HYDROCARBON AND BIOMASS FUEL FIRE FIELD TESTS

L. F. Radke, D. A. Hegg, J. D. Nance, J. H. Lyons, K. K. Laursen,
R. J. Ferek, and P. V. Hobbs
Department of Atmospheric Sciences
University of Washington
Seattle, WA 98195

R. E.Weiss
Radiance Research
Seattle, WA 98177

ABSTRACT

Biomass and hydrocarbon fuel fires are two common sources of obscuring smoke which present significant operational challenges over a broad range of possible viewing wavelengths. This is especially true of very large fires where the primary smoke particles (~0.1 – 0.3 μm diameter) obscure vision by both scattering and absorption (single scattering albedo 0.3 – 0.9) and fire lofted debris and particle coagulation products reduces transmission in both the near and far IR.

Large fires also cause obscuration by atmospheric dynamics. More than 50% of the biomass fires studies were capped with cumulus clouds, 3 or 4 of the largest fires produced precipitation, and one fire generated heavy showers of small hail and repeated lightning discharges. While these fires' smokes experienced efficient cloud and precipitation scavenging, the associated clouds and precipitation itself produced widespread obscuration.

1. INTRODUCTION

We have recently completed airborne studies of the smokes and related fire phenomenon of 17 biomass and 10 hydrocarbon fuel fires. The biomass fires were largely in forested lands and logging debris and varied in areas burned from prescribed (intentional) fires of from 10–700 hectares (over a few hours) to wild fires which ultimately consumed 20,000 hectares (over a period of weeks). The hydrocarbon fuel tests were all much smaller fires ranging in area from 400–700 m^2 and all consumed aviation fuel grade JP-4 in quantities ranging up to 5×10^4 liters. The larger biomass tests produced spectacular fires, towering columns of smoke, interacting capping cumulus clouds and other fire phenomena. For perspective, these large test fires each consumed at least 100,000 metric tons of biomass or the thermic equivalent of nearly a million barrels of oil! While the prescribed fires were visible in the meteorological satellite imagery only as small features, one of the wildfires studied produced a persistent, visible plume more than 1,000 km long. Details of these fires and fuels are given in Table 1.

Our studies of these obscuring smokes focused on the issues which control their atmospheric impact and residence times, namely:

- Smoke amount. What fraction of the fuel becomes smoke? What fire properties control the smoke yield?
- Smoke particle size.
- Smoke optical properties.
- Smoke removal mechanisms.

TABLE 1. **FIRES EXAMINED IN PRESENT STUDY**

Fire	Date	Location	Size (hectare)	Type of Fire	Fuel
Abee	22 Sept 86	Montesano,WA	40	Prescribed	Debris from Douglas Fire & Hemlock
Eagle	3 Dec 86	Ramona,CA	30	Prescribed	Standing Black Sage, Sumac & Chamise
Lodi 1	12 Dec 86	Los Angeles, CA	40	Prescribed	Standing Chaparral, Chamise
Lodi 2	22 June 87	Los Angeles, CA	150	Prescribed	Standing Chaparral, Chamise
Hardiman	28 Aug 87	Chapleau, Ontario	325	Prescribed	Debris from Jack Pine, Standing Aspen and Paper Birch
Wheat	31 Aug 87	Rosalia, WA	~10	Prescribed	Wheat stubble
Myrtle/Fall Creek	2 Sept 87	Roseburg, OR	2,000	Wild Fire	Standing Pine, brush & Douglas Fir
Silver	17-19 Sept 87	Grants Pass, OR	20,000	Wild Fire	Douglas Fire, True Fir and Hemlock
Satsop	19 Sept 87	Satsop, WA	40	Prescribed	Debris from Douglas Fir and Hemlock
Troy	8 Oct 87	Troy, MT	70	Prescribed	Debris from Pine, Douglas Fir and True Fir
Tyndall	15-24 May 88	Tyndall AFB, FL	410 - 729 m^2	Pool	Aviation Fuel (JP-4)
Battersby	12 Aug 88	Timmins, Ontario	718	Prescribed	Jack Pine, White and Black Spruce
Peter Long	22 Aug 88	Timmins, Ontario	217	Prescribed	Jack Pine, White and Black Spruce
Carbonado	27 July 89	Enumclaw, WA	40	Prescribed	Debris from Douglas Fir & Hemlock
Summit	1 Aug 89	Grangeville, ID	100	Wild Fire	
Hill	10 Aug 89	Chapleau, Ontario	486	Prescribed	"Chained" & Herbicidal Paper Birch & Poplar
Hornepayne	12 Aug 89	Hornepayne, Ontario	700	Prescribed	"Chained" & Herbicidal Birch, Poplar & Mixed Hardwoods
Mabel Lake	25 Sept.89	Kelowna, B.C.	29	Prescribed	Debris from Hemlock, Deciduous, Douglas Fir

2. SMOKE AMOUNT

A key element in any discussion of smoke impact, regardless of whether the issue is obscuration or global climate change, is how much smoke does a given fire produce? The traditional approach of accurate fuel inventory and measured consumption rates which was developed for laboratory scale research has proven difficult to apply in field studies. Our approach to measuring particle emission factors (the mass of smoke per unit mass of fuel consumed) has been through the use of the carbon-balance method (Ward et. al, 1982) as adapted for aircraft sampling (Radke et al., 1988). Briefly, the method only requires prior determination of the carbon fraction of the fuel and in plume measurements of all the carbon bearing components. Appropriate ratioing then yields the emission factor for any smoke component regardless of whether it contains carbon.

The measurements were obtained with the University of Washington's Convair C-131A aircraft. The aircraft is well instrumented for both in situ sampling and remote sensing (Radke, 1982 and Hegg et al., 1987). A key ability of the facility is its capability to take large (~1.5 m^{-3}) "grab" samples over sampling distances of a few hundred meters so that, on the scale of the fires, "point" whole air samples can be taken for analysis. A period of a few minutes is required for processing each of these samples.

Biomass and JP-4 fires have rather different temporal characteristics. The biomass fires characteristically begin with intense combustion and long flame lengths as the small dry fuels (leaves, needles, twigs, etc.) burn. The particle emission factors are comparatively small and the smoke appears rather dark at visible wavelengths. This period of flaming combustion is followed by a longer period of less intense "smoldering" combustion with much higher emission factors and light gray to white smokes. This progression is illustrated in Fig. 1 (Mabel Lake fire) where the particle emission factor increases ~x4 as the smoldering combustion fraction of the fire increases (it took most of the first 18 minutes after ignition for the smoke to rise from the surface to the 3 km sampling altitude of the aircraft). Typically the smokes from the biomass fires which we have studied were dominated by smoldering phase combustion. These measurements are qualitatively in good accord with laboratory and smaller field tests where samples were taken just above ground level (Patterson and McMahon, 1984 and Hardy and Ward, 1986).

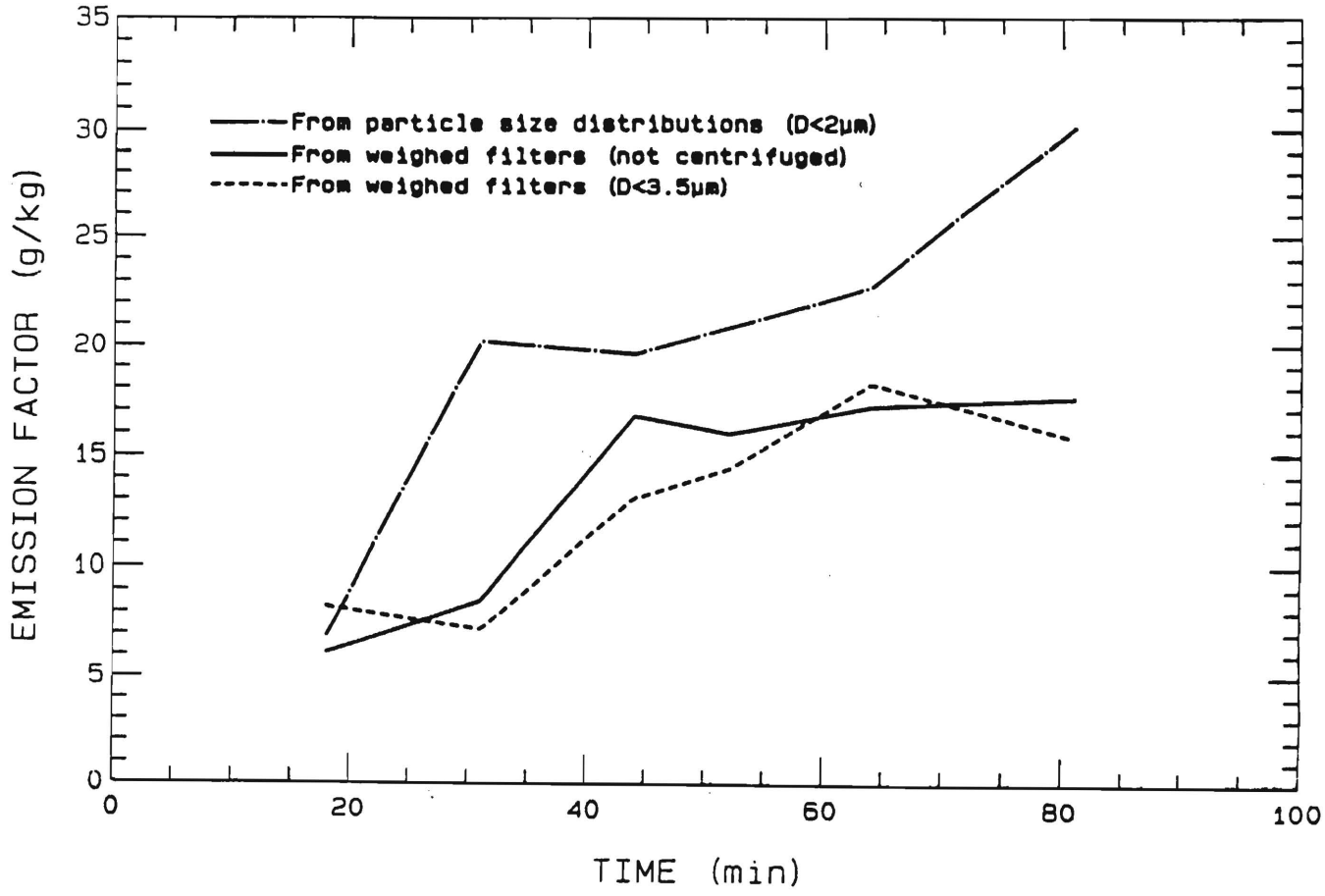

Figure 1. Emission factors for particle mass as a function of time after ignition for the Mabel Lake fire.

On the other hand the JP-4 pool fires where characterized by intense flaming combustion for almost the entire period of the fires, and their smokes were very black. These JP-4 fires showed no clear cut temporal progression in emission factors.

In Table 2 we give the average particle emission factors for each of the fires. Since every fire was sampled throughout the period when significant heat release lofted its plume to altitude, the average emission factor of any given fire is representative of its total smoke production.

The three different columns of emission factors in Table 2 represent results derived from a volume integrated size distribution for particles with diameters < 2 μm and an approximate particle density, smoke particle mass on a weighed filter with an aerodynamic particle cut (<3.5 μm), and a volume integrated size distribution for particles with diameters < 48 μm. Of the three techniques, the weighed filter approach contains the fewest computational uncertainties.

From Table 2 we see that the emission factor for biomass smoke particles <3.5 μm in diameter averages 15.0 g per kilogram of fuel burned. Particles of this size have atmospheric residence times ranging from a few days to weeks and account for almost all the smoke's visual obscuration impact. The coarse and giant (>2 μm and < 48 μm) aerosol, which electron microscopy shows to be a mixture of fuel and soil debris and coagulation products (mostly spheres), average about 20% of the emission mass (an additional 6 g kg^{-1}). Additional production of very large particles (some larger than 5 mm) from the larger test fires is not well quantified but may be important to the obscuration issue in spite of the short atmospheric residence time of these particles.

The large variance in our emission factors is not well understood except that it is related to the combustion environment. Stith et al. (1981) noted an increase in emissions with increasing fuel moisture. Cofer et al. (1989), Ward (1989) and Hegg et al. (1990) all suggest that combustion

TABLE 2. PARTICLE EMISSION FACTORS (IN GRAMS OF SMOKE PER KILOGRAM OF FUEL BURNED) AND SINGLE-SCATTERING ALBEDO AND SPECIFIC ABSORPTION FOR ALL FIRES STUDIED

	Emission factor (derived from size distribution of particles < 2 μm diameter)			Emission factor (from weighed filters containing particles < 3.5 μm diameter)			Emission factor (derived from size distribution of particles < 48 μm diameter)			Mean value of single-scattering albedo $\tilde{\omega}$ (= σ_S/σ_E)	Mean values of specific absorption B_A ($m^2\ g^{-1}$)
	Mean	Standard Deviation	Number of Samples (N)	Mean	Standard Deviation	Number of Samples (N)	Mean	Standard Deviation	Number of Samples (N)		
BIOMASS FUELS											
Abee	35.1	20.3	7	37.4	9.8	3	44.5	23.1	7	ND	ND
Eagle	7.9	5.7	8	11.3	4.8	2	10.8	6.0	8	0.85 (N = 2)	0.67 (N = 2)
Lodi 1	14.3	7.3	16	13.5	4.4	13	17.6	7.9	16	0.89 (N = 13)	0.74 (N = 13)
Lodi 2	15.5	6.5	9	23.0	19.6	8	17.7	7.0	9	0.80 (N = 7)	0.68 (N = 1)
Hardiman	16.2	12.4	11	10.5	3.0	9	21.7	14.6	11	0.87 (N = 9)	0.79 (N = 5)
Wheat	43.8	—	1	ND	—	—	47.9	—	1	NA	ND
Myrtle/FallCreek*	19.5	12.1	10	6.1	3.1	8	29.3	16.5	10	0.84 (N = 4)	0.73 (N = 16)
Silver*	26.4	13.6	2	20.2	12.7	3	32.5	17.1	2	0.90 (N = 2)	0.36 (N = 2)
Satsop	24.6	7.1	2	12.0	—	1	34.3	10.8	2	0.86 (N = 1)	0.38 (N = 1)
Troy	17.1	12.4	5	9.7	3.0	5	30.2	19.5	5	0.82 (N = 3)	0.82 (N = 3)
Battersby	18.2	21.1	11	20.9	10.6	11	20.3	20.7	11	0.84 ± 0.05 (N = 7)	0.89 (N = 4)
Peter Long	ND	ND	ND	16.9	5.1	4	ND	ND	ND	0.84 ± 0.05 (N = 4)	1.39 (N = 2)
Hill	5.5	3.5	6	10.2	6.5	3	6.9	4.3	6	0.84 ± 0.04 (N = 3)	0.59 ± 0.22 (N = 4)
Hornepayne	12.9	9.1	10	10.8	4.7	5	13.3	9.1	10	0.60 ± 0.21 (N = 6)	0.66 ± 0.52 (N = 5)
Carbonado	10.7	7.6	7	ND	—	—	11.1	7.9	7	0.89 (N = 9)	ND
Summit*	17.6	4.1	2	ND	—	—	18.33	4.4	2	0.82 (N = 5)	ND
Mabel Lake	19.9	8.4	5	12.8	4.3	6	23.4	5.9	3	0.82 (N = 12)	0.41 ± 0.06 (N = 14)
Averages	*16.4*	*13.2*	*112*	*15.0*	*10.6*	*81*	*21.2*	*15.4*	*110*	*0.83 ± 0.11 (N = 83)*	*0.64 ± 0.36 (N = 73)*
FOSSIL FUELS											
Tyndall (JP4)	◊	◊	◊	23.1	15.0	21	◊	◊	◊	0.32 (N = 11)	4.10 (N = 10)

* Wild fires
◊ Particle data suspect due to particle composition
NA - Not analyzed
ND - No data

efficiency in open fires, also depends on turbulent airflows for oxygen. Thus some fires, especially with increasing scale, may be characterized by periods of oxygen depletion or thermal quenching of oxidation reactions prior to completion. The result should be a higher production of particulates. Many of the fires studied showed pronounced increases in particle emission factors as the fire became increasingly oxygen-limited. One example is the Battersby fire shown in Fig. 2. Here we use the ratio of CO to CO_2 as the indicator of oxygen availability in the plume with high ratios suggesting limited oxygen.

The ten liquid hydrocarbon fuel fires, which varied only modestly in size and duration, and all of which occurred at the same test pool facility (Tyndall AFB), had an average particle emission factor (< 3.5 μm) of 23 g of smoke per kilogram of JP-4 fuel burned. Despite these fire similarities the ratio of the standard deviation to the mean is identical for the JP-4 and biomass fires (~0.65). Some of the variance in the JP-4 fires appears to be related to wind shear in the boundary layer (emission factors decreasing with increasing shear) and to fire size (as areal extent increased emission factors decreased; see Radke et al. (1990)). Most of the variance, however, remains unexplained.

Thus, given our inability to account for all of the substantial variability of either the biomass or hydrocarbon fires, it could be an error to assume that our studies have bounded the emission factor variability possible for open fires. It seems likely that fires which are more intense or of greater areal extent than the fires studied could have significantly larger smoke particle emission factors.

3. PARTICLE SIZE DISTRIBUTIONS

Consistent patterns of behavior are emerging in our studies of the size distributions of smoke

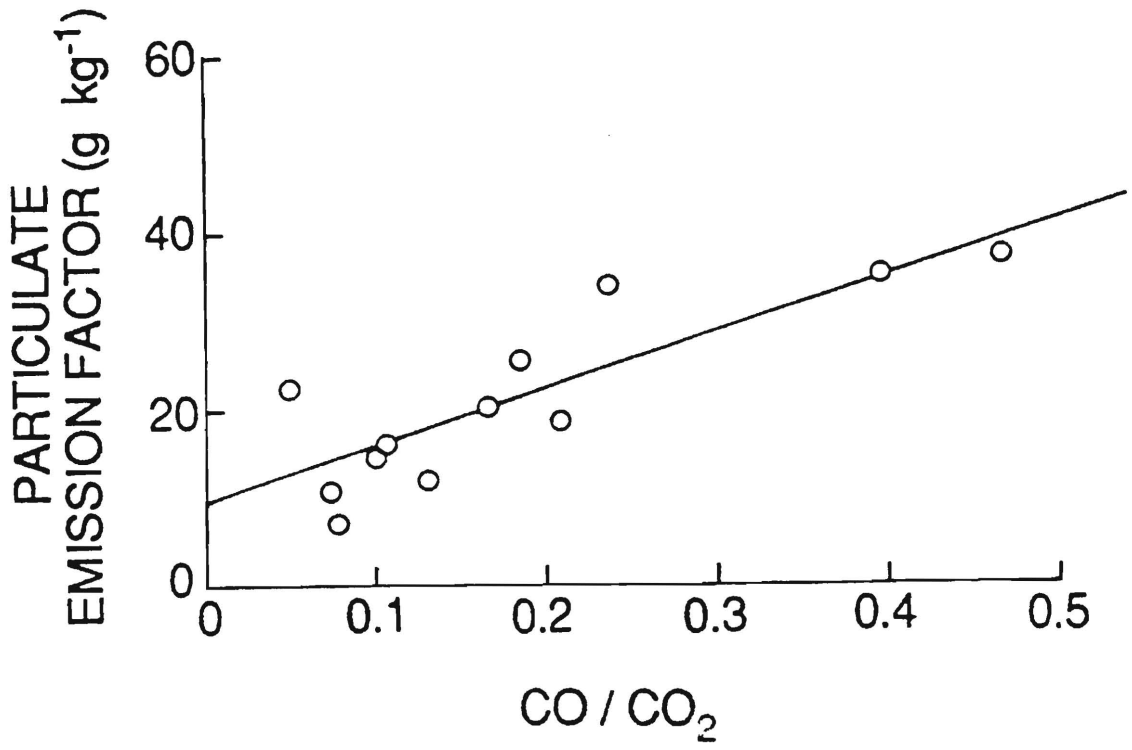

Figure 2. Emission factor for particulates as a function of the CO/CO_2 concentration ratio in the plume from the Battersby fire.

particles from biomass fires. The particle volume distributions in particular show comparatively little variation in shape from one fire to another or during any one fire while near the source, although particle concentrations vary widely. Shown in Fig. 3 are average number and volume distributions measured in the smoke plumes near the sources of three fires. The particles are distributed with size much like other pollution aerosols with a nucleation mode (< 0.1 μm), an accumulation mode (0.1 – 2 μm) and a coarse mode (> 2 μm diameter). For reasons no doubt related to different particle generation mechanisms for the accumulation and coarse mode aerosols, there is a pronounced minimum in the particle volume distributions between 1.0 and 3.0 μm diameter between these two modes. Not only is this characteristic of these fires, but it also seems to be generally true in the atmosphere. The accumulation mode (0.1-2.0 μm) often dominates both the number and volume distributions and it always contributes overwhelmingly to the visible light-scattering coefficient and obscuration. Particles in the accumulation mode consist primarily of tarry, condensed hydrocarbons which are typically spherical in shape. They also contain some water-soluble inorganics (primarily $SO_4^=$ and NO_3^-; Hegg et al., 1987), however, which accounts, in part, for their activity as very efficient cloud condensation nuclei (Radke et al., 1978; Hallet et al., 1989).

The coarse particle mode (>2 μm) shows considerable variations. For example in the Lodi 1 (Chaparral fuel type) fire there was a mode near 10 μm comprised mostly of condensed hydrocarbons aggregated with a significant fraction of soil particles (Cofer et al., 1988). In addition to this mode, an examination of the data from our laser hydrometeor cameras showed that ash and debris particles up to and exceeding 1 mm in diameter were often found in concentrations greater than 10 m^{-3}. While we see large variations in the amount of this super giant aerosol, it is typical of all the large fires studied. Lofting of soil and ash at Lodi 1 has also been reported by Einfeld et al., (1989). The amount of coarse mode particles in biomass smoke is related to fire intensity, horizontal and vertical wind velocities, fine fuel fraction and the characteristics of the soil and biological surface layer. On occasion the mass in the coarse mode exceeds that in the accumulation mode. The coarse mode and especially the super giant aerosol are historically poorly counted and, despite our efforts, are probably underestimated here as well. Near large fires the coarse mode contributes significantly to the smoke's obscuration in the near and far infrared.

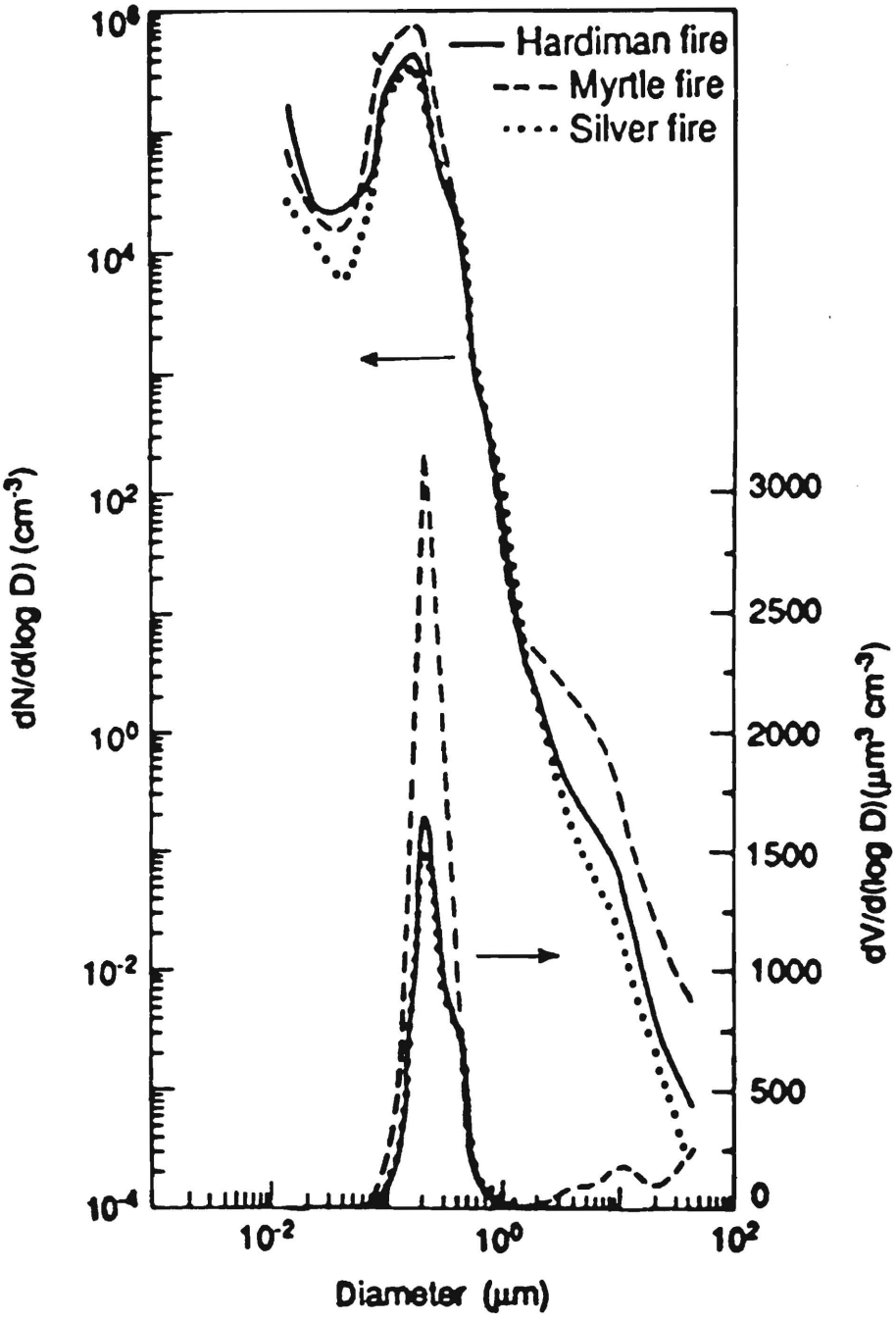

Figure 3. Mean number and volume distributions of particles measured in the smoke plumes near the sources of three fires.

The nucleation mode (<0.1 μm) is the most variable mode in biomass smokes. It is occasionally the most prominent mode in the number distribution, but more often it is much smaller than the accumulation mode. It seldom contains significant particle mass or has any role in obscuration. Its mode concentration is largely driven by coagulation varying primarily with the accumulation mode concentration (see Fuchs, 1964) and by continuing gas-to-particle conversion in the smoke plumes.

Coagulation also affects the mean size of the accumulation mode although particle concentrations need to be rather large for a long period of time for definitive observation. The concentration dependence on coagulation rate is illustrated in Fig. 4 where the smoke from a large multifire wild

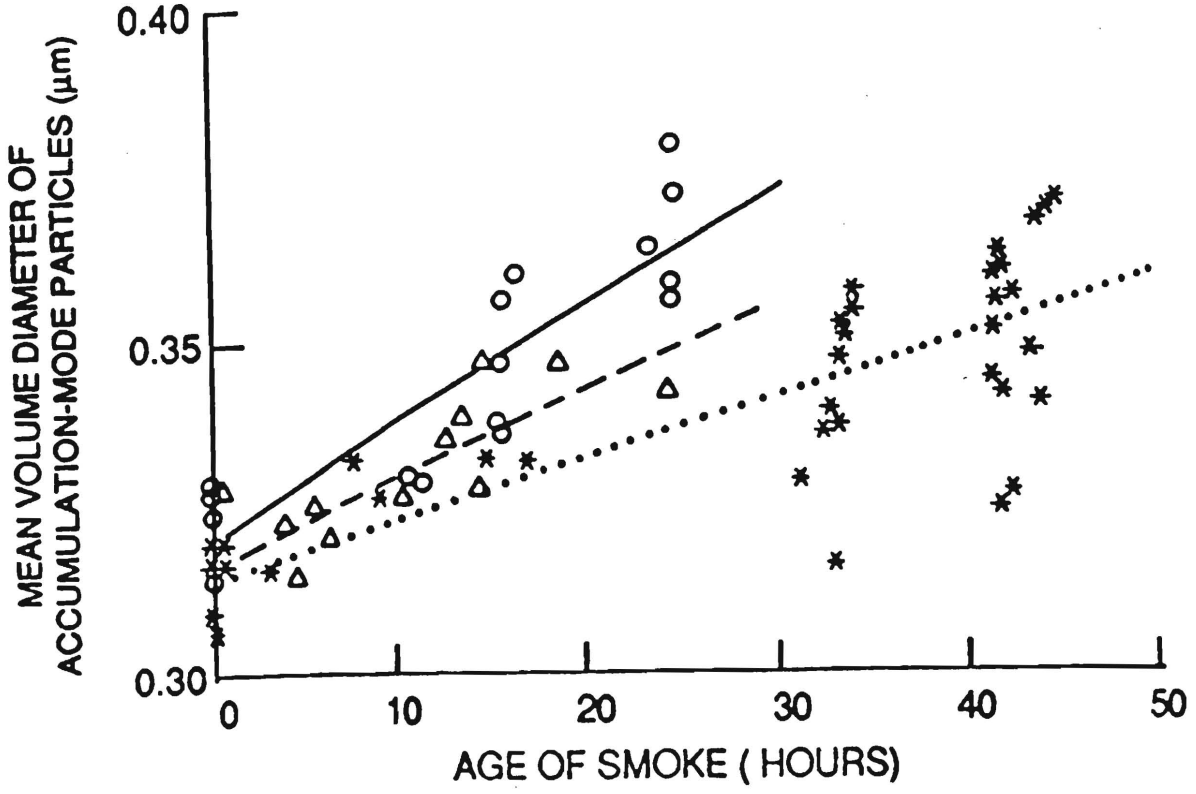

Figure 4. Geometric mean volume diameter of particles in the accumulation mode (0.2 – 2 μm diameter) as a function of the age of the smoke in the plume of the Silver fire. The measurements are differentiated by the value of the light-scattering coefficient due to dry particles as follows: Circles and solid lines : 2×10^{-4} m^{-1} < σ_{sp} < 5×10^{-4} m^{-1} (r = 0.81); triangles and dashed line 5×10^{-4} m^{-1} < σ_{sp} < 10^{-3} m^{-1} (r = 0.77); stars and dotted lines $\sigma_{sp} > 10^{-3}$ m^{-1} (r = 0.89).

conflagration (Silver) was tracked for more than 1000 km (about 48 hours downwind from the source). The geometric mean volume diameter of the particles in the accumulation mode generally increased with age for all samples. The rate of increase was positively correlated with the light-scattering coefficient due to dry particles (σ_{sp}), which is generally proportional to the mass concentration of particles in the accumulation mode (Waggoner et al., 1981). This result is as expected for a process dominated by coagulation.

Intermode coagulation is also evident in the Silver fire data. Samples taken at various distances downwind of the fire showed a general decline with age in the volume concentrations of particles in the nucleation and accumulation modes, while the volume concentrations of particles in the coarse-particle mode increased with age. This, presumably in large part, is the result of coagulation which is a sink for smaller particles and a source for larger particles. These smoke samples were normalized by the CO concentration (which we assumed was conserved in the plume) to eliminate the dilution effects of plume dispersion (for details see Radke et al., 1990a).

The fossil fuel (JP-4) fires also produced prominent nucleation accumulation and coarse particle modes (Fig. 5). However, because the smokes were relatively strong light absorbers and a large fraction of the particles were chain aggregates, there is considerable sizing uncertainty between ~0.4 and 2 μm (see Radke et al. 1990b for a more complete discussion). Electron microscopy showed that most of the particles consisted of two types of chain aggregrates: one comprised of fairly uniform spheres ~0.03 μm diameter and the other of spheres ~0.15 μm diameter. Chain aggregrates of the 0.03 μm particles constituted a significant number of the particles in the accumulation mode, while aggregates of the 0.15 μm particles contributed to both the accumulation and coarse particle modes. Surprisingly, only a few of the aggregates consisted of a combination of both large and small spheres. The size distribution measurements in Fig. 5 reflect the small single or primary spheres (point 1 on curve A'), the large primary spheres (point 2 on curves A and A') and their aggregrates (points 3 and 4 on curve A).

The size distribution of particles in the smoke at the top of the planetary boundary layer (PBL) changed little from the beginning of our measurements (~4 min. after the fuel was ignited) to the end of our measurements (~150 min.). Hence, the formation of the chain aggregates must have occurred rather quickly (on the order on minutes or less) and did not change mu ı the next two hours as the smoke accumulated at the top of the PBL. This lack of further coagulations on time scales of a few hours is consistent with the particle concentrations.

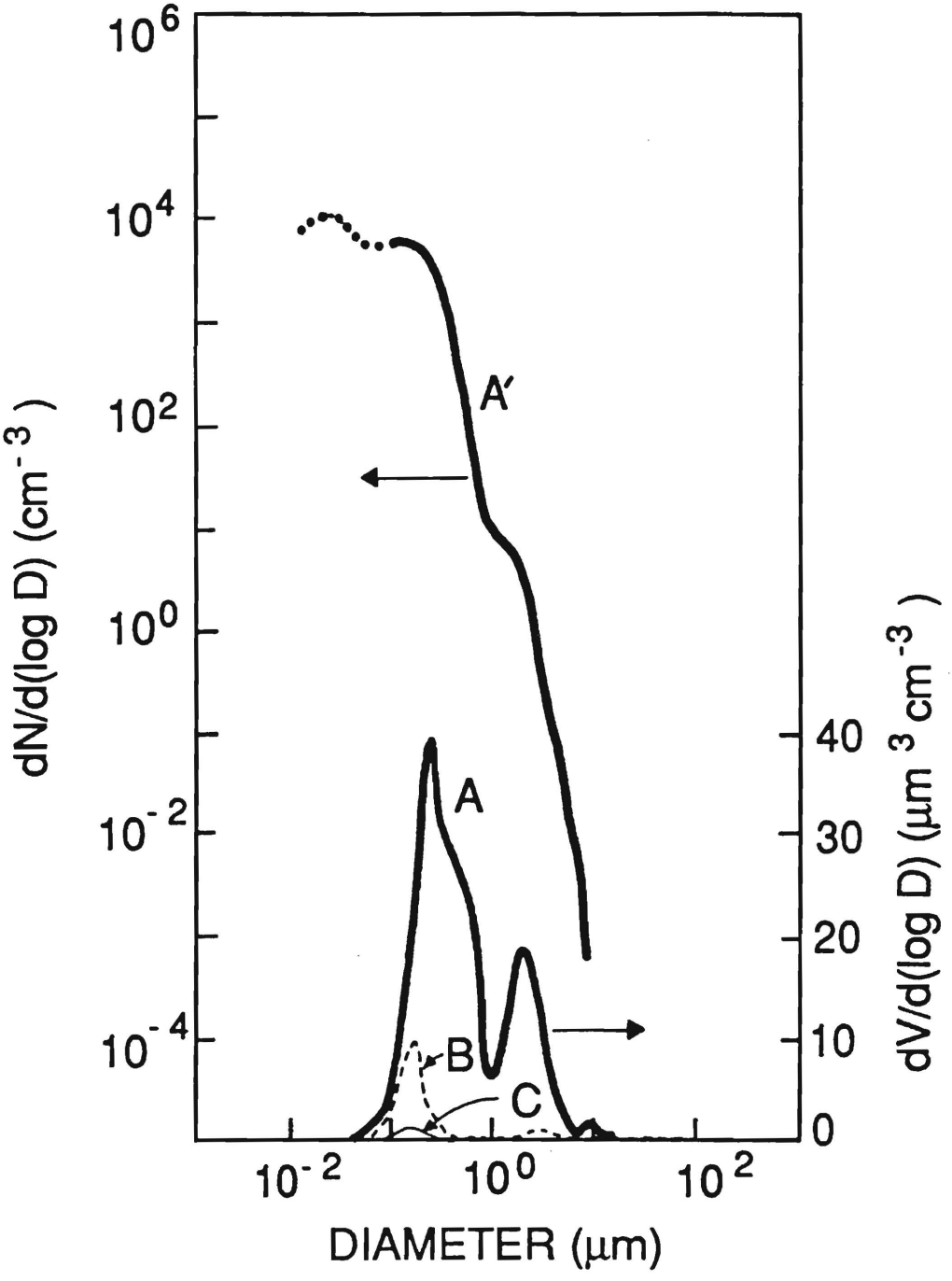

Figure 5. An example of the particle number (A') and volume (A) distributions measured near the top of the planetary boundary layer (PBL) in the smoke from burning aviation fuel. Also shown are particle volume distributions measured in the background air within the PBL (B) and just above the top of the PBL (C). See text for discussion of the uncertainties in sizing absorbing particles. The measurements were made on 19 May 1988.

4. OPTICAL PROPERTIES OF SMOKES

The optical properties are usually described by the volume optical extinction coefficients, σ_e, σ_s, σ_a, where the subscripts indicate the form of extinction, 'e' for total extinction, 's' for scattering and 'a' for absorption; the specific (or mass normalized) extinction, $B_i = \sigma_i/\rho$, where r is mass concentration and 'i' represents any of the extinction coefficients; and the albedo for single scattering, $\tilde{\omega}$ where $\tilde{\omega} = \sigma_s/\sigma_e$. The extinction coefficients depend on the complex refractive index of the particles, their size distribution and concentration. The specific extinction and the albedo for single scattering are normalized to concentration,however, and thus depend only on the fundamental chemical and physical properties of the particles. Specific scattering, $B_s = \sigma_s/\rho$, is not highly variable, normally ranging from about 3 to 4 m^2/g (Waggoner and Weiss, 1980) for submicron aerosol. Specific absorption, however, is dependent on the relative content of elemental (or black) carbon comprising the particles and ranges from 0 m^2/g for particles without any absorption to about 10 m^2/g for submicron size particles of pure soot. Our measurement wavelength is centered on 540 μm providing a good match for the human eye.

Knowing the spatial extent of these optical coefficients, particularly the absorption related properties, for various stages of fire evolution and atmospheric conditions is important to understanding the dynamic properties of the fire and the resulting impact of transported smoke on radiative transfer and visibility.

The measurements were made using high resolution measurements of σ_s, σ_e and particle mass remembering that $\sigma_e = \sigma_s + \sigma_a$. For details see Weiss and Radke (1987) and Radke et al. (1988, 1990b).

The optical properties of particles comprising smokes produced from biomass burning can be highly variable and depend on many factors including the type of fuel burned, the intensity of the fire, flame height, and the stage of combustion (McMahon, 1983; Patterson and McMahon, 1984). As fuel is consumed, biomass fires evolve through several stages in which particles of very different optical characteristics are produced. The chemical and physical description of these particles is that of a highly complex mixture of organic and inorganic material with a majority of the lofted aerosol mass contained in the submicron size range. In the early, flaming stages of combustion when high temperatures and oxygen deprivation prevail, conditions support pyrolytic production of particles consisting of high concentrations of both single spheres and sooty chains that are optically very absorbing. In the later, smoldering stages of combustion, smoke production is dominated by weakly or non absorbing liquid (waxy) and solid particles consisting of organic materials with a range of volatility in addition to non-sooty inorganic materials. Patterson and McMahon (1984) measured specific absorption on filter samples taken from laboratory fires of pine needles at various stages of combustion. They found a substantial increase in the production of elemental (or sooty) carbon in the flaming stage of combustion relative to the smoldering stage with the specific absorption coefficient ranging from 0.04 m^2/g for the smoldering stage to about 1 m^2/g for the flaming stage. These were measurements on smokes in a laboratory environment where burning conditions could be controlled. In large fires of several hectares or more the smokes often consist of complex mixtures combining all combustion stages and domination by one or more phases at any given time and location. However, we have two case studies where this progression of optical properties is evident.

The two fires are the Troy, MT fire (October 8, 1987) and the Mabel Lake fire near Kelowna, B.C. (September 25, 1989). Both were small fires, 70 and 29 hectares respectively, of downed debris consisting of mixed wood types in which there was intense burning in the initial stages of combustion and relatively uncomplicated meteorological conditions. In both fires the aerosol was optically dark during the early stages of intense burning and became less dark as the fires progressed to a predominantly smoldering stage. This result is shown in the time series plots of $\tilde{\omega}$ (Fig. 6) where the single scattering albedo measured at altitudes of 2 to 2.5 km was initially less than 0.7 in both fires and

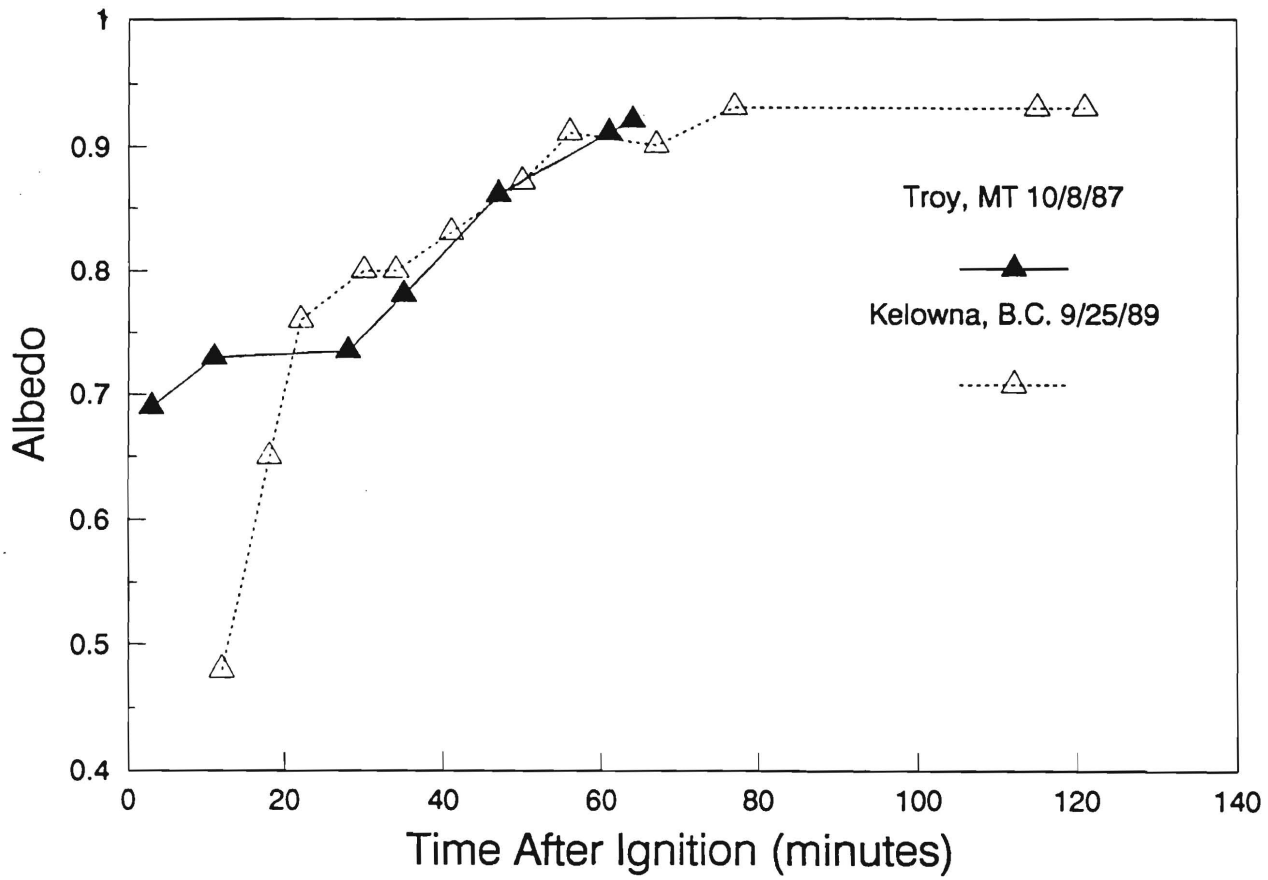

Figure 6.

approached a relatively stable value in the smoke of about 0.9 during smoldering stages. Mean values of specific absorption for both fires were approximately 0.4 m^2/g which is similar to the average values reported by Patterson and McMahon (1984).

Table 2 gives the mean values of $\tilde{\omega}$ and B_A for each of the biomass fires studied and for the entire program. The program average albedo was 0.83 ± 0.11 and the specific absorption was 0.64 ± 0.36 m^2g^{-1} indicating that biomass smokes are typically grey-white in visual appearance to the human eye.

However, all of these fires produced periods (usually less than 10% of the fire's temporal extent) of dark smokes. The largest planned fire in the program produced the darkest plume cross-section average albedo of 0.37. As discussed in Section 1 there is reason to believe that exceptionally large fires might be characterized by oxygen deficient flaming combustion with large particle emission factors and low (dark) albedos. This possibility suggests that it would be desirable to take measurements in the smokes from a larger fire than the largest in this study or in a blow up or mass wild fire.

In contrast to the highly variable optical properties of the biomass smokes, the average value of the single-scattering albedo for all transects of all ten JP-4 fires at Tyndall AFB was remarkably stable at $\tilde{\omega} = 0.32 \pm 0.02$. Since these results are direct measurements of the in situ aerosol, there should be no dependence on particle morphology which is an area of concern for analysis techniques where the sample particles are impacted on a substrate before analysis. Note that the accuracy of our albedo determination is excellent. Its uncertainty in this case is only ~0.01 of the value of the albedo.

The specific absorption (B_A) of the smoke (defined as absorption per unit mass) was obtained from Teflon filters that were exposed to the smoke. The filters were subsequently weighed and light absorption by the particles on the filters was determined using the method described by Weiss et al.

(1979). The average value B_A for the ten Tyndall fires was 4.1 ± 0.52 m^2g^{-1}. The absolute accuracy of the B_A values for these complex aerosols is difficult to define, but since we used our in situ technique to establish the error associated with the filter medium, the error in B_A is largely determined by the error associated with weighing the filter. For these measurements the error in B_A is ~10%. Thus, although the smoke particles were optically quite dark at visible wavelengths ($\tilde{\omega} = 0.32$), they were not as highly absorbing as elemental carbon "soot" which has a specific absorption, B_A, of ~8-10 m^2g^{-1} (Pittock et al., 1986). Turco et al. (1987) suggests this value might be appropriate for oil fires. Our data suggest that only ~50% of the particle mass was elemental carbon, with condensed organic compounds (unburned fuel) comprising a significant fraction of the remainder.

Finally, both JP-4 and biomass smokes have their visible wavelength albedo modified by cloud interaction. Smokes which pass through a cumulus cloud typically experience an increase in albedo of a few to 10% (smoke becomes whiter). Although the exact mechanism for increased albedo from cloud detraining smoke is not known, gas to particle conversion, chain aggregate collapse, coagulation, dilution and albedo dependent scavenging all may be factors.

5. CLOUD AND PRECIPITATION SCAVENGING OF SMOKES

In the present sequence of experiments we have examined 17 biomass fires or fire complexes. Of the 17 experimental periods 10 featured fire capping cumulus clouds and four (Hardiman, Battersby, Hill and Wicksteed) reached cumulonimbus proportions. Of these four, "Hardiman" produced only light to modest precipitation and none may have reached the ground. At the other end of the intensity scale "Hill" developed into a persistent, mature thunderstorm with heavy precipitation.

Our studies show both that large fires can produce capping cumulus clouds which can substantially reduce total smoke emissions and that smokes, especially biomass smokes, are not resistant to cloud and precipitation scavenging. Since scavenging is a pathway for smoke removal, the smoke's ability to interact with cloud processes largely determines the smoke's residence time in the atmosphere.

Our approach to measuring scavenging efficiencies depends on a variety of sampling schemes all of which face some difficulties for a single aircraft experiment. The choice of which approach to try depends on circumstances largely dependent on fire scale. The schemes which we have used are listed below along with a brief critique:

1) Input–Output: This is potentially the simplest and most powerful approach which requires measurement of an aerosol property (mass, size distribution, etc.) along with a conservative tracer believed to be proportional to the aerosol emitted (e.g. CO ?) in the ascending smoke column and exiting the capping cumulus cloud. The conservative tracer allows correction for dilution by the smoke mixing with ambient air inside of the cloud.
*The method requires a period of steady state emission.

2) Emission Factor: We initially believed (based on ground observations) that the evolution of the particulate emission factor would be relatively slow as the phase of the fire moved from flaming to smoldering. Thus a combination of emission factors measured below cloud base, interstitially (between cloud particles) in the cloud, and exiting the cloud would provide a useful measure of scavenging.
*Again, this requires a steady-state fire (something that we generally do not observe), however, unlike 1), a dilution correction is not required.

3) Interstitial: Measure the ratio of the smoke (or a surrogate for smoke) interstitial to the cloud droplets and in the cloud droplets. After converting the amount in the cloud droplets to an equivalent air concentration (see Hegg et al., 1984) the ratio produces directly the scavenging fraction for the accumulation mode aerosol.
*If a surrogate for smoke is used (we used the sulfate accumulation mode aerosol co-emitted integrally with the smoke) one must be satisfied that smoke is scavenged similarly (we are).

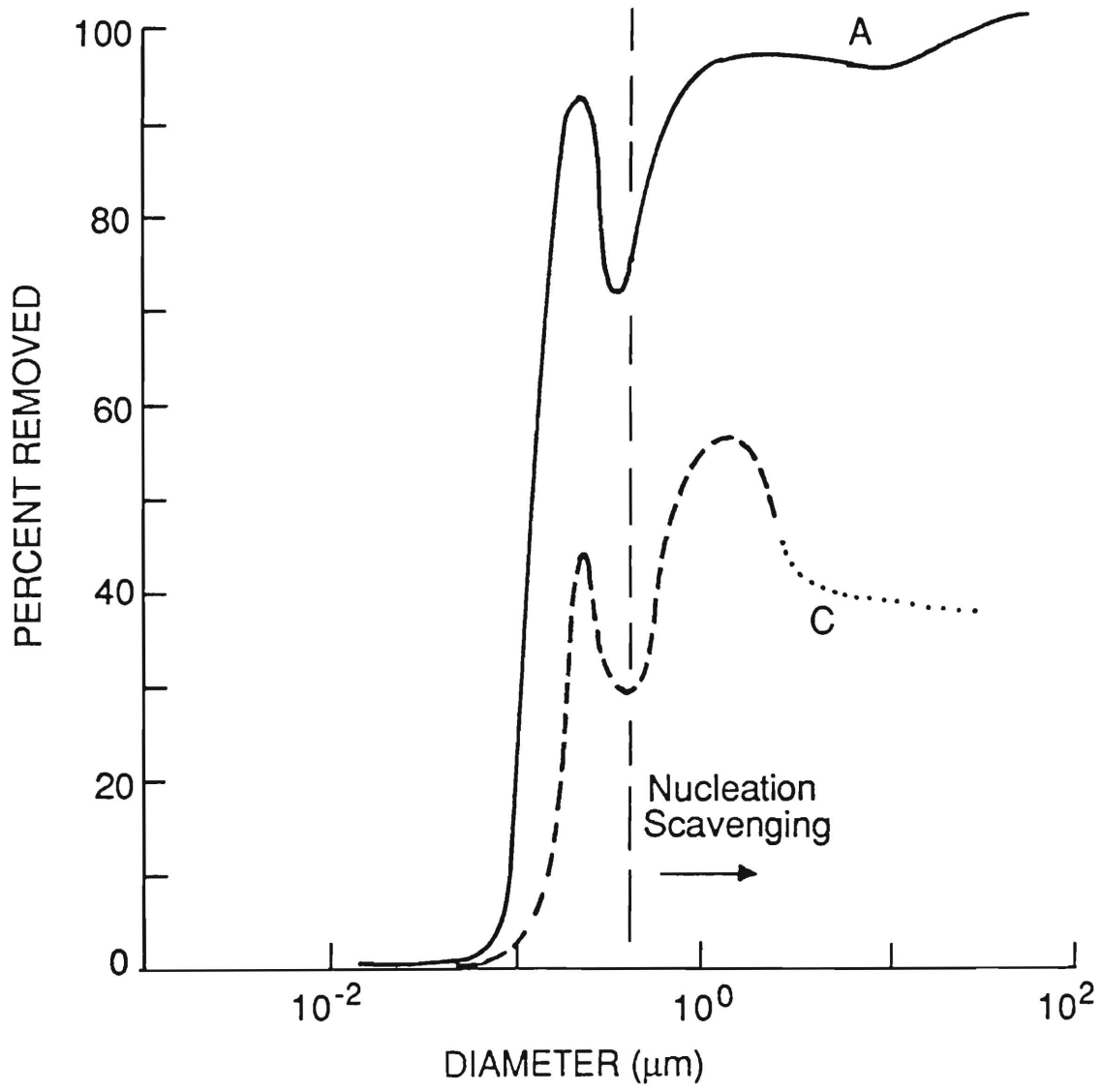

Figure 7. Percentage of the smoke removed by cloud and precipitation scavenging as a function of smoke particle size over the Battersby biomass fire. The vertical line marks the calculated lower size limit of a nucleation scavenging mechanism.

4) Cloud Water: Measure in close time proximity the smoke concentration going into the cloud and the amount of smoke in the cloud water. Using volumetric and cloud liquid water content measurements to yield equivalent air concentrations, the amount of accumulation mode aerosol scavenged is determined. * The problems with 3) apply, in addition to the errors which will be introduced if precipitation has begun.

Our initial efforts focused on 1) Input-Output and 2) Emission Factor methods and of these, only our work with 1) remains active. Method 2) simply does not provide consistent results. Method 1) is most valid using small cumulus because the brief amount of time needed to sample just below cloud base and climb to measure the smoke escaping the cloud allows the period of required steady smoke emissions to be very short.

Of the small cumulus cases examined, especially the several cumulus capped wild fires (Myrtle/Fall Creek) and the Troy prescribed burn, no significant scavenging occurred in the accumulation mode smokes. Significant removal of the supermicron aerosol was observed.

Battersby produced clear results by Method 1. The aerosol property examined was the size distribution. Since the log-log presentation of the input and output smoke size distributions developed by this method somewhat masks the extent of the scavenging, we present the percent removal of smoke particles as a function of particle diameter for two sets of samples in Fig. 7. Here we see most of the supermicron aerosol removed (95-100% in one case), a removal minimum at ~0.35 μm in diameter and increased removal in the center of the smoke accumulation mode mass peak. Hardiman produced similar results, using the same method, with ~80% supermicron removal, ~40% accumulation mode removal, and a removal minimum at ~0.3 μm. We emphasize that these results are for scavenging by all mechanisms. The vertical dashed line in Fig. 7 represents our theoretically predicted minimum particle size for nucleation scavenging which was computed using the cloud droplet size distribution measured just above cloud base. Interestingly, the result of this calculation falls in the region of minimum scavenging efficiency. The mechanism which is responsible for the efficient removal from 0.1 to ~0.3 μm is uncertain. However, it is clear that significant smoke scavenging occurs with the onset of only slight precipitation and appears to grow with precipitation intensity.

The large Hill and Wicksteed biomass fires which produced considerable precipitation allowed scavenging estimates by Methods 3 and 4 which are summarized in Table 3.

TABLE 3. SUBMICRON AEROSOL MASS SCAVENGING EFFICIENCIES USING CLOUD BASE AEROSOL, CLOUD WATER, AND CLOUD INTERSTITIAL AEROSOL SAMPLES.

Fire	Method 3 "Interstitial"	Method 4 "Cloud Water"
Hill		50 ± 30% 40 ± 20%
Hornepayne	75 ± 20%	80 ± 50%

The Hill experiment provided good data for a calculation by Method 4 yielding accumulation mode scavenging efficiencies of 40-50%. The same method applied at Wicksteed showed ~80% removal. Additional measurements obtained at Wicksteed allowed the use of Method 3 which produced a nearly identical scavenging efficiency of 75% for accumulation mode particles. Obtaining identical results by two different techniques is clearly a milestone in our scavenging work.

It is tempting to speculate that the difference between the scavenging efficiencies computed for Hill and Wicksteed is related to the cloud's input smoke flux. The smoke flux at the times the samples were taken was roughly three times greater for Hill's cumulus cloud. If the accumulation mode smoke were being mostly nucleation scavenged, the theoretical studies of Jensen and Charlson (1984) suggest that some scavenging limits could be reached that are inversely proportional to the input concentration. This would be in accord with our observations. However, since it is not clear that nucleation scavenging is the primary route by which the accumulation mode smoke enters the liquid water phase (in fact, Battersby data suggests it is not) our speculation is probably premature.

Regardless, the four large Canadian prescribed burns which produced cumulus complexes have provided us with significant new experimental evidence indicating that scavenging of biomass smokes "promptly" by capping cumulus clouds can be quite efficient. This is not to say that the techniques and data are free from flaws. We frankly recognize that our approach is crude and our data set quite limited (additional valid data may yet be extracted from the 1989 data set). Nevertheless, the picture which emerges from this work is:

- Supermicron smoke aerosol is removed with considerable efficiency in all but the smallest capping cumulus clouds. It is almost certain that these particles participate in early production of precipitation sized particles.

- Accumulation mode smoke aerosol (the bulk of the smoke with potentially great atmospheric residence times) enters the cloud water with great efficiency (40-80%) and is removed from the system with equal efficiency (30-90%) by precipitating cumulus with depths greater than 2 km.

From our JP-4 fire tests we have only a single case where the fire spawned a small capping cumulus cloud. While there is some theoretical and laboratory data to suggest that these smokes would not participate in cloud processes and should remain interstitial to the cloud drops (Hallet et al., 1989) this fragment of data suggests the contrary. Electron micrographs of the chain aggregate smoke showed a remarkable morphological change in the smokes which passed through the clouds. The chains were collapsed into far more compact organization and their single scattering albedo increased slightly. Thus we have reason to believe that hydrocarbon fuels do enter into cloud droplets and cloud processes with ease and thus to suspect that they may be scavenged similarly to biomass smokes.

There is a critical need to resolve the question as to whether fossil fuel smokes will indeed by cloud scavenged with high efficiency. Given the current uncertainties of laboratory studies, field scale studies are needed.

REFERENCES

Cofer III, W. R., J. S. Levine, D. I. Sebacher, E. L. Winstead, P. J. Riggan, J. A. Brass and V. G. Ambrosia, 1988: Particulate emissions from a mid-latitude prescribed chaparral fire. J. Geophys. Res., 93, 5207-5212.

Cofer III, W. R., J. S. Levine, D. L. Sebacher, E. L. Winstead, P. J. Riggan, B. J. Stocks, J. A. Brass, V. G. Ambrosia and P. J. Boston, 1989: Trace gas emissions from chaparral and boreal forest fires. J. Geophys. Res., 94, 2255-2259.

Einfeld, W., B. Mokler, D. Morrison and B. Zak, 1989: Particle and trace element production from fires in the chaparral fuel type. Twenty-Fifth Session of the Air and Waste Management Association, available from D. E. Ward, U.S.D.A. Forest Service, Seattle, WA 98105.

Fuchs, N. A., 1964: The Mechanics of Aerosols. Pergamon Press, New York.

Hallet, J., J. G. Hudson and C. F. Rodgers, 1989: Characterization of combustion aerosols for haze and cloud formation. Aerosol Sci. and Technol., 10, 70-83.

Hardy, C. C., and D. E. Ward, 1986: Emission factors for particulate matter by phase of combustion from prescribed burning. In Preprints, 1986 PNWIS-APCA Annual Meeting, Air Pollution Control Association, Pittsburgh, PA, 151-157.

Hegg, D. A., P. V. Hobbs and L. F. Radke, 1984: Measurements of the scavenging of sulfate and nitrate in clouds. Atmos. Environ., 18, 1939-1946.

Hegg, D. A., L. F. Radke, P. V. Hobbs, C. A. Brock and P. J. Riggan, 1987: Nitrogen and sulfur emissions from the burning of forest products near large urban areas. J. Geophys. Res., 92, 14701-14709.

Hegg, D. A., L. F. Radke, P. V. Hobbs, R. A. Rasmussen and P. J. Riggan,1990: Emissions of some trace gases from biomass fires. J. Geophys. Res. (In press).

Jensen, J. B. and R. J. Charlson, 1984: On the efficiency of nucleation scavenging. Tellus, 36B, 367-375.

McMahon, C. K., 1983: Characteristics of forest fuels, fires and emissions. Paper #83-45.1, presented at the 76th Annual Meeting of the Air Pollution Control Assocation, Atlanta, GA, 19-24 June.

Patterson, E. M. and C. K. McMahon, 1984: Absorption characteristics of forest fire particulate matter. Atmos. Environ., 18, 11,2541-2551.

Pittock, A. B., T. P. Ackerman, P. J. Crutzen, M. C. McCrackan, C. S. Shapiro, and R. P. Turco, 1986: Environmental Consequences of Nuclear War, Volume 1: Physical and Atmospheric Effects. 359 pp., John Wiley & Sons, New York.

Radke, L. F., J. L. Stith, D. A. Hegg and P. V. Hobbs, 1978: Airborne studies of particles and gases from forest fires. J. Air Pollut. Control Assoc., 28, 30-34.

Radke, L. F., 1982: Sulfur and sulfate from Mt. Erebus. Nature, 299, 710-712.

Radke, L. F., D. A. Hegg, J. H. Lyons, C. A. Brock and P. V. Hobbs, 1988: Airborne measurements on smokes from biomass burning. In Aerosols and Climate, edited by P. V. Hobbs and M. P. McCormick, pp. 411-422, A. Deepak Publishing Co, Hampton Virginia.

Radke, L. F., A.S. Ackerman, D. A. Hegg, J. H. Lyons, P. V. Hobbs and J. E. Penner, 1990a. Effects of aging on the smoke from a forest fire: Implications for the nuclear winter hypothesis. J.Geophys. Res. (submitted).

Radke, L. F., J. H. Lyons, P. V. Hobbs and R. E.Weiss, 1990b: Smokes from the burning of aviation fuels and their self-lofting by solar heating. J. Geophys. Res. (In press).

Stith, J. L., L. F. Radke and P. V. Hobbs, 1981: Particle emissions and the production of ozone and nitrogen oxides from the burning of forest slash. Atmos. Environ., 15, 73-82.

Turco, R. F., O. B. Toon, T. P. Ackerman, J. B. Pollack, and C. Sagan, 1987: Climate and smoke: an appraisal of nuclear winter. Presented at Workshop on Environmental Consequences of Nuclear War, February 9-13, Bangkok, Thailand.

Waggoner, A. P. and R. E. Weiss, 1980: Comparisons of fine particle mass concentration and light scattering extinction in ambient aerosol. Atmos. Environ., 14, 623-262.

Waggoner, A. P., R. E. Weiss, N. C. Ahlquist, D. S. Covert, S. Will and R. J. Charlson, 1981: Optical characteristics of atmospheric aerosols. Atmos. Environ., 15, 1891-1909.

Ward, D. E., 1989: Factors influencing the emissions of gases and particulate matter from biomass burning. Presented at the Third International Symposium on Fire Ecology, Freiburg University, Federal Republic of Germany, 15-19 May.

Ward, D. E., D. V. Sandberg, R. D. Ottman, J. A. Anderson, G. G. Hofner and C. K. Fitzsimmons, 1982: Measurements of smokes from two prescribed fires in the Pacific Northwest. Seventy-Fifth Annual Meeting of the Air Pollution Control Association, available from D. E. Ward, U.S.D.A. Forest Service, Seattle, WA 98105.

Weiss, R. E. and L. F. Radke, 1987: Optical properties of Lodi Canyon forest smoke: airborne plume measurements using "in situ" optical extinction, in M. J. Pilat and E. J. Davis (Eds.), Aerosols '87, Elsevier, New York, NY, 261 pp.

NARD

CHEMICAL
RESEARCH,
DEVELOPMENT &
ENGINEERING
CENTER

CRDEC-CR-092

PROCEEDINGS OF THE SMOKE/OBSCURANTS SYMPOSIUM XIV VOLUME II

Adarsh Deepak
SCIENCE AND TECHNOLOGY CORPORATION
Hampton, VA 23666

Walter Klimek
MUNITIONS DIRECTORATE

November 1990

U.S. ARMY
ARMAMENT
MUNITIONS
CHEMICAL COMMAND

THIS DOCUMENT CONTAINS FOREIGN GOVERNMENT INFORMATION

Aberdeen Proving Ground, Maryland 21010-5423

Disclaimer

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorizing documents.

Destruction Notice

For classified documents, follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19, or DoD 5200.1-R, Information Security Program Regulation, Chapter IX. For unclassified/limited distribution documents, use the same standard as "For Official Use Only" material, and destroy by any method that will prevent disclosure of contents or reconstruction of the document. When local circumstances or experience indicates that this destruction method is not sufficiently protective of unclassified limited information, local authorities may prescribe other methods but must give due consideration to the additional expense balanced against the degree of sensitivity.

Distribution Statement

Distribution authorized to U.S. Government agencies and their contractors only because of foreign government information; November 1990. Other requests for this document shall be referred to Commander, U.S. Army Chemical Research, Development and Engineering Center, ATTN: SMCCR-SPS-T, Aberdeen Proving Ground, Maryland 21010-5423.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1990 November	Final, 90 Apr - 90 Apr

4. TITLE AND SUBTITLE
Proceedings of the Smoke/Obscurants Symposium XIV, Volume II

5. FUNDING NUMBERS
C-DAAA15-88-C-0039

6. AUTHOR(S)
Compiled by Adarsh Deepak (Science and Technology Corporation), and Walter Klimek (CRDEC)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Science and Technology Corporation, Hampton, VA 23666

CDR, CRDEC, ATTN: SMCCR-MUM, APG, MD 21010-5423

8. PERFORMING ORGANIZATION REPORT NUMBER
CRDEC-CR-092

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
CDR, CRDEC, ATTN: SMCCR-MUM, APG, MD 21010-5423

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
COR: Walter Klimek, SMCCR-MUM, (301) 671-2260

This is Volume II (pages 361-766) of four volumes.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution authorized to U.S. Government agencies and their contractors only because of foreign government information; Nov 90. Other requests for this document shall be referred to CDR, CRDEC, ATTN: SMCCR-SPS-T, APG, MD 21010-5423.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
This report consists of 60 papers contained in Volumes I and II that, with the six papers (classified information) of Volumes III and IV, comprise the Proceedings of the Smoke/Obscurants Symposium XIV. Papers in this document fall into the following categories: smoke materiel, smoke effects on electro-optical systems, natural obscurants, operational uses of smoke/obscurants, effects of smokes/obscurants on health or the environment, obscuration to sensors overhead, and posters.

14. SUBJECT TERMS
Smoke
Diffusion model development
Smoke obscuration hole statistics
Mass extinction coefficient ratios
(Continued on page ii)

15. NUMBER OF PAGES
418

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR