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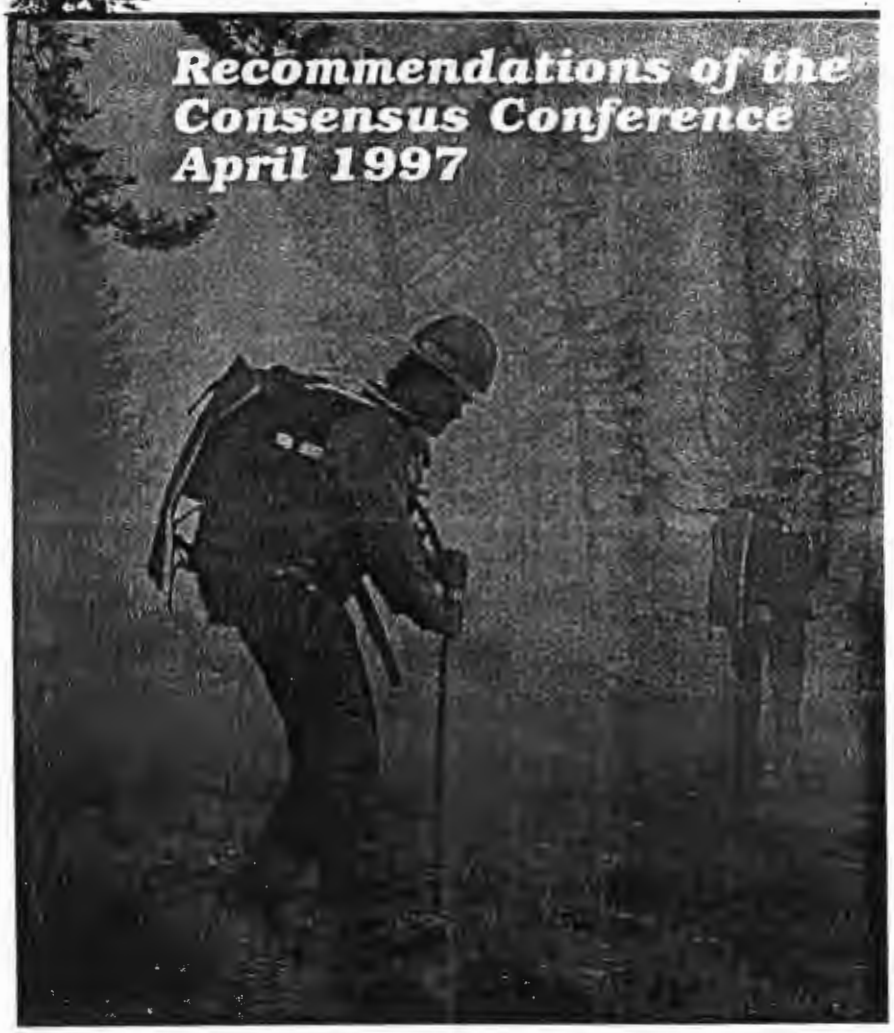
Health Hazards of Smoke

Recommendations of the Consensus Conference April 1997



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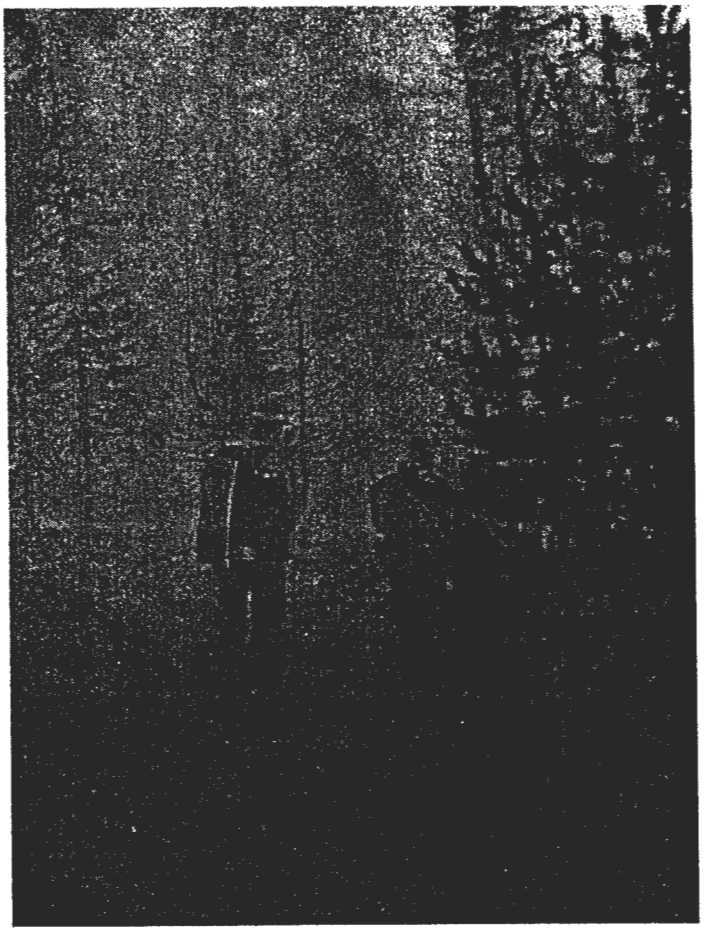
Summary



For decades, firefighters and fire managers have been concerned about the health effects of smoke from wildland and prescribed fires. Early research proved to be inconclusive. A 1985 survey of the fire community indicated that studying the health effects of smoke was not a high priority for fire managers. That position changed dramatically with the 1987 fires of northern California and the 1988 Yellowstone fires, when thousands of firefighters experienced respiratory problems. To address these concerns, the National Wildfire Coordinating Group (NWCG), related agencies, employee groups, and specialists in occupational medicine, industrial hygiene, toxicology, and risk management met in San Diego in 1989. They developed a study plan for determining the immediate and long-term effects of exposure to forest fire smoke.

The comprehensive plan proposed studies in the areas of emissions characterization, employee exposure, health effects, risk assessment, and risk management. NWCG assigned the Missoula Technology and Development Center (MTDC) to serve as the focal point for ongoing and future studies on the effects of wildland fire smoke on firefighters.

The Center convened a technical panel to help guide the project, to review and evaluate existing research, and to identify research and development priorities. The Center published a semiannual report to communicate findings and developments of the Health Hazards of Smoke project to firefighters, fire managers, researchers, regulatory agencies, organizations, and manufacturers.

In April 1997 a conference reviewed progress in each area of the study plan, and reached consensus on the elements of a risk management plan that could be implemented within the existing fire management structure. This document includes the papers presented at that conference and the recommendations for implementing the risk management plan.

In brief, participants concluded that toxic emissions were present in smoke, that the incidence of exposure in excess of Occupational Safety and Health Administration permissible exposure limits was relatively low (fewer than 5% of prescribed fire cases, even less for wildfire), and that documented health effects were moderate and often reversible. Recommendations for risk management include changes in training and tactics to further minimize exposures, and monitoring to increase awareness of smoke and to help limit exposure. Health maintenance recommendations are intended to prevent the spread of illness and ensure healthy immune function. Medical surveillance is needed to track exposures and further research is necessary to fill gaps in our understanding of emissions, exposure, and health effects.

Risk Management Plan: Conference Recommendations

In April 1997, the NWCG Safety and Health Working Team and MTDC sponsored a conference to review progress in each area of the study plan, and to reach consensus on the elements of a risk management plan. This document outlines the comprehensive risk management plan produced at that conference. While some elements of the risk management plan (health maintenance, training, and tactics) should be implemented immediately, others (monitoring) will require a phase-in period. The need for respiratory protection will require further study and development, pending the success of other elements of the program. Finally, certain research projects will receive immediate attention while the attention others receive will depend on program priorities and the availability of adequate funding.

Program Management

The basic authority for safety and health standards is mandated by the Department of Labor, Occupational Safety and Health Administration (OSHA). That authority is contained in documents including:

Occupational Safety and Health Act of 1970

Executive Order 12196, February 26, 1980

29 CFR 1910 Occupational Safety and Health Standards

29 CFR 1960 Basic Program Elements for Federal Employee Occupational Safety and Health Programs

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.

Studies of wildland firefighters indicate the potential for exposure to toxic by-products of combustion. While it is impossible to ensure complete safety in the wildland environment, management has the responsibility to ensure the health and safety of wildland firefighters.

Recommendations

• Develop an interagency Risk Management Plan for fire management activities.

• Develop occupational guidelines for use in field operations to manage employee exposure to the health hazards of smoke.

• Sponsor additional research to improve the understanding of the risks and effects of smoke on employee health based on the hazards and the risk assessment, and to determine the effectiveness of the risk management plan.

Training and Tactics

Exposure studies show that firefighters are sometimes exposed to levels of smoke that exceed OSHA permissible exposure limits. Improvements in training and tactics should further minimize opportunities for exposure.

Recommendations

Training

• Modules on the health hazards of smoke should be developed and included in courses for agency administrators and fire program managers.

• Include a segment on the health hazards of smoke in all appropriate fire training courses at the local, regional, and national levels.

• Develop a course to orient program administrators with responsibilities for implementing respiratory protection or smoke monitoring programs.

• Create a photo series that visually displays a range of smoke conditions and corresponding levels of carbon monoxide.

• Develop a wallet-sized reference card to aid visual recognition of different levels of smoke and carbon monoxide.

• Recommend that fire behavior analysts and safety officers include smoke considerations in their messages and briefings where appropriate.

• Prepare an orientation video suitable for all agency personnel, with emphasis on the effects of smoke on wildland firefighters and what firefighters and fire managers can do to avoid exposure.

Tactics: Wildfire

• Include smoke hazards on the ICS-215A worksheet at planning and briefing sessions.

• Use flank attack as opposed to head attack, where appropriate, in heavy smoke situations.

• Minimize mop-up when possible.

• Adjust operational periods on mop-up to avoid periods of inversion.

• Use time and patience instead of water to put the fire out: use burn piles, allow areas to burn themselves out. Rely on burn-up instead of mop-up.

• In heavy smoke conditions, give up acres to gain control.

• Fire behavior forecasts should discuss smoke and inversion potentials.

• Locate camps and incident command posts in areas that are not prone to inversions.

• Reduce dust by watering roads at the incident, on drier roads leading to the incident, and in the base camp area.

• Use minimum impact suppression techniques (MIST).

Tactics: Prescribed Fire

• Use equipment rather than people, when possible, in holding areas (sprinklers, foam, etc.).

• Design burn plans with "maximum allowable perimeter" to permit minor slopovers.

• Minimize mop-up whenever possible (consider regulatory conflicts regarding hazard tree removal, endangered species, and so forth in risk assessments for fire safety and health).

• Minimize snag falling, consistent with safety concerns, to avoid putting heavy fuels on the ground that will require mop-up.

• Change ignition times and firing patterns to minimize smoke impacts on lighters.

• Address smoke impacts in the job hazard analysis (JHA).

• Rotate personnel out of heavy smoke areas.

• Adjust prescriptions where possible to reduce smoke by providing more complete combustion.

Use visual reference materials and monitoring equipment to reinforce smoke training and tactics, and to document their impact on employee exposure.

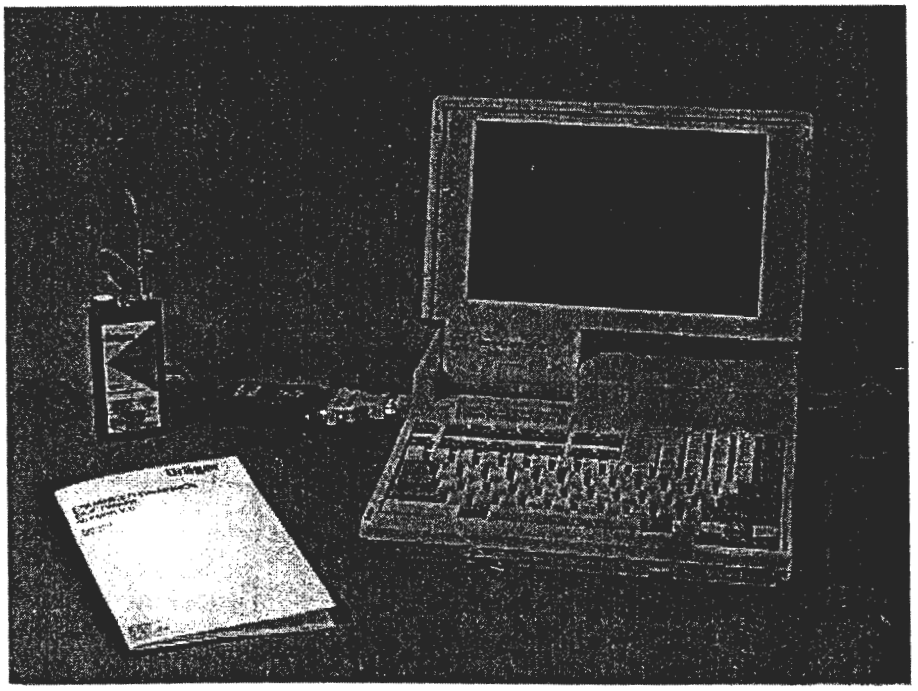
Monitoring

The working group proposed the following actions (in order of importance):

Electronic Dosimeter for CO Exposure Monitoring

A CO exposure monitoring program using electronic datalogging dosimeters is recommended. These relatively simple and inexpensive battery-powered instruments measure CO levels and display and store the data. Stored exposure data may be transferred to a computer at daily or weekly intervals. Each unit, about the size of a pack of cigarettes, is worn near the firefighter's breathing zone during the workshift. The unit weighs less than 8 ounces and costs less than $800. Using the USDA Forest Service as an example, the initial scale of the program is suggested to be on the order of 10 instruments per region, covering different types of crews, using one dosimeter per crew. Data collection would be primarily conducted by fire management or safety/health staff of each participating agency, after initial training. Data collection should employ a standard protocol that includes quality assurance steps so that data would be comparable within and among agencies and from year-to-year.

The program should begin with lab tests of models from potential vendors to establish their accuracy and precision of CO measurement in smoke matrix, then proceed to a field-test to



Carbon monoxide datalogger (left) linked to PC for data storage and analysis.

determine ease of use, ruggedness, effects of dust, water, and temperature and the effectiveness of radio-frequency shielding. Agencies could then negotiate lowest-cost bulk orders for approved models. With a year or two of logistical experience and phased implementation, the program could provide most crews with CO monitoring protection.

Monitoring should endeavor to limit employee exposure below a ceiling of 200 ppm CO and a maximum time-weighted average (TWA) of 25 ppm CO. This limit protects employees from respiratory particulate, formaldehyde, and acrolein as well as carbon monoxide by maintaining exposure levels below OSHA permissible exposure limits (PEL's).

Benefits of this action are:

- Lowest-cost and least-intrusive way to monitor smoke exposure (carbon monoxide is correlated with other hazards in smoke).

- Meets OSHA requirements for routine monitoring of the hazards found in smoke.

- Greatly increases hazard awareness; provides crews and managers with feedback about the hazards of smoke.

- Should provide rapid reduction of overexposure to smoke because of the instruments' alarm features.

- Collects data to define high-exposure and low-exposure situations for each region, tactic, and condition.

- Obtains broad baseline of CO exposure data from which to measure progress at controlling exposures.

- Allows respiratory irritant exposures to be estimated based on correlations of these irritants (formaldehyde, acrolein, and respirable particulate) to CO levels in smoke.

Particulate Matter Characterization

Fully characterize the chemical composition of particulate matter in smoke (both respirable and total particulate) by laboratory evaluation. The composition of particulate (amounts of organic and inorganic chemicals) would be evaluated by detailed chemical analysis. Smoke from unusual fuels from different regions would be cost-effectively compared in this way. Field verification of laboratory results would be necessary, but the lab evaluation will limit the cost of the field exposure assessment to those chemicals (if any) that pose a potential hazard to firefighters.

Benefits of this action are:

- Answers questions about toxic chemicals associated with particulate exposures and the unusual properties of smoke from certain vegetation fires (such as poison oak).

- Guides any further particulate matter exposure characterization in the field.

- May assist in establishing an occupational exposure criteria for smoke particles.

- May establish the link between health effects and exposures, especially by defining additional respiratory irritants in smoke.

- When combined with CO measurement, will better define the relationship between respiratory irritants and CO for field verification. Ultimately, correlations between irritants and CO may be used routinely to estimate exposure to a number of chemicals based on CO monitoring.

Reactive Gas Characterization

Comparative study of reactive gases in smoke should be accomplished using different measurement methods. The use the Fourier transform infrared spectrophotometer (FTIR) allows instantaneous measurements of such gases, yet results are not always in accordance with traditional sorbent-based methods. Side-by-side measurements of reactive gases (such as aldehydes) in smoke using different methods in a lab situation will define whether existing methods introduce biase or artifacts when measuring gase in smoke, and will identify poorl characterized gases for further exposure assessment in the fielc

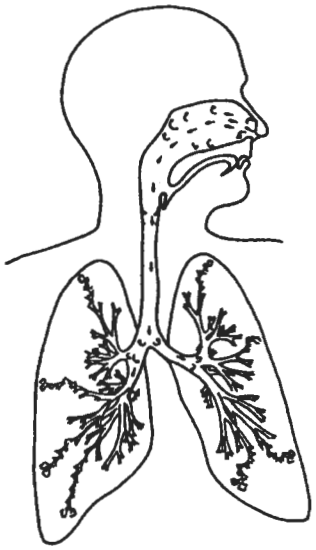
Benefits of this action are:

- Answers questions about toxic gases in smoke and unusual properties of smoke from certain vegetation fires (such as poison oak).

- Guides any further smoke exposure characterization in the field

- May explain the link between health effects and exposures, especially defining additional respiratory irritants in smoke.

• Will better define correlation between respiratory irritants and CO for field verification and ultimately, routine use of correlations to estimate multiple chemical exposure from CO measurement.



Health Maintenance

Analysis of data from medical aid stations at incidents indicates that 30 to 50% of reported visits were due to upper respiratory problems, defined as coughs, colds and sore throats (Vore, 1996). Upper respiratory problems may be due to exposure to smoke, or to exhaustion, stress, or poor nutrition, all of which suppress the immune system and increase the likelihood of upper respiratory infections. Steps should be taken to maintain the health of firefighters' immune systems and to avoid the spread of infection. These steps include but are not limited to the following recommendations.

Recommendations

Health Promotion

• Emphasize the importance of good health and fitness in all training.

• Monitor personnel for signs of fatigue and illness.

• Ensure that firefighters are properly equipped for anticipated conditions (cold nights, rain).

• Provide for good rest and sleeping conditions.

• Encourage a high fluid intake before, during, and after work for all personnel.

• Provide for adequate nutrition and supplements (e.g., antioxidants) if needed.

• Allow sick firefighters adequate time for recovery.

Health Maintenance

• Promote personal hygiene by providing washing facilities near food lines and toilets.

• Limit close contact among firefighters by providing personal sleeping tents.

• Discourage sharing of canteens except in emergencies.

• Encourage personnel to cover their mouth and nose when they cough or sneeze to avoid the spread of infection.

• When symptoms are "above the neck" (stuffy nose, sneezing, scratchy throat), it is safe to continue work. If symptoms include fever, aching muscles, nausea, or diarrhea, hard work should be reduced or curtailed.

• Segregate infected personnel when possible.

• Demobilize crews that have a large number of sick personnel.

• Consider the need for medical assistance when conditions at the incident are severe (e.g., numerous or severe respiratory problems, inversions in fire camps).

Health Video

All fire suppression personnel need to be informed about their role in health maintenance. The video should emphasize:

• Healthy Behaviors, such as washing before eating, not sharing canteens, and minimizing smoke exposure (including cigarettes).

• Physical Fitness is essential for firefighters to perform their arduous work and to adjust to environmental stressors such as heat and altitude. Fitness boosts the body's ability to fight illness and recover from injury. Physical exhaustion suppresses immune function and leads to upper respiratory infections.

• Rest and Sleep are essential for good performance and health. Locate camps in smoke-free areas, supply fire personnel with individual tents and quiet sleeping areas, and adhere to work/rest ratios.

• Nutrition, including energy, nutrients and water, is critical to performance and the function of the immune

system. Provide firefighters adequate energy by serving a variety of foods, including fresh fruits and vegetables; encourage attention to hydration (before, during, and after work); provide supplements, if necessary, to ensure health and performance.

• Stress Management techniques (e.g., relaxation, meditation) should be taught to personnel to help them cope with physical and emotional stresses that are known to suppress immune system function. All personnel should be aware of the different ways stress can affect health and safety and what they can do to minimize the problem.

Respiratory Protection

Respiratory protection should be considered only when other controls, such as training, tactics, and monitoring, fail to protect worker health and safety. It is hoped that monitoring will demonstrate that changes in training, tactics, and other elements of this program will further minimize the already low level of exposure (less than 5% of prescribed fire cases and a lower percentage of wildfire cases exceed OSHA permissible exposure limits). In the meantime, we propose developing a respiratory protection program and a limited pilot project using respirators for selected prescribed burning conditions. These measures would develop the capability to implement a large-scale respirator program, and serve the immediate needs of those working on prescribed fires.

Recommendations

Air-Purifying Respirators

Design and conduct a pilot test of respirator use for *prescribed fire*. Develop and field test a respiratory protection program that meets OSHA requirements (29 CFR 1910.134) (including medical evaluation, monitoring, medical surveillance, fit testing, training, maintenance, records, etc.).

• MTDC will complete a model respiratory protection program and distribute the program to field study sites on computer disks.

• Recommend a NIOSH-certified respirator with 95N multigas cartridges (95 indicates that the filter removes 95% of respirable particulate; N means the respirator is not resistant to oil; multigas indicates removal of organic vapors and acid gases; the cartridge does not remove carbon monoxide).

• Develop and test the training package required to support the respiratory protection program (medical and fit testing, training, maintenance, etc.).

• Establish performance criteria and tests (heat, flame resistance) for air-purifying respirators intended for use on prescribed and wildland fires.

Monitor Regulations and Products

MTDC will continue to monitor new regulations (NIOSH, OSHA) and products (respirators, monitors), and disseminate information as necessary.

New Product Development

If needed, develop, test, and seek NIOSH approval for a respirator designed specifically for the wildland firefighter (e.g., mouthpiece respirator).

Note: Removing carbon monoxid from the breathing air currently requires converting CO to CO_2 in an exothermic reaction. The process adds additional breathin resistance, increases respiratory work with the respiratory stimulus of carbon dioxide, and increases heat stress with the breathing of hot air. No device th is currently available effectively protects the worker from all the hazards in smoke.

Respirators should not be used unless a respiratory protection program is in effect.

Medical Surveillance and Research

A program of medical surveillance is needed to track firefighters' health. In addition, health-related research should be considered to determine the long-term effects of exposure to smoke. Emissions and exposure research should be completed to allow a full assessment of risk.

Recommendations

Medical Surveillance

Establish Baseline—Use a comprehensive, confidential questionnaire that covers medical history, smoking and other exposures (occupational, wood burning), symptoms, or respiratory problems (e.g., asthma, allergies) for all employees involved in wildland fire suppression.

Periodic Followup—Employ a schedule that includes periodic pulmonary function testing for continuing seasonal and career employees.

Research: Health Related

Respiratory Health—Conduct a 5- to 10-year respiratory health effects study to assess the effects of smoke exposure on lung function.

Retrospective Cohort Mortality Study—Consider a retrospective study to assess long-term cancer, heart, and chronic pulmonary disease risks among a cohort of firefighters with many years of experience.

Research: Emissions and Exposures

Crystalline Silica—Crystalline silica, detected in employee exposure studies, is a health hazard that could cause irreversible lung damage. Particulate samples collected at wildfires during 1994 and 1995 provide an opportunity to assess exposure levels and risks. This information is essential to complete a comprehensive risk assessment of pulmonary health risks (Pacific Northwest Research Station).

Lung Function and Exposure—Data on employee exposure and lung function has been collected but not analyzed. Statistical analysis of the data would allow an evaluation of the relationship between smoke exposure and lung function in wildland firefighters (Pacific Northwest Research Station).

Fire Camps—Studies have shown that smoke exposure in fire camps can be high, especially during periods of inversions when smoke is trapped in valleys. Inexpensive monitoring equipment will allow assessment of the exposure to particulate matter and carbon monoxide at fire camps to determine the risk and the need for specific risk management strategies (Pacific Northwest Research Station).

Subject participating in lung function test.

Carbon Monoxide Ratios—There are many toxic compounds and irritants contained in the smoke from burning biomass. Assessment of the ratio of toxic compounds to easily measured carbon monoxide in a variety of vegetation types and from different geographic areas will add confidence and accuracy to estimates of potential exposure (Intermountain Fire Sciences Laboratory).

Ozone Formation—Ozone could be an additional source of respiratory irritation for firefighters. Assessment of ozone exposure would provide additional information for risk assessment and the development of strategies to mitigate exposures (Intermountain Fire Sciences Laboratory).

Risk Communication

In conjunction with the preceding recommendations, a concerted risk communication effort is needed. Risks should be communicated widely, in terms understandable by the average employee. Specific recommendations for dissemination of the outcomes of the Health Hazards of Smoke project include:

- Wide dissemination of the risk management plan and disclosure of the risks of smoke exposure to prospective firefighters.

- A video that reviews the Health Hazards of Smoke project and outlines elements of the risk management plan (video in progress at MTDC).

- Presentations dealing with the Health Hazards of Smoke project and risk management plan at regional and national meetings.

- Periodic updates to review the effectiveness of the risk management plan, new regulations, research, and products (e.g., annual Health Hazards of Smoke report).

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Managing Risk Management

David Aldrich

National Safety Officer
USDA Forest Service Fire and Aviation Management

This conference is an extremely important event. It brings those of you who have worked so diligently over the last 7 years together to summarize the status of your hard work. It brings those of us from the Fire Management and Safety and Health organizations together with you to review and assess the information, and to take the first steps to determine the nature of the hazard that wildland fire smoke represents to our personnel, and begin with risk management. The quantity and quality of your work is remarkable. In 7 years, with less than a million dollars, you have accomplished what others proposed to do at a cost of several million dollars a year over several years.

The presentations at this conference have shown that we now have enough information about wildland fire smoke, employee exposure, and the potential health effects of exposure to develop risk management strategies for our employees. We realize that we don't have all the knowledge we would like to have, but we do have enough to proceed credibly. During the conference it became apparent to me how complex and situational the elements of exposure and health effects are, and how they interact with or are affected by other aspects of the work and the work environment, such as: assignment length, work/rest, fatigue, and nutrition. Here are my thoughts on managing risk management for wildland fire personnel involved with fire use and fire suppression.

Risk management strategies for smoke exposure have to be part of the comprehensive risk management program for firefighters and for persons conducting prescribed burns. The effects of smoke exposure are just one of the elements we must manage in our efforts to meet our primary fire program objective of protecting the health and safety of our employees. The bottom line will undoubtedly require modifying the way we have "done business" in the past, perhaps reducing short-term production, but getting the job done right in the long term, as we have all agreed it should be done.

Risk management must be for wildland fire Service-wide. Total mobility and multi-jurisdictional projects dictate a single approach. The elements of risk analysis are common to all wildland fire agencies, so it would follow that the risk management programs should b similar and could be common. Pragmatically speaking, the challenges of fire management the future demand a single approach, developed and managed by all.

Risk assessment and risk management plans must develop information applicable to all levels of planning and implementation. Broad, programmatic plans must consider the potential effects of smoke exposure and the way in which risk management strategies will affect implementation of the programs. Failure to recognize effects and to plan mitigation w result in flawed programs, compromised employee health, increased costs, improper implementation, or other problems. There must be a continuity of risk assessment/risk management processes with increasing specificity and resolution through subsequent planning levels and to actual project implementation. We have to plan to succeed and that means being as realistic and as comprehensive as possible.

We must get the commitment of all personnel in our agencies, from top management through our field personnel, to the objectives of the program and to the risk management procedures. I think we have to reflect on recent findings regarding fire safety indicating tha while we all make affirmations for safety and commit to implementing safety procedures, tc often we do not ensure that those affirmations are carried out.

The risk management system must be simple, perhaps elegant in its simplicity. The solutio cannot be worse than the problem. We must focus on keeping our workforce healthy, and providing the services we are charged to provide. The data show that there are few exposures that exceed permissible levels, that they happen under conditions that don't surprise us, and that the effects on human health appear to be relatively small. Our approach to risk management should be to provide easily understood guides, proper training, and needed equipment, and to empower knowledgeable and committed people to take the appropriate actions to accomplish the objectives that have been identified.

The job is not completed; it has really just begun. We are closing the book on the original work and starting the first implementation. The risk management system has to have a feedback loop for evaluation of the risk management measures, as well as to examine the effectiveness in terms of long-term risk management goals. We must be able to identify

available knowledge or technology that can help, as well as be ready to identify and work to obtain additional knowledge or technology. The success of the original work in achieving the vision of participants in the San Diego meeting (Ward, Rothman and Strickland 1989) will depend on how well we implement the knowledge in hand, and how well we respond to needs for more or better knowledge in the future.

Finally we need to recognize the National Wildfire Coordinating Group (NWCG) for having the vision and recognizing the need to work on the effects of smoke on firefighters, and for their funding of the project. Dick Mangan, Fire and Aviation Program Leader at the Missoula Technology and Development Center, and Dr. Brian Sharkey, coordinator of the Health Hazards of Smoke Project, deserve special thanks for their enthusiastic pursuit of this critical work, for effectively communicating information and findings, and for delivering, on time, the products of the project. We are in debt to each of the many scientists and technical people who have accomplished the research on a tight budget and in the face of many obstacles. The Health Hazards of Smoke Project has truly been field oriented, and it has provided the direction we need to accomplish the goal of this consensus conference, the development of a risk management program capable of being implemented within the existing fire management organization.

References

Ward, D., N. Rothman, and P. Strickland, The Effects of Forest Fire Smoke on Firefighters: A Comprehensive Study Plan, National Wildfire Coordinating Group, 1989.

Review of Smoke Components

Darold E. Ward, Ph.D.

USDA FS, Intermountain Fire Sciences Laboratory

The mixture of particles, liquids, and gaseous compounds found in smoke from wildland fires is very complex. The potential for long-term adverse health effects is much greater because of this complex mixture. The particles are known to contain many important organic compounds some of which condense to form tarry droplets over a substrate material of ash or graphitic carbon or both. The size distribution of smoke particles is such that a large percentage are respirable. Gaseous compounds in the air adjacent to fires in association with the particles include carbon monoxide, methane, oxides of nitrogen and many organic compounds--some of which are carcinogens and many of which are irritants. Other semi-volatile compounds have a significant vapor pressure at ambient temperature and pressure which results in a gas phase emission and many of these compounds are important from a health standpoint, but have not been adequately quantified. **With the additional data of today, we still do not know what the overall toxicity of smoke is from wildland fires or how this toxicity varies from fire to fire.**

The large variance in the concentration of smoke needs to be evaluated to assess the level of exposure and risk to fireline personnel. The new PM2.5 air quality standard is designed to protect human health and suggests that health is most at risk from particles less than 2.5 μm in diameter. Along with the combustion products is the dust, heat, and remoteness of many of the wildland fires and fire camps. The fire, fuel, and weather vary continuously, which changes the fire dynamics and the dilution occurring in the work environment. The smoke may be extremely dense for a few minutes to several hours or days with the air being relatively clean at other times.

Most of what is known about smoke has been inferred from research done with prescribed fires and from fires burned under carefully controlled laboratory conditions. Many measurements have been made of exposure of firefighters to CO and a few other compounds and the CO has been correlated with some compounds. This paper discusses measurements that have been made, correlations with other compounds, and ratios of compounds to CO (including particulate matter).

COMBUSTION PRODUCTS THAT ARE IRRITANTS OR KNOWN CARCINOGENS

In the study plan developed for the study of smoke related to its effect on the health of wildland firefighters [Ward et al., 1989], several combustion products and classes of combustion products were identified as being critical to know more about to assess their impact on the health of firefighters. These substances are categorized as follows:

1. Particulate matter
2. Polynuclear aromatic hydrocarbons
3. Carbon monoxide
4. Aldehydes
5. Organic acids
6. Semivolatile and volatile organic compounds
7. Free radicals
8. Ozone
9. Inorganic fraction of particles

Particulate matter is highly visible, affects ambient air quality, and has an unknown effect on human health. Particles are abundantly produced by forest fires with source strengths exceeding 0.6 tonnes per second on some large fires [Wade and Ward, 1973]. The mass of particles can be separated into two modes: 1) a fine-particle mode generally considered to be produced during the combustion of organic material with a mean-mass diameter of 0.3 micrometers, and 2) a coarse particle mode with a mean-mass diameter larger than 10 micrometers. Research, both from ground-based sampling [Ward and Hardy, 1989] and airborne sampling systems, shows the bimodal distribution with a small fraction of the total mass (less than 10%) between 2 and 10 micrometers [Radke et al., 1986]. Smoldering combustion releases several times more fine particles than flaming combustion. The fine particles account for up to 90 to nearly 100% of the mass of particulate matter. The percentage of fine particles produced through flaming combustion ranges from 80 to 95% depending on the turbulence in the combustion zone and other factors. The smaller fine particles consist of 60 to 70% organic

carbon [Ward and Hardy, 1989]. Many known carcinogenic compounds are contained with the organic carbon fraction. Roughly, another 2 to 15% is graphitic carbon and the remainder is inorganic ash material [Ward and Core, 1984]. Particles are also known to carry adsorbed and condensed toxicants and possibly free radicals.

Polynuclear Aromatic Hydrocarbons (PAH) is one class of compounds contained in the organic fraction of the fine particle matter. Some of the PAH compounds associated with the particles are carcinogenic. Benzo[a]pyrene, for example, is a physiologically active substance that can contribute to the development of cancer in cells of humans. Examples of PAH compounds are listed in Table 1 for prescribed fires in logging slash, laboratory fires of pine needles, fireplaces, and woodstoves. Not all of the compounds listed in Table 1 are of equal carcinogenicity. More data have been developed for B[a]P than other PAH compounds for smoke from wildland fires. Ward et al. [1989] found for B[a]P that emission factors increased proportionally to the density of live vegetation covering the prescribed fire units. This has not been verified for other ecosystems with live vegetation involved in flaming combustion.

PAH compounds are synthesized from carbon fragments into large molecular structures in low-oxygen environments, such as occurs inside the flame envelope in the fuel-rich region of the flame structure. If the temperature is not adequate to decompose compounds upon exiting from the flame zone, then they are released into the free atmophere and condense or are adsorbed onto the surface of particles. Many different combustion systems are known to produce PAH compounds, and the burning of forest fuels is documented as one of these sources. Little is known about combustion conditions on wildfires, but recent experiments would suggest emissions are not that different from prescribed fires when burning conditions are similar. Evidence suggests that for low-intensity backing fires, the ratio of bezo[a]pyrene to particulate matter is higher by almost 2 orders of magnitude over that for heading fires [McMahon and Tsoukalas, 1978]. For wood stoves, a relationship was established between burn rate and PAH production. Specifically, as the burn rate increased, total organic emissions decreased, but the proportion that was PAH compounds increased. DeAngeles et al. [1980] found the PAH emission rate to be highest over a temperature range of 500 to 800°C. This would be consistent with the low-

intensity backing fire results of McMahon and Tsoukalas [1978].

Carbon monoxide is a colorless and odorless toxic gas. It is produced through the incomplete combustion of biomass fuels. CO is second in abundance to CO_2 and water vapor. The efficiency of the combustion process has been described by the ratio of CO_2 to the sum of CO_2 and CO released by the fire. This ratio is termed modified combustion efficiency (MCE) and is used to correlate with other products of incomplete combustion (CH_4, other hydrocarbons, and particulate matter). Carboxyhemoglobin is created in the blood of humans in response to the exposure to CO, which replaces the capacity of the red blood cells to transport oxygen. Generally, a level of 5% carboxyhemoglobin results from 3 to 4 hours of exposure to CO of concentrations of 35 ppm and may result in firefighters showing signs of disorientation or fatigue.

CO is produced more abundantly from smoldering combustion of forest fuels. Immediately following the cessation of flaming combustion, maximum levels of CO are produced. This phenomena coincides with suppression activities, especially where direct attack methods are being used. As the flames subside, CO is released at the highest rate and, typically, continues at a high rate during the first few minutes of the die down period. For fires burning under high drought conditions, the smoldering combustion can be self-sustaining and consume deep into the duff and in some cases, soil where the organic component of the soil makes up more than 30% of the total. Tremendous amounts of smoke can be produced under severe MCE conditions.

Aldehydes are compounds of which a few are extremely irritating to the mucous membranes of the human body. Some, such as formaldehyde, are carcinogenic and in combination with other irritants may cause an increase in the carcinogenicity of compounds like the PAH compounds. Formaldehyde is one of the most abundantly produced compounds of this class and is released proportional to many of the other compounds of incomplete combustion. Formaldehyde is transformed rapidly to formic acid in the human body with formic acid being removed very slowly.

Acrolein is also known to be produced during the incomplete combustion of forest fuels.

In smoke from cigarettes, acrolein is about 10 times more plentiful than formaldehyde. Acrolein is known to effect respiratory functions at concentrations as low as 100 ppb. Studies of pathogenesis in rabbits exposed to smoke from low-temperature combustion of pine wood [Thorning et al., 1982] suggest that low-molecular-weight aldehydes, including acrolein, are the most likely agents of injury. The ability of scavenger cells in the lung to engulf foreign material of bacteria is decreased through exposure to aldehyde compounds, which may accentuate infections of the respiratory system. Personal communications with Dost [1986] suggest that acrolein has a high likelihood of making a discernible addition to the irritant character of smoke near firelines, and concentrations could be as high as 0.1 to 10 ppm near fires.

Aldehydes as a class of compounds have been difficult to quantify for forest fires and there are still many issues to be worked out. Some recent research by Reinhardt [1994] suggest that acrolein is produced proportional to formaldehyde. On the other hand, Yokelson et al. [1996] using a very straight forward analytical technique were not able to identify acrolein in as high a concentrations as those reported by Reinhardt [1994] and in much less abundance than formaldehyde.

Organic acids are known to form from the combustion of biomass fuels. Yokelson et al. [1997] and McKenzie et al. [1995] have recently made significant progress in characterizing some of the emissions of organic acids including acetic and formic acid finding molar ratios to CO of 7.4 ± 6.2 and 1.5 ± 1.5, respectively. Through the application of the molar ratios of different air toxic compounds to CO, McKenzie et al. [1995] reported possible exposure levels that were well below the allowable time weighted averages (TWA's) based on a peak exposure of firefighters of 54 ppm (based on Reihardt's [1994] data for peak exposure). No single compound is present at a hazardous level except for vinyl acetate and 2-furaldehyde, which are suspected carcinogens (Table II). It should be noted however, that the synergistic effects of some or all of these compounds and others has not been determined.

Semivolatile and volatile organic compounds in smoke contain a wide variety of organic compounds, many with significant vapor pressures at ambient temperatures. Some compounds are partitioned between the gaseous and liquid or solid phase at ambient temperature; e.g., benzene, naphthalene, toluene. Fires are known to produce a variety of these types of compounds, but little characterization work has been done. The phenolic compounds are important because they contain compounds that are very strong irritants and are abundantly produced from the partial oxidation of cellulosic fuels. Various phenolic compounds are used as starting materials in the manufacture of resins, herbicides, and pharmaceutical products. Other PAH compounds of low-molecular weight are contained with the semivolatile class of compounds. Because of the volatility and in some cases reactivity of these compounds, special sampling protocols are required including charcoal adsorption, porous polymer adsorption, and whole-air sampling. These materials are difficult to sample in the environment that firefighters work in, and surrogate methods are needed for correlating exposures of the more volatile materials with the semivolatile components. Methane and carbon monoxide gases are often produced proportional to other products of incomplete combustion and may serve as indicators of their abundance.

Free-radicals are abundantly produced throguh the combustion of forest fuels. The concern lies with how long these materials persist in the atmosphere and their reactivity when in contact with human tissues. Most of the chemical bonding is satisfied through recombination of free-radical groups by condensation within the few seconds of time it takes for the mixture of gases to exit from the flame which should reduce the overall toxicity of the smoke. However, some free-radicals persist up to 20 minutes following formation and may be of concern if firefighters are exposed to fresh aerosols. How much of the organic material remains in a reactive, free-radical state is an unknown quantity.

Ozone concentrations close to fires that are high enough to be concerned about would not be expected. Ozone is formed photochemically near the top of smoke plumes under high sunlight conditions. Generally, ozone is formed in situations where smoke is trapped in valleys or under temperature inversion conditions of the atmosphere, or both. Fire crews working at high

elevation locations may encounter elevated levels of ozone. Any effort to characterize exposure of firefighters to smoke must account for the potential exposure to ozone in areas where crews are working at elevations close to the top of the atmospheric mixing layer. OSHA standards exist for ozone, and the standard would need to be evaluated in conjunction with other materials contained in smoke from burning of biomass fuels.

RATIOS OF COMPOUNDS TO AIR TOXICS

In performing a risk assessment and establishing the relative importance of different compounds from a human health standpoint, a method is needed to estimate the exposure levels based on the measurement of CO and/or particulate matter (PM). Many of the compounds discussed are very difficult to measure which makes breathing space sampling nearly impossible for most of the air toxic compounds. Correlations of air toxic compounds to CO, CH_4, and PM has proven to be an effective way of estimating the release of a number of compounds [Ward, Hao, and Peterson, 1993; McKenzie et al, 1995; Yokelson et al., 1997].

If this method is to be used, then it is important to "safe-side" estimates or to use very specific information for the phase of combustion producing the smoke of concern. For example, ratios of B[a]P to CO and/or to PM for different fuel types show a significant difference between flaming and smoldering combustion and fuel type (Table III). There is almost an order of magnitude difference between emission ratios of B[a]P to CO for flaming in comparison to smoldering ratios. An average weighted emission ratio can be calculated based on the percentage of fuel consumed by phase of combustion producing the emissions contained within the breathing space of a firefighter. If the working conditions are marginal, this may be necessary and can be done by assuming, for example, that the emissions along the fireline consist of 10% from vegetation consumed during the flaming phase and 70% for the first smoldering phase and 20% for the final smoldering phase. The results are illustrated in Table III.

Table 1. Comparison of Polynuclear Aromatic Hydrocarbons from four sources: (1) prescribed fires in logging slash in western Washington and western Oregon [Ward et al., 1989], (2) pine needle litter fuel of Southeast [McMahon and Tsoukalas, 1978], (3) fireplace emissions tests with

green southern pine wood [DeAngelis et al., 1980], and (4) woodstove emissions tests with green southern pine wood [DeAngelis et al., 1980]. Carcinogenicity is from National Academy of Sciences [1972] and is coded as follows: "-" is not carcinogenic; "±" is uncertain or weakly carcinogenic; and "++" or "+++" is strongly carcinogenic.

Compound	Logging slash (mean±SD)	Pine needles (mean±SD)	Fire places	Wood stoves	Carci gnicit
	(µg of compound per g of particulate matter)				
Anthracene/Phenanthrene	42±29	185±72	575	6345	-/-
Methylanthracenes	61±38		692	3147	
Benz[a]anthracene/chrysene	17±8	43±25	117	2276	+/+
1,2-benzanthracene	17±8				+
Chrysene/triphenylene	29±11				
Dibenzanthracenes/dibenzphenanthrenes			4	3	
Fluoranthene	47±23	51±29	125	1153	-
Benzofluoranthene		11±11	133	865	
Benzo(ghi)fluoranthene	11±5				-
Benzo(a)fluoranthene	7±4				
Benzo(b/j/k)oranthenes	26±9				++
Pyrene	42±24	73±46	133	1153	-
Benzo(a)pyrene	13±14	3±2			+!
Benzo(e)pyrene	13±5	6±3			-
Benzopyrenes/perylene			117	578	
Perylene	3±2	2±2			
Indenopyrene	13±14				
Indeno(1,2,3-c,d)pyrene					+
Anthanthrene/dibenzopyrene	6±8		8	1	-
Benzo[ghi]perylene	15±19		117	288	-

Table II. Listing of ratios of air toxic to CO determined for a variety of fuel types. The bold type values in column 3 are the ratios recommended for use in making risk assessments and are calculated from the highest 1 to 3 values listed for each compound in Column 2.

	Literature values	Values to be used for risk assessment
	mean molar ratio to CO ($x10^{-3}$)	mean molar ratio to CO ($x10^{-3}$)
2-furaldehyde	1.50±0.93[McKenzie, et al., 1995]	**1.50**±0.93[McKenzie, et al., 1995]
5-methylfuraldehyde	0.30±0.19[McKenzie, et al., 1995]	**0.30**±0.19[McKenzie, et al., 1995]
2acetylfuran	0.33±0.16[McKenzie, et al., 1995]	**0.33**±0.16[McKenzie, et al., 1995]
phenol	0.32±0.2[McKenzie, et al., 1995]	**0.32**±0.2[McKenzie, et al., 1995]
o-cresol	0.27±0.13[McKenzie, et al., 1995]	**0.27**±0.13[McKenzie, et al., 1995]
m/p-cresol	0.52±0.25[McKenzie, et al., 1995]	**0.52**±0.25[McKenzie, et al., 1995]
guaiacol	0.17±.081[McKenzie, et al., 1995]	**0.17**±.081[McKenzie, et al., 1995]
4-methylguaiacol	1.00±0.83[McKenzie, et al., 1995]	**1.00**±0.83[McKenzie, et al., 1995]
vanillin	0.50±0.57[McKenzie, et al., 1995]	**0.50**±0.57[McKenzie, et al., 1995]
acetol	1.20±1.7[McKenzie, et al., 1995]	**1.20**±1.7[McKenzie, et al., 1995]
vinyl acetate	1.70±2.1[McKenzie, et al., 1995]	**1.70**±2.1[McKenzie, et al., 1995]
2-cyclopenten-1-one	0.20±0.13[McKenzie, et al., 1995]	**0.20**±0.13[McKenzie, et al., 1995]
acetic acid	7.40±6.2[McKenzie, et al., 1995]; 22.6[Yokelson et al., in press]; 8.70±6.1[Hartman et al., 1990]; 1.60±2.4[Talbot et al., 1988]; 8.00±4[Lefer et al., 1994]; 3.20±0.4[Hartman et al., 1990]; 2.60±6.8[Lefer et al., 1994]	7.40±6.2[McKenzie, et al., 1995]; 22.6[Yokelson et al., in press]; 8.70±6.1[Hartman et al., 1990]; **12.1**
formic acid	1.50±1.5[McKenzie, et al., 1995]; 1.6[McKenzie, et al., 1994]; 9.1[Yokelson et al., in press]; 2.60±2[Hartman et al., 1990]; 0.17±0.27[Talbot et al., 1988]; 20[Lefer et al., 1994] 35.00±22[Lefer et al., 1994]	9.1[Yokelson et al., in press]; 35.00±22[Lefer et al., 1994]; 1.6[McKenzie, et al., 1994]; **15.2**
propanoic acid	0.39±0.19[McKenzie, et al., 1995]; 0.66[McKenzie, et al., 1994]	**0.66**[McKenzie, et al., 1994]
3-oxobutanoic acid	0.41±0.44[McKenzie, et al., 1995]	**0.41**±0.44[McKenzie, et al., 1995]
methanol	11.00±9[McKenzie, et al., 1995]; 18.0[Yokelson et al., in press]	11.00±9[McKenzie, et al., 1995]; 18.0[Yokelson et al., in press]

methane	29.00±11[McKenzie, et al., 1995]; 83.4[Yokelson et al., in press]; 45.00±13[Bonsang et al., 1991]; 55.00[Ward et al., 1993]; 140.00±93[Smith et al., 1993]; 58.00±18[Cofer et al., 1990]; 71.00[Ward et al., 1993] ;91.00±3.1[Lobert et al., 1991]; 76.00±13[Griffith et al., 1991]	83.4[Yokelson et al., in press]; 140.00±93[Smith et al., 1993]; ;91.00±3.1[Lobert et al., 1991];**104.8**
ethane	2.50±1.2[McKenzie, et al., 1995]; 9.4[Yokelson et al., in press]; 4.00±1.4[Bonsang et al., 1991]; 6.80±5.2[Lobert et al., 1991]	9.4[Yokelson et al., in press]; 4.00±1.4[Bonsang et al., 1991]; 6.80±5.2[Lobert et al., 1991];**6.7**
ethene	12.00±9[McKenzie, et al., 1995]; 13.5[Yokelson et al., in press] 17.00±9.1[Bonsang et al., 1991]; 12.00±8.7[Lobert et al., 1991]	12.00±9[McKenzie, et al., 1995]; 13.5[Yokelson et al., in press] 17.00±9.1[Bonsang et al., 1991]; **14.2**
glycol	10.8[Yokelson et al., in press]	**10.8**[Yokelson et al., in press]
formaldehyde	17.3[Yokelson et al., in press]	**17.3**[Yokelson et al., in press]
ammonia	26.0[Yokelson et al., in press]	**26.0**[Yokelson et al., in press]
HCN	4.0[Yokelson et al., in press]	**4.0**[Yokelson et al., in press]
1,3-butadiene	1.10[Hao et al., in press]	**1.10**[Hao et al., in press]
Benzene	2.13[Hao et al., in press]	**2.13**[Hao et al., in press]
Toluene	1.79[Hao et al., in press]	**1.79**[Hao et al., in press]
o-xylene	0.24[Hao et al., in press]	**0.24**[Hao et al., in press]
m,p-xylene	0.43[Hao et al., in press]	**0.43**[Hao et al., in press]
n-hexane	0.06[Hao et al., in press]	**0.06**[Hao et al., in press]
pyruvic aldehyde	6.2[McKenzie, et al., 1994]	**6.2**[McKenzie, et al., 1994]
crotonic acid	0.21[McKenzie, et al., 1994]	**0.21**[McKenzie, et al., 1994]

Table III. Example of application of data for prescribed fires in the Pacific Northwest and for the example used an estimate of emissions exposure of 10% flaming, 70% primary smoldering, and 20% secondary smoldering. The ratios can be multiplied by the concentration of CO to calculate either B[a]P or PM exposure. If only PM exposure is available, CO can be calculated and B[a]P estimated along with other air toxics found in Table II.

Phase of combustion	CO (ppm)	PM ($\mu g/m^3$)	B[a]P ($\mu g/m^3$)	B[a]P/CO ($\mu g/m^3$/ppm)	B[a]P/PM ($\mu g/g$)	PM/CO ($\mu g/m^3$/ppm)
F	140	15740	0.1284	0.0009	8.2	112.4
S1	113	8391	0.1608	0.0038	42.8	74.3
S2	26	1214	0.1024	0.0067	126.4	46.7
Weighted	98.3	7690.5		0.00409	56.06	78.2

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Employee Exposure Review

Health Hazards of Smoke Conference, Missoula, MT April 8, 1997

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This presentation aims to summarize work done to assess firefighter exposure to smoke. The assessment is important to define where we stand in terms of compliance with occupational exposure limits, but also to provide data for a risk assessment to determine the significance of the health risks.

Occupational Exposure Limits

Limit	CO (ppm)	PM3.5 (mg/m^3)	Formal-dehyde (ppm)	Acrolein (ppm)	Benzene (ppm)
OSHA PEL	50	5	0.75 (2.0)	0.1 (0.3)	1 (5)
ACGIH TLV	25	3	0.3	0.1 (0.3)	0.5 (2.5)
NIOSH REL	35 (200)	n/a	0.016 (0.1)	0.1 (0.3)	0.1 (1)

A variety of occupational exposure limits exist, ranging from the OSHA Permissible Exposure Limits to the ACGIH Threshold Limit Values and the NIOSH Recommended Exposure Limits. These are shown above for comparison. Short-term Exposure Limits (STELs) and ceiling limits (instantaneous upper limits) designed to control peak exposures to fast-acting toxins are shown in parentheses.

Note that OSHA revised the PELs for CO and many other contaminants in the 1980s to be consistent with the NIOSH RELs, but after several years a legal challenge forced them to withdraw the more stringent standards. Because the original revision was undertaken in response to scientific evidence demonstrating the 50 ppm standard was inadequate, many industrial hygienists consider compliance with OSHA limits to be insufficient to avoid adverse health effects.

Exposure Limits

- Adjust for extended workshifts:

CO PEL = 50 x 8/(hours worked)--for 14-hour shift, the adjusted PEL is 29 ppm

- Account for multiple pollutants:

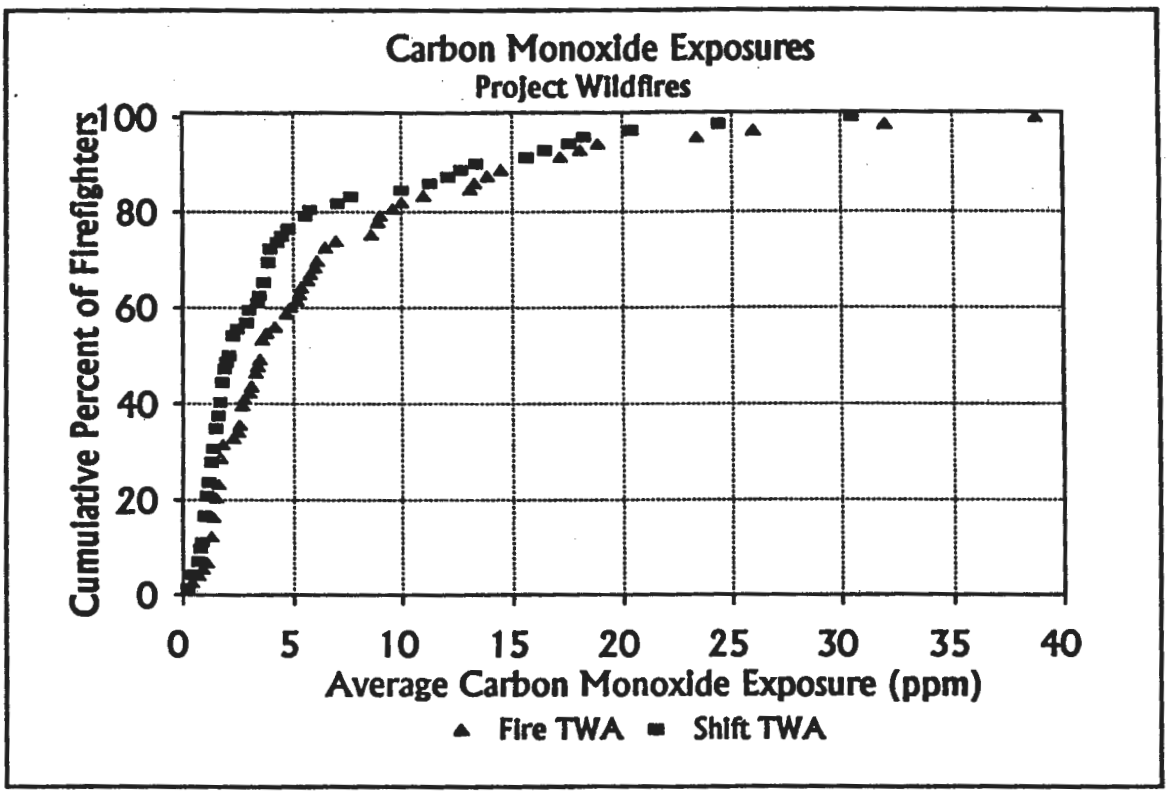
Sum the respiratory irritants--PM3.5, acrolein and formaldehyde

Because occupational exposure limits are based on avoiding adverse health effects during a career of standard 8-hour workshifts, adjustment of the basic exposure limits is recommended to account for the increased uptake of contaminants during a longer workshift. One common formula for doing so is given above.

As well, the total impact of multiple contaminants that affect the same target organ(s) should be considered when evaluating a workplace. A recommended way to do this is to sum each contaminant divided by its respective exposure limit. In smoke, respirable particulate (PM3.5), acrolein and formaldehyde all affect the eyes and respiratory system--primarily through irritation. Thus the formula would be:

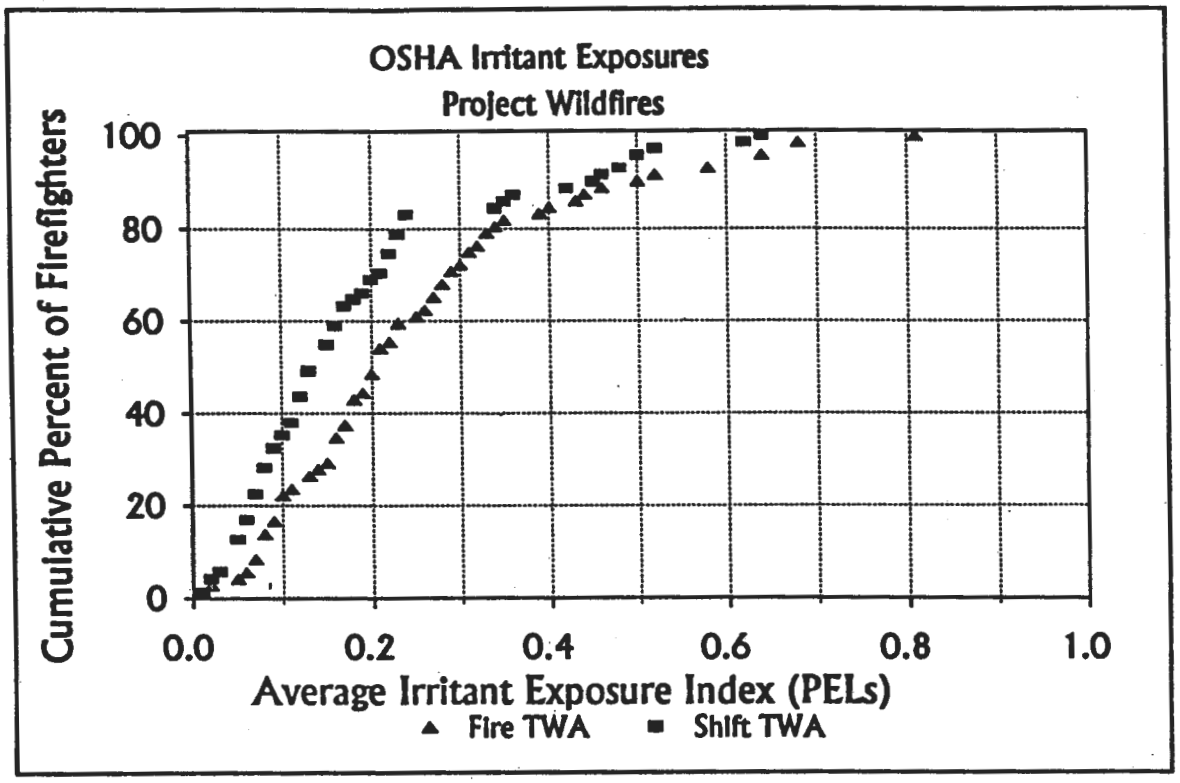
PM3.5 exposure/PM3.5 exposure limit + acrolein exposure/acrolein exposure limit + formaldehyde exposure/formaldehyde exposure limit

This calculates a unitless "irritant exposure index". There are other respiratory irritants in smoke that have not been measured, so this formula underrepresents the true respiratory irritant exposure.

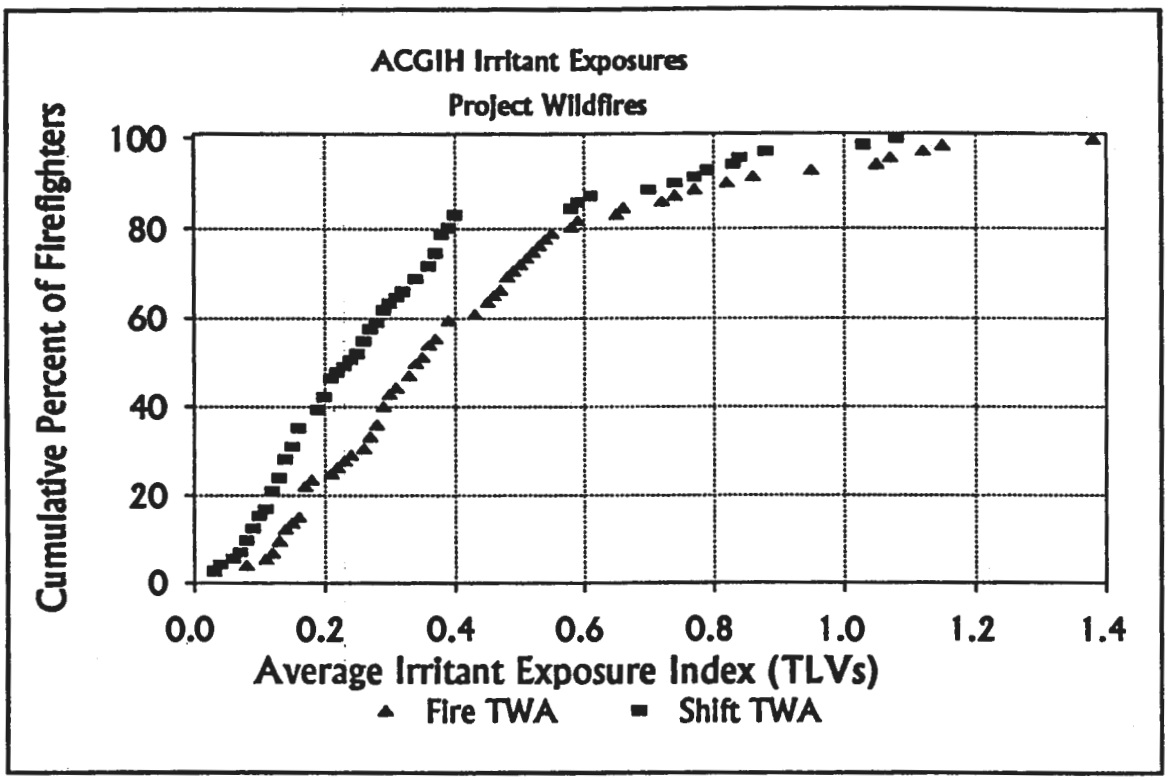


Shown above is an example of the exposure to CO among firefighters at project (extended) wildfires. The CO concentration is on the x-axis, and the percent of firefighters studied is on the y-axis. Both shift-average (Shift TWA) and fireline-average (Fire TWA) exposures are shown.

It is apparent that about 81% of the firefighters at project fires had fireline-average CO exposures that were at or below 10 ppm CO. Only a very small percentage of firefighters had shift-average exposures above the PEL adjusted for a 14-hour workshift (29 ppm). Thus shift-average overexposure to smoke is a limited problem at project wildfires. Note that the Shift TWA exposures are less than the Fire TWAs because of unexposed time traveling to and from the fire.

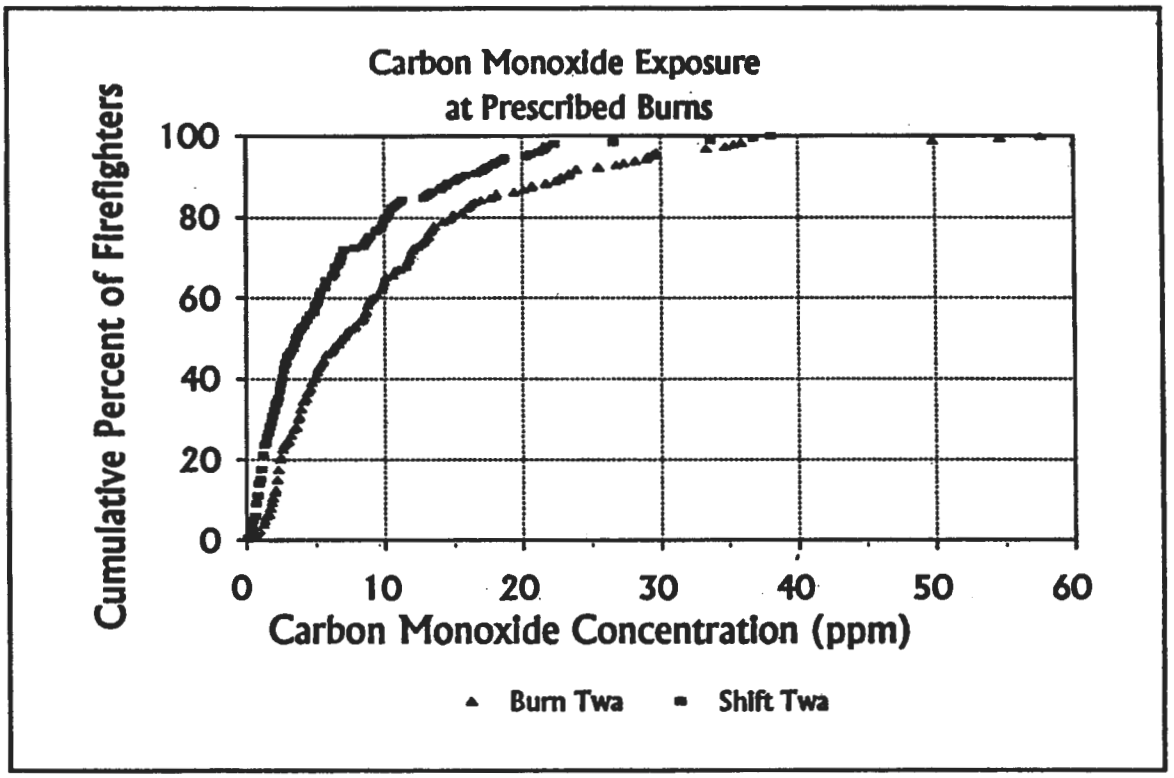


Exposure to respiratory irritants is similar to CO, but none of the irritant exposures exceed the index based on the current OSHA PELs. A shift-average overexposure would be any that exceeded 1.0 on the unitless irritant index scale. No adjustment for the extended workshift is recommended because the irritant effects are thought to be independent of the number of hours worked.



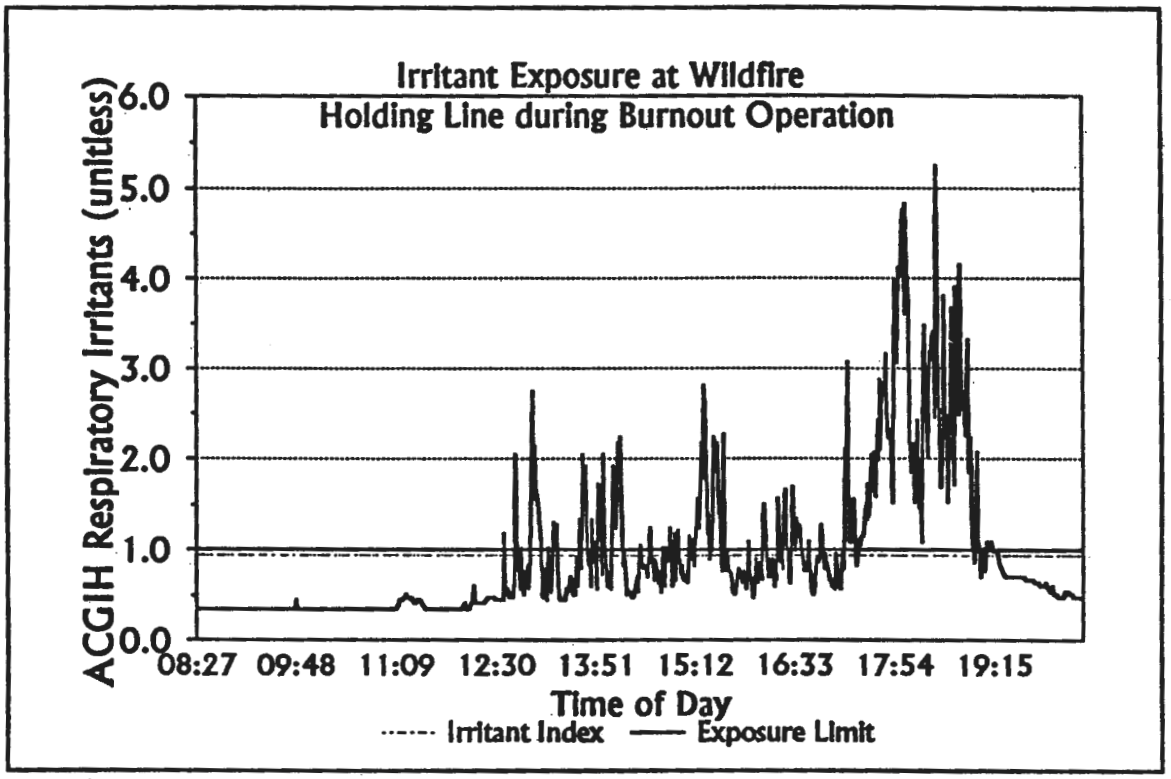
Using the ACGIH TLVs as the occupational exposure limits results in a different interpretation, in that about 3% of the firefighters monitored had exposures that exceeded an irritant index of 1.0 calculated with the TLVs. This is important because the TLVs are well-regarded as incorporating the latest scientific evidence.

Based on this view, the exposure to respiratory irritants is significant, but may be manageable because it only occurs in a minority of cases.

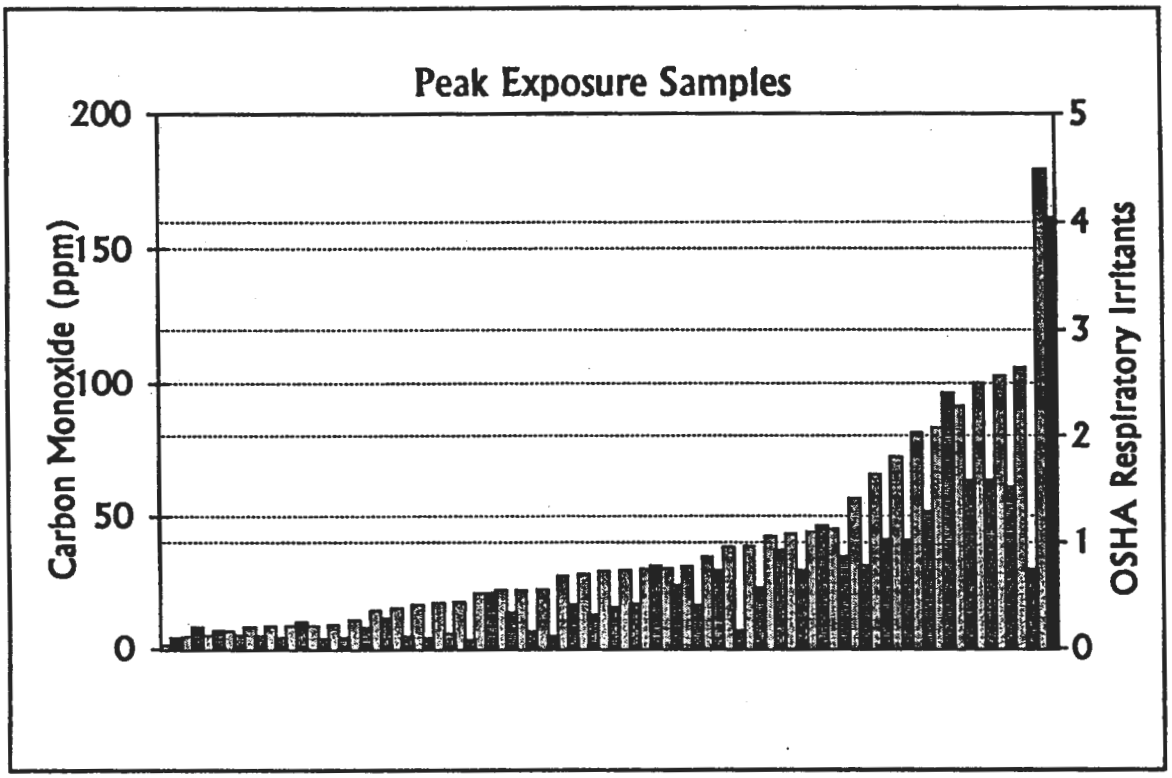


Smoke exposure has been found to be worse at prescribed burns than at wildfires. The data above are from prescribed burns in the Pacific Northwest. Note there are a larger percentage of exposures that exceeded a 25 ppm TLV than there were at the project wildfires monitored.

We believe that smoke exposure is more of a problem at prescribed burns because the firefighters feel that they must control the fire within the prescribed boundaries at all costs. At wildfires, firefighters can often pull back to a more feasible fireline location. The increasing problem of residential influx to wildland areas may cause more overexposure to smoke as firefighters feel compelled to protect structures despite heavy smoke situations.



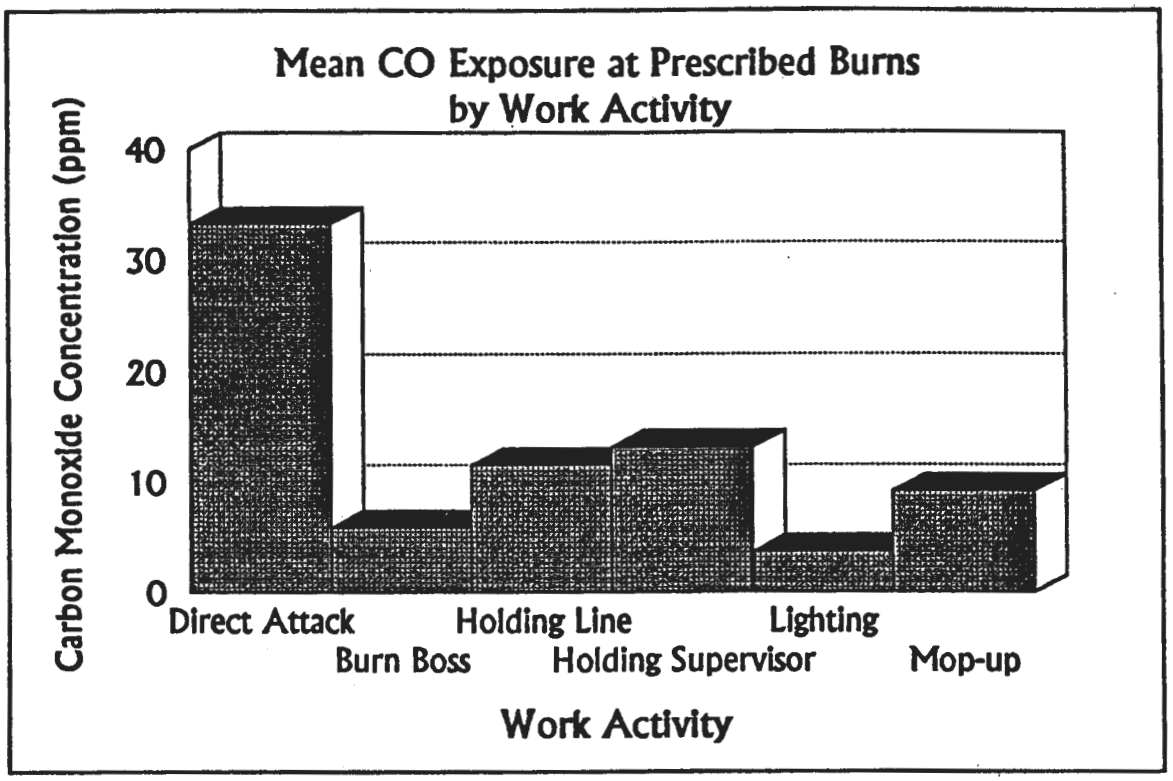
During initial attack, peak exposures to CO and respiratory irritants can exceed short-term exposure limits; CO levels can exceed 200 ppm for short periods. Peak exposure situations also occur during fireline holding actions, with peak exposures to respiratory irritants easily exceeding an irritant exposure limit of 1.0 calculated based on the ACGIH TLVs. Here is an example of respiratory irritant exposure at a project wildfire where the crew was assigned to hold fireline during a burnout in the afternoon. The wind increased during the afternoon, causing significant smoke exposure.



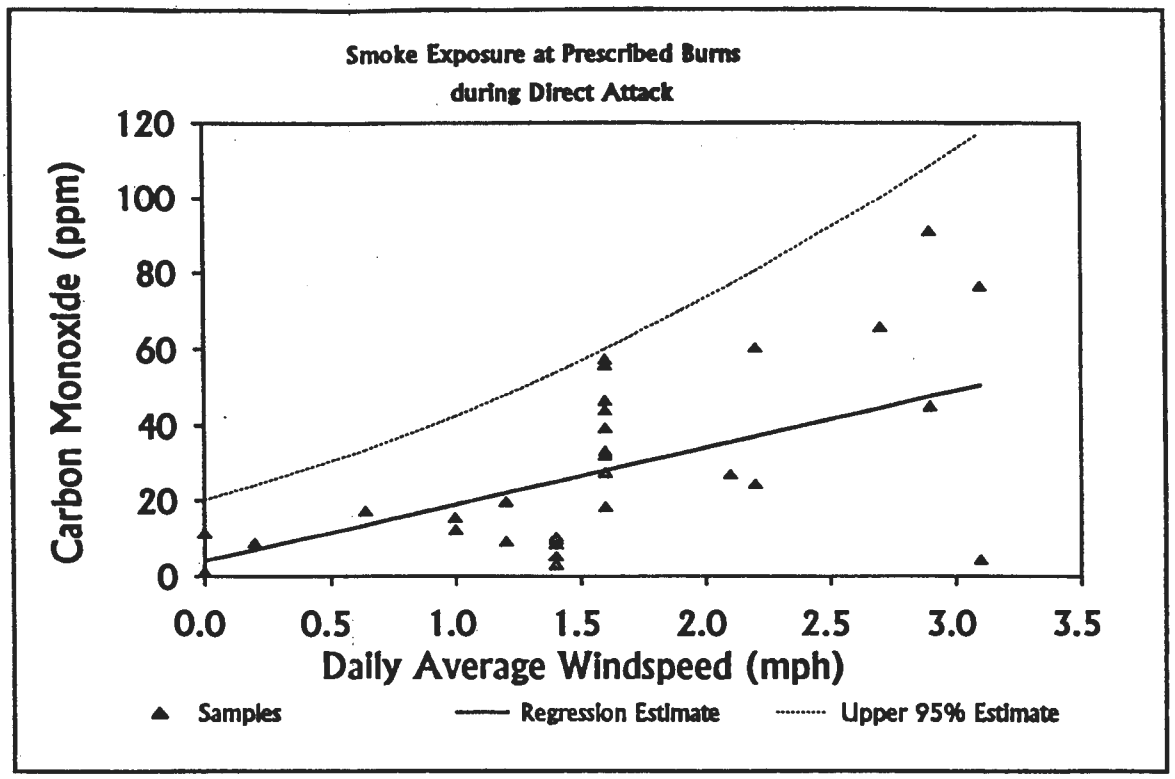
Initial attack is not the only place that peak exposure situations occur. The data above are peak exposure samples obtained from firefighters during initial attack, project wildfires and prescribed burns. These samples are typically 15 minutes in duration to meet minimum sample quantity requirements to enable measurement of the irritants. The scale for the carbon monoxide level during each peak sample period is on the left, and the scale for the respiratory irritant exposure (using the OSHA PELs as the divisor) is on the right. The STELs for acrolein and formaldehyde were used along with a STEL for PM3.5 based on a recommended excursion limit of 3 times the shift-average PEL.

Note that nearly 1/3 of the peak irritant exposures were above the STEL of 1.0, with some as much as 4 times the STEL. Using the ACGIH TLVs as the divisors in the respiratory irritant index resulted in the highest samples to be over 10 times the STELs. The CO levels averaged over the 15-minutes were not as high, but probably did exceed the former 200 ppm ceiling limit for brief periods during the 15-minute samples.

The point here is that a high proportion of firefighters' peak exposures exceed short-term exposure limits, much more than exceed shift-average exposures.



There appear to be differences in smoke exposure potential among various work activities on the firelines. Benzene is unusual in that gasoline is a major source of exposure in addition to smoke, thus the highest benzene exposures (which were well below TLVs) were among sawyers, lighters and portable pump operators. For the other components of smoke (including respiratory irritants), the smoke exposure differed by work activities as shown above, which are data from prescribed burns in the Pacific Northwest. Direct attack of spot-fires and holding firelines were higher-exposure activities than lighting or mop-up. Windspeed and position relative to the fire are also factors that control smoke exposure.



One consistent observation at fires is that the ambient windspeed contributes to smoke exposure potential, if firefighters must be downwind of the fire. This graph of data from prescribed burns demonstrates this point, but it is somewhat misleading in that the "daily average windspeed" was measured at a single point near the fireline, and averaged over an entire workshift, thus it is an insensitive measurement dampened by periods with little or no wind. There were periods in the day when the windspeed was well over 10 miles per hour, and those periods were associated with the individual CO exposures denoted by the triangles.

Wind measurements that were averaged over the same period as the CO samples would be a more meaningful scale. At initial attack fires, such measurements showed that the CO exposure was approximately 3 times the windspeed minus 10. So a 20 mile-per-hour wind would be associated with CO levels of about 50 ppm for those firefighters working downwind edges of the fire.

It should be noted that the other extreme are inversion conditions which trap smoke in valleys. These situations can cause exposures on the fireline and in fire camps to exceed 50 ppm CO.

Summary

- Most Smoke Exposure is well below guidelines--only 1-10% are above limits.
- Overexposures are observed for carbon monoxide and respiratory irritants (aldehydes and PM3.5).
- Overexposures are obvious to trained observers.
- Most overexposures related to "must" situations.

Summary (cont.)

- Higher exposures during direct attack, mobile attack, holding line in adverse situations such as windy conditions.
- Peak exposure situations exceed STELs and cause most of the shift-average overexposures.
- Manage peak exposures and we'll control all exposures.

Health Effects of Exposure

Brian J. Sharkey, Ph.D.

USDA Forest Service Missoula Technology & Development Center and
University of Montana Human Performance Laboratory

For decades, firefighters and fire managers have been concerned about the effects of smoke on wildland firefighters. Interest in the health hazards of smoke intensified after the 1987 and 1988 fire seasons, leading to the development of a comprehensive plan to study emissions, employee exposure, health effects, risk assessment, and risk management (Ward, Rothman, and Strickland,1989). Studies of the emissions in vegetative smoke indicate the potential for exposure to hazardous emissions. And recent employee exposure studies show that firefighters are exposed to levels exceeding OSHA permissible exposure limits in a small percentage of cases studied. This report summarizes some of the potential health effects of short, intermediate, and long-term exposure to the health hazards of smoke.

Short-erm Exposure

Immediate effects of exposure include symptoms of sore eyes (tearing), cough, and running nose. Data from field first aid stations indicate that 30 to 50% of visits are for upper respiratory problems (cold, cough, sore throat). Some studies indicate that upper respiratory symptoms and problems increase over the course of the fire season. While upper respiratory problems may be due in part to smoke, they may also result from physical exhaustion, psychological stress, and poor nutrition, all factors known to suppress the function of the immune system. The spread of upper respiratory infections may be exacerbated by poor health habits and conditions in fire camps.

The average adult has from one to six colds annually, with approximately 40% caused by rhinoviruses. Athletes and exercise enthusiasts with upper respiratory infections (URI) commonly continue to participate in recreational and competitive sports. Upper respiratory infections caused by rhinoviruses are restricted to the upper respiratory tract. They do not alter pulmonary function measures, or impair submaximal or maximal exercise performance (Weidner et al., 1997). Viruses that produce viremias (virus in the blood) can infect a wide variety of host tissues, including skeletal muscle. When symptoms are "above the neck" (stuffy nose, sneezing, scratchy throat), it is safe to continue work or exercise. If symptoms

include fever, aching muscles, nausea, or diarrhea, hard work or training should be postponed (R. Eichner, M.D., personal communication).

Carbon Monoxide—Carbon monoxide (CO) can cause headaches, dizziness, and nausea, and can impair mental function. Studies of firefighters indicate the potential for overexposure to CO. However, studies of U.S. firefighters (Jackson and Tietz, 1979) and Australian bushfire fighters (Brotherhood, Budd, and Jeffrey, 1990) indicate that cigarette smokers go to a fire with more carbon monoxide in their blood (carboxyhemoglobin-COHb) than nonsmoking firefighters have in their blood at the end of a work shift. Documented cases of inversions (Happy Camp, 1987) indicate elevated CO levels in fire camps, levels with the potential to affect the mental function and decisionmaking of incident command personnel.

Blood carbon monoxide levels rise during the period of exposure, taking 8 hours exposure at 35 ppm CO to achieve a blood CO level of 5% COHb, the upper limit deemed by OSHA to be consistent with good health (Figure 1). Smokers' COHb levels range from 5 to 10% throughout the day. Firefighters are seldom exposed to elevated levels throughout the entire working day, so average exposure is relatively low (4.1 ppm; Reinhardt, Black, and Ottmar, 1995). Since air-purifying respirators do not remove CO from the breathing air, it will be necessary to monitor CO levels to ensure firefighter health and safety and compliance with OSHA standards.

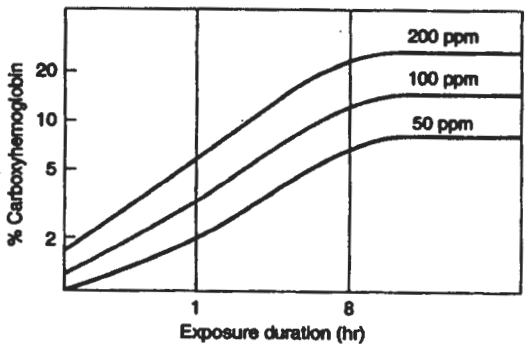


Figure 1—Carbon monoxide (ppm) and %COHb.

Pulmonary Function—Studies of firefighters indicate a small but statistically significant decline in lung function from the beginning to the end of the work shift, and from the beginning to the end of the fire season (Bechtley, et al., 1994). Follow-up indicated a return to normal values after a period free from exposure. The respiratory system is over built for its duties, with a maximal breathing capacity (180 liters/minute) that far exceeds ventilatory

requirements at maximal exercise levels (120 liters/minute). Since the ventilatory requirements of firefighting range from 40 to 60 liters/minute, the small (1 to 3%) decline in lung function is not apparent to firefighters.

Intermediate Effects

Days and weeks of smoke exposure can lead to more persistent health effects, including potential suppression of the immune system. Smoke can deaden the ciliary action that sweeps larger particles out of the respiratory tract for expectoration. Without this "ciliary escalator" to clean the lower respiratory tract, particles would slide deeper into the respiratory tract, causing congestion, coughing, and other problems. When such problems are combined with immunosuppression due to smoke, exhaustion, stress, and poor nutrition, the stage is set for bronchitis, and for a prolonged recovery.

Respirable particulate is able to reach the alveolar region of the lung. These small particles are slowly removed by mucus movement up the ciliary escalator, by absorption, or by macrophage destruction. Particulate overload may cause sequestration compartments and formation of chemical reactants. Respirable particulate may transport PAH (polycyclic aromatic hydrocarbon) carcinogens deep into the lungs (Figure 2).

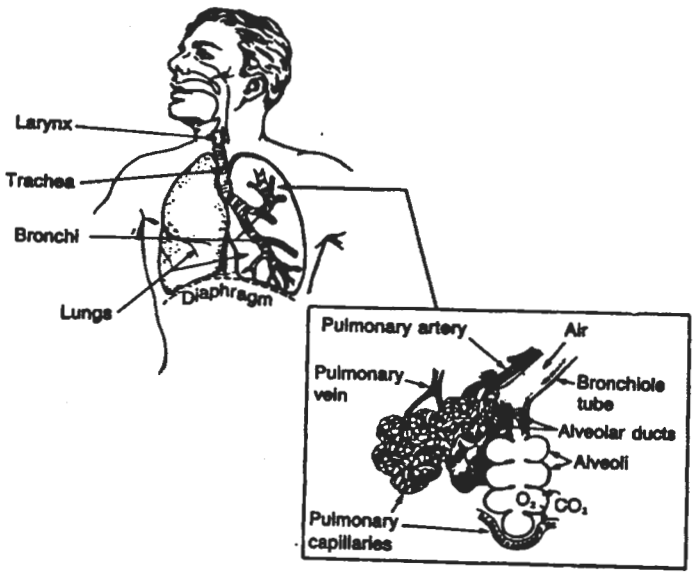


Figure 2—The respiratory system.

In spite of these potential problems, the healthy lung has a remarkable ability to recover from the effects of smoke when it is provided time to recover.

Long-Term Exposure

Little is known about the long-term effects of smoke exposure. Several models, including cigarette smoking, urban air pollution, and structural firefighting have been used to infer possible risks. The literature on cigarette smoking suggests the potential for:

- Coronary artery disease and stroke
- Chronic obstructive pulmonary disease
- Cancer (including the lung and other sites)

However, cigarette smokers reach these end points after decades of daily smoke exposure. Firefighting is seasonal, and exposures are intermittent and episodic. Urban air pollution studies suggest the potential for long-term health effects, especially from fine particulate. But these epidemiological studies encompass the entire range of the population, from the very young to the frail elderly, and do not mirror the population involved in wildland firefighting.

Structural firefighters risk exposure to smoke containing a wide range of toxic substances. Studies do not consistently show an increased risk of heart disease among structural firefighters, but those who smoke have a greater risk of heart and pulmonary disease, and lung cancer. Pulmonary function changes and chronic lung disease have been shown in some studies of structural firefighters, but the effects have not been associated with years of service or exposure, suggesting greater effects in a small subgroup of workers. While several studies fail to find an increased risk for lung cancer among structural firefighters, others have shown increases in brain, bladder, or other cancers.

Retrospective mortality/morbidity studies have not been done to determine the long-term effects of exposure to forest fire smoke. The population of long-term wildland firefighters is limited, exposure data is nonexistent, and potential exposure to other hazards (e.g., smoking, radon, wood burning, or air pollution) confounds the data. Case studies of firefighter retirees indicate the complexity of the problem. A fire manager who died of lung cancer was a long-time smoker; a retired firefighter recovering from open-heart surgery had a strong family history of the disease. Neither of these firefighter retirees spent much time on fires during their last 10 years of employment.

A prospective study of health effects may be required to determine the long-term effects of exposure. The study will require a large initial population, entry level information on

respiratory health and pulmonary function, accurate career-long exposure data, and many years to reach a conclusion. Information concerning the prospective study is included in the Surveillance/Research section of this report.

Pulmonary Function—MTDC has measured the pulmonary function of firefighters before the last four fire seasons. The data indicate that firefighters score above the normative values for pulmonary function. However, the rate of decline in function was somewhat faster for firefighters than for the population at large (Sharkey, et al., 1995). Interestingly, as with structural firefighters, a small subset of workers accounted for a substantial portion of the decline in lung function.

Individual Response

Frequent reference in the literature to individual responses to smoke suggest that a subset of workers may be more susceptible to the health hazards of smoke. Some individuals are hypersensitive because of asthma and allergies. Exposure to smoke or other contaminants (e.g., western red cedar) can lead to sensitization in some individuals. Once sensitized, workers may be affected to a greater degree when exposed to the smoke from forest fires. Methacholine challenge tests conducted on wildland firefighters before and after a fire season showed a significant relationship between methacholine sensitivity and a history of allergies, and a relationship between sensitivity and a history of asthma. All firefighters showed an increase in sensitivity at the end of the season (Harrison et al., 1992).

How can we protect susceptible individuals from the effects of exposure to smoke? Pre-employment medical screening, or pulmonary function or methacholine testing could identify individuals with hypersensitive airways. However, pre-employment screening is outlawed under the Americans With Disabilities Act (ADA). Employed individuals can be tested, but pulmonary function tests are not definitive. Methacholine tests are expensive and require that a physician be present. When sensitive individuals are identified, the ADA requires the employer to make a reasonable accommodation to the disability. Since 15% or more of the general population is classified as asthmatic, and even more suffer with allergies, fire managers could be faced with making a reasonable accommodation for thousands of seasonal employees. And it is not certain that a reasonable accommodation can be found.

An air-purifying respirator is a burden for an asthmatic. A powered air-purifying respirator (PAPR) could be used, but the weight is substantial, the noise presents a safety hazard to the wearer, and the battery would need to be recharged daily. Pending resolution of these

issues, prospective firefighters should be informed about the nature and risks of wildland firefighting before employment, and should be trained to recognize and avoid hazardous conditions on the job.

Summary and Conclusions

Smoke from wildland fires contributes to short-term and intermediate health effects. The effects have been shown to be reversible in most cases. Long-term exposure has the potential to cause or exacerbate health problems such as coronary artery disease, chronic obstructive pulmonary disease, and cancer. However, little data exists to confirm or deny a higher risk for wildland firefighters. Individuals with asthma, allergies, or the capacity to develop reactive airways are more likely to be susceptible to the effects of smoke.

Fire managers should educate firefighters about the health hazards of smoke. They should institute a program to monitor crew exposure, and establish practices that serve to avoid smoke exposure and maintain a healthy immune system in firefighters. Such practices include tactics to avoid exposure to smoke, improved fitness and rest schedules to avoid exhaustion, minimizing stress by communication, concern, and cooperation; and providing adequate nutrition, including antioxidants and foods that help maintain a healthy immune system.

Finally, a surveillance system is needed to track smoke exposures to help determine the effects of long-term exposure on the health of wildland firefighters.

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Assessment of the Health Risks of Chronic Smoke Exposure for Wildland Firefighters

Thomas F. Booze, Ph.D., and Timothy E. Reinhardt

We are presenting the results of a screening health risk assessment for wildland firefighters exposed to smoke from wildfires and prescribed burns. A screening health risk assessment makes use of limited resources to help in identifying areas where significant health risk might be present as well as to identify areas where health risk is not significant. This is done in part by making assumptions about exposure where suitably specific data is absent. These assumptions are designed to be protective of health and to result in estimates of risk that are greater than that which actually occur.

This screening risk assessment focused on a list of chemicals of potential concern (COPC) that had been identified in previous studies (1,2). Respirable particulate matter (RPM), an important COPC in smoke, was omitted from this assessment because acceptable toxicity values were not readily available (It is included in on-going work which will be an extension of the risk assessment reported here. This work will be published when finished). A list of the COPCs evaluated in this assessment is shown below.

- Acrolein
- Anthracene
- Benzene
- Benzo(a)anthracene
- Benzo(a)pyrene
- Benzo(b)fluoranthene
- Benzo(k)fluoranthene
- Carbon monoxide
- Chrysene
- Fluoranthene
- Formaldehyde
- Indeno(1,2,3-cd)pyrene
- Phenanthrene
- Pyrene

Average and reasonable maximum exposures (RME) were estimated for Type I and Type II hand crews for both wildfires and prescribed burns. Engine crews were omitted because insufficient data were found to estimate their exposures. The average exposures are based on the mean of available exposure data while the RME exposures are based on the upper 95% confidence limit of the mean of the same exposure data. For example, the risk for the average wildfire exposure of a Type I crewmember was based on an exposure of 8 years, 64 days per year, and 9.4 hours per day. The RME risk was based on an exposure of 25 years, 97 days per year, and 9.4 hours per day. Average estimates for Type II crewmembers were 7 years, 10 days per year, and 9.4 hours per day with the RME exposure being 25 years, 46 days per year, and 9.4 hours per day. The hours per day and the concentration of COPCs were different for prescribed burns and wildfires.

Cancer risks and noncancer hazard indices were estimated for Type I and Type II crewmembers at both wildfires and at prescribed burns and are presented below. It was assumed that a firefighter spent their career at wildfires only or prescribed burns only. The scope of this risk assessment precluded the analysis of time spent at a combination of fire types. It is likely that if such a combination was evaluated that the highest cancer risk would be less and the highest total hazard index would be less.

Cancer Risk Summary

Crew Type	COPC	Wildfires	Prescribed Burns
Type I (RME)	Total	**3.0E-04**	**6.0E-05**
	Benzene	**1.6E-04**	**2.1E-05**
	Formaldehyde	**1.2E-04**	**3.8E-05**
	Benzo(a)pyrene	**7.0E-06**	9.1E-07
	Benzo(b)fluoranthene	**1.5E-06**	1.9E-07
	Indeno(1,2,3-cd)pyrene	**1.7E-06**	2.2E-07
Type I (mean)	Total	**2.4E-05**	**2.6E-06**
	Formaldehyde	**1.2E-05**	**1.5E-06**
	Benzene	**1.1E-05**	9.8E-07
Type II (RME)	Total	**1.4E-05**	**7.8E-05**
	Benzene	**7.6E-05**	**2.7E-05**
	Formaldehyde	**5.9E-05**	**4.9E-05**
	Benzo(a)pyrene	**3.3E-06**	**1.2E-06**
Type II (mean)	Total	**3.2E-06**	**1.3E-06**
	Formaldehyde	**1.6E-06**	8.1E-07
	Benzene	**1.5E-06**	5.2E-07

Risks equal to or greater than 1.0E-06 are in **bold**.

Hazard Index Summary

Crew Type	COPC	Wildfires	Prescribed Burns
Type I (RME)	Total	226	118
	Acrolein	226	118
Type I (mean)	Total	99.4	17.5
	Acrolein	99.3	17.5
Type II (RME)	Total	107	152
	Acrolein	107	152
Type II (mean)	Total	15.5	10.5
	Acrolein	15.5	10.4

Contributor listed only if greater than 1.0. All other COPC (anthracene, carbon monoxide, fluoranthene, formaldehyde, phenanthrene, and pyrene) have an HI less than 1.0.

The carcinogenic risk is an upper bound estimate of the probability of developing cancer over a lifetime of exposure. The true risk probably does not exceed the risk estimate, and may actually be less. Estimated COPC cancer risks were calculated for each firefighter type by multiplying the calculated exposures by the appropriate cancer slope factor. Benzene and formaldehyde were found to be the most significant contributors to cancer risk; polynuclear aromatic hydrocarbons did not contribute significantly to this risk.

The potential for developing non-carcinogenic adverse health effects from chronic exposure was characterized by calculating the hazard index (HI) of the chemical-specific exposures. The HI is the estimated exposure divided by the reference dose. An HI greater than 1.0 indicates the potential for an adverse effect. Acrolein was the only COPC with an HI greater than 1.0. Although the HI is significantly greater than 1.0 this does not mean that an adverse effect is likely. In the case of acrolein the inhalation dose is based on the most sensitive adverse effect, the effect occurring at the lowest dose. The nasal passage response to irritation is the most sensitive effect and is the basis for the RfD. The concentration of acrolein used in this assessment ranged from 0.01 to 0.04 mg/m^3, which is well below the NIOSH and ACGIH occupational exposure limits of 0.23 mg/m^3.

In summary, this screening-level risk assessment indicates that further risk assessment efforts should be focused to only a few COPCs, and shows that adverse health effects are unlikely for the others, based on the available data and assumptions used. The contribution of respirable particulate matter to the total risk is being evaluated and will be reported elsewhere. The risk levels or HIs identified for the remaining chemicals (acrolein, benzene, and formaldehyde) may be further evaluated, but based on this assessment they are within the ranges considered to be acceptable by regulatory agencies. The first step to improving the risk estimates would be a sensitivity analysis to determine how much of an effect is exerted on the total risk by each component of the risk assessment. Based on this analysis, a hierarchy of data needs can be constructed and resources may be allocated to replace these uncertain assumptions with more representative data.

Exposure Monitoring

Health Hazards of Smoke Conference, Missoula, MT April 9, 1997

Tim Reinhardt, Radian International
Roger Ottmar, USDA Forest Service, PNW Research Station

This presentation summarizes the objectives and a suggested strategy for a firefighter smoke exposure monitoring program. The program would be an agency-wide effort to define the current baseline and track future progress towards controlling smoke exposure among firefighters. A simplified approach is recommended to acquire the needed information in a cost-effective way.

Why monitor smoke exposure?

- Liability management.
- Determine progress towards goals.
- Achieve regulatory compliance.
- Commitment to employee health.

Monitoring Objectives

- Representative of "firefighters".
- Directed at important pollutants.
- Accurate and Precise.
- Inexpensive--Affordable for wide use.
- Simple--Could be implemented with minimal training.
- Integrated--not a burden.

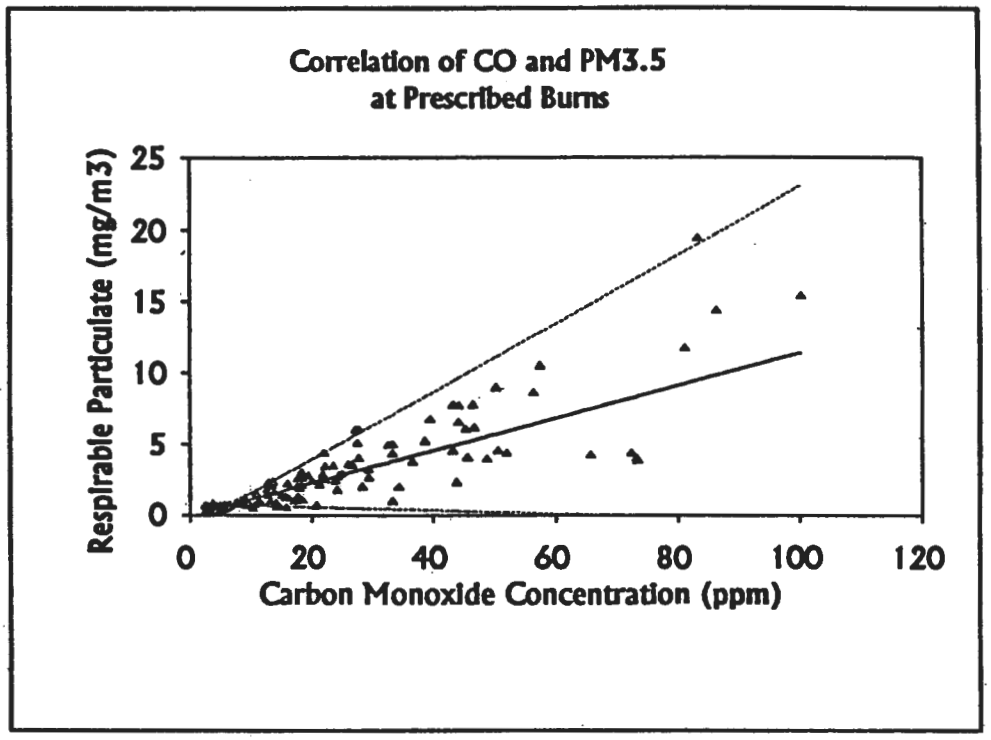
Important Pollutants

- Focus on those we know are problem:
  - Carbon monoxide
  - Respiratory irritants
- Secondarily, assess significance of the "Unknowns"
  - total particulate
  - crystalline silica

Carbon monoxide monitoring provides the key information firefighters and fire managers need to work safely, because CO is an identified hazard and it always accompanies other hazardous components of smoke. Therefore, establishing a routine CO monitoring program should be the initial priority. The CO monitoring program must be planned and well-integrated into the incident management system to ensure that it occurs (even in dynamic situations) without imposing an unnecessary burden on firefighting activities.

Total particulate matter is a potential inhalation hazard that is not entirely correlated to CO levels because entrained soil dust adds to the particulate in smoke. Assessing exposure to total particulate matter can be done once routine CO monitoring programs are in place. For example, a small percentage of firefighters who are monitored for CO can also be monitored for total particulate exposure using a personal sampling pump. Such limited investigations are a manageable adjunct to the CO monitoring program.

As crystalline silica in dust is a concern, archived total and respirable particulate samples could be reanalyzed for crystalline silica content. By analyzing already-sampled filters, the needed information can be obtained without incurring the expense of a field monitoring effort.



The cost of monitoring the important respiratory irritants in smoke is very high. However, data show that exposure to formaldehyde, acrolein and respirable particulate (PM3.5) can be estimated from the CO measurement results. As shown above for PM3.5, the contaminants in smoke that cause respiratory irritation are highly correlated with CO. Similar results have been found for acrolein and formaldehyde. If data from the western U.S. can be bolstered with data from other regions, these correlations can be used to calculate the total respiratory irritant level in smoke from just a CO measurement. Thus the objective of monitoring all the key hazards in smoke can be met by monitoring only CO, at a greatly reduced cost.

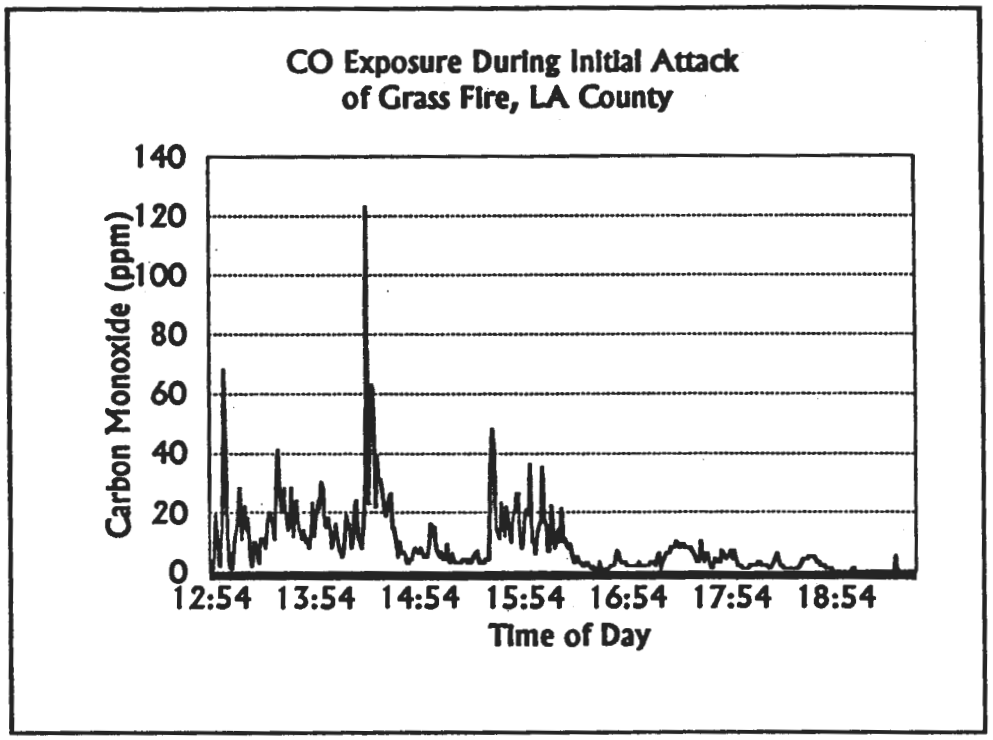
Electronic CO Dosimeter

- Relatively inexpensive: $900-1200 including calibration equipment.
- No subsequent sample analysis cost.
- Minimal support equipment.
- Highly portable.
- Lightweight.
- Simple.

A cost-effective way to meet smoke exposure monitoring objectives uses electronic dosimeter technology to monitor CO exposure among firefighters. Available from many manufacturers, these devices use an electrochemical sensor cell to constantly monitor CO levels in the air. Worn near the face, they are battery-powered devices about the size of a pack of cigarettes. Most have built-in alarm functions to alert crews when CO approaches unhealthful levels. The datalogging versions of these instruments record the CO level vs. time, data retrievable by a computer. These "dataloggers" provide records of monitoring results that are valuable training tools for fire crews.

The datalogger is ideal because it records accurate CO levels minute-by-minute without requiring anything else of the user--the firefighter only has to keep wearing the device during the shift. When concerned about smoke levels, a quick glance at the display of the dosimeter shows the current CO level and the accumulated average exposure for the firefighter.

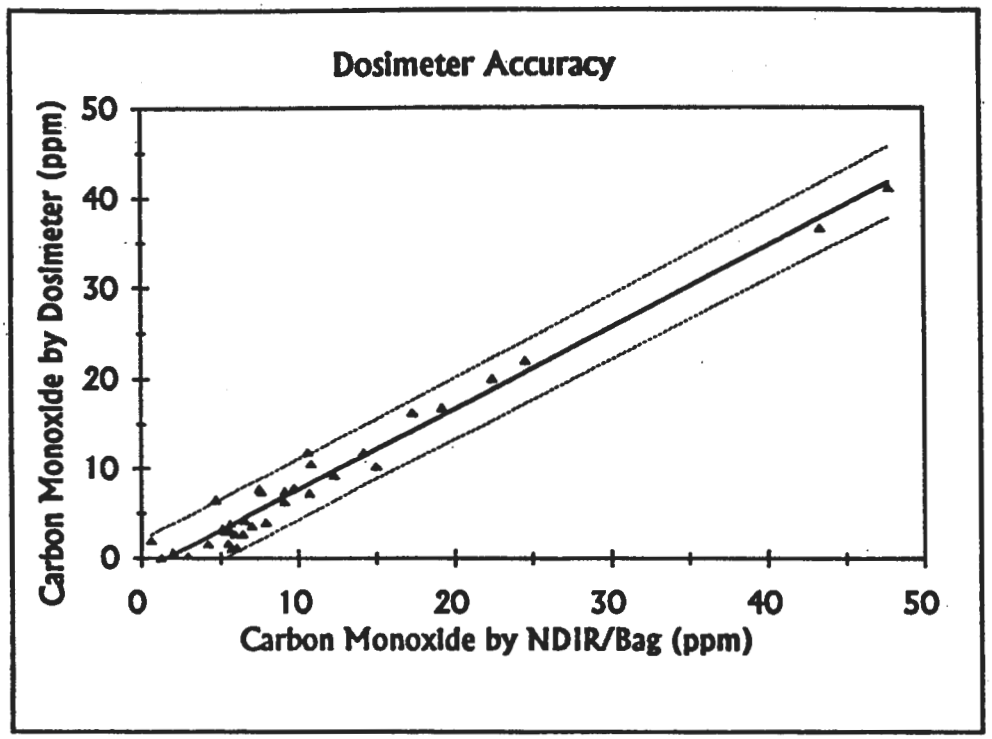
With training, a safety officer or other designated individual could set up and calibrate these devices in minutes, then deploy one per crew for automated data collection during the shift. Data can be retrieved after the shift, or after several shifts for multi-day assignments.



As an example of the detailed exposure data that can be obtained, this graph shows the CO levels that a firefighter encountered during initial attack of a grass fire in southern California. The proposed monitoring program would obtain such a record for every firefighter monitored.

Making sense of this data requires simple notation of key changes in the work activity and fire situation while the monitor is being worn. A crew foreman or firefighter could be assigned this responsibility, which only requires a pen, a pad-sized data form and a watch keeping accurate time. At key moments, just a few descriptive words and a time-of-day entry are all that's necessary.

Matching the datalogger record with the workday notes can be done via computer, and the results can then be shared with the firefighter or crew. The data can also be retained for more sophisticated analysis of exposure during certain fireline situations and to track long-term trends in exposure.



As shown by the data above, the electronic CO dosimeter results agree with other, more complicated methods of CO measurement. The best results can only be obtained through a strict adherence to protocols, however. The graph above plots CO monitoring results on the X-axis that were obtained from a labor-intensive gas bag collection among firefighters followed by infrared spectroscopy analysis in a laboratory. On the Y-axis are electronic dosimeter results obtained at the same time from the same firefighters. The data are in good agreement, although the dosimeter results are biased slightly low, a problem that could be controlled through adherence to a quality assurance plan and standard operating procedures (SOPs) for data collection.

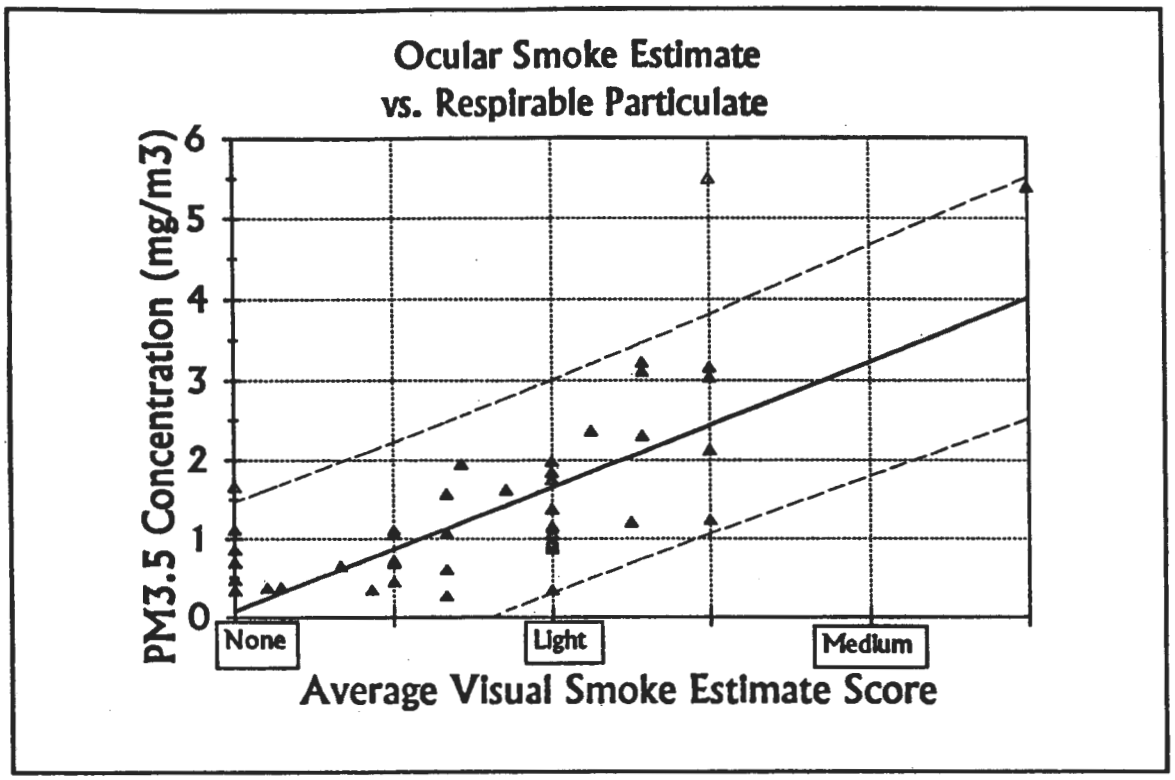
Ensure Data are Accurate and Precise by:

- Standard methods.
- Trained monitoring personnel.
- Quality assurance plan and indicators.
- Independent review of data quality.

A routine CO monitoring program must use simple equipment and standard methods so that data collection can be successfully accomplished on a broad scale by staff with minimal background in industrial hygiene. The monitoring program must include a quality assurance plan which includes data quality indicators. These quality control indicators are the only way to ensure that the data collected under the program meets the data quality objectives.

Typical indicators include field replicates, field blanks, and independent calibration checks. Field replicates indicate the precision of the exposure measurements. Field blanks and calibration checks provide a measure of the accuracy of the exposure measurements, and help to determine the cause of inaccurate results. Incorporating such quality assurance elements adds roughly 10% to the cost and 25% to the complexity of the program, but without them the data are of unknown reliability and useless for the monitoring objectives.

Annual review of data quality is recommended to identify problems in data collection, analysis or reporting that can go unnoticed by those generating the data. The data quality review is best done by an objective expert so that the monitoring program receives thorough, yet impartial review.



For those with no access to monitoring equipment of any kind, there is some hope that a rough estimate of smoke exposure is possible. The data above are from project wildfires, where an observer noted the apparent smoke exposure within 20-minute intervals. The average smoke estimate is on the x-axis, and the actual exposure to PM3.5 is on the y-axis. Note that there is a correlation, although it is highly variable.

Based on this example, any smoke that was considered "medium" in intensity would average about 3 mg/m3, but could range up to nearly 5 mg/m3. Similar results are found for the other pollutants in smoke, but the correlations are not even this strong. More data and detailed analysis is needed before we can say we don't need objective data such as the CO dosimeter provides.

Suggested Plan

- Select CO dosimeter carefully (test several models vs. standard method).
- Develop SOPs, train, and maintain eqpt.
- Monitor widely, share data.
- Adhere to QA plan.
- Limited irritant and total particulate monitoring to improve correlations.
- Analyze archived samples for crystalline silica to determine significance.

Benefits of Using Dosimeters

- Directly monitors CO--provides instant feedback to crews.
- Surrogate for correlated respiratory irritants.
- Datalogging capability for crew debriefing/incident analysis.
- Simple and inexpensive.

Potential Drawbacks

- Correlations with respiratory irritants need refinement--also must get concurrence from regulators.
- Accountability of monitoring--potential for misuse.
- Potential for useless data if QA plan not implemented.
- Ignores total particulate matter exposure.

Respiratory Protection

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The Missoula Technology and Development Center (MTDC) has previously studied respiratory protection (Thompson and Sharkey, 1966), and firefighter exposure to carbon monoxide (Jackson and Tietz, 1979). In 1989 National Wildfire Coordinating Group assigned MTDC to coordinate the Health Hazards of Smoke project. Part of that responsibility involved work in the area of respiratory protection, including a field survey of respirator use, ongoing literature and product reviews, laboratory and field studies of respirators, participation on National Fire Protection Association and American National Standards Institute committees, and interaction with firefighters, scientists, fire managers, regulators (National Institute of Occupational Safety and Health and the Occupational Safety and Health Administration), manufacturers, and others interested in the effects of smoke on wildland firefighters. This report summarizes some of these activities.

Field Survey

Based on field interviews, a questionnaire was constructed to assess field use of respiratory protective devices by wildland firefighters during wildfire suppression or prescribed burning. Responses from 300 Federal and State agency employees indicated some prior use of respiratory protection. About 82.2% thought the hazards of smoke warranted respiratory protection, especially during direct attack (70.4%), line holding (79.8%), and mop-up (64.8%). Of those who had used a device for respiratory protection, 75% reported that it reduced productivity. Surprisingly, while 69.1% reported problems with communication, only 7.1% reported problems with a beard, with glasses (12.6%), or with a hard hat and goggles (5.5%). Half of the respondents expressed concern that a device that provided protection from some but not all hazards could provide a false sense of security. The results indicate firefighter concern for the health hazards of smoke, that the perceived need for protection

increases with prior respirator use, and that fit and other problems are minor and should be manageable with proper training (Driessen, Sharkey, and Buskirk, 1992).

Respirator Studies

Air-purifying respirators (APR's) have been shown to decrease work performance through breathing resistance, increased dead space, heat stress, and respirator weight. They increase the sense of breathlessness (dypsnea) during strenuous effort and have been shown to cause claustrophobia. This section summarizes a series of studies that measured the effects of wearing APR's.

All studies were conducted in the University of Montana Human Performance Laboratory, under the terms of a memorandum of understanding with MTDC. All protocols were reviewed and approved by the University Institutional Review Board to ensure proper use of human subjects. Studies have been reported in the Occupational Medicine and Physiology research section of the American College of Sports Medicine. A review of each study and a discussion of its implications is followed by a summary addressing the purposes of that phase of the project.

This section summarizes the results in terms of the major purposes of the studies.

1. To compare the effects of APR's with varying breathing resistance on work performance. The studies employed the type of protection likely to be needed by wildland firefighters, as identified in the deliberations leading to NFPA 1977 Protective Clothing and Equipment for Wildland Firefighting (specifically comparing a high-efficiency particulate air filter (HEPA) with a high-efficiency particulate air filter that includes protection form organic vapors and acid gases (HEPA + OV/AG).

APR's decrease work performance significantly. They reduce both maximal and prolonged work performance, and blunt the pulmonary response to vigorous work. When identical masks equipped with different cartridges (HEPA vs. HEPA + OV/AG) were compared, the decline in performance with the respirator was proportional to the breathing resistance. It should be noted that, in general, resistance increases with respiratory protection. The HEPA filter protects against inhalation of particulate. The addition of organic vapor/acid gas protection (HEPA + OV/AG) doubles the breathing resistance and doubles the decline in work performance. It is important that the protection be appropriate to the exposure (Sharkey and Mead, 1992; 1993; Thompson and Sharkey, 1966).

Additional protection against carbon monoxide exposure could be achieved, but at a considerable physiological cost. Converting carbon monoxide to carbon dioxide is an exothermic reaction that raises the temperature of the inspired air, increasing breathing rate and the sense of fatigue. The increase in carbon dioxide, the main respiratory stimulus, causes an additional increase in pulmonary ventilation. Finally, the material used to remove carbon monoxide adds to the resistance of the device, causing an even greater decline in performance. Protection from all the health hazards in smoke from wildland fires and prescribed burns would require protection from particulate, organic vapors/acid gases, and carbon monoxide.

Breathing zone exposure studies of firefighters have shown occasional exposures in excess of OSHA permissible exposure limits. Studies of the health effects of smoke have found small but statistically significant changes in pulmonary function over the course of a season. The long-term consequences of these changes and the potential for more serious effects have not been determined.

2. To compare the effects of APR's on the performance of upper and lower body work. Recent studies of upper body work have shown lower levels of pulmonary ventilation, which could exacerbate the effects of wearing an APR.

While APR's consistently reduced submaximal and maximal work performance on the treadmill, arm work (cranking) was not reduced significantly ($P < 0.07$). This outcome was surprising since recent studies have shown diminished levels of pulmonary ventilation during work with the arms. We had hypothesized a significant effect of APR use on sustained arm work, but the combined male/female difference was not significant. The results did show a significant reduction in arm peak VO_2 and peak ventilation. The decline in arm performance with the respirator was 4% for males and 8.3% for females. More will be said regarding male/female comparisons in the next section of this summary (Rothwell, deLorenzo-Green, and Sharkey, 1994).

These comparisons were made on an upper body (arm cranking) exercise device, which was used to isolate the arms and allow an accurate measurement of work performance. Work with hand tools usually involves the arms, trunk, and legs, often with trunk flexion (involving restriction of the pulmonary apparatus). So the marginal effects on performance measured in this trial may not reflect the full effect of the APR on work with hand tools. Subsequent tests on simulated fireline construction support the findings of the initial study

(Rothwell and Sharkey, 1996). Within the limits of these studies, the APR significantly reduced peak output and ventilation during arm work, but did not cause a statistically significant reduction in sustained performance.

3. To evaluate the effects of APR use on women. An extensive review of the literature revealed few studies in which women had been included as subjects. Since women comprise a large percentage of the firefighting work force, and since their pulmonary function capacities are, on average, smaller than those of men, it is important to understand the effect of APR's on their ability to perform arduous work.

Pulmonary function measures are associated with body size. It is understandable that the average valves for forced vital capacity are 67% as high for females as males (3.7 vs. 5.5 L for FVC), and for maximal ventilatory volume are 72% as high for females as males (131 vs. 182 L/min for MVV). In one study, females scored 43.4 ml/kg/min compared to 49.4 for males on treadmill max (VO_2), and 44.9 min vs. 40.1 for males on a field test (Pack Test). These differences were not statistically significant.

On upper body strength tests, females averaged 51% of male values (80 lb vs. 156.7 lb) for the bench press, and 47.7% (45.6 lb vs. 95.6 lb) for the arm curl. These results are consistent with the literature that shows females averaging about 50% of males on upper body strength tests. On leg strength tests, females averaged 64.7% of males on the leg press (313.3 lb vs. 484.4 lb). This value is similar to those in the literature where females typically average 70% of male values. When strength values are calculated per kilogram of lean body weight, females typically average 70% of male arm strength scores and 100% of male leg strength scores.

Females averaged 53.1% of males (39.7 watts vs. 74.7 watts) on the arm ergometry test, reflecting the differences in upper body strength. The decrement in performance with the APR was 3.3 watts for females and 3.0 watts for males. Neither difference was statistically significant. However, the percentage change was greater for females (8.3% vs. 4% for males).

Based on the results of our studies it appears that females who score 45 (ml/kg/min) on the VO_2 max or step test (or 45 min on the pack test) have sufficient pulmonary capacity and are not adversely affected by the APR.

4. To evaluate possible predictors of the ability to work while wearing a respirator, including pulmonary function, fitness and field tests. The 11-step respirator program mandated by OSHA (29 CFR 1910.134) stipulates that "Persons should not be assigned to tasks requiring use of respirators unless it has been determined they are physically able to perform the work and use the equipment." At present no test or battery of tests can unequivocally determine the ability to work with an APR.

Early attention focused on the maximal ventilatory volume (MVV) as an indicator of breathing capacity and an individual's ability to work with a respirator. The MVV value is first adjusted for the effects of the respirator:

$$\text{adjusted MVV} = (\text{MVV} \times 0.49) + 29 \text{ L/min}$$

The adjusted MVV is reduced by half to reflect day-long work capacity.
If the final score falls below the ventilatory cost of firefighting (40-60 L/min), the candidate would have difficulty working with the respirator.

For example: MVV = 120; adj MVV = 87.8 L/min x 0.5 = 43.9 L/min

Our results confirmed the theoretical value of the test, but the correlations with performance were not sufficiently high to use the test in job selection. Similarly, the peak inspiratory flow rate (PIFR) promised to provide information concerning the ability to perform prolonged work against the resistance of a respirator. However, the correlations with performance were no better than those based on standard pulmonary function measures (e.g., FEV1, Forced Expiratory Volume in 1 Second). Therefore, it would appear that the basic pulmonary function test provides sufficient data concerning lung function, and that additional analyses (MVV or PIFR) do not add measurably to the prediction of performance.

Maximal oxygen intake (VO_2 max) and step test scores were significantly correlated to performance with the respirator. In addition, these measures of aerobic fitness were highly correlated to pulmonary function measurements. Aerobic fitness, or VO_2 max, is defined as the ability to take in, transport, and use oxygen. This measure of fitness includes information about the function of the pulmonary function apparatus. A Step Test score of 45 provides assurance of an individual's ability to work with a respirator. In the study of upper body work, arm strength scores were also correlated to performance with an APR and to the field (Pack Test). Strength measures improve the prediction of performance, and the field (Pack Test) includes a muscular fitness component.

The Pack Test (3-mile field test carrying a 45-lb pack) was correlated to performance with the APR and to aerobic and muscular fitness tests. The American Industrial Hygiene Association (AIHA) recommends that a respirator should be worn for at least 30 minutes, and during part of this time, workers should exert themselves to the level that would be required on the job. The Pack Test provides information concerning fitness and the ability to work with a respirator. The energy cost of the Pack Test is similar to that demanded on the job (22.5 ml/kg/min). MTDC has conducted laboratory and field studies that confirm the effectiveness of the Pack Test, both as a predictor of work capacity and as an indication of the ability to work with an APR (Sharkey and Rothwell, 1995).

Conclusions

1. Although respirators reduce work capacity, they may be necessary to minimize hazardous exposures. Managers need to know that it will take more time or more firefighters to get the job done when firefighters are wearing an APR. In heavy smoke conditions, such as hot-spotting on a prescribed fire, a respirator may be required to get the job done.

2. Respirators do not seem to impose a disproportional effect on upper body work performance.

3. Female firefighters who meet the current standard for aerobic fitness will be able to perform while wearing a respirator.

4. The ability to work while wearing an APR can be predicted with laboratory or field fitness measures, pulmonary function tests, or a job-related work capacity test such as the Pack Test.

Field Evaluations

MTDC conducted field evaluations of a variety of APRs. Firefighters engaged in wildfire suppression and prescribed burning used disposable or maintenance-free devices, half-face or full-face respirators. Disposables were acceptable for short-term use, but they deteriorated in the heat during several hours of use. Maintenance-free half-face devices were satisfactory, except for the heat stress found with all face masks. Full-face masks were preferred for long-term use on prescribed fire because of the eye protection, but workers often complained of headaches, a sign of excess CO exposure.

Firefighters expressed an interest in a lightweight respirator that is easy to put on and take off, designed specifically for wildland firefighters. A mouthpiece respirator meets the following criteria: lightweight, inexpensive, easy to don and doff, no heat stress, self storing, no problems with beards, glasses, or facial irregularities (e.g., scars). However, current mouthpiece devices are only approved (NIOSH) for escape purposes. And available products are not designed with the large diameter breathing tubes necessary to accommodate the ventilation rates (40-60 L/min) encountered during wildland firefighting.

Any device used by wildland firefighters should be tested for performance in the heat, and for the flammability of exposed filter material. Full face devices protect the eyes, but remove an important early warning of exposure—eye irritation.

Respiratory Protection Program

OSHA requires a written respiratory protection program before respiratory protection can be used. To provide employees adequate protection and comply with the OSHA respiratory protection standard (CFR 29, 1910: 134I), the program must include:

1. Written Operating Guidelines covering the selection and use of respirators for each task or operation where they are employed. The employer must develop a formal written document that addresses each of the following points.
2. Respirator Selection: Respirators must be selected on the basis of the hazard to which the employee is exposed. Guidance concerning respirator selection is contained in ANSI Z88.2-1992.
3. Training: Employees must be instructed and trained in the proper use and limitations of the respirators to which they are assigned. Respirators must be tested for fit and they should not be used if facial hair, eye glasses or other factors interfere with the seal of the face piece.
4. Approved Respirators: Respirators approved by NIOSH or accepted by OSHA must be used when they are available. The respirator must provide adequate protection against the particular hazard for which it has been designed in accordance with standards established by competent authorities (NIOSH, ANSI).
5. Respirator Assignment: Where practical, respirators should be assigned to individual employees for their exclusive use. When it isn't practical, the next step becomes even more important.

6. Cleaning: Respirators must be cleaned and disinfected. Those used exclusively by one employee should be cleaned daily. Devices used by more than one employee must be thoroughly cleaned and disinfected after each use.
7. Storage: Respirators must be stored in a convenient, clean and sanitary location.
8. Inspection and Maintenance: Routinely used devices must be inspected during cleaning. Worn or deteriorating parts must be replaced. Respirators for emergency use must be inspected at least monthly.
9. Monitoring: Appropriate surveillance of work area conditions and the degree of employee exposure must be maintained.
10. Inspection and Evaluation: There must be regular inspections and evaluations to assess the continued effectiveness of the respiratory protection program.
11. Medical Evaluation: Employees should not be assigned to work tasks that require the use of respirators unless they have been determined to be physically able to perform the work and use the equipment. The local physician must determine what health and physical conditions are pertinent. The respirator user's physical condition should be reviewed periodically.

MTDC is developing a model respiratory protection program to meet these requirements. The program includes information of medical evaluation, respirator selection and fitting, monitoring, etc., as mandated in CFR 29 1910:134. The program will be made available on a floppy disk.

NIOSH Respirator Guide

OSHA and NIOSH are updating the standards that regulate the use and certification of respirators in the workplace. Under the new regulations (42 CFR Part 84) NIOSH will certify three classes of filters (N, R and P) with three levels of efficiency (95%, 99%, and 99.97%) in each class. The efficiency indicates the degree to which the filter removes small (0.3 um) particulate.

N series (Not resistant to oil) particulate respirators are for protection from particulates that are free of oil or other severely degrading aerosols. These respirators have no time limitations.

R series (Resistant to oil) respirators may be used for protection from degrading aerosols for no longer than one shift.

P series (Oil proof) filters can be used for protection from any particulate aerosol. They have no time limitations.

All N, R, and P particulate filters must be discarded when they become soiled or damaged, or when breathing becomes difficult.

Assigned protection factors (APF's) are numbers given to classes of respirators, such as half-face or full-face, that indicate the anticipated maximum protection the respirator can provide. A respirator with an APF of 10 could be expected to protect a worker exposed to air concentrations up to 10 times the permissible exposure level (PEL) for a particular toxic chemical, such as formaldehyde. If the contaminant level is up to 50 times the PEL, a full-face respirator is required. If the level of exposure exceeds 50 times the PEL, a self-contained breathing apparatus (SCBA) must be used.

MTDC studies show that breathing resistance increases and work output decreases in proportion to the level of protection. For example, resistance for a HEPA filter with OV/AG protection is greater than for a HEPA filter without OV/AG protection, and resistance for the HEPA filter is greater than for a disposable filter.

HEPA + OV/AG > HEPA > Disposable half-mask

Since exposure studies have not indicated high levels of particulate for most prescribed fire or wildfire conditions, a filter efficiency of 95% should be sufficient. And since oil is not a typical component of vegetative smoke, an N series filter will be appropriate for firefighters.

Note: Removing carbon monoxide from the breathing air currently requires converting of CO to CO_2 in an exothermic reaction. The process adds additional breathing resistance, increases respiratory work with the respiratory stimulus of carbon dioxide, and increases heat stress with the breathing of hot air. No currently available device protects the worker from all the hazards in smoke.

Conclusions

While respiratory protection may sometimes be advised for those engaged in prescribed burning, studies have not confirmed the need for respirators for wildland firefighters. Devices would be required in fewer than 5% of cases studied. Training, tactics, monitoring, and other controls should be instituted and evaluated before a full-scale respirator program is considered. Pilot programs for prescribed burning will assist in developing of the various elements of the respiratory protection program, including training, fit testing, and medical evaluation.

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Risk Management Planning

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Risks are an accepted part of the business of wildland fire management, both on wildfires and on prescribed burns. If we wanted wildland fire personnel to work in a risk-free environment, we would have to avoid actions that entail "risk":

- Direct attack;
- Helirappelling;
- Igniting prescribed fires;
- Smokejumping.

As Fire Managers, we know that a risk-free environment, or "no action," is not a viable option in a wildland fire program: lives would be threatened, valuable resources lost, and opportunities for applying prescribed fire would be foregone. Several other approaches can be used to address the risks that a wildland fire fighter must face on a daily basis:

- Acceptance—Recognizing the risk that fire personnel face from exposure to wildland fire smoke on prescribed fires and wildfires, and living with that risk without taking any action;
- Avoidance—Identifying those conditions that are potentially hazardous to personnel, and ensuring that no exposure occurs;
- Mitigation—Identifying those conditions that may present a risk to fire personnel, and taking steps to remove the adverse effects of those risks so that exposures fall within an acceptable range.

Mitigation, or "risk management," is the result all of us have hoped for during the past 6+ years of work, and is the expected product of this conference.

Before we decide how to mitigate the risks from wildland fire smoke, we need to have a quick reality check with the factors that come into play when we are involved with wildland fire:

First, what is our MISSION? Are we conducting a prescribed burn to enhance the natural resources in a smoke-sensitive area, or in an area where little or no public concern has been expressed? Is the resource we are protecting from the risk of wildfire an area of threatened or endangered plant or animal species, or general forest ground with no unique features? Is the area politically sensitive, or does it include areas of urban-wildland interface?

Are our PERSONNEL experienced and highly trained, or are they relatively inexperienced and unable to readily recognize the hazards of the wildland fire workplace? What has been their exposure to high concentrations of wildland fire smoke over the recent days, weeks, and months?

Are ECONOMICS of the fire area and the adjacent area an important concern? Is this fire adjacent to private land, or in a public area of extraordinary value? Are more costly mitigation measures acceptable to the Line Officer and the public?

What are the POLITICS affecting the fire operations? Is this a Prescribed Natural Fire in Wilderness threatening to escape prescription and cross the Wilderness boundary? Are you conducting a prescribed burn against the property boundary of a vocal opponent of Forest Service fire policies? What is the attitude of the local media toward fire, both prescribed fire and wildfire?

After all these factors have been fully addressed, it's time to start planning the risk management actions to ensure both the short- and long-term well being of our wildland fire personnel:

1. Identify the risk—Is it short-term exposure during periods of initial attack, moderate duration exposure during holding operations on a prescribed burn, or long-term exposure during an extended mop-up operation?

2. Evaluate the risk—How often does it occur? What is the severity of the exposure?

3. Implement risk control techniques—Eliminate the hazard, or mitigate the exposure to bring it within acceptable limits.

We have previously identified the risk: smoke, from both wildfires and prescribed burns. Our next step is to evaluate the risk to the firefighter's health, both from the perspective of a single exposure and over the long term. We must develop procedures to effectively monitor the exposure of the firefighters, keeping in mind that many of the effects of smoke exposure may not show up for many years and may be affected by outside influences such as tobacco use, other employment and/or hobbies, or environmental factors such as wood stoves.

Risk control is the next, and most complex step, in the risk management planning process. For fire managers dealing with the smoke from wildfires, our options are often more limited than when we deal with prescribed fire—but OPTIONS are the key in both scenarios:

- Both workers and management have a vested interest in doing a job safely, efficiently, and with a minimum of risk. Effective training to identify and mitigate risks is a critical first step.
- Strategy and tactics are the real-time, on-the-ground techniques that fire managers use on prescribed fires and wildfires to accomplish the mission and ensure the safety and well-being of the firefighters. It is possible to do both, but the burden is on the fire manager to prepare a plan that effectively "manages the exposure."

Remember, the "responsibility" for ensuring a safe work environment rests with us as fire managers. To redeem those responsibilities, we must do all the actions identified above: identify, evaluate, mitigate, and lastly, monitor success through a program that ensures that risk management efforts are effective.

The key aspect of a successful risk management plan is to "manage" the risk, the exposure, and the mitigation. The continued success of our fire management programs, and the health of our fire personnel, is at stake.