

## Conference Papers

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### Managing Risk Management

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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 be similar and could be common. Pragmatically speaking, the challenges of fire management in 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 will 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 that while we all make affirmations for safety and commit to implementing safety procedures, too often we do not ensure that those affirmations are carried out.

The risk management system must be simple, perhaps elegant in its simplicity. The solution cannot be worse than the problem. We must focus on keeping our workforce healthy, and on providing the services we are charged to provide. The data show that there are few exposures that exceed permissible levels, that they happen

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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 and Rothman, 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.

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## Review of Smoke Components

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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 PM<sub>2.5</sub> air quality standard is designed to protect human health and suggests that health is most at risk from particles less than 2.5  $\mu\text{m}$  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 atmosphere 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 benzo[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<sub>2</sub> and water vapor. The efficiency of the combustion process has been described by the ratio of CO<sub>2</sub> to the sum of CO<sub>2</sub> 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<sub>4</sub>, 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  $7.4 \pm 6.2$  and  $1.5 \pm 1.5$ , 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 through 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<sub>4</sub>, 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	Carcinogenicity
	(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 ( $\times 10^{-3}$ )	mean molar ratio to CO ( $\times 10^{-3}$ )
2-furaldehyde	$1.50 \pm 0.93$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>1.50 \pm 0.93</math></b> <sup>[McKenzie, et al., 1995]</sup>
5-methylfuraldehyde	$0.30 \pm 0.19$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.30 \pm 0.19</math></b> <sup>[McKenzie, et al., 1995]</sup>
2acetylfuran	$0.33 \pm 0.16$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.33 \pm 0.16</math></b> <sup>[McKenzie, et al., 1995]</sup>
phenol	$0.32 \pm 0.2$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.32 \pm 0.2</math></b> <sup>[McKenzie, et al., 1995]</sup>
o-cresol	$0.27 \pm 0.13$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.27 \pm 0.13</math></b> <sup>[McKenzie, et al., 1995]</sup>
m/p-cresol	$0.52 \pm 0.25$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.52 \pm 0.25</math></b> <sup>[McKenzie, et al., 1995]</sup>
guaiacol	$0.17 \pm .081$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.17 \pm .081</math></b> <sup>[McKenzie, et al., 1995]</sup>
4-methylguaiacol	$1.00 \pm 0.83$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>1.00 \pm 0.83</math></b> <sup>[McKenzie, et al., 1995]</sup>
vanillin	$0.50 \pm 0.57$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.50 \pm 0.57</math></b> <sup>[McKenzie, et al., 1995]</sup>
acetol	$1.20 \pm 1.7$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>1.20 \pm 1.7</math></b> <sup>[McKenzie, et al., 1995]</sup>
vinyl acetate	$1.70 \pm 2.1$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>1.70 \pm 2.1</math></b> <sup>[McKenzie, et al., 1995]</sup>
2-cyclopenten-1-one	$0.20 \pm 0.13$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.20 \pm 0.13</math></b> <sup>[McKenzie, et al., 1995]</sup>
acetic acid	$7.40 \pm 6.2$ <sup>[McKenzie, et al., 1995]</sup> , $22.6$ <sup>[Yokelson et al., in press]</sup> , $8.70 \pm 6.1$ <sup>[Hartman et al., 1990]</sup> , $1.60 \pm 2.4$ <sup>[Talbot et al., 1988]</sup> , $8.00 \pm 4$ <sup>[Lefer et al., 1994]</sup> , $3.20 \pm 0.4$ <sup>[Hartman et al., 1990]</sup> , $2.60 \pm 6.8$ <sup>[Lefer et al., 1994]</sup>	$7.40 \pm 6.2$ <sup>[McKenzie, et al., 1995]</sup> , $22.6$ <sup>[Yokelson et al., in press]</sup> , $8.70 \pm 6.1$ <sup>[Hartman et al., 1990]</sup> , <b>12.1</b>
formic acid	$1.50 \pm 1.5$ <sup>[McKenzie, et al., 1995]</sup> , $1.6$ <sup>[McKenzie, et al., 1994]</sup> ; $9.1$ <sup>[Yokelson et al., in press]</sup> , $2.60 \pm 2$ <sup>[Hartman et al., 1990]</sup> , $0.17 \pm 0.27$ <sup>[Talbot et al., 1988]</sup> , $20$ <sup>[Lefer et al., 1994]</sup> $35.00 \pm 22$ <sup>[Lefer et al., 1994]</sup>	$9.1$ <sup>[Yokelson et al., in press]</sup> , $35.00 \pm 22$ <sup>[Lefer et al., 1994]</sup> , $1.6$ <sup>[McKenzie, et al., 1994]</sup> , <b>15.2</b>
propanoic acid	$0.39 \pm 0.19$ <sup>[McKenzie, et al., 1995]</sup> , $0.66$ <sup>[McKenzie, et al., 1994]</sup>	<b><math>0.66</math></b> <sup>[McKenzie, et al., 1994]</sup>
3-oxobutanoic acid	$0.41 \pm 0.44$ <sup>[McKenzie, et al., 1995]</sup>	<b><math>0.41 \pm 0.44</math></b> <sup>[McKenzie, et al., 1995]</sup>
methanol	$11.00 \pm 9$ <sup>[McKenzie, et al., 1995]</sup> , $18.0$ <sup>[Yokelson et al., in press]</sup>	$11.00 \pm 9$ <sup>[McKenzie, et al., 1995]</sup> , $18.0$ <sup>[Yokelson et al., in press]</sup>

Table II (continued)

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

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 (µg/m <sup>3</sup> )	B[a]P (µg/m <sup>3</sup> )	B[a]P/CO (µg/m <sup>3</sup> /ppm)	B[a]P/PM (µg/g)	PM/CO (µg/m <sup>3</sup> /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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