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Abstract

Emissions of particulate matter from prescribed fire in Georgia were sampled from an airplane and from various points on the ground. The source strength for the fire was determined, and an average emission factor for particulate matter of 10.3 g kg^{-1} calculated from an analysis of four methods for determining emission factors. In one method, readings on plume cross sections were taken at different distances from the source with an integrating nephelometer. The relative humidity was above 55%, and correction factors were applied to the indicated nephelometer concentrations. The mass-to-b_{scat} ratio decreased from 0.23 at 40% relative humidity to 0.14 at 90%. The total number of particles decreased by a factor of 2.6 from 0.8 km to 7.4 km downwind from the fire. For the 0.3- to 0.5-μm size range, the number of particles increased by a factor of 4 over the same distance.

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Introduction

Forest fires, whether prescribed or wild, emit particulate matter into the atmosphere. Production of this material from forest fires in the United States has been estimated at 3.6 teragrams (10^{12} g) per year (Ward, et al. 1976[1]). Large wildfires are believed to emit particulate matter at a rate on the order of 1 million grams per sec (Wade and Ward 1974[2]). The effects of this large mass of particulate matter have never been fully evaluated--partly because the character and quantity of effluents produced are poorly understood. Perhaps the biggest asset of prescribed burning is that it reduces forest biomass at a low cost, and thereby reduces the threat of impaired air quality and timber values due to high-intensity wildfires.

Only a modest amount of information is available on the nature of the smoke in forest fire plumes. Ward and Lamb (1970)[3] and Vines, et al. (1971)[4] found approximately Gaussian horizontal distributions of particulate matter in plume cross sections. Fritschen, et al. (1970)[5] and Murphy, et al. (1976)[6] utilized a nephelometer mounted in an aircraft for documenting plume concentrations resulting from the burning of forest debris. Adams and Koppe (1976)[7] made similar measurements on debris disposal fires in Montana. A recent study by Radke, et al. (1978)[8] documented the particle size distribution from a prescribed fire in western Washington. Their observations are consistent with those of Sandberg and Martin (1975)[9], Ryan and McMahon (1976)[10], MacArthur (1966)[11], Vines, et al. (1971)[4]. The general consensus is that forest fires produce particles with a number mean diam near 0.1 μm and a mass mean diam near 0.3 μm. Radke, et al. (1978)[8] also attempted to relate their particle mass measurements to fuel burned on the ground. They report a particulate matter emission factor (EF_p) of 40 g kg^{-1} for the burn. However, all fuel parameters and fuel consumption rates were estimated after the fire.

The most detailed descriptions of forest fire smoke have been reported by the Australian CSIRO research groups (Vines, et al. 1971[4]; Evans, et al. 1976[12]; Evans, et al. 1977[13]). They report EF_p less than 20 g kg^{-1} for bush fire smoke based on the following independent techniques: (a) flux of particulate matter through a vertical cross section derived from plume traverses with a nephelometer; (b) use of a theoretical CO_2 emission factor in conjunction with measurements of CO_2 and particulate matter concentrations; and (c) laboratory measurements of particulate matter production and fuel consumption. In this work, some of the problems inherent in describing plume concentrations with an integrating nephelometer were recognized and the nephelometer response adjusted.

The studies of Radke, et al. (1978)[8] and Evans, et al. (1977)[13] comprise the best information available on EF_p values derived from airborne measurements. However, their findings were not verified with simultaneous, independent measurements of particulate matter emissions near the source.

On February 28, 1975, we set a prescribed fire on the Waycross State Forest in southeastern Georgia, and we carefully monitored fire emissions on the ground as well as in the air. In conjunction with the aircraft sampling, ground crews sampled emissions at the fire source and recorded fuel, weather, and fire behavior. This was one of 10 such fires monitored in this manner, but this Paper is confined to the Waycross burn because the data on it are superior.

In this Paper, we discuss methods of sampling particulate matter and compare EF_p values calculated by four independent techniques. We show the effect of relative humidity on the response of an integrating nephelometer to forest fire smoke. These data represent, for an open combustion source, the only known attempt to simultaneously measure source strength and emission factors at the source and at different cross section locations downwind from the source.

Methods

The field experiments were designed to yield both surface and aerial observations of combustion products quality and quantity. In addition, site selection and description were carefully considered. Fuel parameters affecting fuel consumption (McNab, et al. 1978[14]; Hough and Albini 1978[15]), weather on the site, and weather spatially removed from the site were of special interest as these parameters influence fire behavior, emission production, and dispersion of the combustion products.

Fuel, Weather, and Fire Behavior

The Waycross State Forest was selected because fuels and topography are typical of much of the Southern Coastal Plain, where prescription fires are more common than in the rest of the Nation. The understory (Figure 1) is saw palmetto (*Serenoa repens* (Bartr.) Small) and gallberry (*Ilex glabra* (L.) Gray); the overstory is a mixture of slash pine (*Pinus elliottii* Engelm.) and longleaf pine (*Pinus palustris* Mill.). Differences in elevation are minor (less than 2 m km^{-1}) in and around the test area.

Approximately 14 ha were burned in two stages. In the first stage, a single line of fire 841 m long was set to back into the wind, normal to the wind direction. A second line of fire, approximately 100 m downwind from the first, was ignited about 1.5 hr after the first. Thus, smoke from the two lines of fire merged forming one column.

An 0.5-ha subplot was located adjacent to the end of the first line of fire and the fuel, fire behavior, and emission parameters were intensively sampled on this area. Fuel samples were taken prior to and following each fire to determine gravimetrically the fuel consumed by the fire. Samples from the various size classes of fuels expected to burn were collected, brought to the laboratory, and ovendried at 103°C to determine fuel moisture content. Rate of spread, flame height, and flame velocity were measured at periodic intervals during the experiment. The fire consumed fuel at a rate of 13.1 kg s^{-1} during the first 1.5 hr and 14.6 kg s^{-1} thereafter. The fire rate of spread for the first 1.5 hr was 0.88 cm s^{-1}. The mean for the two lines of fire which burned for an additional hr was 0.47 cm s^{-1}.

Windspeed, wind direction, ambient temperature, and relative humidity were sampled continuously at two ground locations. At one location (a 26.8-m-high tower that extended about 5 m above the treetops), these parameters were observed at heights of 1.4 m, 16.8 m, and 26.8 m. Windspeed and direction at 1.4 m and 6.1 m heights were also continuously recorded by an independent system at a nearby site. The mean temperature, relative humidity, and windspeed at 1.4 m were 23°C, 55%, and 0.80 m s^{-1} in the forest stand. Upper air soundings of temperature, dewpoint, and windspeed were taken by the National Weather Service (NWS) in Waycross, Georgia, about 30 km northwest of the research site.

Sampling of Emissions

Emissions were sampled at three locations: (1) at fixed points on the surface near the fireline, (2) near the fire from a moving station wagon, and (3) from an aircraft.

On the 0.5-ha subplot, samples were taken from five 12.2-m-high towers with filters spaced at intervals up the towers. Three towers were along the fireline and two towers were positioned at 15 m intervals downwind from the fire. A previous paper describes the use of the towers for determining source strength and EF_p (Ward, et al. 1974)[16]. The concentration of particulate matter was determined at each height and then multiplied by the volume of gases moving past the tower. The total flux of particulate matter divided by the ovendry weight of fuel consumed during the sample period yields EF_p. Andersen samplers were positioned near each tower along the fireline to determine the mass of particulate matter by particle size class. At one tower bag gas samples were collected in conjunction with the particulate matter samples. The general schematic of apparatus in relation to the fire is illustrated by Figure 2.

The station wagon was equipped with an electric mobility analyzer an integrating nephelometer, and various other filter and grab bag sampling devices. This roving unit took samples close to the source and at strategi locations downwind from the source.

A twin-engine 1964 Cessna[a/] model 336 was equipped with particle size analyzers, nephelometer, and gas analyzers. Its twin-engine centerline thrust design and minimum safe flying speed (160 km hr^{-1}) make the Cessna model 336 ideal for plume monitoring. The basic configuration of the aircraft and the instrument package have been described by Adams and Koppe (1969)[17].

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a/ Mention of trade names throughout this Paper does not constitute endorsement by the U. S. Department of Agriculture.

Results

Emission factors (EF_p) from full-scale fires are difficult to measure. Particularly for aerial sampling, results are best when a uniform fuel is burning at a constant rate, and when windspeed and direction are relatively constant. Instruments must respond rapidly to changing plume concentration since most plumes originate from sources 1000 m or less in width. Data from the Waycross burn are ideal for several reasons. Nephelometer readings and particle size distributions were observed from the air and the ground, and three-dimensional particulate matter concentration was measured near the surface. Wind profile, temperature profile, and relative humidity were continuously recorded. Fuel consumption and fire behavior were adequately documented.

Sampling provided four independent sets of data for calculation of emission factors (EF_p):

1. Particulate matter concentrations measured by the integrating nephelometer in the airplane (mass flux method). Four different cross sections through the plume were observed.

2. Particulate matter concentrations measured with the CN counter in the airplane (volume flux method). Same cross sections in 1 above.

3. Particulate matter concentrations determined from 47-mm filters positioned on 12.2-m towers cross sectioning the plume close to the source (mass flux method).

4. Particulate matter, CO_2, CO, and total hydrocarbon concentrations collected coincidentally along a 12.2-m tower close to the source (carbon balance method).

Emission Factors From Nephelometer Measurements

The nephelometer has been reported to be sensitive to the character of the particles and gases in the atmosphere (Ahlquist and Charlson 1967[18]; Vines, et al. 1971[4]; and Evans, et al. 1976[12]). To compensate for the response characteristics of the nephelometer to different atmospheres, Vines, et al. (1971)[4] and Evans, et al. (1976)[12] collected particulate matter concentration samples with filters and an electrostatic precipitator in conjunction with the nephelometer. In this way, the coefficient relating measured mass concentration to the measured scattering coefficient (b_{scat}) was adjusted from 0.38 for ambient aerosols in the Seattle area (Charlson, et al. 1969[19]), to 0.23 (Vines, et al. 1971[4]) and 0.32 (Evans, et al. 1976[12]) for aerosol from prescribed burns in Australia.

Similarly, our experience with the nephelometer indicates a need to adjust the mass to b_{scat} ratio for prescribed fire smoke generated from fuels burned in the Southeastern United States. The rate of particle growth in smoke is a function of relative humidity, and this relationship varies with the substances in smoke (Butcher and Charlson 1972[20]). For example, some aerosols are hygroscopic or consist of substances which adsorb vapor readily. Activated carbon is one such material which may be similar

to the carbon fraction of a forest fire plume. Because of the suspected effect of relative humidity on light scattering by smoke particles, a series of laboratory experiments were conducted to define the relationship.

Small samples of slash pine needle fuel were burned in an environmentally controlled combustion laboratory. The temperature was held between 26° and 29°C. The aerosol in the 762-m^3 cubically-shaped room was mixed by fans. After the smoke was thoroughly mixed with the air, a 15-min sample of the air was taken with three 37-mm teflon filters at 4 lpm and two 47-mm glass fiber filters at a flow rate of 28 lpm. The particulate matter concentration was compared to b_{scat}, as measured with the integrating nephelometer. The results, plotted in Figure 3, closely agree with the mass-to-b_{scat} ratios determined by Vines[4] (0.23) and Evans (0.25 to 0.32) at lower humidities. Our values are about 10% smaller than the mass-to-b_{scat} ratio previously determined by Tangren (1979)[21] for field observations at 30 to 40% RH. The differences will be resolved through further investigation. To correct the nephelometer mass determinations, an aerosol mass-to-b_{scat} curve was developed for a range of humidity conditions and applied to the traverse data of mass concentration from the experimental fires.

Little is known about the atmospheric moisture content gradient with height during the fire. We think that relative humidity increased with height and that the mixing ratio remained constant throughout the smoke plume at 9.8 g kg^{-1}. This assumption seems reasonable because the mixing height exceeded 2000 m (Figure 4) and the lapse rate as determined from temperature measurements from the aircraft was near the normal dry adiabatic lapse rate of 9.8°C km^{-1}. Temperature monitored by the aircraft for a given altitude, therefore, was used to enter the pseudoadiabatic chart for determining the saturation mixing ratio for the prevailing conditions. It was determined from the stoichiometric combustion of the forest fuel and from the amount of water evaporated from the fuel that the water vapor entering the atmosphere from these sources would have an insignificant effect on the mixing ratio--less than 0.05% at the downwind cross sections.

Table I lists the traverse concentrations measured with the integrating nephelometer for cross sections flown at 805 m, 3360 m, and 7355 m downwind from a single line of backing fire and at 805 m from the double lines of fire. The particulate matter mass concentration profiles for each traverse have been plotted by altitude and isopleth lines indicating regions of equal concentration. The results (Figure 5) indicate an approximately Gaussian horizontal distribution. As indicated, the flux of particulate matter was computed for each traverse from the product of the cross sectional area associated with the traverse, the windspeed at that altitude, and the corrected mean nephelometer response along the traverse. The result is a mass flux for a given increment of the cross section. By summing the increments, mass flux rates for particulate matter (or source strengths) of 273, 207, 280, and 236 g s^{-1}

are obtained for the cross sections. Emission factors were determined to be 19.4, 14.8, 19.6, and 16.2 g kg^{-1} for the 805-, 3360-, and 7355-m cross sections for the single line of backing fire and 805-m cross section for the double line of backing fire, respectively.

One further adjustment can be made to these data. Surface particulate matter concentrations under the plume downwind from the source were found to be very near ambient. Instead of assuming a constant concentration from the surface to the altitude of the lowest traverse, one can assume a linearly increasing function from zero to the concentration measured at the location of the lowest traverse. This change alters the mass flux estimate from a mean EF_p of 17.5 g kg^{-1} to 15.5 g kg^{-1}.

Plume Particle Size Distribution and Emission Factors

The size distribution for the smoke particles was determined with the electric mobility analyzer (EMA) (Ryan and McMahon 1976[10]) and was extended into the larger particle size range on the basis of the particulate matter mass distribution determined with an Andersen sampler. Although the density of particulate matter may be other than unity (Corn, et al. 1971[23]), unit density was assumed (Radke, et al. 1978[8] and Wantanabe and Takemoto 1974[22]) for the particulate matter. For example, Australian research has shown for bush fire smoke that the aerosol consists of primarily carbon and condensed organics and some ash (Evans, et al. 1976[12]). The carbon and ash may be expected to have densities greater than 1 g cc^{-1}. Nevertheless, the mean logarithmic particle diameter for each size class was used for computing the volume of a representative particle in that size class, and unit density was assumed. The individual particle mass was divided into the total mass of particulate matter collected in that size range. Through this method, the particle number and volume size distributions were developed for particles of diameter 0.01 to 10 μm (Figure 6).

Although we recognize a changing particle size distribution with time, for purposes of calculating an EF_p, we considered it to be conserved throughout the plume. Furthermore, we assumed that the CN counter detected all of the particles. The EF_p values were then computed by applying a volume per particle ratio of 209.48×10^{-5} μm^3 $particle^{-1}$. Table II summarizes the mean particle count by traverse for each of the cross sections as measured by the CN counter and the Bausch and Lomb particle counter. The CN count was multiplied by the volume per particle and this product by unit density to yield the mass transport represented by each traverse. The resulting mass transport is listed by cross section in Table II and is 97.2, 36.9, 34.8, and 72.9 g s^{-1} for the cross sections taken at 805, 3360, 7355, and 805 m downwind from the source, respectively. The last cross section represents a sample from the two lines of backing fire. Emission factors computed for these mass flux rates are 7.4, 2.8, 2.7, and 5.0 g kg^{-1}, respectively. These EF_p are lower than those determined with the integrating nephelometer by a factor of 3. Under estimation may be caused by the unit density assumption or by not incorporating a correction factor for a changing particle size distribution with distance from the source.

The particle size distribution changed as the plume moved downwind. Mass flux of particulate matter as determined by the integrating nephelometer remained fairly constant for the three traverses. However, the particulate matter mass flux as determined from the CN data dropped off rapidly. It can be seen from Table II that the total number of particles moving downstream decreased by a factor of 2.6, but that there was a factor of 4 increase in the number of particles between 0.3 and 0.5 μm. The number of particles between 0.5 and 10 μm decreased. A constant response from the integrating nephelometer while the total number of particles decreased supports the idea of particle coagulation in transit. In effect, the increased scattering efficiency due to the particles accumulating in the 0.3- to 0.5-μm size range is thought to offset the loss of scattering by the greater number of small diam particles observed for the 805-m cross section. We find a strong tendency to accumulate 0.3- to 0.5-μm particles, as did Friedlander (1977)[24] and Willeke and Whitby (1975)[25] in their analyses of combustion aerosols.

Surface Particulate Matter Concentration and Emission Factors

The three-dimensional concentration of particulate matter was monitored close to the source along one 50-m section of fireline. A rapid decline in smoke concentration near the ground was observed from the downwind cross section extending 30 m away from the source (Figure 7). The particulate matter concentration dropped from a high of 16 mg m^{-3} to about 2 mg m^{-3} 30 m from the source. An EF_p was determined from the particulate matter concentration data from samples along the fireline.

Particulate matter source strength can be determined from the 12.2-m tower data using the measured horizontal windspeed associated with each particulate matter concentration sample if the time sampled is short enough to preclude losses of particulate matter over the top of the 12.2-m portable towers. Usually samples were collected over a 15- to 20-min period. An EF_p can also be computed if the fuel consumed is known (Ward, et al. 1974[16]). A source strength of 1.44 g s^{-1} m^{-1} of fireline and an EF_p of 8.1 g kg^{-1} were calculated from these ground observations.

Ryan, et al. (1979)[26], in a companion paper, report on a technique for supporting an array of samplers from a balloon. In this manner, emissions can be sampled at greater heights, but conditions for the operation of such a system are very exacting.

Carbon Balance and Emission Factors

EF_p can also be determined by the carbon balance method. Particulate matter, CO, CO_2, and THC (total gaseous hydrocarbons) were observed simultaneously at five heights on one 12.2-m tower located at the fire. The top three sample locations (2.1, 3.0, and 6.1 m) have been used for these calculations primarily because the combustion products sampled at these locations are considered to be representative of the total combustion process. Samples from lower points contain a high proportion of the products of smoldering combustion. The consumed fuel was assigned an average

elemental composition of $C_6H_9O_4$ (Byram 1959[27]). The primary advantage of using a carbon balance is that the amount of fuel contributing to the formation of gases and particulate matter at any given sample location is assessed independently of prefire and postfire fuel samples. The previous three methods for determining EF_p require before- and after-fire samples of fuel.

Total fuel consumed and contributing to the formation of particulate matter was determined at five sample locations on the 12.2-m tower close to the fire (Table III). The fuel consumption required to produce the carbon-containing species is: 0.9067, 2.3474, 1.1161, 0.2654, and 0.1135 g m^{-3} of air. These values correspond to particle concentrations of 0.0106, 0.0141, 0.0179, 0.2654, and 0.1135 g m^{-3} and yield EF_p values of 11.7, 6.0, 16.0, 75.0, and 105.7 g kg^{-1}. The mean EF_p determined by the carbon balance method is 11.2 g kg^{-1} for the top three sample locations. This estimate is close to the EF_p of 8.1 g kg^{-1} determined by the tower plume flux method.

The bottom two EF_p, 75.0 and 105.7 g kg^{-1}, taken at heights of 0.6 and 1.2 m are thought to represent emissions from smoldering combustion. It should be noted, however, that due to entrainment, variations in windspeed, and other factors, emissions from the smoldering and flaming combustion processes are not completely separable, but mix as the plume leaves the source. Other tests are underway at the Southern Forest Fire Laboratory to validate the carbon balance method for determining EF_p and emission factors for other gases. Obviously, the carbon balance method requires considerably less effort in determining fuel consumption. We had hoped to utilize the technique for assessing EF_p from the aircraft data. However, CO_2 levels were marginally above background and too variable for precise calculation of EF_p. The low altitude at which samples were taken and the CO_2 emissions from the forest vegetation are likely causes for failure.

Discussion

Emission factors for particulate matter (EF_p) calculated by the four independent techniques were:

	Location				
	805 m	3360 m	7355 m	805 m	Surface towers
	g kg^{-1}				
Integrating nephelometer	19.4	14.8	19.6	16.2	
CN counter	7.4	2.8	2.7	5.0	
Mass flux					8.1
Carbon balance					11.2

Each of these EF_p values is useful in interpreting the data. If one assumes a particle density other than unity, possibly 1.5 g cm^{-3} (e.g., graphite's density ranges from 2.30 to 2.72 g cm^{-3}), then the average EF_p by the CN counter method would be higher. However, the integrating nephelometer

EF_p determinations would still be greater than those of the CN counter by a factor of almost three. As mentioned previously, the total flux of particles declined with distance from the source. Had this been accounted for, the comparability between the CN counter and integrating nephelometer methods would have been improved since the EF_p values for the 3360- and 7355-m cross sections would have been higher.

The nephelometer response was adjusted for the effect of relative humidity on the measured scattering coefficient for a given mass of aerosol. These corrections were based on a laboratory experiment in which a fresh aerosol was produced for several selected humidity environments. Had the aerosol been allowed to age in an open environment, the mass-to-b_{scat} ratio might have been altered to an even greater extent. This would be expected primarily because of the accumulation of particles in the 0.3- to 0.5-μm size range, which includes the particles having the greatest light scattering efficiency. Thus, the EF_p values would probably be reduced further than indicated in Figure 3.

The two methods for determining EF_p values at the source using the 12.2-m towers yielded similar results. In using the carbon balance technique, it is important that the samples be positioned in that part of the plume representative of the combustion process being quantified. In our case, five samples were taken--two of these were within 1.5 m of the ground. Due to the increased buoyancy created by the higher rate of fuel conversion to energy through the flaming combustion process, a natural stratification of the aerosol was produced. It is known from laboratory experiments that smoldering combustion produces higher EF_p than flaming combustion (Ryan and McMahon 1976[10]). Thus, the samples taken nearest the ground were considered to represent smoldering combustion. Samples taken higher on the tower, from 2 to 6 m, were considered to be a mixture of aerosol from smoldering and flaming combustion (see Table III).

Conclusions

Averaging of the EF_p values derived by the four techniques would indicate a true EF_p for the palmetto-gallberry fuel of 10.3 g kg^{-1}. The estimate by each of the four methods was within a factor of 2 of this average. That is reasonably close for emission estimates under forest conditions.

Variance between sampling methods was reduced by correcting the nephelometer data for the relative humidity effect on the mass-to-b_{scat} ratio. For fresh aerosol produced by burning pine needles, it was found that the mass-to-b_{scat} ratio decreases from 0.23 at 40% relative humidity to 0.14 at 90% relative humidity.

The flux of particles decreased by a factor of 2.6 between 0.8 km and 7.4 km downwind from the fire. In addition, the number of particles in the 0.3- to 0.5-μm size range increased by a factor of 4. This changing particle size distribution suggests a dynamic condition for the mix of combustion products contained in this forest fire plume.

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Table I. Data used for computing particulate matter emission factors (EF_p), including all cross sections through smoke plume with listing of plume width, windspeed, particulate matter concentration, as determined from corrected nephelometer measurements, and mass flux of particulate matter.

Traverse No.	Altitude (m)	Plume width (m)	Section height (m)	Windspeed ($m\ s^{-1}$)	Calculated RH (%)	Ratio of mass/b_{scat}	Particulate matter Conc $\mu g\ m^{-3}$	Particulate matter Flux $g\ s^{-1}$
Distance downwind from fire = 805 m, time = 1246 EDT								
4	183	3205	177.5	2.29	65	0.181	37.6	49.0
3	244	4017	61.0	3.61	67	0.179	10.9	9.7
2	305	3526	53.5	4.12	68	0.177	28.0	21.8
7	351	3838	76.0	4.28	69	0.176	19.4	24.2
8	457	4179	91.0	4.64	72	0.173	29.6	52.1
9	533	2945	91.5	4.90	75	0.167	20.6	27.2
10	640	2559	107.0	5.26	80	0.160	48.0	69.1
								253.1
$EF_p = \frac{253.1}{13.084} = 19.4\ g\ kg^{-1}$								
Distance downwind from fire = 3360 m, time = 1310 EDT								
16	274	6199	283	2.74	68	0.178	12.1	58.1
15	366	5023	92	4.33	69	0.176	13.3	26.7
14	457	4021	92	4.64	72	0.173	12.0	20.6
13	549	4547	122	4.95	76	0.166	12.9	35.5
12	701	4886	106	5.46	83	0.156	17.6	49.8
11	762	1298	61	5.67	86	0.152	5.0	2.3
								193.0
$EF_p = \frac{193.0}{13.084} = 14.8\ g\ kg^{-1}$								
Distance downwind from fire = 7355 m, time = 1325 EDT								
17	274	4134	328	2.74	68	0.178	12.9	47.9
18	457	7118	168	4.64	72	0.173	14.4	79.9
19	610	5642	152	5.15	78	0.162	6.9	30.5
20	762	4353	152	5.67	86	0.152	13.1	49.2
21	914	2751	152	6.18	94	0.145	18.7	48.4
								255.8
$EF_p = \frac{255.8}{13.084} = 19.6\ g\ kg^{-1}$								
Distance downwind from fire = 805 m, time = 1443 EDT								
34	213	2600	254	2.61	66	0.180	33.9	58.5
32	366	2600	51	4.33	69	0.176	22.6	13.7
37	488	2100	122	4.74	73	0.170	29.6	35.9
38	610	1800	137	5.15	78	0.162	14.0	17.8
39	762	1700	152	5.67	86	0.152	24.8	36.4
40	914	2800	152	6.18	94	0.145	13.7	36.0
41	1067	2800	152	6.57	98	0.140	13.6	37.9
								236.2
$EF_p = \frac{236.2}{14.554} = 16.2\ g\ kg^{-1}$								

Table II. Particle flux by size class and total flux of CN particles for four different cross sections.

Traverse No.	Altitude (m)	CN	Particle size class in μm 0.3-0.5	0.5-0.7	0.7-1.0	1.0-2.0	2.0-10.0
			---(Particles x 10^6 s^{-1})---				
	Distance downwind from fire = 805 m, time = 1246 EDT						
4	183	0.178 x 10^{12}	2.72	9.20	13.03	0.96	0.14
3	244	0.028	1.64	2.71	1.18	0.02	0.00
2	305	0.034	5.46	3.62	0.41	0.00	0.00
7	351	0.026	2.28	4.30	1.58	0.00	0.00
8	457	0.051	15.28	6.85	1.39	0.00	0.00
9	533	0.038	7.79	7.96	2.34	0.00	0.00
10	640	0.109 x 10^{12}	5.40	19.46	11.29	0.10	0.00
Total		0.464 x 10^{12}	40.57	54.09	31.22	1.08	0.14
	Distance downwind from fire = 3360 m, time = 1310 EDT						
16	274	0.039 x 10^{12}	52.11	4.18	0.67	0.00	0.00
15	366	0.020	16.68	3.10	0.42	0.00	0.00
14	457	0.019	15.04	2.48	0.39	0.00	0.00
13	549	0.055	20.81	3.93	0.38	0.00	0.00
12	701	0.040	39.35	6.79	1.22	0.00	0.00
11	762	0.003 x 10^{12}	0.97	0.21	0.04	0.00	0.00
Total		0.176 x 10^{12}	144.96	20.69	3.12	0.00	0.00
	Distance downwind from fire = 7355 m, time = 1325 EDT						
17	274	0.030 x 10^{12}	32.41	4.72	0.45	0.00	0.00
18	457	0.060	57.20	9.04	0.78	0.00	0.00
19	610	0.016	21.00	3.19	0.18	0.00	0.09
20	762	0.030	32.42	4.73	0.15	0.00	0.00
21	914	0.030 x 10^{12}	33.24	4.44	0.34	0.00	0.00
Total		0.166 x 10^{12}	176.27	26.12	1.90	0.00	0.09
	Distance downwind from fire = 805 m, time = 1438 EDT						
34	213	0.136 x 10^{12}	14.79	17.60	9.53	0.00	0.00
32	366	0.071	5.22	6.25	1.86	0.00	0.00
37	488	0.039	18.01	6.40	1.54	0.00	0.00
38	610	0.021	14.41	1.19	0.00	0.00	0.00
39	762	0.040	27.06	5.17	0.34	0.00	0.00
40	914	0.041	33.27	4.05	0.20	0.00	0.00
41	1067	0.034 x 10^{12}	26.22	2.03	0.19	0.00	0.00
Total		0.382 x 10^{12}	138.98	42.69	13.66	0.00	0.00

Table III. Calculation of particulate matter emission factors by the carbon balance technique for determining the quantity of fuel consumed.

Tower Height (m)	--Carbon by species--- CO[1]	CO_2[2]	THC[3]	Particulate[4]	Total	Equivalent Fuel[5]	Particulate Matter	EF_p $g\ kg^{-1}$
	$g\ m^{-3}$							
6.1	0.0132	0.3296	0.0973	0.0101	0.4502	0.9067	0.0106	11.7
3.0	0.0024	0.7484	0.4014	0.0134	1.1656	2.3474	0.0141	6.0
2.1	0.0045	0.1343	0.3985	0.0170	0.5542	1.1161	0.0179	16.0
1.2	0.0000	0.0612	0.0517	0.0189	0.1318	0.2654	0.0199	75.0
0.6	0.0004	0.0446	0.0000	0.0114	0.0564	0.1135	0.0120	105.7

1/ Calculation of carbon from CO

$$\frac{(C_{CO} - \text{Background})}{10^6} \frac{(28\ g)}{gmol} \frac{(gmol)}{24.5\ \ell} \frac{(1000\ \ell)}{m^3} \frac{(12\ g\ c)}{28\ g\ CO}$$

2/ Calculation of carbon from CO_2
Same as above except use molar ratio of 12 g c $(44\ g\ CO_2)^{-1}$.

3/ Calculation of carbon from hydrocarbon
Same as above except use molar ratio of 72 g c $(78\ g\ HC)^{-1}$.

4/ Calculation of carbon from particulate matter (95% carbon).

5/ Fuel elemental analysis of $C_6H_9O_4$ with the ratio of carbon to fuel being 49.7%.

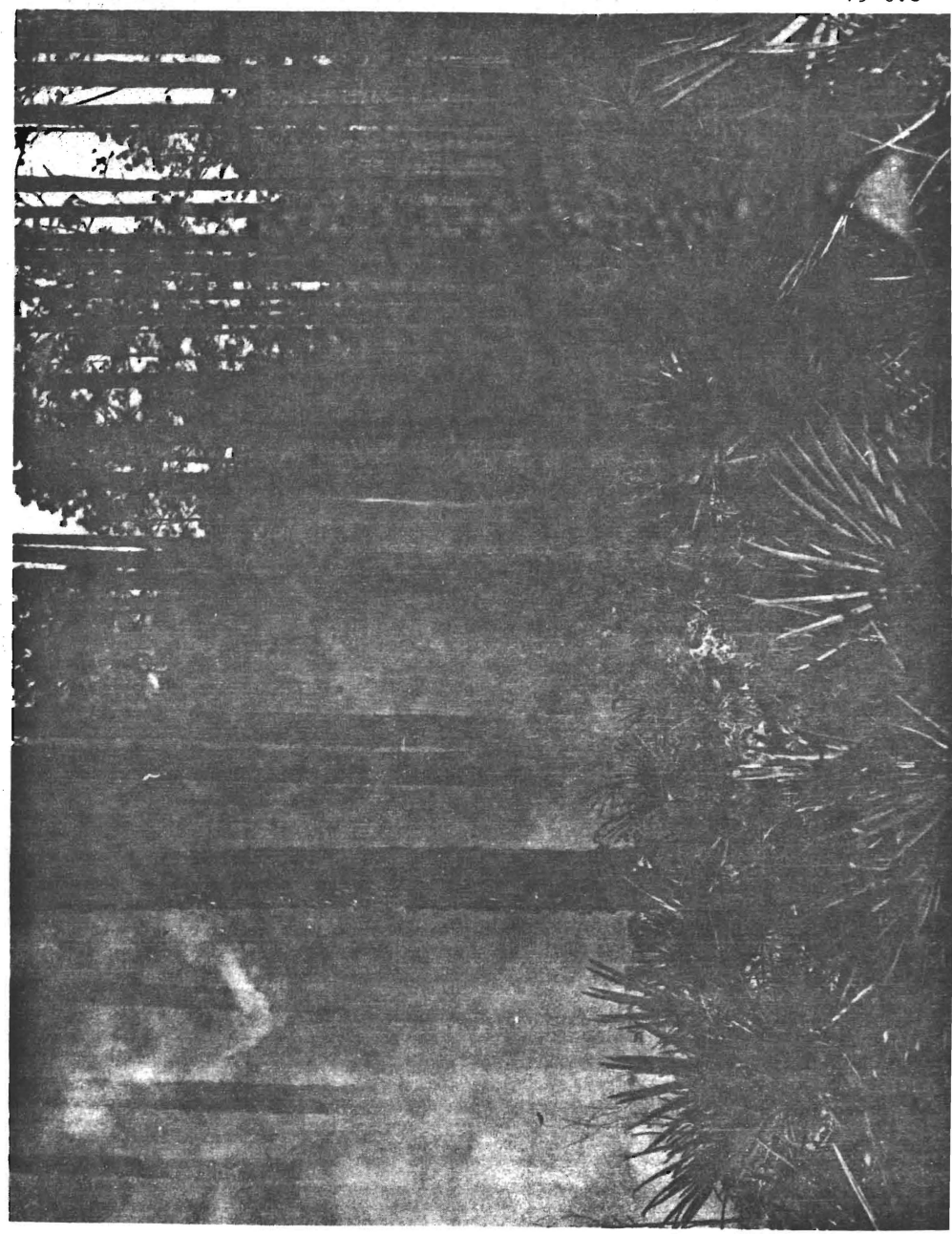

Figure 1. A prescribed backing fire reduces the accumulated understory vegetation (palmetto-gallberry) in a slash longleaf pine forest.

LEGEND:

(T1) 12.2-M TOWER
(E) ELECTRIC GENERATOR
(T2) 26.8-M TOWER FOR METEOROLOGY OBSERVATIONS
(V) VACUUM PUMP
(A) ANDERSEN SAMPLER
(W) ELECTRIC MOBILITY ANALYZER
(G) GAS SAMPLING

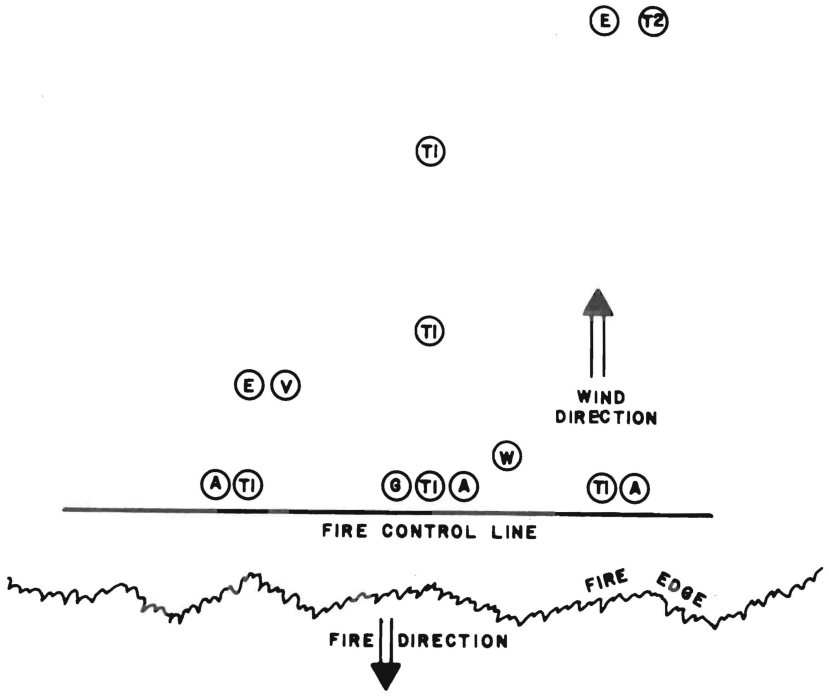

FIGURE 2. SCHEMATIC OF INSTRUMENT LOCATIONS FOR SURFACE SAMPLING CLOSE TO THE FIRE.

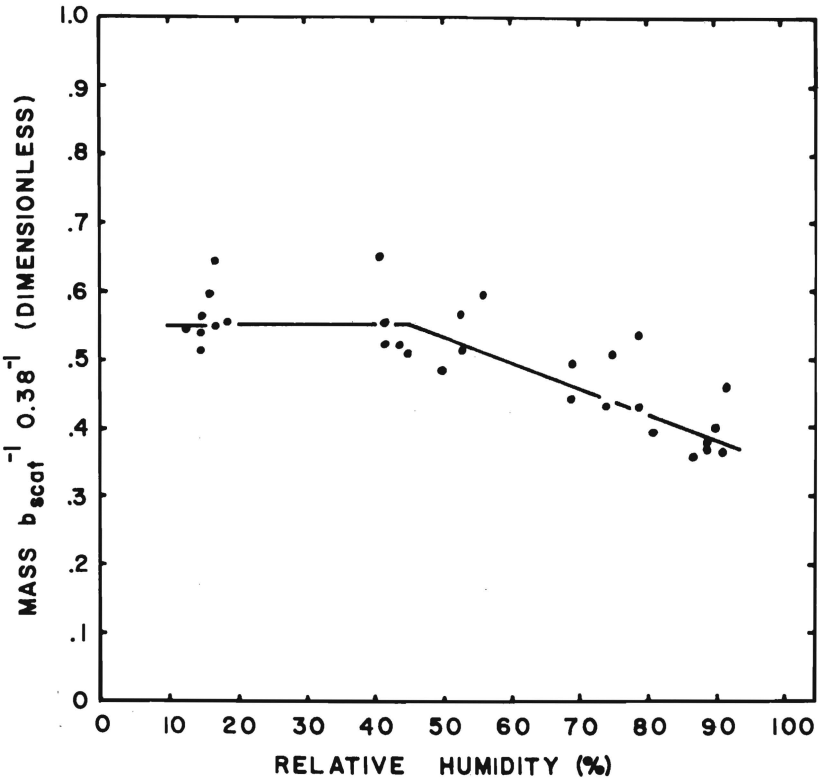

FIGURE 3. MASS/b_{scat} AS AFFECTED BY RELATIVE HUMIDITY FOR SMOKE FROM SLASH PINE NEEDLES BURNED IN A 762 m^3 CONTROLLED ENVIRONMENT COMBUSTION FACILITY.

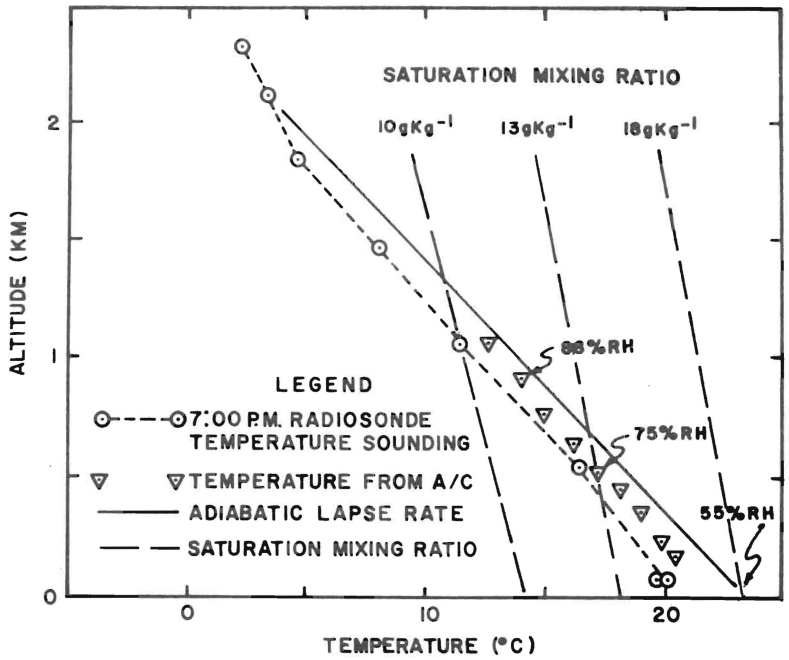

FIGURE 4. PSEUDOADIABATIC CHART SHOWING RADIOSONDE SOUNDING AND AIRCRAFT SOUNDING OF TEMPERATURE. MIXING HEIGHT IS IN EXCESS OF 2000 METERS WITH R.H. INCREASING FROM 55% AT THE SURFACE TO AROUND 90% FOR THE HIGHEST TRAVERSE.

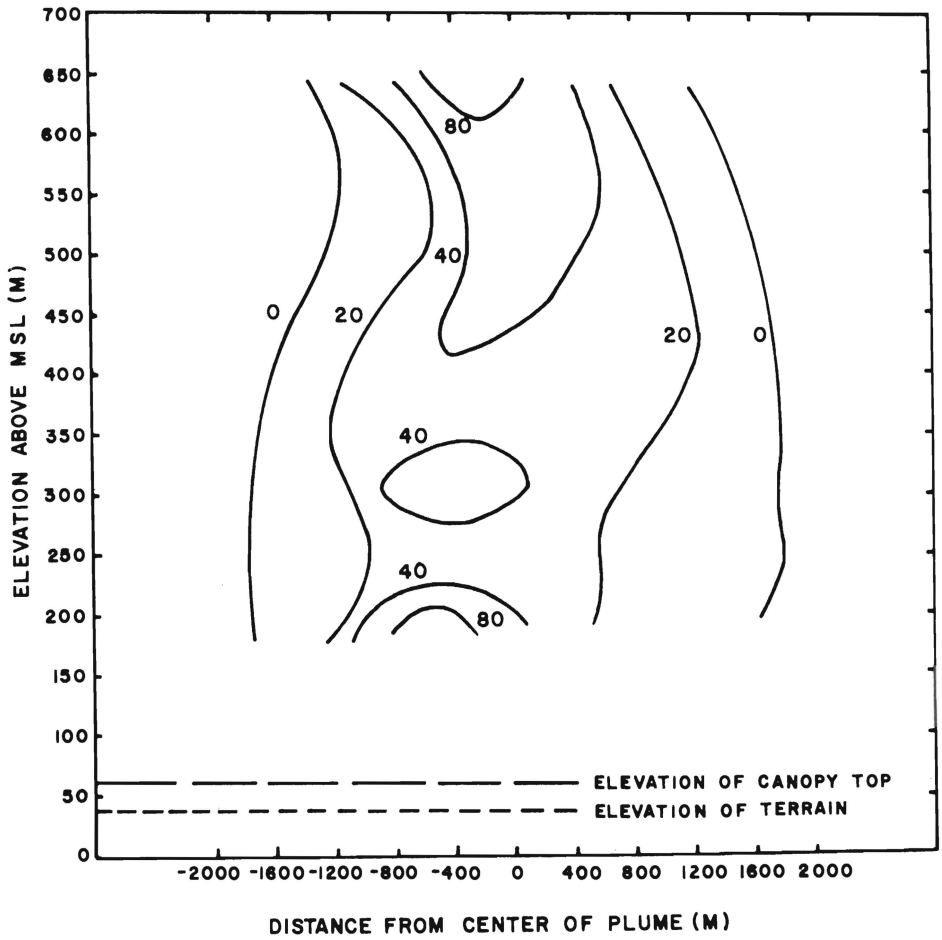

FIGURE 5. PARTICULATE MATTER CONCENTRATION ISOPLETHS FOR THE PLUME CROSS SECTION 805 METERS DOWNWIND FROM THE SOURCE.

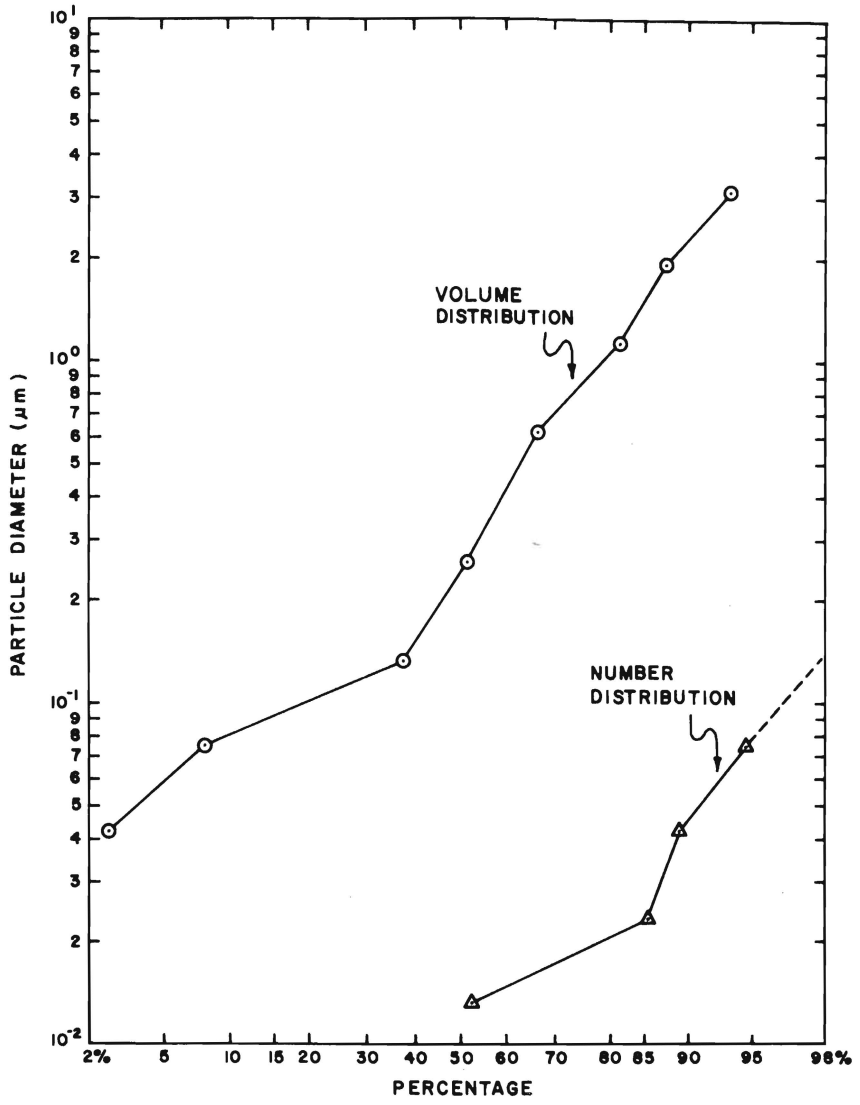

FIGURE 6. CUMULATIVE PERCENTAGE OF NUMBER OF PARTICLES AND VOLUME OF PARTICLES BY PARTICLE DIAMETER.

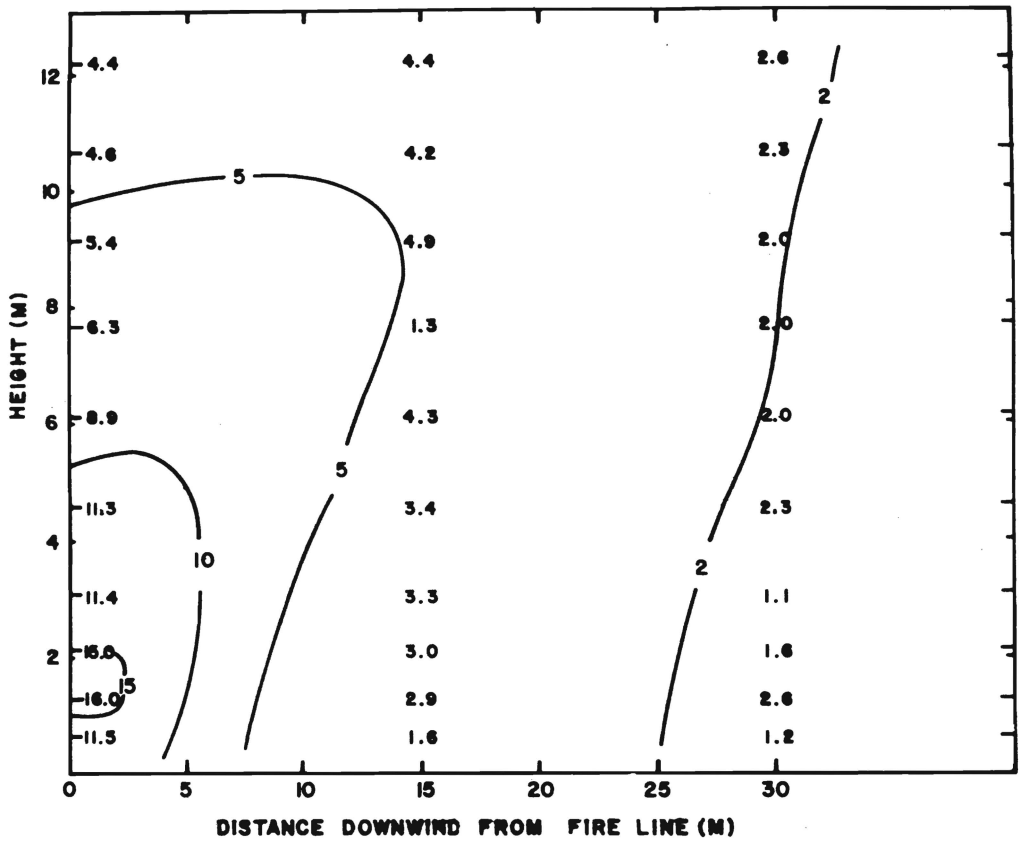

FIGURE 7. PARTICULATE MATTER CONCENTRATION ISOPLETHS DOWNWIND FROM FIRELINE 30 METERS.