

Effects of Fire Behavior on Prescribed Fire Smoke Characteristics: A Case Study

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Biomass burning on a global scale injects a substantial quantity of gaseous and particulate matter emissions into the troposphere. Some of these combustion products are known to accumulate in the atmosphere and are implicated in observed changes in tropospheric composition and chemistry. The practice of open burning of biomass has come under close examination as a result of its pollution potential. In the United States, most biomass burning is managed in order to limit pollutant release. Recently, it has been inferred that biomass burning may produce a net increase in the concentration of "greenhouse gases" and particles in the atmosphere. Estimates of the quantity of biomass consumed globally per year vary widely, but generally Seiler and Crutzen's (1980) estimate of $5 \times 10^{15} \text{ g yr}^{-1}$ (grams per year) is regarded as accurate to within a factor of 2. The degree of consumption of total available biomass is affected by the quantity of biomass present, size distribution of the fuel, precipitation history for the site, condition of the vegetation, local meteorology, and a host of other factors. Combustion characteristics vary widely from vegetation types ranging from tropical grasslands to subarctic forest. As a result, the total emissions released are a complex function of many variables (Ward, 1990). Factors contributing to the total release of a particular pollutant species from a biomass fire can be quantitatively described by the following expression:

$$M_x = M_f \times A \times f_c \times EF_x$$

where M_x is the mass yield of a particular gaseous or particulate species, M_f is the fuel load in mass per unit area, A is the area burned, f_c is the fractional consumption of the total fuel load, and EF_x is the emission factor for the species of interest. Here, *emission factor* is defined as the mass release of a particular species per unit mass of fuel consumed. Ward and Hardy (1984) showed that emission factors for particulate matter and gaseous products are functions of the phase of combustion (flaming or smoldering). The work described here further demonstrates the impor-

tance of combustion phase on the release of incomplete products of combustion. More specifically, in this chapter we report results from a study that was designed to measure all of the terms noted in the above expression in an effort to derive an estimate of the total release of important pollutant species from a well-characterized fire. Ground and aircraft measurements were coordinated to yield a relatively complete picture of fire behavior and accompanying smoke production. Results from these measurements are then integrated over the lifetime of the fire and compared to less rigorous methods of estimating pollutant yield.

Experimental Methods

Fire Site Characteristics and Measurements

A 0.43 square kilometer (km^2) site in northwestern Montana, shown in Figure 50.1, was selected for this particular study. The fuel consisted of logging slash resulting from the clear-cut harvesting of true fir and western larch commercial timber from the site. The material left on the site was not of commercial value and provided much of the biomass fuel consumed by the fire. Prefire site characterization included a fuel inventory accomplished by taking a random transect across the site and tallying all fuel material within the transect into fuel size categories. Extrapolations were then made to the total area to be burned. Fuel moisture was also determined from a number of wood sections by specimen weighing, oven drying, and final weighing. Estimates of fuel consumption were obtained by fastening wires around the circumference of selected fuel in each size category. Following the fire, the wires were pulled tight, and the excess wire length used as a measure of fuel mass consumption in each fuel category. The fire was lit with hand-carried torches from the center of the plot outward in concentric circles. An observer was positioned in a suitable location to map the fire progression on all nine subunits throughout the duration of the fire. Fire characteristics such as the ignition time, duration and extent

Table 50.1 Sampling and analysis methods used on the instrumented aircraft

Analyte or parameter	Analytical method
Particle size and count (0.01–0.5 μm)	Grab sample—mobility analyzer
Particle size and count (0.1–3 μm)	Wing-mounted laser optical spectrometer
Particle size and count (2–32 μm)	Wing-mounted laser optical spectrometer
Light scattering coefficient @ 475 nm	Integrating nephelometer
Fine particle (<3 μm) mass concentration	Collect particulate on Teflon filter—gravimetric analysis
Fine particle nonvolatile and volatile carbon concentration	Collect particulate on quartz filter—combustion analysis
Carbon dioxide and carbon monoxide	Continuous analyzers—gas filter infrared absorption

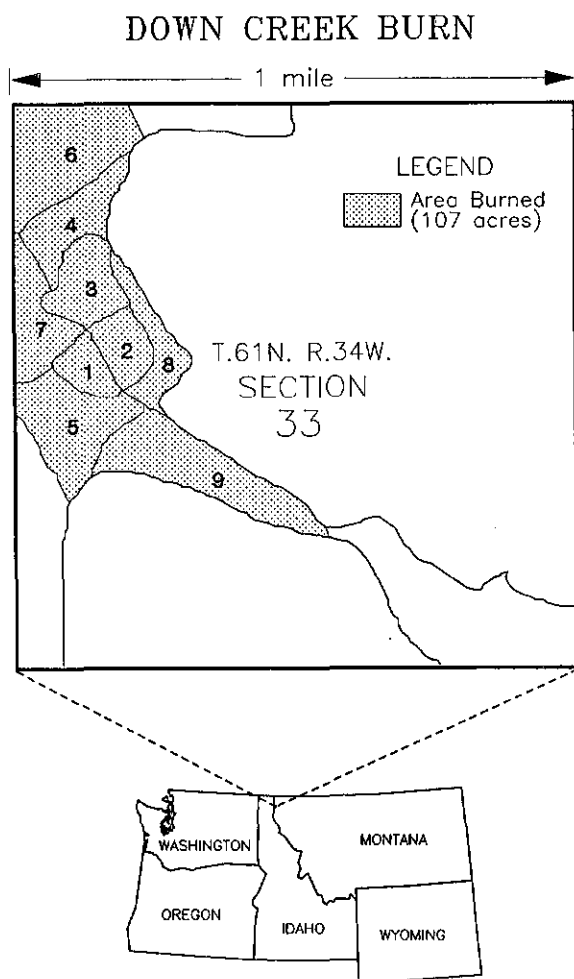


Figure 50.1 Map of burn location with inset showing the nine subunits.

of the flaming phase, and the onset of the smoldering phase were recorded for each of the nine subunits.

Instrumented Aircraft Measurements

The Sandia National Laboratories instrumented De-Havilland Twin Otter aircraft was used as a sampling platform during the fire. The aircraft was equipped with a number of sampling systems as outlined in Table 50.1. Particle size distributions over the range of 0.01 to 30 micrometer diameter were measured using mobility and wing-mounted laser optical particle counters. Gas sampling was carried out for carbon dioxide and carbon monoxide with continuous monitors using gas filter correlation infrared absorption techniques. Particulate material was collected through an external probe that extended forward of the aircraft windshield and terminated in a 1 m³ capacity bag positioned in the rear compartment of the aircraft, as schematically shown in Figure 50.2. The bag was filled to capacity in about 5 seconds while the aircraft was flying through smoke. Immediately following sampling, the grab sample was pumped through a series of cyclones with a 3 micrometer aerodynamic diameter cut point. The sample was then routed through a flash lamp nephelometer and finally through quartz and Teflon filters. Sample volumes were determined by time integrated measurement of

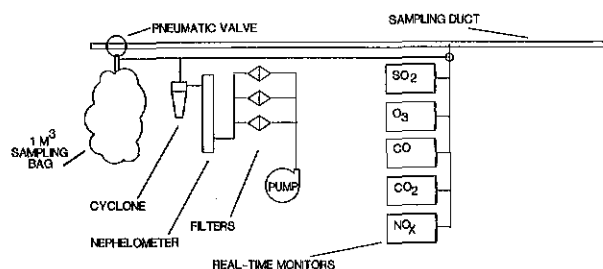


Figure 50.2 Schematic diagram of the sampling configuration on the instrumented aircraft.

air flow through each of the filters using mass flow meters output continuously logged by a data acquisition system. Postsampling analysis on the filters included gravimetric analysis, X-ray fluorescence elemental analysis, and particulate carbon analysis by a two-step combustion procedure as given by Johnson et al. (1981). Eight smoke samples were collected that covered all phases of the fire from the initial lighting phase to the final smoldering phase.

Emission factors for the gases and particulate categories of interest were calculated from samples collected with the aircraft using a chemical element balance method (Ward et al. 1982; Radke et al., 1988) whereby total combustion-derived carbon in the plume is used as a tracer for total mass consumption at the ground. The concentration ratio of a particular species to the total combustion-derived carbon concentration in the same parcel of plume air sampled with the aircraft is corrected to account for the carbon fraction of the fuel consumed. The resulting expression is given by

$$EF_x = \frac{[X] \times f_c}{[C_{total}]}$$

where EF_x is the emission factor for a given plume component x , $[X]$ is the measured plume concentration of the component, $[C_{total}]$ is the total combustion-derived carbon concentration in the same plume sample, and f_c is the dry fuel carbon fraction, which in this case is taken to be 0.5 according to Byram (1959).

Results

Fuel Loading and Consumption

Results from the pre- and postfire biomass inventories provided a measurement of the fuel consumption listed in Table 50.2. The total solid wood fuel loading was estimated at 13.5 kg m^{-2} . About 70% of the mass of the large diameter fuel was contained in the 8 to 23 and 23 to 50 cm diameter categories. The thick duff layer consisting of partially decomposed needles, cones, and twigs covering the forest floor increased the total fuel loading at the site to 24.1 kg m^{-2} . Nearly all of the fuel was consumed in fuel-size categories smaller than 23 cm. Duff consumption was estimated at about 60% of the total duff on the site. Total fuel consumption (woody fuels, litter, and duff) was 17.6 kg m^{-2} , which was 73% of the total biomass fuel on the site. The percent consumption by fuel categories and phase of combustion was as follows: 58.5% and 3.4% for the woody fuel for flaming and smoldering

Table 50.2 Measured fuel loading and consumption

Fuel diameter (cm)	Mass loading (kg m^{-2})	Mass consumption
0–0.5	0.87	100
0.5–2.5	1.46	100
2.5–7.5	1.25	100
7.5–23	6.81	87
23–50	2.44	50
50+	0.52	30
Total woody fuel	13.35	81
Duff layer	10.71	62
Total woody + duff	24.06	73

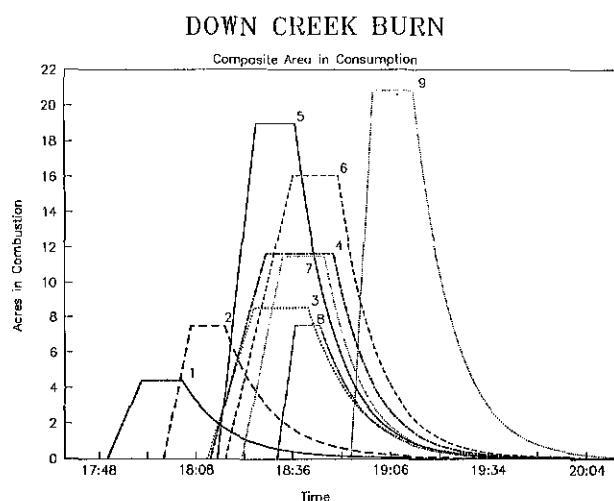


Figure 50.3 A plot of combustion history for each of the nine subunits. The lighting phase is indicated by a steep linear increase, the flaming phase by a horizontal segment, and the smoldering phase by an exponential decay.

phases, respectively; and 12.5% and 25.6% for the duff fuel for the flaming and smoldering combustion phases, respectively. The high proportion of total fuel consumed by this fire was attributed to the low moisture content of the fuels (ranging from 13% to 28%) at the time of the fire.

Time-Resolved Fire Behavior

Figure 50.3 is a plot of the progress of ignition of the nine subunits of the plot shown in Figure 50.1. A ground-based observer periodically drew in isopleth lines showing the location of the fire front on each of the subunits. The time of ignition is indicated by the steep positive-sloped lines in Figure 50.3 for each of the subunits. The duration of the flaming phase for

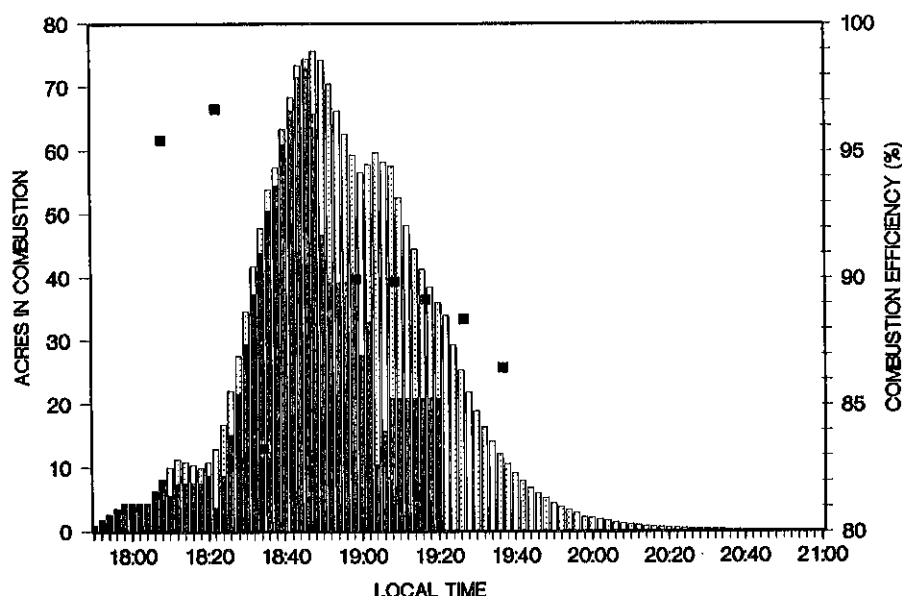


Figure 50.4 A plot of combustion history with all subunits combined. Dark shading represents flaming combustion and light shading represents smoldering combustion. Combustion efficiency for each of the eight aircraft smoke samples is shown by black squares.

each subunit is indicated by the flat portion of the curve, and the smoldering period is shown by the exponential decay curves for each of the subunits. An empirically derived half-life of 9.5 minutes (Ward and Hardy, 1984) is used to define the rate of change for the fuel consumption during the smoldering combustion phase. A composite merging of the flaming and smoldering phase of combustion activity from all nine subunits is shown in Figure 50.4. The period of extensive flaming phase combustion during the first 60 minutes of the fire is of particular significance and is well correlated with the characteristics of the emissions produced during that period.

Combustion Efficiency

A term called *combustion efficiency* has been used by Ward and Hardy (1984) to characterize the completeness of the oxidation of released carbon during the combustion of biomass fuels. Combustion efficiency is a particularly sensitive parameter that represents the degree of contribution from flaming and smoldering combustion in a volume of smoke. It is quantitatively given by the following:

$$\text{Comb eff (\%)} = \frac{[C_{\text{CO}_2}]}{[C_{\text{total}}]} \times 100$$

where C_{CO_2} is the background corrected CO_2 carbon as measured in the plume sample, and C_{total} is the sum of all forms of background corrected carbon in the

same plume sample. C_{total} in this case includes carbon from both gaseous (CO_2 , CO, methane, and non-methane hydrocarbons) and particulate species (volatile and nonvolatile carbon) in the plume. The combustion efficiencies for the eight samples collected throughout the burn are shown in Figure 50.4 superimposed on the time history of the fire to illustrate the changes in combustion efficiency throughout the fire period. The combustion efficiencies range, with the exception of one outlier, from about 96% at the onset of the fire when flaming conditions were predominant, to about 85% during smoldering conditions during the later stages of the fire. An observed 83% combustion efficiency for the third sample, although collected early in the fire, suggests that this particular plume sample originates from smoldering combustion from a smoke region outside the major smoke column that was normally sampled with the aircraft. The range of combustion efficiencies observed during this fire are similar to measurements made in fires in Canada (Susott et al., 1991), Brazil (Ward et al., 1991), and the western United States (Ward and Hardy, 1990).

Particle and Gas Emission Factors

A plot of fine particulate and volatile particulate carbon emission factors is given as a function of sample combustion efficiency in Figure 50.5. Fine particle emission factors in the range of 2 to 4 g kg^{-1} were measured during the flaming periods. Increases on

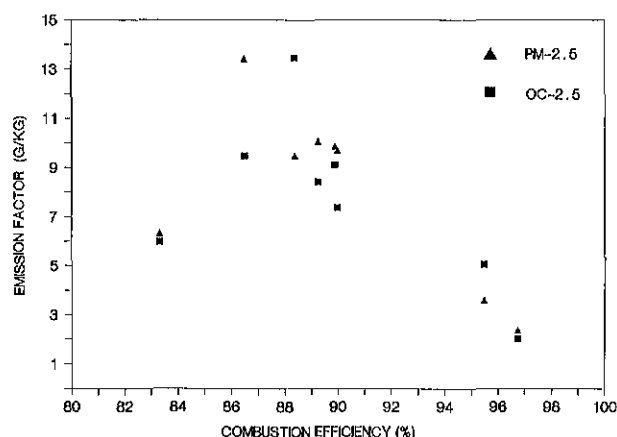


Figure 50.5 PM_{2.5} and nonvolatile carbon particulate (OC_{2.5}) emission factors as a function of combustion efficiency for all samples collected with the instrumented aircraft.

the order of threefold are observed for samples collected during periods when smoldering combustion was dominant. An opposite although more variable trend was observed for nonvolatile or elemental carbon measurements where emission factors were high during flaming combustion and decreased during smoldering combustion. During flaming combustion, the fine particles contained about 30% elemental carbon by weight. In the smoldering phase the elemental carbon content of the fine particles dropped to about 4%. These measurements clearly suggest that changes in the combustion efficiency of smoke samples are accompanied by changes in the composition of the particulate matter. During the predominantly flaming phase, the content of the particulate matter is low in organic carbon and high in elemental carbon. During smoldering combustion the opposite relation appears valid. These observations are consistent with measurements made by Ward and Hardy (1991) on the particulate matter content of smoke collected from both flaming and smoldering combustion using tower-based sampling systems positioned over large area fires.

Elements such as potassium, sulfur, iron, and lead were detected by X-ray fluorescence on most of the filter samples. Potassium emission factors were relatively constant throughout the duration of the fire with an average emission factor of 0.107 g kg^{-1} . The ratio of fine particle mass to fine particle potassium ranges from about 90 for the flaming periods to 180 for the smoldering periods. Particulate sulfur emissions showed a clear correlation with fine particle emission factors and ranged from low levels of about 0.03 g kg^{-1} during flaming phase to about 0.07 g kg^{-1}

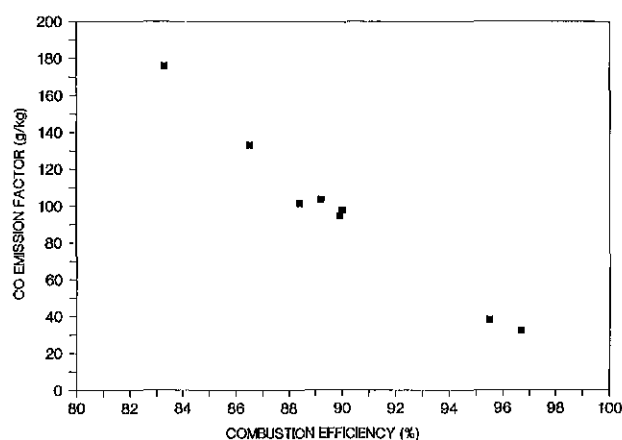


Figure 50.6 Carbon monoxide emission factors as a function of combustion efficiency for all samples collected with the instrumented aircraft.

during the smoldering phase. Lead emissions were relatively uniform over the entire fire period and at a low level of about 2 mg kg^{-1} .

Carbon monoxide emission factors calculated for each of the eight plume samples are plotted as a function of sample combustion efficiency and are shown in Figure 50.6. The CO yield can be observed to increase from about 40 g kg^{-1} to about 120 g kg^{-1} as the fire progresses into the smoldering phase. A least squares regression analysis with the CO emission factor as the dependent variable and combustion efficiency as the independent variable reveals a linear relationship with a slope of $-10.52 (0.58)$, an intercept of $1043 (7)$ with a coefficient of determination (R^2) of 0.982 .

A summary of differences between smoke emission factors for selected pollutant species from flaming and smoldering phase combustion is given in Table 50.3. An arithmetic mean of the emission factors for the first two samples was chosen to represent the flaming phase of the fire. Similarly, the smoldering category is represented by an average of the final two aircraft samples collected during the latter stages of the fire. A comparison of the overall emission factor averages from all eight aircraft samples with the combustion phase specific results shows that the overall averages do not fall at the midpoint between the flaming and smoldering phases but are closer to the smoldering values. Even though an analysis of the fuel consumption shows that approximately 71% of the fuel was consumed during the flaming phase, the average emission factors more closely represent the mix of emissions that would be expected for the smoldering phase. Since the rate of fuel consumption during

Table 50.3 Measured smoke emission factors for flaming and smoldering combustion phases and overall averages

Species or parameter	Emission factor (g kg ⁻¹)		
	Flaming	Smoldering	Overall
Fine particulate (<3 micron)	3.0	11.5	8.10 (3.47)
Elemental carbon (<3 micron)	0.8	0.5	0.55 (0.27)
Organic carbon (<3 micron)	3.6	11.5	7.61 (3.19)
Carbon dioxide	1733	1576	1621 (74)
Carbon monoxide	35.0	117.2	96.9 (43.7)
Single scatter albedo	0.75	0.97	0.90 (0.10)
Specific scattering	5.8	9.1	8.00 (1.80)
Coefficient @ 480 nm (m ² g ⁻¹)			

Note: The uncertainty (one standard deviation) for the overall average is given in parentheses.

flaming combustion is high, the time duration of the flaming phase was short relative to the much longer smoldering phase, during which the remaining 29% percent of the fuel was consumed. As a result, emission factor averages from the eight samples collected over the duration of the fire are skewed toward the smoldering condition.

Particle Size Distributions

Particle size data collected during the first two and final two aircraft passes were examined in detail in order to observe effects of fire behavior on particle size distributions. The first two aircraft samples were collected during a flaming phase as illustrated by calculated combustion efficiencies of 0.95 and 0.96. The last two samples were collected during smoldering conditions as evidenced by combustion efficiencies of 0.88 and 0.87. Number distributions for these four passes are shown in Figure 50.7. Although significant differences between the flaming and smoldering samples are not observed, some subtle differences can be noted. The samples from flaming combustion show an elevated condensation nuclei mode in the 0.02 to 0.04 micron particle diameter range when compared to the smoldering phase distributions. An upward shift in the number mode diameter can also be observed in the smoldering samples, although it is, at best, only about 0.1 micrometer in magnitude. A plot of cumulative volume less than 3 micrometer particle diameter is shown in Figure 50.8 for the same four samples. Here again a slight upward shift of about 0.05 micron in the median volume diameter is observed in the smoldering phase smoke samples.

Carbon Distribution

The apportionment of carbon among the major products of combustion is shown in Table 50.4 for the

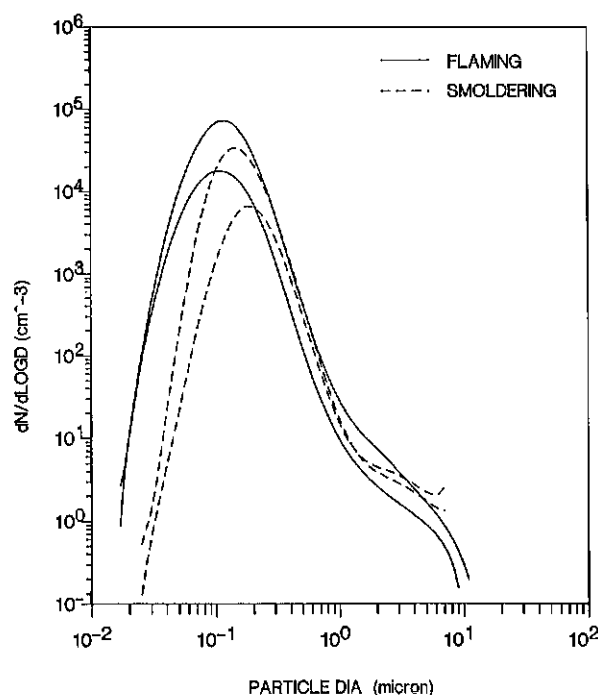


Figure 50.7 Particle number distributions for the first two (flaming) and final two (smoldering) smoke plume penetrations with the instrumented aircraft.

flaming and smoldering phases of combustion. Gaseous volatile organic carbon compounds were not quantified during this experiment. We have used a model of Ward et al. (1990) to predict emission factors for methane and nonmethane hydrocarbons. This model is derived from measurements of combustion efficiency as well as methane and nonmethane hydrocarbon emissions from a number of prescribed burns in the Pacific Northwest. During both flaming and smoldering conditions, in excess of 96% of the carbon is released as CO₂ and CO. During flaming conditions the volume ratio of CO to CO₂ is 3.1×10^{-2} . This ratio increases to 1.2×10^{-1} during smoldering conditions. Volatile and nonvolatile carbon particulate material accounts for 0.85% of the total released carbon in the flaming phase and nearly 2.4% during the

smoldering phase. The first three categories—namely, CO₂, CO, and volatile organic particulate carbon—account for in excess of 99% of the carbon released in both flaming and smoldering phases.

Estimates of Total Pollutant Release

We calculated the total release of various gas and particle species during both flaming and smoldering periods by breaking down the total fire interval into flaming and smoldering periods and applying phase-specific emission factors (Table 50.3, columns 2 and 3) and measured fuel consumption for each phase. These estimates are given in units of kg m⁻² in Table 50.5. The total from flaming and smoldering phases is compared to estimates of total release using average emission factors (Table 50.3, column 4) from all aircraft samples collected and total fuel consumption. Using the average CO yield results in a 64% overestimate of the total CO emissions when compared to the

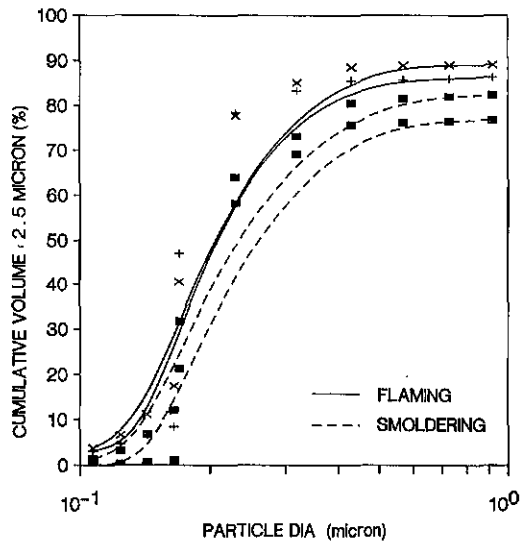


Figure 50.8 Cumulative volume (<2.5 micron diameter) distribution for the first two and final two smoke samples.

Table 50.4 Species contribution to total mass release of carbon from flaming and smoldering phases

Species	Carbon contribution (% by weight)	
	Flaming	Smoldering
Carbon dioxide	95.8%	86.6%
Carbon monoxide	3.0	10.1
Organic carbon particulate	0.7	2.3
Elemental carbon particulate	0.2	0.1
Methane ^a	0.2	0.5
Nonmethane hydrocarbons ^a	0.1	0.4

a. Estimated from earlier work by Ward (1991).

Table 50.5 Total mass release of significant pollutants

Species	Mass release (kg m ⁻²)				
	Flaming	Smoldering	Total ^a	Average ^b	Ratio ^c
CO ₂	21.5	8.0	29.4	28.3	0.96
CO	0.43	0.60	1.03	1.69	1.64
O	0.062	0.055	0.117	0.133	1.13
EC	0.010	0.003	0.012	0.010	0.77
CH ₄	0.035	0.045	0.080	0.102	1.22
TNMHC ^d	0.031	0.031	0.062	0.076	1.22
PM2.5	0.037	0.058	0.095	0.141	1.48

a. Total is the sum of mass release from the flaming and smoldering categories.

b. Average is determined by use of average emission factors as measured over the duration of the fire.

c. Ratio is calculated with "Average" as the numerator and "Total" as the denominator.

d. TNMHC refers to total nonmethane hydrocarbons.

sum of CO yields from flaming and smoldering periods. Similarly, the PM_{2.5} emissions determined by an average emission factor are about 50% higher than the sum of the phase-specific emission yields. The agreement for other carbonaceous species such as volatile and nonvolatile carbon is somewhat better and is likely a result of the fact that the difference between flaming and smoldering emission factors is less pronounced for these species.

Conclusions

Measurements of smoke emissions were made of the 0.43 km² Down Creek fire in northwestern Montana using an instrumented aircraft and smoke sampling system flown periodically through the smoke column. Results from these tests demonstrated an expected change in the characteristics of the emissions as the fire progressed from flaming to smoldering conditions over a period of about two hours. Combustion efficiencies ranged from 95% conversion of released fuel carbon to CO₂ during the flaming phase to 85% conversion during the smoldering phase. The overall fuel mass consumption was about 70%, with consumption of 81% of the woody fuel and 62% of the duff layer.

The median particle diameter became larger for smoke derived from smoldering combustion sampled toward the latter stages of the fire. Although these particle size changes are not likely to be significant in terms of the mass release of particulate matter and its atmospheric transport, they are accompanied by appreciable changes in smoke optical properties. An enhanced scattering deficiency is observed in smoldering samples and is consistent with predictions based on Mie theory for an upward shift in the particle median volume diameter. This observation becomes important in the context of radiative transfer through the smoke plume.

A comparison of measured emission factors from flaming and smoldering periods indicates about a threefold increase in CO, PM_{2.5}, and volatile organic particulate carbon (for particles <2.5 micrometers in diameter) for emissions from smoldering combustion. These emission factor increases are at least partially offset by a reduced fuel consumption during the smoldering phase. Total fuel consumption for the Down Creek prescribed fire was 12.4 kg m⁻² for the flaming phase and 5.0 kg m⁻² for the smoldering phase. An approximate threefold increase in emission factors is then offset by about a 2.5-fold reduction in fuel consumption in the smoldering phase. Taken together, the net result is an approximate 50% increase in the

total release of such pollutant species as PM_{2.5} and CO during smoldering conditions as compared to flaming periods.

Results suggest that knowledge of fuel consumption by phase of combustion (flaming vs. smoldering) is important in making accurate estimates of the characteristics of smoke emissions from individual fires. Contributing factors such as fuel type, fuel loading, and meteorological history vary significantly by region and should be taken into account when compiling estimates of fuel consumption rates during both flaming and smoldering fire conditions.

Acknowledgments

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