
EX.LCL	123	69	12	12	12	7.6	4.3	0.53	0.03
EX.UCL	164	96	21	21	21	14	7.8	0.77	0.07
KM.mean	108	55	5.5	5.5	5.5	3.5	2.0	0.63	0.04
KM.LCL	96	49	4.9	4.9	4.9	3.1	1.8	0.52	0.02
KM.UCL	119	60	6.1	6.1	6.1	3.9	2.2	0.74	0.05
Xp.obs (95th %)	255	131	18	18	18	11	5.9	1.9	0.17
Xp (95th %)	518	306	56	56	56	36	21	1.8	0.16
Xp.LCL	440	256	44	44	44	28	16	1.4	0.10
Xp.UCL	609	365	72	72	72	47	27	2.3	0.27
Maximum	1500	933	108	108	108	64	36	3.1	0.28
n (# of obs)	417	415	417	417	417	417	417	79	79
Nondetect (%)	1.7	1.2	1.7	1.7	1.7	1.7	1.7	10	38
f (% > OEL)	1.1	8.9	5.6	7.9	10.7	11	12	17	9.1
f.LCL (%)	0.73	7.2	4.4	6.4	8.8	8.8	10	12	5.4
f.UCL (%)	1.7	11	7.2	9.8	13	13	14	23	14
fnp (% > OEL)	0.48	1.7	0.24	0.48	1.7	0.96	3.4	19	8.9
fnp.LCL (%)	0.09	0.8	0.01	0.09	0.79	0.33	2.0	12	4.2
fnp.UCL (%)	1.5	3.1	1.13	1.5	3.1	2.2	5.2	28	16

fires, ranging from 5.6% of exposures exceeding the 50 ppm PEL to 10.7% exceeding the 25 ppm TLV®. We are confident that this percentage does not exceed 7.2% and 13%, respectively.

The average highest shift-average CO exposure at project fires was 10 ppm, and could be as high as 14 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 64 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 11 ppm, and we are 95% confident that fewer than 5% would have shift average exposures above 47 ppm. We estimate that 11% of the shift average exposures exceed the recommended shift-average NWCG 2012 guideline for CO of 16 ppm and are 95% confident that this percentage does not exceed 13%.

The average highest 24-hour-average CO exposure at project fires was 5.8 ppm and could be as high as 7.8 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 36 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 5.9 ppm, and we are 95% confident that fewer than 5% would have 24-hour exposures above 27 ppm. We estimate that 12% of the 24-hour exposures at suppression fires exceed the recommended shift-average NWCG 2012 guideline for CO of 8 ppm and are 95% confident that this percentage does not exceed 14%.

Respirable Particulate. The average highest exposure to respirable particulate was 0.64 mg/m^3 and could be as high as 0.77 mg/m^3 (95th percentile upper confidence limit). We estimate that 17% of exposures exceed the NWCG RMC recommended exposure of 1.0 mg/m3 and are 95% confident that this percentage does not exceed 23%.

Crystalline Silica. The average highest exposure to crystalline silica was 0.04 mg/m^3 and could be as high as 0.05 mg/m^3 (95th percentile upper confidence limit). We estimate that 8.9% of exposures exceed the OSHA PEL of 0.1 mg/m3 and are 95% confident that this percentage does not exceed 16%.

Initial Attack Wildfires Summary
Table 9 provides the results from the analysis for initial attack fires from 2009-2011 (n=60). The average shift duration on these fires was 12:24 (hh:mm) with a maximum of 16:30 and minimum of 3:30. The average fireline duration was 4:13 with a maximum of 10:18 and minimum of 0:51. These data have no non-detects, so we can use a standard parametric method for analysis. The statistically-estimated exposures are estimates based on the number of samples and the variability in the actual data.

The average highest 1-minute exposure value provides the peak exposure level for each firefighter on every shift. This is a good value to compare against the IDLH standard. The average highest (1-minute average) CO exposure at initial attack fires was 69 ppm, but this average could be as high as 101 ppm (95th percentile upper confidence limit). The highest 1-minute CO exposure measured was 210 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 153 ppm, and we are 95% confident that fewer than 5% of initial attack firefighters would have 1-minute exposures above 385ppm. We estimate that 0.2% of the 1-minute exposures exceed the OEL of 1,200 ppm (IDLH) and are 95% confident that this percentage does not exceed 0.90%.

The average highest 5-minute CO exposure at initial attack fires was 46 ppm, and the average could be as high as 73 ppm (95th percentile upper confidence limit). The highest measured 5-minute exposure was 129 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 79 ppm and we are 95% confident that fewer than 5% of firefighters would have 5-minutes exposures above 285 ppm. We estimate that 4.1% of the 5-minute exposures exceed the 5-minute OEL of 200 ppm and are 95% confident that this percentage does not exceed 8.2%.

Eight-hour exposures were also calculated for each firefighter. A rolling eight-hour exposure was calculated and can be compared to 8-hour duration OELs. In cases where the firefighter was on the line

Table 9. Statistical summaries for initial attack wildfires (T.Reinhardt)

	Maximum Carbon Monoxide Exposures (in parts per million)							Maximum Fireline-Average Respirable Particulate Exposures (in milligrams per cubic meter)	
Statistic	**1-Minute Average**	**5-Minute Average**	**8-Hour Average**	**8-Hour Average**	**8-Hour Average**	**Shift (13-hr) Average**	**24-Hour Average**	**Respirable Particulate (Smoke)**	**Respirable crystalline silica**
Exposure Limit	**1200**	**200**	**50**	**35**	**25**	**16**	**8**	**1.0**	**0.1**
Exposure Limit Source	NIOSH IDLH	NIOSH Ceiling, State STEL	OSHA PEL	State PEL	State PEL, ACGIH TLV, NIOSH REL	NWCG 2012 Guideline	NWCG 2012 Guideline	NWCG Risk Management Committee	OSHA & State PEL
EX (mean)	69	46	5.3	5.3	5.3	3.0	1.9	0.93	0.28
EX.LCL	47	29	2.8	2.8	2.8	1.7	1.0	0.50	0.08
EX.UCL	101	73	9.9	9.9	9.9	5.0	3.5	1.7	1.0
KM.mean	52	29	3.5	3.5	3.5	2.2	1.3	0.90	0.21
KM.LCL	42	23	2.2	2.2	2.2	1.5	0.76	0.45	0.05
KM.UCL	62	35	4.8	4.8	4.8	3.0	1.7	1.3	0.36
Xp.obs (95^{th} %)	153	79	12	12	12	7.9	4.3	3.1	0.66
Xp (95^{th} %)	250	174	20	20	20	11	7.2	3.2	1.0
Xp.LCL	163	107	11	11	11	6.5	3.9	1.5	0.32
Xp.UCL	385	285	38	38	38	20	13	6.9	3.4
Maximum	210	129	33	33	33	19	13	3.8	1.7
n (# of obs)	60	60	50	50	50	50	50	21	21
Nondetect (%)	3.3	3.3	0	0	0	0	0	52	38
f (% > OEL)	0.21	4.1	1.5	2.5	3.9	3.1	4.4	26	36
f.LCL (%)	0.04	1.9	0.46	0.90	1.6	1.2	1.9	14	22
f.UCL (%)	0.90	8.2	4.1	6.0	8.3	7.0	9.1	43	52
fnp (% > OEL)	0	0	0	0	2.0	2.0	2.0	33	43
fnp.LCL (%)	0	0	0	0	0.10	0.10	0.10	17	25
fnp.UCL (%)	4.9	4.9	5.8	5.8	9.1	9.1	9.1	54	63

for more than eight hours, the highest eight-hour exposure is used in our analysis. When the firefighter was on the line for less than eight hours, the eight-hour exposure is calculated by adding the appropriate amount of time at zero exposure to the time at the measured fireline exposure, so the calculation can be made on an eight-hour exposure.

The average highest 8-hour TWA CO exposure at initial attack fires was 5.3 ppm, which is less than any of the OELs that could be adopted, but the average could be up to 9.9 ppm (95th percentile upper confidence limit). The highest observed 8-hour TWA exposure was 33 ppm, which is above the ACGIH TLV and NIOSH REL. Based on the exposure data, 5% of the exposures were found to be higher than 12 ppm, and we are 95% confident that fewer than 5% of firefighters would have 8-hour exposures above 38 ppm. We estimate that 1.5% to 3.9% of exposures exceed the relevant 8-hour OELs at initial attack fire, ranging from 1.5% of exposures exceeding the 50 ppm PEL to 3.9% exceeding the 25 ppm TLV®. We are 95% confident that these percentages do not exceed 5.8% to 9.1%, respectively.

Shift exposures were also determined for each firefighter by using the total exposure during fireline operations and adding the total shift time to the calculations. The shift exposure is a TWA that includes exposure (or zero exposure) off the fireline. If the firefighters were in an inversion and were exposed even though they were not on the fireline, this would be included in the shift average. The average highest shift-average CO exposure at initial attack fires was 3.0 ppm, and this average could be as high as 5.0 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 19 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 7.9 ppm, and we are 95% confident that fewer than 5% of firefighters would have shift average exposures above 20 ppm. We estimate that 3.1% of the shift average exposures at initial attack fires exceed the recommended shift-average NWCG 2012 guideline for CO of 16 ppm and are confident that this percentage does not exceed 7.0%.

The average highest 24-hour-average CO exposure at initial attack fires was 1.9 ppm and could be as high as 3.5 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 13 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 4.3 ppm, and we are 95% confident that fewer than 5% of firefighters would have 24-hour exposures above 13 ppm. We estimate that 4.4% of the 24-hour exposures exceed the recommended shift-average NWCG 2012 guideline for CO of 8 ppm and are 95% confident that this percentage does not exceed 9.1%

Respirable Particulate. The average highest exposure to respirable particulate was 0.90 mg/m^3 and could be as high as 1.3 mg/m^3 (95th percentile upper confidence limit). We estimate that 33% of exposures exceed the NWCG RMC recommended exposure of 1.0 mg/m3 and are 95% confident that this percentage does not exceed 54%.

Crystalline Silica. The average highest exposure to crystalline silica was 0.21 mg/m^3 and could be as high as 0.36 mg/m^3 (95th percentile upper confidence limit). We estimate that 43% of exposures exceed the OSHA PEL of 0.1 mg/m3 and are 95% confident that this percentage does not exceed 63%.

Prescribed Natural Fire Summary
Table 10 provides the results from the analysis for prescribed natural fires from 2009-2011 (*n*=83). The average shift duration on these fires was 13:33 (hh:mm) with a maximum of 16:30 and minimum of 6:24. The average fireline duration was 10:14 with a maximum of 14:00 and minimum of 4:00. These data have no censored data. The statistically-estimated exposures are estimates based on the number of samples and the variability in the actual data.

The highest average 1-minute exposure value provides the peak exposure level for each firefighter on every shift. This is a good value to compare against the IDLH standard. The average highest (1-minute average) CO exposure at prescribed natural fires was 137 ppm, but this average could be as high as 205 ppm (95th percentile upper confidence limit). The highest 1-minute CO exposure measured was 371 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 257 ppm, and we are 95% confident that fewer than 5% of firefighters would have 1-minute exposures above 801 ppm. We estimate that 1.4% of the 1-minute exposures exceed the OEL of 1,200 ppm (IDLH) and are 95% confident that this percentage does not exceed 3.2%.

The average highest 5-minute CO exposure at prescribed natural fires was 92 ppm, and the average could be as high as 158 ppm (95th percentile upper confidence limit). The highest measured 5-minute exposure was 166 ppm. Based on the exposure data, 5% of the exposures were found to be higher than 121 ppm, and we are 95% confident that fewer than 5% of firefighters would have 5-minute exposures above 588 ppm. We estimate that 9.2% of the 5-minute exposures exceeded this 5-minute OEL of 200 ppm and are confident that this percentage does not exceed 14%.

The average highest 8-hour TWA CO exposure at prescribed natural fires was 33 ppm, which is less than any of the OELs that could be adopted, but the average could be as high as 92 ppm (95th percentile upper confidence limit). The highest observed 8-hour TWA exposure was 45 ppm, which is above the REL and TLV. Based on the exposure data, 5% of the exposures were found to be higher than 28 ppm, and we are 95% confident that fewer than 5% of firefighters would have 8-hour exposures above169 ppm. We estimate that between 7.2% and 12% of the 8-hour exposures exceed the relevant 8-hour OELs at prescribed natural fires, ranging from 7.2% of exposures exceeding the 50 ppm PEL to 12% exceeding the 25 ppm TLV®. We are confident that these percentages do not exceed 12% to 17%, respectively.

The average highest shift-average CO exposure at prescribed natural fires was 17 ppm and could be as high as 46 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 26 ppm. Based on the exposure data, 5% of the shift-average exposures were found to be higher than 17 ppm, and we are 95% confident that fewer than 5% would have shift average exposures above 93 ppm. We estimate that 11% of the shift average exposures at prescribed natural fires exceed the recommended shift-average NWCG 2012 guideline for CO of 16 ppm and are 95% confident that this percentage does not exceed 16%.

The average highest 24-hour-average CO exposure at prescribed natural fires was 13 ppm and could be as high as 37 ppm (95th percentile upper confidence limit). The highest measured shift-average CO exposure was 17 ppm. Based on the exposure data 5% of the shift-average exposures were found to be higher than 11 ppm, and we are 95% confident that fewer than 5% of firefighters would have 24-hour exposures above 65 ppm. We estimate that 13% of the 24-hour exposures at prescribed natural fires exceed the recommended shift-average NWCG 2012 guideline for CO of 8 ppm and are 95% confident that this percentage does not exceed 18%.

Respirable Particulate. The average highest exposure to respirable particulate was 0.30 mg/m^3 and could be as high as 0.42 mg/m^3 (95th percentile upper confidence limit). We estimate that 6.3% of exposures exceed the NWCG RMC recommended exposure of 1.0 mg/m^3 and are 95% confident that this percentage does not exceed 26%.

Crystalline Silica. The average highest exposure to crystalline silica was 0.01 mg/m^3 and could be as high as 0.01 mg/m^3 (95th percentile upper confidence limit). We estimate that 0% of exposures exceed the OSHA PEL of 0.1 mg/m^3 and are 95% confident that this percentage does not exceed 17%.

Table 10. Statistical summaries for prescribed natural fire (T.Reinhardt)

	Maximum Carbon Monoxide Exposures (in parts per million)							Maximum Fireline-Average Respirable Particulate Exposures (in milligrams per cubic meter)	
Statistic	**1-Minute Average**	**5-Minute Average**	**8-Hour Average**	**8-Hour Average**	**8-Hour Average**	**Shift (13-hr) Average**	**24-Hour Average**	**Respirable Particulate (Smoke)**	**Respirable crystalline silica**
Exposure Limit	**1200**	**200**	**50**	**35**	**25**	**16**	**8**	**1.0**	**0.1**
Exposure Limit Source	NIOSH IDLH	NIOSH Ceiling, State STEL	OSHA PEL	State PEL	State PEL, ACGIH TLV, NIOSH REL	NWCG 2012 Guideline	NWCG 2012 Guideline	NWCG Risk Management Committee	OSHA & State PEL
EX (mean)	137	92	33	33	33	17	13	0.29	0.01
EX.LCL	91	54	12	12	12	6.6	4.6	0.19	0.01
EX.UCL	205	158	92	92	92	46	37	0.45	0.02
KM.mean	87	43	6.2	6.2	6.2	3.8	2.3	0.30	0.01
KM.LCL	71	35	4.5	4.5	4.5	2.7	1.6	0.18	0.01
KM.UCL	102	50	8.0	8.0	8.0	4.8	3.0	0.42	0.01
Xp.obs (95^{th} %)	257	121	28	28	28	17	11	0.81	0.02
Xp (95^{th} %)	523	354	81	81	81	46	31	0.78	0.02
Xp.LCL	342	213	39	39	39	22	15	0.42	0.02
Xp.UCL	801	588	169	169	169	93	65	1.46	0.03
Maximum	371	166	45	45	45	26	17	1.04	0.02
Geometric mean	44	19	1.1	1.1	1.1	0.71	0.40	0.21	0.01
GSD (unitless)	4.5	6.0	14	14	14	13	14	2.2	1.5
n (# of obs)	83	83	83	83	83	83	83	16	16
Nondetect (%)	3.6	3.6	3.6	3.6	3.6	3.6	3.6	44	38
f (% > OEL)	1.4	9.2	7.2	9.3	12	11	13	2.5	0
f.LCL (%)	0.55	5.7	4.2	5.7	7.6	7.0	8.5	0.22	0
f.UCL (%)	3.2	14	12	14	17	16	18	15	0.15
fnp (% > OEL)	0	0	0	1.2	8.4	7.2	9.6	6.3	0
fnp.LCL (%)	0	0	0	0.06	4.0	3.2	5.0	0.3	0
fnp.UCL (%)	3.5	3.5	3.6	5.6	15	14	17	26	17

Fire summary data
Table 11 provides a summary of exposure by fire type. Although a small estimate, project fires and prescribed natural fires show the highest incidence of firefighters exceeding the 1-minute NIOSH IDLH OEL. This pattern is repeated for the 5-minute NIOSH ceiling and through each relevant OEL. It could be that the cause of firefighters exceeding the longer-term exposures is a direct result of the short-term exposures.

As can be seen in Table 11, estimated exposures are higher for prescribed natural fires. These fires are managed for resource benefit and often burn for a very long time, in some cases several months. It appears that firefighters are experiencing higher exposures on these fires and simultaneously they are experiencing them for longer periods. Fire managers must consider the risk to firefighter exposure when making decisions on long-term fire management strategies.

The NWCG 2012 guidelines were developed from the interim OELs recommended by the SETG. These OELs are especially important to consider because they acknowledge that wildland smoke contains numerous human irritants, several of which target the same organs. Therefore, in order to provide for the safety of wildland firefighters, the shift and 24-hour CO exposures must be carefully monitored. Based on the exposure data, wildland firefighters are exceeding these OELs at each fire type. Most notably, on project fires and prescribed natural fires the estimate for 24-hour exposure is 12% and 13% but could be as high as 14% and 18%, respectively. This could put wildland firefighters at increased risk for both short-term and long-term health and safety consequences.

Overhead Exposure (2012)
Of note, there was only one instance of the 41 overhead positions monitored that exceeded any of the OELs evaluated. In this case the firefighter was actually running a chainsaw, which is not a typical work assignment for overhead personnel. The individual in this case, an Engine Boss trainee, was the only person on the crew who was qualified to operate the saw.

Based on the overall results from the overhead data, it appears that our hypothesis that exposure to smoke declines as individuals advance in their careers may be correct.

VII. RECOMMENDATIONS

Although other hazards of wildland firefighting – snags, heat stress, rolling materials, driving, fatigue, etcetera – must be considered while managing for smoke exposure, inhalation hazards must be considered in the overall risk management process.

As we have seen, many researchers have made recommendations to wildland fire management agencies. These recommendations fall into two general categories: the need for additional exposure data and methods to minimize exposure. Many of these recommendations are consistent from study to study.

Table 11. Exposures by Fire Type

	% Exceeding 1-Minute (NIOSH 1200 ppm)	%Exceeding 5-minute (NIOSH 200 ppm)	% Exceeding 8-Hour OSHA 50 ppm, (NIOSH 35 ppm)	% Exceeding Shift (NWCG 16 ppm)	% Exceeding 24-Hour (NWCG 8 ppm)
Fire Type					
Project	1.1[1] (1.7)[2]	8.9 (11)	5.6, 10.7 (7.2, 13)	11 (13)	12 (14)
Prescribed NF	1.4 (3.2)	9.2 (14)	7.2, 12 (12, 17)	11 (16)	13 (18)
Prescribed Fire	0.15 (0.55)	6.7 (11)	3.5/8.8 (6.5, 14)	9 (14)	9.5 (14)
Initial Attack	0.2 (0.9)	4.1 (8.2)	1.5, 3.9 (5.8, 9.1)	3.1 (7.0)	4.4 (9.1)

[1] Maximum likelihood estimate
[2] 95th percentile upper confidence limit

Recommendations on data needs:

- Increase the sample size of exposure data
- Expand the geographic area of samples
- Expand the data to include the many activities that firefighters engage in
    - Holding, high-exposure situations, initial attack, fuel types, ICPs, prescribed fires
- Measure crystalline silica.

Recommendations for mitigation and training:

- Minimize mop-up
- Develop a medical surveillance program
- Rotate crews to clean air
- Develop wildland fire-specific OELs
- Train firefighters on smoke hazards.

Despite the many recommendations made in the past, there appears to be no documented evidence that these recommendations have been implemented by formal direction or policy from the USFS. Smoke exposure and the associated hazards are not required components of firefighter training through all the basic and intermediate levels of wildland firefighting training requirements (Hyde et al. 2011). Not until an individual reaches the intermediate level of the prescribed fire program is there serious mention of smoke exposure. At this junction the focus is on ambient air quality, smoke monitoring for public exposure/view sheds, and NAAQS requirements.

In the spring of 2012, recommendations were provided to the RMC to close Task Statement 2008-4. The recommendations were based on the preliminary analysis from this study and were developed to reduce exposures and provide guidance for additional actions by NWCG member agencies. These recommendations were presented to the NWCG Executive Leadership Team which distributed the NWCG Memorandum: NWCG #006-2012, titled “Monitoring and Mitigating Exposure to Carbon Monoxide and Particulates at Incident Base Camps.” This document provides “recommendations” to reduce exposure but does not constitute official direction from any member agency.

In June of 2012 I was told to write a briefing paper for the USFS on firefighter smoke exposure and to include recommendations to mitigate exposure. This briefing paper was to be reviewed and approved by the USFS FAM management officials to be used to develop policy for the USFS. To date, this paper has not been acted on. As was the case with the recommendations from Reinhardt and Ottmar (1997, 2000) and Sharkey et al. (1997), the USFS has not developed an official policy to mitigate exposure or develop training for wildland firefighters on the health effects of wildland smoke.

Firefighter safety is always the stated primary objective at all fires, wildland or prescribed. However, when smoke exposure is discussed and, as we have seen, presents a hazard to firefighters, the agency appears to be reluctant to adequately address this issue.

One plausible explanation for this lack of action is upper level managements' unwillingness to assume risk and thereby transfers that risk to firefighters. Agency leadership, whether District Rangers, Forest Supervisors, Regional Foresters, and Washington Office employees, have to date placed firefighter inhalation safety below concerns expressed by other groups. When faced with public, media, or appointed/elected officials concerns about wildland fire smoke, agency administrators' typical response is to throw more manpower at the fire. Even when the fire may pose no threat to the public and in fact may be beneficial to the land, full containment and extensive mop-up is often ordered, even demanded. Wildland smoke may present hazards to the general public and be temporarily inconvenient, but agency managers who have a clear responsibility to their employees often place the employees' health and safety below other concerns. I have witnessed many times and heard numerous accounts from firefighters who are asked to mop-up areas far inside the line only to reduce smoke to distant communities even though that smoke presents no danger to the fire escaping the control lines. Firefighters and aerial resources (pilots) are often sent on search and destroy missions to put out a smoke far interior of the fireline because someone is concerned about it. Mop-up standards should be guided by two simple measures: whether it is deep enough to keep the fire from escaping and short enough to provide the maximum protection for firefighters. Not until agency administrators are willing to stand up to the public, elected officials, or whomever and make it clear that firefighter safety truly is their first concern can this exposure be mitigated.

Regardless of the lack of action, the USFS is legally required under 29 CFR 1960 Section 1960.30 to "ensure the prompt abatement of unsafe and unhealthful conditions."

Smoke Monitoring Plan

One of the recommendations I made, as did many others, was to implement a long-term smoke monitoring plan. I have been tasked with this as a new project for FY2013. This plan will provide guidance on random sampling of firefighters and incident personnel. It will be a statistically-based monitoring plan to determine whether exposures are being lowered, remaining the same, or increasing over the long-term. This plan will include a component to assess whether the other recommendations in NWCG Memo #006-2012 are being implemented and effective. It will be important to determine if the recommended OELs for CO (8 ppm/24 hours and 16 ppm/13 hour shift) are being met. The plan will provide guidance on mitigation and actions to take when exposures reach a critical level. Guidance for incident base camp monitoring and critical exposure levels will also be included. Additional elements of the plan will include the necessary equipment, field protocols, training, and logistics necessary to implement the monitoring.

A comprehensive smoke monitoring plan is needed to help increase firefighter and incident personnel safety. Although the plan will be written, there will be a cost to implement it. Trained observers and equipment will be needed to measure exposures at the designated frequency. However, it remains to be seen if the USFS will fund and implement this plan. As Aldrich (Sharkey et al., 1997) makes clear, in order to be effective there must be a commitment from all personnel from the highest level to the firefighters on the line.

Training

Every line-qualified firefighter is required to take the Wildland Fire Safety Training Annual Refresher (WFSTAR) each year to maintain his/her qualifications. I will be involved in developing a module for the WFSTAR training for 2014. This module will provide a brief synopsis of the hazards of wildland smoke and an overview of the findings of this study, specifically areas of concern and methods to decrease exposure.

The most important aspect required to decrease exposure and protect firefighter health will be to make agency administrators and management accept their responsibility to their employees. Education and training can provide them with the knowledge of the hazards and actions they can take.

Mop-Up

Reducing the amount of time firefighter's mop-up will be crucial to reducing their exposure to CO, PM4 and SiO_2. During the four years of this study, I had many opportunities to observe firefighters engaged in mop-up. One observation that I made, which was corroborated by many of the other assessment personnel, was that firefighters often exceed the stated mop-up objectives. There are two obvious causes for this. First, when a crew completes the mop-up assignment, the individual responsible for the crew or the division supervisor often tells them to extend the mop-up depth. This is often done in order to "keep the crew busy," not because there is an operational or safety need. Crew leaders, division supervisors, and other overhead personnel must understand that this only places firefighters at increased risk of exposure to the many hazards of mop-up. Once crews accomplish their mission, if there are no other immediate needs and concerns, supervisors should provide them time to rest and prepare for the next assignments or they can be repositioned to other areas of the fire where they are needed.

The second cause appears to be the "can-do" attitude of wildland firefighters. These men and women are proud and dedicated, so when a mission is accomplished they freely go beyond the necessary requirements in an effort to make their section of the line better than the rest. Both of these causes must be addressed in training. When crews are engaged in mop-up, they must understand that more is not better; more is potentially more dangerous.

Instituting Interim OELs

The briefing paper that was submitted in June of 2012 included the recommendation that the USFS adopt the SETG interim OELs for CO exposure. Currently this has not been accepted. If and when it is, an active management plan must be adopted to ensure these OELs are being met. In addition to "accepting" these OELs, the agency must implement the monitoring plan cited above to ensure they are being met.

Career Exposure

I am currently working through the past 10 years of dispatch records from the National Interagency Coordination Center. These records provide the name of each crew that was ordered to a fire assignment, the crew's estimated time of arrival, estimated time of departure, travel times, etcetera. Some of these files contain over 10,000 rows of data, each of which needs to be reviewed for errors, inconsistencies, redundancies etcetera. Eventually these data will be used to determine the average number of days crews spend on large fires each year and be extrapolated to use in determining career length exposure risk. The

SETG will continue to work with the data from this study and other relevant research to determine if there is any increased risk to wildland firefighters.

VIII. CONCLUSIONS

Bullock et al. (2006) described seven steps of an assessment strategy. The Wildland Firefighter Study was designed to follow each of the steps relevant to the study, and successfully completed steps 1-4 and 7:

1. An exposure assessment plan was written and followed
2. Characterization of the workplace and workforce was done
3. Exposure assessment was completed
4. Additional information on health effects is continuing with the Smoke Exposure Task Group, and ongoing communication of the findings and data maintenance.

7. Communication of the findings has begun as presentations have been given at several federal agency meetings and additional presentations are scheduled. Data maintenance is also ongoing.

Health hazard controls for unhealthy exposures have been recommended to NWCG and the USFS (step 5). Upon completion of the Smoke Monitoring Plan, reevaluation of exposures will continue as outlined in step 6.

A Sea Change

Throughout the four years of this study, I have had the opportunity to work with many wildland firefighters and Incident Management Teams. This study could not have been completed without their support and assistance. There was one consistent theme I heard repeatedly: this is great work, it's about time, and thanks for doing this. Firefighters and IMT personnel not only supported the work, they encouraged it and unequivocally provided and offered any support I or the other assessment personnel required. In many cases they were willing to go beyond any reasonable level of support to ensure we were able to accomplish our work.

The support and interest in this study makes it clear that firefighters and managers realize there is a need to fully understand the level of exposure, any risk they may face, and a strong desire to mitigate and minimize any harmful exposure. These are the men and woman who will eventually benefit most from this study and who will be critical in making the changes necessary to significantly reduce exposure.

As the results of this study are shared with these individuals, they will be empowered to enforce mitigation strategies and communicate the reasoning to higher-level agency employees.

Education is an essential component in creating change. However, change must become important to USFS line officers; they must fully support the change strategy and be willing to "take the heat" from other sectors of society. Once they understand the risk of smoke inhalation, they must be committed to accepting their role as leaders. Overcoming the obstacles these managers face in making change will require a close look at the issues and concerns that have created and allowed the USFS to disregard the recommendations made by many respected professionals in the past.

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APPENDICES

APPENDIX A. FIELD DATA COLLECTION FORMS

Form 1

CO - PM - Form One

Incident - IMT - Information		
		Date:

SDTDC Crew Leader:	
SDTDC Crew Members:	

Equipment Kit Number:	

Incident Information:

Fire Name:	
Fire Number:	
ICP Phone #:	
ICP Location	
Complexity Level:	

Incident Management Team:

Team Name:	
Incident Commander	*Name:*
	Email:
	Phone:
Deputy IC	*Name:*
	Email:
	Phone:
Safety Officer	*Name:*
	Email:
	Phone:
Operations Section Chief	*Name:*
	Email:
	Phone:
Operations Section Chief	*Name:*
	Email:
	Phone:
Point of Contact	*Name:*
	Email:
	Phone:

Fire Locations:

State(s):	
Ownership(s):	

Form 2

CO - PM - Form Two

Fire Crew Information

Date:

Fire Name:				
Crew Name:		**#Crew Members:**		
Crew Type:	□ I □ I (IHC) □ II □ II (IA)	□ Agency □ Contract	□ Dozer	□ Engine
Home Unit:				
Crew Superintendent Engine Captain	*Name:*			
	Email:			
	Phone:			
Captain/Forman Engine Operator	*Name:*			
	Email:			
	Phone:			
Captain/Forman Engine Operator	*Name:*			
	Email:			
	Phone:			

Years Experience*	**# of Crew**	**Qualifications****	**# Years**
1 - 2 Years		Superintendent	
3 - 5 Years		Asst. Sup./Captain	
6 - 10 Years		Engine Operator	
11 - 15 Years		Squad boss	
16 + Years		Squad boss	
		Squad boss	
		Squad boss	
		Other	

*Years Experience: List number of crew members by years of experience on this type of crew.

**Qualifications: List number of years the individual has been qualified and actively engaged in this position. Include years with other crews, not just current crew.

Number of days on Current Assignment:	
Number of assignments this season:	
Number of days on assignments this year:	

Form 3

CO - PM - Form Three					
Daily Fire Crew Report:					
			Date:		
Fire Crew Name:					
Fire Name:					
Operational Period (Time on Shift)					
Time on Shift:			End of Shift:		
Pre/Post Fireline Activity:			**Activity Description:**		
#	Start:	End:	10	Briefing	
			11	Driving	
			12	Hiking	
			13	Lunch Break	
			14	Transition Break	
			15	Rest Break	
			16	Operational Break	
			17	Safety Break	
			18	Retool	
			19	Preparation	
			20	Other	
			21	Other-Travel	
GPS File Name:					
Notes					

Form 4

CO Dosimeter - IH Pump Start/End - Form Four				
Date:		**Location:**		
Fire Name				
Crew Name				
CO - PM Exposure Monitoring Data				
FF Name:			**Age**	**Yrs Exp**
Dos. ID:	**Log Time**	**Time**	**COHb**	**%SpO2**
Color				
Log Start				
Log Stop				
FF Smoke Assessment: None N-Very Little Low Mod High VH				
IH Pump ID				
Filter Number				
Cyclone ID				
Battery ID				
Calibrator ID				
PreFlow Rate				
Pump Start				
Pump Stop				
Minute Display				
PostFlow Rate				
L Level	☐ **L 1**	☐ **L 2**		
PM	☐ **4**	☐ **2.5**	☐ **1**	
Flow rate: PM 2.5 = 1.5 Lpm Calibration limit: 1.47 - 1.53				
Flow rate: PM 4 = 1.05 Lpm Calibration limit: 1.029 - 1.071				
Field Blank ID:				
Pump Start			Pump Start	
Pump Stop			Pump Stop	
Notes:				

Form 4 B

CO Dosimeter - Start/End - Form Four B				
Date:		**Location:**		
Fire Name				
Crew Name				
CO - PM Exposure Monitoring Data				
FF Name:			**Age**	**Yrs Exp**
Dos. ID:	**Log Time**	**Time**	**COHb**	**%SpO2**
Color				
Log Start				
Log Stop				
Notes:				
FF Smoke Assessment: None N-Very Little Low Mod High VH				
CO - PM Exposure Monitoring Data				
FF Name:			**Age**	**Yrs Exp**
Dos. ID:	**Log Time**	**Time**	**COHb**	**%SpO2**
Color				
Log Start				
Log Stop				
Notes:				
FF Smoke Assessment: None N-Very Little Low Mod High VH				

Activity Codes

Fire Activity Codes			
1.1	Handline.Direct.Scratch	2.1	Handline.Indirect.Scratch
1.5	Handline.Direct.Saw yer	2.5	Handline.Indirect.Saw yer
1.7	Handline.Direct.Sw amper	2.7	Handline.Indirect.Sw amper
1.8	Handline.Direct.Engine	2.8	Handline.Indirect.Engine
1.9	Handline.Direct.Pump	2.9	Handline.Indirect.Pump
1.10	Handline.Direct.Squad	2.10	Handline.Indirect.Squad
1.11	Handline.Direct.Firefigher	2.11	Handline.Indirect.Firefighter
1.12	Handline.Direct.Wet Mop Up	2.12	Handline.Direct.Dry Mop Up
1.13	Handline.Direct.Dozer Boss	2.13	Handline.Indirect.Dozer Boss
3.1	Dozer Line.Direct	7	Line Preparation
3.2	Dozer Line.Indirect	7.1	Initial Attack
4	Cold Trailing	8.1	ICP.Stationary
		8.2	ICP.Supply
5.1	Improving.Direct	8.3	ICP.Ground
5.2	Improving.Indirect	8.4	ICP.Other
		9.1	Rx.Lighter
6.1	Holding.Direct	9.2	Rx.Holder
6.2	Holding.Indirect	9.3	Rx.Burn Boss
6.3	Holding.Firefighter	9.4	Suppression.Lighter
6.4	Holding.Squad	9.5	Suppression.Holder
6.5	Holding.Engine	9.6	Suppression.Burnboss
6.6	Engine.Pump.Operator	9.7	Rx Fire Effects Monitor
6.7	Holding.Pump	0	Smoke Mitigation
Non-Fire Activity Types			
10	Briefing	16	Operational Break
11	Driving	17	Safety Break
12	Hiking	18	Retool
13	Lunch Break	19	Preparation
14	Transition Break	20	Other
15	Rest Break	21	Other-Travel
Crew Types			
1	I - Force Account		
2.1	II - Force Account	3.1	II(IA) - Force Account
2.2	II - Contract	3.2	II(IA) - Contract

Activity Codes continued

Fire Activity Codes - Overhead Positions			
1.14	Planning Meeting Camp		
1.15	Planning Meeting Direct	**2.15**	Planning Meeting Indirect
1.16	Scouting (ground) Direct	**2.16**	Scouting (ground) Indirect
1.17	Reconnaissance (air)		
1.18	Administrative Camp		
1.19	Administrative Direct	**2.19**	Administrative Indirect
Non-Fire Activity Types			
21	Other		
	- Incident within an Incident		
	- Medivac		
	- Injury		
	- Traffic/Vehicle Accident		
	- Structure Protection		

Form 7

CO - PM Hourly Observation - Form Seven

Fire Name:			Record # _______ of _______
Crew Name:			
# of Crew Online:			**Fire Behavior:**
Date:			☐ **Smoldering**
Start Time:			☐ **Surface**
Fuel Model (13):			☐ **Torching**
Inversion Present	☐ **Yes**	☐ **No**	☐ **Crowning**
Slope %(+ / -):			☐ **Spotting**
Up/Downwind	☐ **Up**	☐ **Down**	
Temp:			**Flame Height:**
RH:			☐ **0-2 FT**
Wind Speed:			☐ **2-4 FT**
Wind Dir:			☐ **>4 FT**
Slope Aspect:			
Canopy %:			**Fire Activity:**
Barometic Pres.			☐ **Backing**
UpHill/DownHill	☐ **Up**	☐ **Down**	☐ **Head**
End Time:			☐ **Flank**

Dosimeter ID/color		**Activity**	**Start**	**End**

Image Time / Dos ID		**Smoke Level**
		☐ **NS** ☐ **VL** ☐ **L** ☐ **M** ☐ **H** ☐
		☐ **NS** ☐ **VL** ☐ **L** ☐ **M** ☐ **H** ☐
		☐ **NS** ☐ **VL** ☐ **L** ☐ **M** ☐ **H** ☐
		☐ **NS** ☐ **VL** ☐ **L** ☐ **M** ☐ **H** ☐
		☐ **NS** ☐ **VL** ☐ **L** ☐ **M** ☐ **H** ☐

Crew Mitigation Measures - Notes

Form 8

CO Monitoring 15 Minute Weather - Form Eight

Fire Name:		Record # ________ of ________	
Crew Name:		**Fire**	**Slash:**
Firefigher Name:		☐ **Crowning**	☐ **Heavy**
Date:		☐ **Torching**	☐ **Moderate**
Start Time:		☐ **Spotting**	☐ **Light**
Dosimeter:		☐ **Ground**	
Task:			**Flame Height:**
Fuel Model:		**Brush**	☐ **0-1 FT**
Slope %:		☐ **0-2 FT**	☐ **2-4 FT**
Temp:		☐ **2-4 FT**	☐ **>4 FT**
RH:		☐ **4-6 FT**	
Slope Aspect:		☐ **>6 FT**	**Canopy:**
Elevation:			☐ **Open**
End Time:		**Fire Activity:**	☐ **Closed**
		☐ **Backing**	
		☐ **Head**	**Fuel Loading:**
		☐ **Flank**	☐ **Continuous**

Imaging Reference #s:

Notes:

15 Minute Weather:

	0		**15**
Smoke Con		Smoke Con	
Wind Dir		Wind Dir	
Wind Speed		Wind Speed	
Downwind		Downwind	
Upwind		Upwind	
Downhill		Downhill	
Uphill		Uphill	

	30		**45**
Smoke Con		Smoke Con	
Wind Dir		Wind Dir	
Wind Speed		Wind Speed	
Downwind		Downwind	
Upwind		Upwind	
Downhill		Downhill	
Uphill		Uphill	

Form 10

CO Monitoring Datalogger Calibration - From 10					
Date:					
Fire Name:					
Dos ID	**Time**	**NIST***	**Pass**	**Fail**	**Name**
Notes:					
***NIST A:** Lot 561155 Cyl 22 Test # 822/272801-06, 822/274081-06, 13641, 12618A, 13181A, 12604A					
NIST C: Lot 614696 Cyl 28 Test # 822/272801-06, 822/274081-06, 12617A, 13641, 13161A, 13162A, 12618A					
NIST D: Lot 1166342 Cyl 24					
NIST E: Lot 1166342 Cyl 19					

Data Collection Summary

Parameter	Totals	R1*	R2	R3	R4	R5	R6	R8	R10
Days of Observations	**200**	6	25	50	22	45	20	29	3
Wildland Fires	**57**	2	10	5	5	9	6	19	1
Prescribed Fires	**23**	0	0	14	3	2	0	4	0
States	**17**	1	3	2	2	1	2	5	1
Crew Observations	**160**	4	11	44	7	60	21	7	6
Engine Observations	**40**	0	0	12	6	3	2	17	0
Dozer Observations	**20**	0	0	0	0	0	5	15	0
Overhead Observations	**41**	2	17	0	9	0	7	6	0
Individual Overhead Positions	**15**	-	-	-	-	-	-	-	-
Firefighters Observed	**667**	14	50	172	62	190	86	76	17
ICPs/Spike Camps Observed	**81**	4	16	24	15	2	20	0	0
Crew Shift Hours	**2098.26**	54.00	143.93	549.72	74.45	820.45	298.32	68.97	88.42
Engine Shift Hours	**503.24**	0.00	0.00	138.55	85.57	42.00	30.75	206.37	0.00
Dozer Shift Hours	**251.61**	0.00	0.00	0.00	0.00	0.00	57.88	193.73	0.00
Overhead Shift Hours	**572.75**	32.00	252.93	0.00	123.93	0.00	85.88	78.00	0.00
Log Hours	**9072.35**	252.25	918.67	2381.32	923.72	2054.43	1460.13	861.72	220.12
FF Log Hours	**7517.47**	174.78	626.63	1924.03	647.97	2017.88	1044.33	861.72	220.12
ICP/Spike Camp Log Hours	**1554.88**	77.47	292.03	457.28	275.75	36.55	415.80	0.00	0.00
Crew Log Hours	**5394.73**	148.48	394.93	1460.98	312.68	1955.07	812.45	90.02	220.12
Engine Log Hours	**1252.32**	0.00	0.00	463.05	226.58	62.82	87.15	412.72	0.00
Dozer Log Hours	**479.50**	0.00	0.00	0.00	0.00	0.00	120.52	358.98	0.00
Overhead Log Hours	**531.53**	26.30	231.70	0.00	108.70	0.00	78.85	85.98	0.00
Particulate Matter Hours	**3361.15**	156.05	575.07	1139.35	553.90	124.67	615.28	196.83	0.00

*USFS Region

APPENDIX B. Master MS Excel Workbook

Incident Information (Worksheet 1)

Incident Information	
Date:	
SDTDC Crew Leader:	
SDTDC Crew Members:	
Equipment Kit Number:	1
Fire Name:	
Fire Number:	
ICP Phone #:	
ICP Location:	
Complexity Level:	
GPS File Name:	

Shift	**Start**	**End**	**Total**
Total Shift:	6:30	19:30	13:00

Fireline	**Start**	**End**	**Total**
Total Time:	7:49	19:20	11:31

Incident Management Team	
Team Name:	
Incident Commander:	
Deputy IC:	
Safety Officer:	
Division Supervisor:	
Division Supervisor:	
Operations Section Chief:	
Operations Section Chief:	
Point of Contact:	

Fire Location	
State(s):	Arizona, New Mexico
Ownership(s):	USFS, State & Private

Fire Crew Information (Worksheet 2)

Fire Crew Information			
Date:			
Fire Name:	0		
Crew Name:			
# of Crew Members:	21		
		Agency or Contract	**Dozer or Engine**
Crew Type:	I (IHC)	Agency	
Home Unit:			
Crew Superintendent	*Name:*		
	Email:		
Engine Captain	*Phone:*		
Captain/Forman	*Name:*		
	Email:		
Engine Operator	*Phone:*		
Captain/Forman	*Name:*		
Engine Boss	*Email:*		
Engine Operator	*Phone:*		

Years Experience*	**# of Crew**
1 - 2 Years	8
3 - 5 Years	6
6 - 10 Years	6
11 - 15 Years	1
16 + Years	

Number of days on Current Assignment:	4
Number of assignments this season:	2
Number of days on assignments this year:	28

Worksheet 2 continued

Qualifications**	# Years
Superintendent	14
Asst. Sup./Captain	11
Asst. Sup./Captain	9
Squad boss	
Squad boss	
Squad boss	
Squad boss	
Other	

CO-PM Exposure Monitoring Data (Worksheet 3)

Dosimeter 1 ID	Fire Fighter Name		Yrs Exp	Time	COHb	%SpO2
3D			5	7:48	1	96
Smoke Assessment:				12:24	4	97
Log Start:	6:00	**Log Stop:**	19:22	18:38	1	95

Dosimeter 2 ID	Fire Fighter Name		Yrs Exp	Time	COHb	%SpO2
3J			6	7:48	0	97
Smoke Assessment:				12:24	3	95
Log Start:	6:00	**Log Stop:**	19:21	18:37	1	92

Dosimeter 3 ID	Fire Fighter Name		Yrs Exp	Time	COHb	%SpO2
3H			7	7:48	0	97
Smoke Assessment:				12:15	4	96
Log Start:	6:00	**Log Stop:**	19:22	18:37	1	96

Dosimeter 4 ID	Camp Name		
3E	ICP		
Smoke Assessment:			
Log Start:	0:00	**Log Stop:**	22:25

Fire Fighter Name:		0	**Fire Fighter Name:**		ICP
IH Pump ID	1B		**IH Pump ID**	1A	
Filter Number	168360		Filter Number	188241	
Cyclone ID	1C		Cyclone ID	1D	
Battery ID	1B		Battery ID	1A	
Calibrator ID	1A		Calibrator ID	1A	
PreFlow Rate	1.0463		PreFlow Rate	1.0463	
PostFlow Rate	1.1506		PostFlow Rate	1.056	
% Difference	-9.50		% Difference	-0.92	
Pump Start	7:47		Pump Start	6:21	☐ Add 24 Hours to Stop Time
Pump Stop	19:20		Pump Stop	22:24	
Calculated Min.	693		Calculated Min.	963	
Minute Display	693		Minute Display	964	
Average Flow Rate	1.09845		Average Flow Rate	1.05115	
Volume	761.22585	Enter "<" below if ND:	Volume	1012.25745	Enter "<" below if ND:
PM (mg/m3):	**1.349**		PM (mg/m3):	**0.098**	<
Silica (mg/m3):	**0.049**		Silica (mg/m3):	**0.005**	<
PM	4		PM	4	

Field Blank ID:	188206

User Format (Worksheet 4, partial)

Activity				Fire Information				Environment Information												Fire Information			Smoke Level				Activity
Activity	Dosimeter ID	Start Time	End Time	Record	Start Time	End Time	Number of Crewmembers	Fuel Model	Inversion Present?	Slope	Up/Downwind	Temp	RH	Wind Speed	Wind Direction	Slope Aspect	Canopy	Barometric Press	Up/Downhill	Fire Behavior	Flame Height (ft)	Fire Activity	Record	Dosimeter ID	Image Ref #	Smoke Level	Total Time
10	All	6:30	7:19	-	-	-	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0:49
11	All	7:19	7:27	-	-	-	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0:08
10	All	7:27	7:49	-	-	-	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0:22
1.5	3J	7:49	8:49	1.1	7:49	8:49	21	10	No	25	Downwind	68	11	1-2	South-East	West	50	22	Downhill	Smoldering	0-2 FT	Backing	1	3J,3D	8:09	L	1:00
1.7	3D	7:49	8:49	1.2	7:49	8:49	21	10	No	25	Downwind	68	11	1-2	South-East	West	50	22	Downhill	Smoldering	0-2 FT	Backing	1	3H	8:07	VL	1:00
2.12	3H	7:49	8:49	1.3	7:49	8:49	21	10	No	25	Downwind	68	11	1-2	South-East	West	50	22	Downhill	Smoldering	0-2 FT	Backing	1	3J,3D	8:13	L	1:00
12	3J,3D	8:49	9:03	2.1	8:49	9:49	21	10	No	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	1	3H	8:14	L	0:14
2.12	3H	8:49	9:49	2.2	8:49	9:49	21	10	No	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	1	3J,3D	8:28	L	1:00
15	3J,3D	9:03	9:15	2.3	8:49	9:49	21	10	No	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	1	3H	8:36	NS	0:12
2.12	3J,3D	9:15	9:35	2.4	8:49	9:49	21	10	No	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	1	3H	8:38	NS	0:20
15	3J,3D	9:35	9:49	2.5	8:49	9:49	21	10	No	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	1	3J,3D	8:42	VL	0:14
12	3J,3D	9:49	9:53	3.1	9:49	10:49	21	10	No	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	2	9:03	3J,3D	L	0:04
2.12	3H	9:49	10:49	3.2	9:49	10:49	21	10	No	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	2	9:21	3J,3D	L	1:00
14	3J,3D	9:53	9:56	3.3	9:49	10:49	21	10	No	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	2	9:22	3J,3D	L	0:03
2.12	3J,3D	9:56	10:49	3.4	9:49	10:49	21	10	No	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	2	9:32	3H	VL	0:53
2.12	3H	10:49	11:49	4.1	10:49	11:49	21	10	No	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	2	-	-	-	1:00
12	3J,3D	10:49	11:00	4.2	10:49	11:49	21	10	No	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	3	9:58	3J,3D	L	0:11
15	3J,3D	11:00	11:10	4.3	10:49	11:49	21	10	No	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	3	10:10	3J	L	0:10
2.12	3J,3D	11:10	11:49	4.4	10:49	11:49	21	10	No	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	3	10:22	3J,3D	L	0:39
2.12	3J,3D	11:49	12:15	5.1	11:49	12:49	21	2	No	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	3	10:30	3H	VL	0:26
2.12	3H	11:49	12:00	5.2	11:49	12:49	21	2	No	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	3	10:31	3D	L	0:11
13	3H	12:00	12:30	5.3	11:49	12:49	21	2	No	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	4	10:49	3J,3D	L	0:30
13	3J,3D	12:15	12:45	5.4	11:49	12:49	21	2	No	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	4	11:05	3H	VL	0:30
2.12	3H	12:30	12:49	5.5	11:49	12:49	21	2	No	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	4	11:26	3J,3D	VL	0:19
2.12	3J,3D	12:45	12:49	5.6	11:49	12:49	21	2	No	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	4	11:41	3J,3D	VL	0:04
2.12	3J,3D	12:49	13:49	6.1	12:49	13:49	21	2	-	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	5	11:55	3J,3D	L	1:00
2.12	3H	12:49	13:11	6.2	12:49	13:49	21	2	-	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	5	-	-	-	0:22
12	3H	13:11	13:17	6.3	12:49	13:49	21	2	-	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	5	-	-	-	0:06
14	3H	13:17	13:49	6.4	12:49	13:49	21	2	-	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	5	-	-	-	0:32
14	3H	13:49	14:05	7.1	13:49	14:49	21	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	5	-	-	-	0:16
2.12	3J,3D	13:49	14:00	7.2	13:49	14:49	21	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	5	-	-	-	0:11
14	3J,3D	14:00	14:15	7.3	13:49	14:49	21	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	6	12:59	3J,3D	L	0:15
2.12	3H	14:05	14:49	7.4	13:49	14:49	21	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	6	13:06	3J,3D	L	0:44
2.12	3J,3D	14:15	14:49	7.5	13:49	14:49	21	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	6	13:07	3H	VL	0:34
2.12	All	14:49	15:32	8.1	14:49	15:49	21	10	No	25	Downwind	77	7	2-4	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	6	13:21	3J,3D	L	0:43
2.12	3J,3D	15:32	15:49	8.2	14:49	15:49	21	10	No	25	Downwind	77	7	2-4	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	6	13:39	3D	L	0:17
15	3H	15:32	15:49	8.3	14:49	15:49	21	10	No	25	Downwind	77	7	2-4	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	6	13:45	3J,3D	L	0:17
2.12	All	15:49	16:45	9.1	15:49	16:49	21	10	No	25	-	75	6	2-3	North-West	North-West	50	21.94	Downhill	Surface	0-2 FT	Backing	7	14:19	3D	VL	0:56
15	All	16:45	16:49	9.2	15:49	16:49	21	10	No	25	-	75	6	2-3	North-West	North-West	50	21.94	Downhill	Surface	0-2 FT	Backing	7	14:25	3J	L	0:04
15	All	16:49	16:55	10.1	16:49	17:49	21	10	No	25	Upwind	71	8	1-2	North-West	North-West	50	21.94	-	Smoldering	0-2 FT	Backing	7	14:39	3H	L	0:06

Analysis Format (Worksheet 5, partial)

Fire ID	Julian.Date	Crew Type	Record. Num	Activity Type	Start Time (hr)	Start Time (min)	# of Crewmembers	Inversion Present?	Fuel Model	Slope (%)	Up/Downwind	Temp (°F)	RH (%)	Wind Speed (mph)	Wind Dir	Slope Aspect	Canopy (%)	Barametric Pressure (in-Hg)	Up/Down hill	Fire Behavior	Flame Height (ft)	Fire Activity	Stop Time (hr)	Stop Time (min)	Total Time (hr)	Total Time (min)
010000_0_	-36525	I (IHC)	-	10	6	30	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	19	0	49
010000_0_	-36525	I (IHC)	-	11	7	19	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	27	0	8
010000_0_	-36525	I (IHC)	-	10	7	27	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	49	0	22
010000_0_	-36525	I (IHC)	1.1	1.5	7	49	21	No	10	25	Downwind	68	11	1-2	South-East	West	50	22	Downhill	Smoldering	0-2 FT	Backing	8	49	1	0
010000_0_	-36525	I (IHC)	1.2	1.7	7	49	21	No	10	25	Downwind	68	11	1-2	South-East	West	50	22	Downhill	Smoldering	0-2 FT	Backing	8	49	1	0
010000_0_	-36525	I (IHC)	1.3	2.12	7	49	21	No	10	25	Downwind	68	11	1-2	South-East	West	50	22	Downhill	Smoldering	0-2 FT	Backing	8	49	1	0
010000_0_	-36525	I (IHC)	2.1	12	8	49	21	No	10	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	9	3	0	14
010000_0_	-36525	I (IHC)	2.2	2.12	8	49	21	No	10	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	9	49	1	0
010000_0_	-36525	I (IHC)	2.3	15	9	3	21	No	10	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	9	15	0	12
010000_0_	-36525	I (IHC)	2.4	2.12	9	15	21	No	10	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	9	35	0	20
010000_0_	-36525	I (IHC)	2.5	15	9	35	21	No	10	25	Downwind	70	8	1-3	South-West	North	50	22.01	Downhill	Smoldering	0-2 FT	Backing	9	49	0	14
010000_0_	-36525	I (IHC)	3.1	12	9	49	21	No	10	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	9	53	0	4
010000_0_	-36525	I (IHC)	3.2	2.12	9	49	21	No	10	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	10	49	1	0
010000_0_	-36525	I (IHC)	3.3	14	9	53	21	No	10	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	9	56	0	3
010000_0_	-36525	I (IHC)	3.4	2.12	9	56	21	No	10	70	Upwind	69	8	6-8	South-East	North-East	50	21.98	-	Smoldering	0-2 FT	Backing	10	49	0	53
010000_0_	-36525	I (IHC)	4.1	2.12	10	49	21	No	10	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	11	49	1	0
010000_0_	-36525	I (IHC)	4.2	12	10	49	21	No	10	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	11	0	0	11
010000_0_	-36525	I (IHC)	4.3	15	11	0	21	No	10	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	11	10	0	10
010000_0_	-36525	I (IHC)	4.4	2.12	11	10	21	No	10	5	Downwind	70	8	3-5	South-East	West	50	21.95	Downhill	Smoldering	0-2 FT	Backing	11	49	0	39
010000_0_	-36525	I (IHC)	5.1	2.12	11	49	21	No	2	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	12	15	0	26
010000_0_	-36525	I (IHC)	5.2	2.12	11	49	21	No	2	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	12	0	0	11
010000_0_	-36525	I (IHC)	5.3	13	12	0	21	No	2	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	12	30	0	30
010000_0_	-36525	I (IHC)	5.4	13	12	15	21	No	2	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	12	45	0	30
010000_0_	-36525	I (IHC)	5.5	2.12	12	30	21	No	2	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	12	49	0	19
010000_0_	-36525	I (IHC)	5.6	2.12	12	45	21	No	2	5	Downwind	74	7	3-5	Variable	South-West	50	21.9	-	Smoldering	0-2 FT	Backing	12	49	0	4
010000_0_	-36525	I (IHC)	6.1	2.12	12	49	21	-	2	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	13	49	1	0
010000_0_	-36525	I (IHC)	6.2	2.12	12	49	21	-	2	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	13	11	0	22
010000_0_	-36525	I (IHC)	6.3	12	13	11	21	-	2	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	13	17	0	6
010000_0_	-36525	I (IHC)	6.4	14	13	17	21	-	2	10	-	77	7	3-5	South	West	50	21.93	-	Smoldering	0-2 FT	Backing	13	49	0	32
010000_0_	-36525	I (IHC)	7.1	14	13	49	21	No	10	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	14	5	0	16
010000_0_	-36525	I (IHC)	7.2	2.12	13	49	21	No	10	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	14	0	0	11
010000_0_	-36525	I (IHC)	7.3	14	14	0	21	No	10	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	14	15	0	15
010000_0_	-36525	I (IHC)	7.4	2.12	14	5	21	No	10	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	14	49	0	44
010000_0_	-36525	I (IHC)	7.5	2.12	14	15	21	No	10	25	Downwind	77	7	3-5	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	14	49	0	34
010000_0_	-36525	I (IHC)	8.1	2.12	14	49	21	No	10	25	Downwind	77	7	2-4	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	15	32	0	43
010000_0_	-36525	I (IHC)	8.2	2.12	15	32	21	No	10	25	Downwind	77	7	2-4	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	15	49	0	17
010000_0_	-36525	I (IHC)	8.3	15	15	32	21	No	10	25	Downwind	77	7	2-4	North-West	North-West	40	21.93	Downhill	Surface	0-2 FT	Backing	15	49	0	17
010000_0_	-36525	I (IHC)	9.1	2.12	15	49	21	No	10	25	-	75	6	2-3	North-West	North-West	50	21.94	Downhill	Surface	0-2 FT	Backing	16	45	0	56
010000_0_	-36525	I (IHC)	9.2	15	16	45	21	No	10	25	-	75	6	2-3	North-West	North-West	50	21.94	Downhill	Surface	0-2 FT	Backing	16	49	0	4
010000_0_	-36525	I (IHC)	10.1	15	16	49	21	No	10	25	Upwind	71	8	1-2	North-West	North-West	50	21.94	-	Smoldering	0-2 FT	Backing	16	55	0	6

Definitions (Worksheet 6)

Fire Activity Codes			
1.1	Handline.Direct.Scratch	**2.1**	Handline.Indirect.Scratch
1.5	Handline.Direct.Saw yer	**2.5**	Handline.Indirect.Saw yer
1.7	Handline.Direct.Sw amper	**2.7**	Handline.Indirect.Sw amper
1.8	Handline.Direct.Engine	**2.8**	Handline.Indirect.Engine
1.9	Handline.Direct.Pump	**2.9**	Handline.Indirect.Pump
1.10	Handline.Direct.Squad	**2.1**	Handline.Indirect.Squad
1.11	Handline.Direct.Firefigher	**2.11**	Handline.Indirect.Firefighter
1.12	Handline.Direct.Dry Mop Up	**2.12**	Handline.Direct.Wet Mop Up
1.13	Handline.Direct.Dozer Boss	**2.13**	Handline.Indirect.Dozer Boss
3.1	Dozer Line.Direct	**7**	Line Preparation
3.2	Dozer Line.Indirect	**7.1**	Initial Attack
4	Cold Trailing	**8.1**	ICP.Stationary
		8.2	ICP.Supply
5.1	Improving.Direct	**8.3**	ICP.Ground
5.2	Improving.Indirect	**8.4**	ICP.Other
6.1	Holding.Direct	**9.1**	Rx.Lighter
6.2	Holding.Indirect	**9.2**	Rx.Holder
6.3	Holding.Firefighter	**9.3**	Rx.Burn Boss
6.4	Holding.Squad	**9.4**	Suppression.Lighter
6.5	Holding.Engine	**9.5**	Suppression.Holder
6.6	Engine.Pump.Operator	**9.6**	Suppression.Burnboss
6.7	Holding.Pump	**0**	Smoke Mitigation
Non-Fire Activity Types			
10	Briefing	**16**	Operational Break
11	Driving	**17**	Safety Break
12	Hiking	**18**	Retool
13	Lunch Break	**19**	Preparation
14	Transition Break	**20**	Other
15	Rest Break	**21**	Other-Travel
Crew Types			
1	I - Force Account		
2.1	II - Force Account	**3.1**	II(IA) - Force Account
2.2	II - Contract	**3.2**	II(IA) - Contract

Master Exposure Data (Worksheet 7 partial)

		Dosimeter 1	3D							Dosimeter 2	3J							Dosimeter 3	3H							Dosimeter 4	3E				
Daily Index Time	Dos. time	CO (ppm)	CO peak	Temp (C)	CO 5 min. (ppm)	CO 8 hr (ppm)	Peak events	Activity	Dos. time	CO (ppm)	CO peak	Temp (C)	CO 5 min. (ppm)	CO 8 hr (ppm)	Peak events	Actvity	Dos. time	CO (ppm)	CO peak	Temp (C)	CO 5 min. (ppm)	CO 8 hr (ppm)	Peak events	Actvity	Dos. time	CO (ppm)	CO peak	Temp (C)	CO 5 min. (ppm)	CO 8 hr (ppm)	Peak events
15:20	15:20	18	34	28	12.8	13.40		2.12	15:20	7	16	28	3.4	14.58		2.12	15:20	18	32	29	13.8	7.21		2.12	15:20	0	0	28	0	0.08	
15:21	15:21	9	17	28	12.2	13.42		2.12	15:21	3	10	28	3.2	14.58		2.12	15:21	12	19	29	12.4	7.24		2.12	15:21	0	0	28	0	0.08	
15:22	15:22	7	9	28	11.2	13.43		2.12	15:22	2	8	28	2.4	14.59		2.12	15:22	11	19	29	11.8	7.26		2.12	15:22	0	0	28	0	0.08	
15:23	15:23	6	9	28	10.8	13.44		2.12	15:23	0	0	28	2.4	14.59		2.12	15:23	7	9	29	11.2	7.28		2.12	15:23	0	0	28	0	0.08	
15:24	15:24	12	18	28	10.4	13.47		2.12	15:24	0	0	28	2.4	14.59		2.12	15:24	6	9	29	10.8	7.29		2.12	15:24	0	0	28	0	0.08	
15:25	15:25	9	11	28	8.6	13.49		2.12	15:25	0	0	28	1	14.59		2.12	15:25	9	12	29	9	7.31		2.12	15:25	0	8	28	0	0.08	
15:26	15:26	7	11	28	8.2	13.50		2.12	15:26	4	11	28	1.2	14.60		2.12	15:26	7	11	29	8	7.32		2.12	15:26	0	6	28	0	0.08	
15:27	15:27	10	16	28	8.8	13.52		2.12	15:27	10	15	28	2.8	14.62		2.12	15:27	24	32	29	10.6	7.37		2.12	15:27	0	0	28	0	0.08	
15:28	15:28	6	10	28	8.8	13.54		2.12	15:28	11	13	28	5	14.64		2.12	15:28	18	26	29	12.8	7.41		2.12	15:28	0	0	28	0	0.08	
15:29	15:29	4	10	25	7.2	13.54		2.12	15:29	4	9	25	5.8	14.65		2.12	15:29	9	16	27	13.4	7.43		2.12	15:29	0	0	28	0	0.08	
15:30	15:30	2	12	25	5.8	13.55		2.12	15:30	2	9	25	6.2	14.65		2.12	15:30	9	12	27	13.4	7.45		2.12	15:30	0	0	28	0	0.08	
15:31	15:31	10	19	25	6.4	13.57		2.12	15:31	13	19	25	8	14.68		2.12	15:31	17	24	27	15.4	7.48		2.12	15:31	0	0	28	0	0.08	
15:32	15:32	0	7	25	4.4	13.57		2.12	15:32	1	7	25	6.2	14.68		2.12	15:32	9	19	27	12.4	7.50		2.12	15:32	0	0	28	0	0.08	
15:33	15:33	12	17	25	5.6	13.59		2.12	15:33	11	16	25	6.2	14.70		2.12	15:33	12	20	27	11.2	7.53		15	15:33	0	0	28	0	0.08	
15:34	15:34	17	21	25	8.2	13.63		2.12	15:34	16	21	25	8.6	14.73		2.12	15:34	19	24	27	13.2	7.56		15	15:34	0	0	28	0	0.08	
15:35	15:35	11	16	25	10	13.64		2.12	15:35	14	21	25	11	14.76		2.12	15:35	15	24	27	14.4	7.58		15	15:35	0	0	29	0	0.08	
15:36	15:36	5	9	25	9	13.65		2.12	15:36	5	11	25	9.4	14.77		2.12	15:36	15	22	27	14	7.61		15	15:36	0	0	29	0	0.08	
15:37	15:37	7	9	25	10.4	13.66		2.12	15:37	3	8	25	9.8	14.78		2.12	15:37	11	13	27	14.4	7.63		15	15:37	0	0	29	0	0.08	
15:38	15:38	10	16	25	10	13.68		2.12	15:38	9	14	25	9.4	14.80		2.12	15:38	12	16	27	14.4	7.64		15	15:38	0	0	29	0	0.08	
15:39	15:39	3	10	25	7.2	13.69		2.12	15:39	2	10	25	6.6	14.80		2.12	15:39	10	13	27	12.6	7.66		15	15:39	0	0	29	0	0.08	
15:40	15:40	3	9	25	5.6	13.69		2.12	15:40	4	11	25	4.6	14.81		2.12	15:40	6	10	27	10.8	7.68		15	15:40	0	0	29	0	0.08	
15:41	15:41	7	19	25	6	13.71		2.12	15:41	4	12	25	4.4	14.82		2.12	15:41	7	12	27	9.2	7.69		15	15:41	0	0	29	0	0.08	
15:42	15:42	9	16	25	6.4	13.73		2.12	15:42	9	16	25	5.6	14.84		2.12	15:42	12	22	27	9.4	7.72		15	15:42	0	0	29	0	0.08	
15:43	15:43	6	11	25	5.6	13.74		2.12	15:43	3	11	25	4.4	14.84		2.12	15:43	9	20	27	8.8	7.74		15	15:43	0	0	29	0	0.08	
15:44	15:44	5	11	25	6	13.75		2.12	15:44	6	11	25	5.2	14.85		2.12	15:44	13	18	27	9.4	7.76		15	15:44	0	0	29	0	0.08	
15:45	15:45	2	6	29	5.8	13.75		2.12	15:45	0	9	26	4.4	14.85		2.12	15:45	3	10	24	8.8	7.77		15	15:45	0	0	29	0	0.08	
15:46	15:46	0	0	29	4.4	13.75		2.12	15:46	3	16	26	4.2	14.86		2.12	15:46	7	19	24	8.8	7.78		15	15:46	0	0	29	0	0.08	
15:47	15:47	2	10	29	3	13.76		2.12	15:47	3	13	26	3	14.87		2.12	15:47	17	26	24	9.8	7.82		15	15:47	0	0	29	0	0.08	
15:48	15:48	2	10	29	2.2	13.76		2.12	15:48	50	187	26	12.4	14.97		2.12	15:48	30	52	24	14	7.88		15	15:48	0	0	29	0	0.08	
15:49	15:49	9	50	29	3	13.78		2.12	15:49	13	31	26	13.8	15.00		2.12	15:49	11	21	24	13.6	7.90		15	15:49	0	0	29	0	0.08	
15:50	15:50	12	60	29	5	13.81		2.12	15:50	1	9	26	14	15.00		2.12	15:50	13	19	24	15.6	7.93		2.12	15:50	0	0	29	0	0.08	
15:51	15:51	7	15	29	6.4	13.82		2.12	15:51	9	13	26	15.2	15.02		2.12	15:51	17	23	24	17.6	7.97		2.12	15:51	0	0	28	0	0.08	
15:52	15:52	8	12	29	7.6	13.84		2.12	15:52	10	14	26	16.6	15.04		2.12	15:52	27	39	24	19.6	8.02		2.12	15:52	0	0	28	0	0.08	
15:53	15:53	2	6	29	7.6	13.84		2.12	15:53	4	8	26	7.4	15.05		2.12	15:53	13	21	24	16.2	8.05		2.12	15:53	0	0	28	0	0.08	
15:54	15:54	0	7	29	5.8	13.84		2.12	15:54	0	0	26	4.8	15.05		2.12	15:54	13	18	24	16.6	8.07		2.12	15:54	0	0	28	0	0.08	
15:55	15:55	6	12	29	4.6	13.85		2.12	15:55	7	10	26	6	15.06		2.12	15:55	14	20	24	16.8	8.10		2.12	15:55	0	0	28	0	0.08	
15:56	15:56	3	8	29	3.8	13.86		2.12	15:56	2	7	26	4.6	15.07		2.12	15:56	17	26	24	16.8	8.14		2.12	15:56	0	0	28	0	0.08	
15:57	15:57	3	11	29	2.8	13.87		2.12	15:57	2	11	26	3	15.07		2.12	15:57	7	18	24	12.8	8.15		2.12	15:57	0	0	28	0	0.08	
15:58	15:58	7	9	29	3.8	13.88		2.12	15:58	9	20	26	4	15.09		2.12	15:58	10	18	24	12.2	8.16		2.12	15:58	0	0	28	0	0.08	
15:59	15:59	24	51	29	8.6	13.93		2.12	15:59	33	67	26	10.6	15.16		2.12	15:59	7	11	24	11	8.18		2.12	15:59	0	0	28	0	0.08	
16:00	16:00	0	6	29	7.4	13.93		2.12	16:00	0	7	26	9.2	15.16		2.12	16:00	7	22	24	9.6	8.19		2.12	16:00	0	0	28	0	0.07	
16:01	16:01	4	0	0	7.6	13.94		2.12	16:01	3	18	27	9.4	15.16		2.12	16:01	8	20	22	7.8	8.21		2.12	16:01	0	0	28	0	0.07	
16:02	16:02	8	17	29	8.6	13.96		2.12	16:02	9	18	27	10.8	15.18		2.12	16:02	14	25	22	9.2	8.24		2.12	16:02	0	0	28	0	0.07	
16:03	16:03	10	15	29	9.2	13.98		2.12	16:03	12	15	27	11.4	15.21		2.12	16:03	15	25	22	10.2	8.27		2.12	16:03	0	0	28	0	0.07	
16:04	16:04	14	18	29	7.2	14.01		2.12	16:04	9	13	27	6.6	15.23		2.12	16:04	19	26	22	12.6	8.31		2.12	16:04	0	0	28	0	0.07	
16:05	16:05	11	17	29	9.4	14.03		2.12	16:05	0	7	27	6.6	15.22		2.12	16:05	16	22	22	14.4	8.33		2.12	16:05	0	0	28	0	0.06	
16:06	16:06	0	6	29	8.6	14.02		2.12	16:06	0	0	27	6	15.15		2.12	16:06	10	15	22	14.8	8.34		2.12	16:06	0	0	28	0	0.06	

Occupational Exposure Metrics (Worksheet 8)

Insert Activity

Fire Date:	1/0/1900
Fire Name:	
Crew Name:	
Crew Type:	I (IHC)

		Shift Dur.	Fireline Dur.	Log Dur.	Activity
Dosimeter ID 1:	3D				
Firefighter Name 1:		13:00	11:31	13:22	Direct Swamper,Cold Trailing,Wet Mop Up
Shift Start 1:	6:30				
Log Start 1:	6:00				
Fireline Start:	7:49				
Fireline Stop:	19:20				
Log Stop 1:	19:22				
Shift Stop 1:	19:30				

CO Data						Time	Time	Activity	Activity
24-Hr CO	Shift CO	Fireline CO	Max 8-hr CO	Max 5-min CO	Max 1-min CO	5-min Max	1-min Max	5-min Max	1-min Max
5.0	9.2	10.4	14.0	86.8	127	8:36	8:36	1.7	1.7

PM Start:	PM Finish:	PM mg/m³:	PM size:	Quartz mg/m³:	CO PPM:	Quartz %	Sil.Mix PEL mg/m³
7:47	19:20	1.349	4	0.049	10.32756	3.6	1.8

		Shift Dur.	Fireline Dur.	Log Dur.	Activity
Dosimeter ID 2:	3J				
Firefighter Name 2:		13:00	11:31	13:21	Direct Swamper,Cold Trailing,Wet Mop Up
Shift Start 2:	6:30				
Log Start 2:	6:00				
Fireline Start:	7:49				
Fireline Stop:	19:20				
Log Stop 2:	19:21				
Shift Stop 2:	19:30				

CO Data						Time	Time	Activity	Activity
24-Hr CO	Shift CO	Fireline CO	Max 8-hr CO	Max 5-min CO	Max 1-min CO	5-min Max	1-min Max	5-min Max	1-min Max
5.4	9.9	11.2	15.2	123.4	158	8:32	8:36	1.5	1.5

PM Start:	PM Finish:	PM mg/m³:	PM size:	Quartz mg/m³:	CO PPM:	Quartz %	Sil.Mix PEL mg/m³
7:47	19:20	1.35	4	0.049	11.16739	3.6	1.8

		Shift Dur.	Fireline Dur.	Log Dur.	Activity
Dosimeter ID 3:	3H				
Firefighter Name 3:		13:00	11:31	13:22	Cold Trailing,Wet Mop Up
Shift Start 3:	6:30				
Log Start 3:	6:00				
Fireline Start:	7:49				
Fireline Stop:	19:20				
Log Stop 3:	19:22				
Shift Stop 3:	19:30				

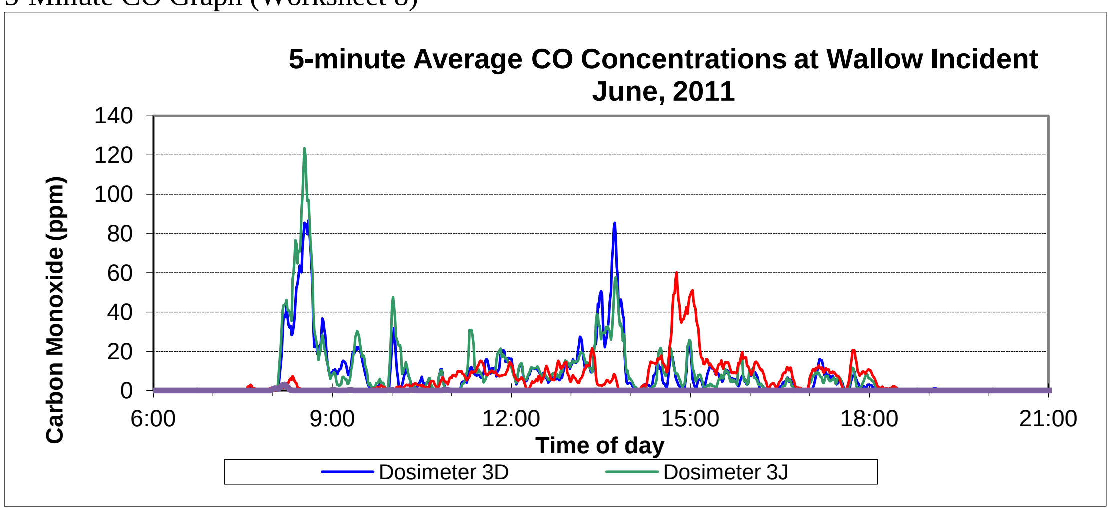
CO Data						Time	Time	Activity	Activity
24-Hr CO	Shift CO	Fireline CO	Max 8-hr CO	Max 5-min CO	Max 1-min CO	5-min Max	1-min Max	5-min Max	1-min Max
3.4	6.3	7.1	9.9	60.2	76	14:46	14:42	2.12	2.12

		Log Dur.
ICP ID:	3E	
Camp Name:	ICP	22:25
Log Start:	0:00	
Log Stop:	22:25	

CO Data				Time	Time
24-Hr CO	Max 8-hr CO	Max 5-min CO	Max 1-min CO	5-min Max	1-min Max
0.03	0.08	3.2	5	8:12	8:12

PM Start:	PM Finish:	PM mg/m³:	PM size:	Quartz mg/m³:	CO PPM:	Quartz %	Sil.Mix PEL mg/m³
6:21	22:24	< 0.098	4	< 0.005	0.041537	5.1	1.4

5-Minute CO Graph (Worksheet 8)



1- and 5-Minute Maximum Environmental Information (Worksheet 9)

	Fuel Model-1 min	Inversion-1	Slope-1	Up/Downwind-1	Temp-1	RH-1	Windspeed-1	Wind Direction-1	Slope Aspect-1	Canopy-1	Up/Downhill-1	Fire Behavior-1	Flame Height-1	Observer Smoke-1	Photo-1
FireFighter 1	10	No	25	Downwind	68	11	1-2	South-East	West	50	Downhill	Smoldering	0-2 FT	8:28-L	8:28-3J,3D
FireFighter 2	10	No	25	Downwind	68	11	1-2	South-East	West	50	Downhill	Smoldering	0-2 FT	8:28-L	8:28-3J,3D
FireFighter 3	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	Downhill	Surface	0-2 FT	14:39-L	14:39-3H

	Fuel Model-5	Inversion-5	Slope-5	Up/Downwind-5	Temp-5	RH-5	Windspeed-5	Wind Direction-5	Slope Aspect-5	Canopy-5	Up/Downhill-5	Fire Behavior-5	Flame Height-5	Observer Smoke-5	Photo-5
FireFighter 1	10	No	25	Downwind	68	11	1-2	South-East	West	50	Downhill	Smoldering	0-2 FT	8:28-L	8:28-3J,3D
FireFighter 2	10	No	25	Downwind	68	11	1-2	South-East	West	50	Downhill	Smoldering	0-2 FT	8:28-L	8:28-3J,3D
FireFighter 3	10	No	25	Downwind	77	7	3-5	North-West	North-West	40	Downhill	Surface	0-2 FT	14:39-L	14:39-3H

MSA Periodic File (Worksheet 10, partial)

Date	CO		°C
	Avg	Peak	
8:26	62	109	20
8:27	74	115	20
8:28	64	101	20
8:29	64	116	20
8:30	101	147	20
8:31	91	198	20
8:32	107	199	20
8:33	60	210	21
8:34	64	131	21
8:35	76	166	21
8:36	127	205	21
8:37	72	145	21
8:38	25	42	21
8:39	16	32	21
8:40	30	92	21
8:41	15	27	21
8:42	25	43	21
8:43	36	81	21
8:44	16	40	21
8:45	0	0	21
8:46	24	50	21
8:47	38	60	21
8:48	25	60	21
8:49	59	109	21
8:50	38	102	21
8:51	17	43	21
8:52	17	33	21
8:53	11	21	21
8:54	14	25	21
8:55	11	30	21
8:56	1	10	21
8:57	6	10	21
8:58	9	20	21
8:59	19	28	21
9:00	11	17	21
9:01	7	18	21
9:02	4	16	21
9:03	13	24	21
9:04	8	12	21

APPENDIX C. PHOTO GALLERY

Winema IHC Rooster Rock Fire 090710 – Smoke and particulate exposure during mop up

Payson IHC 110410 – Lighter on prescribed fire

Wolf Creek IHC Rooster Rock Fire 080710 – Particulate exposure during hike

Texas FS Initial Attack 082111 – Particulate exposure during dozer operations

Baker River IHC Oak Flat Fire 082010 – CO dosimeter and cyclone for PM4 measurement

Black Eagle Crew, Grouse Fire YNP 063009 – Smoke and particulate exposure during mop-up

Roosevelt IHC Tumblebug Fire 092609 – Smoke exposure during inversion