

## ABSORPTION PROPERTIES AND GRAPHITIC CARBON EMISSION FACTORS OF FOREST FIRE AEROSOLS

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**Abstract.** Data on the optical absorption properties (expressed as a specific absorption,  $B_a$ ) of the smoke emissions from fires with forest fuels have been determined for a series of low-intensity field fires and a series of laboratory scale fires. The  $B_a$  data have been used to estimate the emission factors for graphitic carbon [ $EF(C_e)$ ] for these test fires to provide data needed for regional visibility studies, tropospheric air chemistry studies, and studies evaluating nuclear winter scenarios.

## Introduction

The potential of emissions from large scale fires with forest or wildland fuels to reduce visibility or to modify air chemistry in tropical areas has been generally recognized. Several research groups [see, e.g., Crutzen et al., 1984] have recently pointed out that such fires, started as a result of a nuclear exchange, could have severe climatic consequences leading to what has been called a "nuclear winter." If we are to assess the significance of these effects, we need better knowledge of the characteristics of the smoke emissions from such fires. In particular, because of their importance in determining radiative effects, we need information on the total particulate emission factors, [ $EF(PM)$ ], the amount of particulate matter emitted for a given amount of fuel (expressed as the ratio grams of aerosol per kilogram of fuel burned); the emission factor for graphitic carbon, the highly absorbing elemental carbon component of soot, [ $EF(C_e)$ ]; and the resulting relative absorption of light by the smoke.

The smoke characteristics of large scale wildland fires have not been well documented due to the experimental difficulties associated with such measurements. Smaller scale prescribed fires, those planned for specific land management objectives, have, however, been the subject of much research [see, for example, reviews by McMahon (1983) or by Ward (1985)]. These prescribed fires are useful in evaluating the effects of large scale wildfires because such measurements allow us to investigate the effects of variation in fuel or combustion properties on smoke properties, which allows us to scale our results from the conditions

of the measured fires to the different conditions of the large scale wildland fires.

We have measured the optical absorption properties and particle emission factors for smoke emissions from a series of prescribed fire field experiments in the Pacific Northwest. These data and earlier laboratory data of Patterson and McMahon (1984) have been used to determine  $EF(C_e)$  values for these fires and to investigate the variation in fire conditions.

## Aerosol Radiative Parameters

The fractional loss of energy from a light beam is given by the extinction coefficient  $\sigma_e$  (with units of inverse length), which is the sum of the scattering coefficient  $\sigma_s$  and the absorption coefficient  $\sigma_a$ .

The radiative effects of a given amount of smoke may be determined by calculating the ratio of the radiative property of interest (extinction, scattering, or absorption) to the measured particle concentration.

One particular relation of interest is the specific absorption  $B_a$ , the ratio of  $\sigma_a$  to the mass concentration of the aerosol,  $M_v$ ,

$$B_a = \frac{\sigma_a}{M_v} \quad (1)$$

$B_a$  is a direct measure of the effectiveness of the aerosol in producing absorption. In addition, since the absorption of these smoke emissions is due primarily to graphitic carbon, the measured values of  $\sigma_a$  for the smoke and previously measured values of  $B_a$  for graphitic carbon may be used in equation (1) to determine  $C_e$  concentrations for the aerosol.

## Specific Absorption Data For Field and Laboratory Fires

$B_a$  values were measured for the smoke emissions from a series of field test burns in the Pacific Northwest of broadcast (scattered) logging residues as fuel. For the test fires, total particulate matter samples for  $B_a$  measurements for each combustion phase (flaming, F; first smoldering, S1; and second smoldering, S2) from locations up to 20 meters above fires of at least 1 hectare in size. A more complete description of these fires is given in Ward and Hardy (1984).

The absorption was measured for  $\lambda = 632.8$  nm using the diffuse transmission technique of Patterson and Marshall (1982), the same technique

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TABLE 1.  $B_a$  and Emission Factor Data for a Series of Prescribed Burns of Broadcast Logging Slash in the Pacific Northwest (Ward and Hardy, 1984).

TEST FIRE*	FIRE** PHASE	$B_a$ ( $m^2/g$ )	EF(PM) (g/kg)	EF(Ce)+ (g/kg)
CAT	F1	.37	15.6	.85
	S1	.24	13.8	.50
	S2	.26	11.7	.46++ <.63>
HEBO	F	.28	23.4	.96
	S1	---	12.2	--- <.96>
MARIA 1	F	.34	23.5	1.18
	S1	.18	20.4	.55
	S2	.20	20.3	.61 <.78>
DLAKE 1	F	.68	10.2	1.03
	S1	.40	14.1	.83
	S2	.36	13.4	.71 <.86>
DLAKE 2	F	.55	11.6	.94
	S1	.25	14.1	.52
	S2	---	12.4	--- <.65>

\* Fire designation follows Ward and Hardy (1984)

\*\* F = Flaming; S = Smoldering

+ EF(Ce) determined using  $B_a$  data

++ < > emission weighted fire averages

used in the earlier laboratory study. The mass concentration was determined gravimetrically from the filter samples. These absorption and mass concentration data were used to calculate  $B_a$  for these samples; the  $B_a$  data for these field fires, arranged by fire and combustion phase, are shown in Table 1.  $B_a$  values measured during flaming combustion range from 0.28 to 0.68  $m^2/g$ ; the  $B_a$  values measured during smoldering combustion show a decrease from those measured during the flaming phases by about a factor of two.

The laboratory data of Patterson and McMahon (Table 2), by comparison, showed an even greater decrease in  $B_a$  values during smoldering combustion. The lab procedure allows fire to move rapidly or slowly across a 1.1  $m^2$  fuel bed of dead pine needles. Experiments were conducted in a large (700  $m^3$ ) controlled environment combustion laboratory with smoke samples collected in a large funnel and stack apparatus located above the fire [for further details, see Patterson and McMahon (1984)]. The laboratory approach enables one to replicate experiments and to more clearly delineate between flaming and smoldering combustion phases. As shown in Table 2, the  $B_a$  values for flaming combustion for the lab fires ranged from 0.67 to 2.36  $m^2/g$  and decreased dramatically to ~0.04  $m^2/g$  in those cases in which only smoldering occurred. For those fires in which the distinction between flaming and smoldering was not apparent,  $B_a$  values had a more narrow range similar to the field data in Table 1. Two laboratory

fires containing a live fuel component also showed  $B_a$  values that were similar to the field data, with  $B_a$  values that decreased from 0.68  $m^2/g$  in the flaming phase to 0.25  $m^2/g$  in the smoldering phase.

Smoldering forest fuels are known to produce copious emissions which consist primarily of low absorption tan or yellow submicron liquid organic droplets which condense out of the vapor and gas phase just above the fuel surface and which produce a white smoke. In contrast, combustion efficiency is higher and overall smoke production is lower during flaming processes, in which the highly absorbing graphitic carbon soot particles can be formed. We expected, then, that  $B_a$  values would be significantly higher in flaming combustions than in smoldering combustions and that fires with high values of EF(PM) would be associated with low absorption smoke, while fires with low EF(PM)'s would be associated with high absorption smoke.

This relationship is seen in Figure 1, which

TABLE 2.  $B_a$  and Emission Factor Data for a Series of Experimental Pine Needle Burns Conducted at the Southern Forest Fire Laboratory

FIRE SERIES	FIRE PHASE	$B_a$ ( $m^2/g$ )	EF(PM) (g/kg)	EF(Ce) (g/kg)
01	F1	.81	19.0	2.30
	F2	1.35 <.93>	27.0 <21.0>	5.40 <2.90>
02	F1	2.27	7.6	2.60
	F2	1.28 <1.60>	9.6 <8.2>	1.80 <2.00>
03	F1	.94	5.9	.82
	F2	.80 <.88>	10.5 <8.3>	2.31 <1.10>
04	F1	1.75	3.0	.78
	F2	.45 <.65>	13.8 <8.8>	.92 <.85>
05	F1	2.36	3.6	1.26
	F2	.95	72.5	10.20
	T	.58 <1.26>	--- <15.3>	--- <2.90>
06	F1	1.55	7.0	1.61
	T	.62 <.98>	52.4 <13.6>	4.81 <2.00>
07	F1	.67	10.0	.99
	T	.17	70.0	1.76
	S1	.04	87.0	.52
	S2	.04 <.16>	67.0 <45.5>	.40 <1.10>
08	F1	1.22	6.7	1.21
	T	.20	53.0	1.57
	S1	.05	102.0	.76
	S2	.07 <.15>	114.0 <60.9>	1.18 <1.30>
09	F1	.88	9.1	1.19
	T	.61 <.73>	40.0 <14.5>	3.61 <1.60>

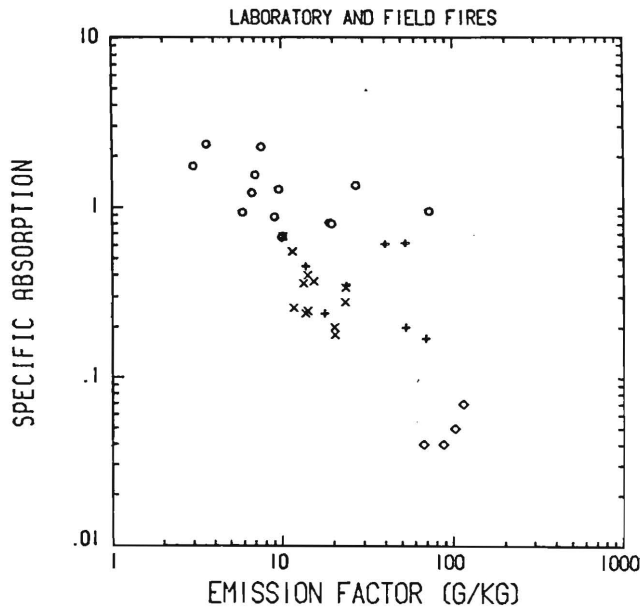


Fig. 1. Specific Absorption [ $B_a$ ] values plotted against particulate matter emission factors [EF(PM)] for individual fire phases for laboratory and field fires. The field data are indicated by x's; the laboratory data are segmented into three phases -- flaming (o), smoldering (◊), and transitional (+).

shows  $B_a$  values measured during the different combustion phases for both lab and field fires plotted against the EF(PM) values measured for these phases. The field data are indicated by x's; the laboratory data are segmented into three phases: flaming (o), smoldering (◊), and transitional (+). The transitional phase is characterized by a combination of smoldering with periodic bursts of flames. Although there is considerable scatter, the decrease in  $B_a$  with increasing EF(PM) is readily apparent.

The laboratory data cover the reported range of EF(PM) values determined in earlier laboratory studies [McMahon, 1984]; but the fuel consisted primarily of one fuel type -- a pine needle litter fuel. The field fires reported here also represent only one type of fire (broadcast burning) in one fuel type (forest residues). How well the combined lab and field data represent the full range of wildland fires is not known at this time. Larger fractions of green fuel components coupled with high energy release rates as found in crown fires may enhance the soot-forming mechanism, but even high intensity crown fires exhibit both flaming and smoldering components.

There is some evidence [Ward and Hardy, 1984; Sandberg, 1974] that EF(PM) decreases with increasing fire reaction intensity (rate of energy released per unit time and unit area of fire), suggesting that  $B_a$  may also be related to fire intensity. Our laboratory and field data support this hypothesis; a quantitative relationship is, however, beyond the scope of this report.

#### Emission Factors of Graphitic Carbon

Emission factors for graphitic carbon,  $EF(C_e)$ , have been determined for each of the fire phase

data points shown in Figure 1. These  $EF(C_e)$  were determined from the absorption, mass concentration, and fuel consumption data following procedures described by Patterson and McMahon (1984). We assumed a  $B_a$  value of  $6.75 \text{ m}^2/\text{g}$  at  $632.8 \text{ nm}$  for graphitic carbon, a value that is based on graphitic carbon data of Szkarlat and Japar (1981), with appropriate corrections for the wavelength difference between the Szkarlat and Japar data and our data. The  $C_e$  data were then used in the determination of the  $EF(C_e)$ . The data for the separate phases of the fires were combined to determine an average  $EF(C_e)$  for each of the field fires and each of the laboratory fire series.  $EF(C_e)$  values for each fire phase and for the total fire are shown in Table 1 for the field test fires and in Table 2 for each of the laboratory fire series.

The field data show that  $EF(C_e)$  values for samples collected during flaming combustion range from  $0.8 \text{ g/kg}$  to  $1.2 \text{ g/kg}$  with an average value of  $1.0 \text{ g/kg}$ . The total fire  $EF(C_e)$  values are somewhat lower, ranging from  $0.6$  to  $0.9 \text{ g/kg}$ , with an average of  $2.9 \text{ g/kg}$ .

$EF(C_e)$  determined for the laboratory fires range from  $0.7$  to  $2.5 \text{ g/kg}$ , a range that is greater than the range for the field test fires. The geometric mean value of  $EF(C_e)$  for the laboratory fires is  $1.6 \text{ g/kg}$ , a value that is higher than the mean of the field fires. This difference reflects a decreased importance of smoldering combustion in the lab fires relative to the field fires due to differing fuels (the lab fires burned pine needle litter fuel and the field fires burned both woody fuel and partially decomposed materials) and differing fire conditions.

Based on the data discussed above, we feel that an  $EF(C_e)$  of  $1 \text{ g/kg}$  is a reasonable estimate of the  $EF(C_e)$  for most forest fires. Our measurements show a variation of a factor of 2 to 3 about this estimated value -- a range that probably encompasses the range of variability of naturally occurring emissions.

It should be pointed out that there are potential uncertainties regarding the effects of organic coatings on the measured absorption of the graphitic carbon. However, a comparison discussed by Patterson and McMahon (1984) indicates that our methodology is consistent with other methodologies for determining  $C_e$  concentrations. In addition, Ward and Core (1984) measured  $C_e$  emission factors of the same field fires using a thermal-optical technique [Johnson et al., 1981] to determine  $C_e$  concentrations. The two data sets are in excellent agreement, with a correlation coefficient of 0.85 between the data sets and average values of  $C_e$  emission factors that are quite close --  $0.7 \text{ g/kg}$  for the Ward and Core data compared with  $0.8 \text{ g/kg}$  for our data.

By comparison, a literature survey by Crutzen (1984) suggested that an "average" EF(PM) for forest fires is  $60 \text{ g/kg}$ , of which 10% is elemental carbon. This corresponds to an  $EF(C_e)$  of  $6 \text{ g/kg}$ , which was used to estimate the atmospheric effects of many fires initiated by non-urban nuclear strikes. A recent National Academy of Science report [NRC, 1985] assumes a  $C_e$  emission factor of  $3 \text{ g/kg}$  for forest fuel fires and of  $6 \text{ g/kg}$  averaged over both urban and forest fuel fires. Our data indicate that the actual value is significantly less than the earlier estimates. We realize, of course, that our measurements cover only

a limited range of fuel and fire variables and that additional data are needed.

#### Summary and Conclusions

We have measured the specific absorption coefficient,  $B_a$ , of the smoke emissions from a series of laboratory and field fires with forest fuels. We have also calculated  $EF(PM)$  and  $EF(C_e)$  values for these fires.  $B_a$  values measured for the field (broadcast residue) test fires ranged from 0.28 to 0.68  $m^2/g$  for flaming combustion and decrease by about a factor of two in smoldering combustion. By comparison, previously measured  $B_a$  values for laboratory (pine needle) fires ranged between 0.67 to 2.36  $m^2/g$  in flaming combustion, decreasing to  $\sim 0.04 m^2/g$  in smoldering combustion.  $B_a$  was found to be inversely related to  $EF(PM)$ , and there are indications that  $B_a$  can be quantitatively related to fire reaction intensity.

Since most fires contain both a flaming and a smoldering phase, average values in many fires will be less than 1  $m^2/g$ . Our data, then, indicate that field burns such as those measured during this study, produce relatively low absorption smoke, a finding that is qualitatively supported from burning woodland materials.

$EF(C_e)$  values determined for the laboratory pine needle fires range from 0.8 to 2.9 g/kg, with an average of 1.6 g/kg. Similar estimates of  $EF(C_e)$  for the field burns show a range of 0.6 to 0.9 g/kg with an average value of 0.8 g/kg. Our data suggest that a value of 1 is a reasonable estimate of the average  $EF(C_e)$  value for a variety of forest burning conditions.

These measured  $C_e$  emission factors are significantly less than earlier estimated values used to model the effect of mass fires from nuclear strikes. As such they provide important new information on the radiative characteristics of these emissions. While this data should significantly reduce the uncertainties concerning radiative effects of forest fire smokes, we again emphasize that our data set is a limited set that consists of low intensity field fires and smaller scale laboratory fires. Further work is needed to determine the absorption characteristics of these smoke emissions and the relationship of these absorption characteristics to fire behavior for fires with different scales and different fuel types.

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