

000

82-8.4

MEASUREMENT OF SMOKE FROM TWO
PRESCRIBED FIRES IN THE PACIFIC NORTHWEST

DAROLD E. WARD
DAVID V. SANDBERG
ROGER D. OTTMAR

USDA, FOREST SERVICE
SEATTLE, WASHINGTON

JERRY A. ANDERSON

METEOROLOGY RESEARCH, INC.
SANTA ROSA, CALIFORNIA

GEORGE C. HOFER

USEPA, REGION X
SEATTLE, WASHINGTON

CHARLES K. FITZSIMMONS

USEPA, ENVIRONMENTAL MONITORING
LAS VEGAS, NEVADA



**For Presentation at the 75th Annual Meeting of the
Air Pollution Control Association**

New Orleans, Louisiana

June 20-25, 1982

8231

Abstract

The information presented is directed to environmental scientists and land managers concerned with the quantity of, and methods for reducing, criteria pollutants produced from open burning of forest residues. This report documents the first in a series of paired-unit demonstrations in which utilization levels and sources of pollution are measured. Ultimately, results will lead to technology and cost guidelines for reducing emissions of pollutants from prescribed fires in the Pacific Northwest.

Two clearcut units in the Willamette National Forest of western Oregon were yarded to different specifications: 8" x 10' (20.3 cm x 3 m) and 6" x 6' (15.2 cm x 1.8 m). In conjunction with accurate monitoring of fuel consumption and fire behavior, particulate matter (TSP), CO, NO_x, and O₃ emissions were sampled from an aircraft platform. A ground-based sampling system was used for sampling TSP, CO, and CO₂. Total fuel consumed was 650 metric tons and 450 metric tons for the two units. Weighted average emission factors from both units for TSP was 20.0 g kg⁻¹. A reduction of 31% in TSP emissions was demonstrated as a result of decreasing the amount of fuel burned by 3.14 kg m⁻² (14 short tons per acre).

NOTE TO EDITORS

**Under the new federal copyright law,
publication rights to this paper are
retained by the author(s).**

Introduction

Forest burning is a substantial source of air pollutant emissions. To meet forest management objectives, it is necessary to burn unutilized residues (slash) left after timber harvest. The trend is toward an increased demand for slash as a source of fiber and biomass for energy, which is gradually decreasing emissions from slash burning. An interagency research program of the United States Forest Service, Environmental Protection Agency, and Department of Energy is evaluating the effectiveness of increased utilization as an emission reduction technique. One of our objectives is to encourage utilization of residues by demonstrating the concomitant improvement in air quality.

This report documents the first of a series of paired-unit demonstrations in which utilization levels and pollutant source strength are measured. It represents the first effort in the Pacific Northwest in which aircraft sampling of emissions was supplemented by ground-based samplers in conjunction with accurate monitoring of fuel consumption and fire behavior.

In the West, prescribed fires are primarily used for silviculture and wildfire prevention. It is important to protect forests from wildfire both for economic reasons and because wildfires produce nine times as much particulate matter nationally as do prescribed fires. Emissions from wildfires enter the atmosphere at an uncontrolled rate over an unspecified period of time. Cooper⁽¹⁾ reports that for the southeastern United States, through prescription burning, the severity of losses caused by wildfires can be reduced while, at the same time, improving regional air quality. Timber harvest residue consisting of woody and other vegetative material, both living and dead, adversely affects reforestation. There is a need to remove these materials to optimize the environmental conditions for regeneration. Prescribed fires are commonly used for this purpose. But adequate knowledge does not exist to manipulate fires and fuelbeds to minimize the production of pollutants.

Prescribed fires contribute an estimated 0.4 million metric tons of particulate matter (TSP) per year in the United States, primarily in the West and Southeast.⁽²⁾ Based on an emission factor of 32.5 g kg^{-1} , an estimate of annual TSP production from prescribed burning in Oregon and Washington is 0.1 million metric tons.⁽³⁾ Emissions data from prescription burning are important because the smoke from these burns may be the major source of TSP. An example of this contribution can be realized by considering a source contributing 10% on an annual basis. If this were concentrated during 1 month, the contribution would be 57% of TSP during that month.

To complicate matters, more than 95% of smoke generated by forest fires is in the fine-particle range (less than $2 \mu\text{m}$ in diameter). Most smoke management activities are directed toward optimizing the timing of prescribed fires to avoid situations in which high concentrations of TSP may produce visual range impairment and/or levels of TSP that might adversely impact local air quality.⁽⁴⁾ If additional gains in air quality are to be made, methods will be needed for controlling emissions at the source.

Obviously, reducing the mass of fuel consumed by increased utilization directly reduces emissions production. Secondary effects, such as a reduction in fuel-dependent duff consumption (duff consists of accumulations of decayed organic matter on the forest floor) and fire behavior changes, are not so obvious. To measure these effects requires that aircraft sampling be used for an integrated evaluation of emissions and that surface monitoring be used to sort out the direct and secondary effects. It is important, in assessing any control strategy, that the costs of performing that operation be weighed against the benefits derived. Our Forest Residues and Energy Program is performing that type of analysis.

Prior Work

Most of the emissions research for forest fires during the past decade has been accomplished for the purpose of defining emission factors for criteria pollutants from the burning of forest residues. (Emission factors, EF, are defined in terms of the mass of pollutant produced per unit mass of fuel consumed, usually expressed in pounds per ton, or g kg^{-1} .) Sandberg⁽⁵⁾ reports emission factors (1) to be approximately inversely proportional to fire intensity, (2) to average 12 g kg^{-1} for fuel with needles burned in the laboratory, and (3) to be 14 g kg^{-1} for similar fuels burned under field conditions. Stith et al.,⁽⁶⁾ from an aircraft platform, sampled three prescribed fires in the State of Washington. They measured significant increases in O_3 concentration in forest fire plumes, source strengths for TSP of up to 15 g kg^{-1} , and EF_{TSP} (emission factor for TSP) from 2 to 20 g kg^{-1} . These emissions were measured without good fuel consumption quantification data.

In Australia, Vines et al.⁽⁷⁾ sampled emissions from bush fires and determined that the range of EF_{TSP} is from 7 to 20 g kg^{-1} of fuel consumed. In the Pacific Northwest, Sandberg et al.⁽⁸⁾ measured EF_{TSP} and EF_{CO} values averaging 6 g kg^{-1} and 98 g kg^{-1} , respectively. For fuels in the Southeast, Ward et al.⁽²⁾ and Ryan and McMahon⁽⁹⁾ found EF_{TSP} values ranging from 3 to 62 g kg^{-1} where EF_{TSP} is dependent on fuel type, fire type, and weather variables.

Methods

Description of Harvested Units

Two timber harvest clearcut units approximately 90 km east of Eugene, Oregon, on the Willamette National Forest, were selected. The units were part of the Green Mountain Timber Sale Wood Utilization Study, which investigated harvest costs and utilization potential on paired units logged to different minimum size removal requirements. Sale layout and logging methods were typical of National Forest operations in old-growth forests.

The units were similar except for the amount of woody material removed (Table I). Unit A was YUM yarded (yarding unmerchantable material) to a minimum piece size of 8" x 10' (20.3 cm x 3 m). Unit B was yarded to a piece size of 6" x 6' (15.2 cm x 1.8 m). Pieces larger than 16" x 2' (40.6 cm x 0.6 m) were also removed from Unit B. Similar (+10%) volumes of merchantable (sold per net volume) and utility (sold per acre) logs were removed; but removal of lower quality per-acre material was 42 tons per acre (9.42 kg m⁻²), or 45%, greater on Unit B. Preburn slash loading differences between Units A and B were significant only in the size class of pieces larger than 6 inches in diameter (15.2 cm).

Table I. Description of Green Mountain Timber Sale, Units A and B, Willamette National Forest, Oregon

Unit Characteristic	Unit A	Unit B
Size, in acres	16 (6.5 ha)	17 (6.9 ha)
Elevation, in feet	2000-2400 (600-730 m)	2300-2500 (700-760 m)
Aspect	E	NE
Percent Slope	20-50	10-50
Yarding Specifications, minimum piece size	8" x 10' (20.3cm x 3m)	6" x 6' & 16" x 2' (15.2cm x 1.8m & 0.4m x 0.6m)
Timber Volume Removed, in tons/acre ^a		
Merchantable & Utility Logs ^b	324 (72.6 kg m ⁻²)	292 (65.5 kg m ⁻²)
Other PAM ^c and Wood Fiber	94 (21 kg m ⁻²)	136 (30.5 kg m ⁻²)
Preburn Slash Loadings (Ton/A)		
0" to 6" (15.2cm) diameter	11 (2.5 kg m ⁻²)	10 (2.2 kg m ⁻²)
larger than 6" (15.2cm)	14 (3.1 kg m ⁻²)	1 (.2 kg m ⁻²)

^aSource: "Green Mountain Timber Sale Wood Utilization Study," report on file at the USDA Forest Service Willamette National Forest, Eugene, OR.

^b"Utility logs" includes both Special Cull and Utility (Pulp) grade logs. The tonnages removed are equivalent to 72 thousand board feet (MBF) per acre on Unit A and 66 MBF per acre on Unit B.

^cPer-acre material (per m² material).

Fuel Consumption

Wires were wrapped around approximately 40 logs located in each unit. The preburn and postburn wire measurements allowed the calculation of a diameter reduction caused by the fire. The diameter reduction was converted to percent fuel consumed.⁽¹⁰⁾ Prior to burning, two hundred iron spikes were driven flush with the top of the duff layer. After the fire, the exposed length of each spike was measured to the top of the remaining duff and to mineral soil. The amount of duff consumed for each burn was determined using this method.⁽¹¹⁾

Fire behavior and the progress of ignition of each unit was recorded by a trained observer. These data were used to calculate the percent area of the Units in the flaming and smoldering stages of combustion for a specific time.⁽¹²⁾

Emissions Sampling

Emission sampling was done on both days from a twin-engine Beechcraft Queen Air airplane sampling platform. In addition, on Unit B, a tower and cable system was used to support sampling equipment over a portion of the burn area. Emission concentration data were used in calculating emission flux and emission factors.

Aerial. The instruments aboard the aircraft during the sampling program are listed in Table II, along with response characteristics and the techniques of analysis. Sample line inlets are diagramed in figure 1. Further information regarding sampling manifold configuration is available in the final data report.⁽¹³⁾

The aircraft sampling system was used to cross section the smoke plume approximately 2 km downwind from the burn areas. Several individual traverses were made along paths at right angles to the plume trajectory. Four cross sections consisting of 4 to 12 traverses were flown--1 for Unit A and 3 for Unit B. In addition, several plume orbits were flown at the 2- and 9-km downwind distance for plume-chemistry and nephelometer calibration purposes during times when cross sections were not being made. Along with the real-time observations of combustion product concentration in the smoke plume, samples of the gases were collected in teflon bags and particulate matter samples on stretched teflon filters for selected passes and orbits.

Table II. Queen air instrumentation.

Parameter	Sampler Manufacturer And Model	Analysis Technique	Time Response (to 90%)	Approximate Resolution
NO/NO _x	Monitor Labs 8440	Chemiluminescence	5 - 10 s	10 ppb
b _{scat}	MRI 1550 (heated)	Integrating Nephelometer	5 s	20 x 10 ⁻⁶ m ⁻¹
O ₃	Monitor Labs 8410	Chemiluminescence	5 s	5 ppb
CO	Energetics Science, Inc.	Electro-chemical cell	15 s	0.1 ppm
Temperature	YSI/MRI	Bead Thermister/ Vortex Housing	5 s	0.5° C
Dew Point	Cambridge Systems 137	Cooled Mirror	0.5 s/° C	0.5° C
Altitude	Validyne	Absolute Pressure Transducer	1 s	6 m
Indicated Airspeed	Validyne	Differential Pres- sure Transducer	1 s	0.1 ms ⁻¹

Flux. To calculate emissions flux, it was necessary to determine the plume dimensions and windspeed for the time and altitude of each traverse. The depth, D, (in m) for each traverse was (1) the distance between the traverse above and below divided by 2, or (2) the total distance above or below if for a top- or bottom-of-plume traverse (see figure 2). The width of the plume, W, (in m) was determined to a minimum threshold measurement of the emission concentration above background. Windspeed, U, (in m s⁻¹) was taken from PIBAL soundings made at hourly intervals. An incremental flux (g s⁻¹) was computed by multiplying the dimensions of the plume represented by the traverse by the windspeed and emissions concentration at that altitude as given by the following equations:

$$\text{Flux}_{\text{TSP}} = \text{DWU}(b_{\text{scat}})k_1 \quad (1)$$

$$\text{Flux}_{\text{NOX}} = \text{DWU}(\text{NO}_x)k_2 \quad (2)$$

$$\text{Flux}_{\text{CO}} = \text{DWU}(\text{CO})k_3 \quad (3)$$

Where

b_{scat}, NO_x, and CO are instrument response factors; and k₁, k₂, and k₃ are sensitivity factors.

Surface. On Unit B, the equipment used for sampling the particulate matter and gases was supported by a tower and cable system. The cable formed a continuous loop which allowed the operator to extend a 2.5-cm diameter vacuum hose and umbilical electrical line approximately 70 m into the burn area at a height of 8 m or 16 m above the burn. Particulate matter samples were collected simultaneously with 4 gas samples which were taken immediately above the fire during sampling periods (figure 3). The 47-mm Gelman Type A glass fiber filter mats were operated at 10 liters per minute (lpm) flow by using flow-limiting orifices between the vacuum line and open-faced filter holders. Constant flow rate splitter valves were used on 6-volt diaphragm pumps to fill the grab sample bags.

Gases. Gas grab samples were collected for the purpose of doing a carbon balance. By quantifying CO₂, CO, and THC (total hydrocarbons) gases and particulate matter; an accurate assessment of the fuel consumed in producing these emissions can be made.⁽¹⁴⁾ The gas grab samples were analyzed on a Baseline Industries Model 1030A gas chromatograph which converts CO and CO₂ to methane through a catalytic process before quantification by a flame ionization detector. Quality assurance of all sampling and analytical systems was provided by an independent contractor.

Results

Sampling periods were dictated by weather factors that would be suitable for both aircraft sampling and prescribed burning operations. The two units were burned early in the morning, before upcanyon winds could make the fires uncontrollable. Unfortunately, a cloud layer developed which restricted sampling on the first day. While burning Unit A, the smoke plume mixed into a cloud layer at 1500 m altitude, with about 50% of the plume being sampled (Table III). On the second day, insufficient lift of the plume was obtained to safely traverse under the plume; hence, about 70% of the smoke was measured. These percentages were estimated by the sampling crew.

The units were burned on successive days in July 1981, beginning at 0648. Preburn coarse woody-fuel moistures averaged 32% for Unit A and 30% for Unit B. Fuels were hand lit in strips approximately 30 feet (9 m) wide, and each unit took approximately 3-1/2 hours to ignite. An attempt was made to produce identical firing times and fire intensities.

Table III. Fuel consumption rate for periods of time when plume cross sections were flown.

Unit	Plume Cross Section	Date	Sample Period Time		Rate of Fuel Consumption (kg s ⁻¹)
			Start	End	
A	1	07/13/81	0758	0847	28.1
B	2	07/14/81	0749	0804	23.5
B	3	07/14/81	0904	0921	20.5
B	4	07/14/81	1013	1025	41.3
A & B	Weighted Average ^a				29.0
B only	Weighted Average ^a				30.0

^aWeighted averages were calculated using the following formula:

$$\bar{W} = \frac{\sum_{i=1}^j (\dot{W}_i W_i)}{\sum_{i=1}^j W_i}$$

Where,

\bar{W} = weighted average

\dot{W}_i = rate of fuel consumption for plume cross section i

W_i = fuel consumed during the i^{th} plume cross section sampling period, and

j = number of cross sections.

Fuel Consumption

The total duff and woody fuels consumed, as determined from field observations, was 650 metric tons for Unit A and 450 metric tons for Unit B. The rate of fuel consumption averaged 29.0 kg s⁻¹ (based on a weighting procedure) during the four periods when emissions flux was measured (Table III). The fuel consumption rate on Unit A was similar to the average rate during the sampling periods on Unit B. Based on experience, it was estimated that half of the fuel consumption on each unit occurred during flaming combustion. This suggests that the emissions flux during the flaming stage for the two units should be about equal, and that an emission factor calculated by dividing the emissions flux by the fuel consumed should represent a midrange value between emission factors for the flaming and smoldering combustion processes.

Emissions Flux

Emission flux data for the portion of the plume sampled were calculated by multiplying the average emission concentration at a given altitude by the area represented by that transect and the windspeed in that segment of the plume (Equations 1 to 3). These flux data were then summed in a given cross section to give the total emission flux for the fire during that period of time. Figure 4 illustrates a typical emission concentration profile for b_{scat} NO_x , NO , O_3 , and CO during 1 traverse of the plume flown at an altitude of 1311 m above mean sea level (msl), 2 km downwind from Unit B at 0904 on July 14, 1981. Data for 2 additional cross sections were collected on July 14 and for 1 cross section on July 13. The concentration from each traverse was plotted and concentration isopleth drawings constructed for 1 cross section (figure 5).

The period from 0904 to 0921 is represented by the PIBAL observations taken at 0900 on July 14, 1981. Other PIBAL soundings were made at 1-hour intervals, and the sounding made closest in time to that of the cross section was used in computing the downwind flux.

On July 14, three orbits were flown in the plume 2 km from the source. During each orbit, TSP (without size segregation) was collected on preweighed 25-mm stretched teflon filters. The average mass concentration for each filter was divided by the average scattering coefficient, as measured by the integrating nephelometer during the filter exposure period, which provided an average TSP mass concentration to scattering coefficient ratio (mass-to- b_{scat}) of $0.41 \pm 0.12 \text{ g m}^{-2}$ (k_1 in equation 1). In addition, the TSP on the filters was subjected to particle-induced X-ray emission spectroscopy (PIXE) for determining the abundance of heavy elements (results presented on page 14).

The individual plume flux values for each cross section for TSP, NO_x (reported as NO_2), and CO are shown in Table IV. Average weighted TSP flux from Unit B was 647 g s^{-1} , compared to 526 g s^{-1} from Unit A. Oxides of nitrogen flux was also similar from the two units. The flux values were corrected to account for estimated plume volumes not sampled because of clouds or terrain. Grab samples of gases along traverses did not produce adequate CO_2 concentration resolution for calculating CO_2 flux.

Emission Factors

Emission factors were calculated in two ways. The emission mass flux, as determined from the aircraft samplers, was divided by the rate of fuel consumption (flux method). The second method uses the data collected from the surface-based system (carbon-balance method). Similarity of calculated emission factors between methods would tend to verify our sampling and computational methods.

Table IV Summary of emissions flux at 2 km downwind.

Unit #	Plume Cross Sect.	Est. of Plume Sampled (%)	Corrected ^a Emission Flux		
			TSP	NO _x	CO
			---(g s ⁻¹)---		
A	1	50-75	526	44	---
B	2	70-80	637	60	2180
B	3	70-80	417	24	1574
B	4	70-80	<u>767</u>	<u>84</u>	<u>5599</u>
A & B	Weighted Average ^b		579	51	---
B only	Weighted Average ^b		647	58	3176

^aTabular values were calculated using the smaller estimate of percent of plume sampled.

^bWeighted average flux. (See footnote a in Table III, where flux is substituted for \bar{W}_i .)

Flux Method. Emission factors for TSP, NO_x, and CO (listed in Table V) were calculated by dividing plume emission flux (Table IV) by fuel consumption rate (Table III). The pooled emission factor for TSP from the four passes was 20 g kg⁻¹.

Carbon-Balance Method. Several previous investigations have relied heavily on subjective estimates of fuel consumption.⁽⁶⁾ This can be circumvented if the carbonaceous gases are sampled and monitored reliably. The CO₂ contains approximately 90% of the carbon in the emissions from a typical prescribed fire of wildland fuels. The remainder of the carbon from the fuel can be partitioned between the CO, THC, and TSP in the appropriate ratios of 8.5%, 0.5%, and 1%, respectively. During the smoldering phase of a fire, the contribution of particulate matter, CO and THC can be much larger--possibly as high as 60-70%.⁽⁴⁾

The surface sampling system diagramed in figure 3, was used for collecting gaseous and TSP samples for Green Mt. Unit B and two other fires.⁽¹⁵⁾ Averages for the composite data are presented in Table VI, from which comparisons between data for Unit B and other units are made.

Table V. Emission factors as determined by dividing the flux of emissions by the rate of fuel consumption.

Unit	Plume Cross Section	Emission Factors			
		TSP	NO _x -----(g kg^{-1})-----	CO	
A	1	18.7	1.6	---	28.1
B	2	27.2	2.6	92.8	23.4
B	3	20.3	1.2	76.8	20.5
B	4	18.6	2.0	135.6	41.2
Mean \pm Standard Deviation ^a		21.2 \pm 4.0	1.8 \pm 0.6	102 \pm 30	
A and B	Weighted Average ^b	20.0	1.8	---	
B only	Weighted Average ^b	21.6	1.9	105.9	

^aMean and standard deviation for all 4 cross sections (3 cross sections for CO).

^bWeighted average emission factors. (See Table III, where EF values are substituted for \bar{W}_i .)

Heavy Elements

Particulate matter and heavy element concentrations above background levels were determined from 9 stretched teflon filters (7 from the smoke plume and 2 background samples). These data were used in calculating emission factors for heavy elements (Table VII) by multiplying the ratio of heavy elements present per unit weight of particulate matter by the mean EF_{TSP} of 20.0 g kg^{-1} (weighted average from Table V).

Plume Chemistry

Figure 6 summarizes the gas and particle concentration data obtained for the plume chemistry orbits downwind from Unit B. The gaseous, b_{scat} , and filter weight data are averages of the sample observations made while circling in the smoke plume at 2 distances (2 and 9 km) from the source. The excess ozone concentrations at 2 km were quite low during the initial sampling when the NO_x concentrations were high (figure 6). However, at 9 km, elevated ozone concentrations were measured as NO_x concentrations diminished. The ozone concentration in the plume 9 km downwind was roughly double the background concentration. Based on the data set from this program, no estimate of location or concentration of the maximum excess ozone is possible.

Table VI. Summary of Unit B surface-based emission factor data and the average emission factors for other units sampled in Oregon during 1981.(15)

Test Area	Stage of Combustion	Number of Samples	Emission Factors ^a		
			CO ₂	CO	TSP
			----- (g kg ⁻¹) -----		
Unit B	Smoldering	1	1329	263	21
Other Units	Flaming	2	1760+ 113.1	46.2+ 11.0	12.0+0.6
	Smoldering	4	1504+ 156	154+ 29	28.5+11.6

^aEF values for particulate matter are calculated using the following formula. The concentration of other gases can be substituted for TSP to calculate EF_{CO}, EF_{CO2}, etc.

$$EF_{TSP} = \frac{(TSP)F}{C_{CO} + C_{CO2} + C_{THC} + C_P}$$

TSP is the particulate matter concentration (mg m⁻³)

F is the carbon ratio of fuel consumed (0.497)

C_{CO} is the carbon fraction of CO (mg m⁻³)

C_{CO2} is the carbon fraction of CO₂ (mg m⁻³)

C_{THC} is the carbon fraction of THC (mg m⁻³)

C_P is the carbon fraction of particulate matter (mg m⁻³)

Discussion

Comparison of emission factors

Emission factors calculated by dividing the flux of emissions by the fuel consumption rate are in agreement with other values.(5,6,15) Particulate matter emission factors from the 4 sample periods should be close to 20.3 g kg⁻¹, assuming a 50% flaming/50% smoldering weighted average from data in Table VI (e.g., EF_{TSP} = 0.50(12.0) + 0.50(28.5) = 20.3 g kg⁻¹). Actually, an average EF_{TSP} of 20.0 g kg⁻¹ was measured for all sample periods (21.6 g kg⁻¹ for Unit B).

The EF_{CO} measured value of 105.9 g kg⁻¹ compares to the combustion stage weighted value of 100.1 g kg⁻¹. Our one surface observation of EF_{CO} is 263 g kg⁻¹, which was taken during the nonconvective-lift stage of the fire. This value is about 70% higher than other observations made for other tests (Table VI). But it is well within the range, 250 to 400 g kg⁻¹, observed by Sandberg et al.(8) More data are needed before good interpretation of this high EF_{CO} can be made.

Table VII. Emission factors for several heavy elements based on an emission factor for particulate matter of 20.0 g kg⁻¹.

Element	EF _X ^a (mg kg ⁻¹)
Na	12.3
Mg	162.4
Al	41.6
Si	74.0
P	11.9
S	21.4
Cl	-
K	57.9
Ca	226.4
Mn	17.6
Fe	7.2
Zn	7.0

^aEF_X is the mass of the element per unit mass of fuel consumed (g kg⁻¹) calculated by the formula (X/g TSP)(20.0 g TSP/kg fuel).

Likewise, our observations of EF_{NOX}, in terms of NO₂, range from 1.2 to 2.6 g kg⁻¹ and compare favorably with the results of Clements and McMahon⁽¹⁶⁾ of 0.4 to 2.2 g kg⁻¹ for samples of slash pine wood and needles pyrolyzed in a small-scale TG furnace.

It is possible to back-calculate fuel consumption from the CO flux measurements made from Unit B. Although we were not able to accurately measure the flux of CO₂, we assume CO was conserved over distance from the surface sampling location to the location of the cross sections, 2 km downwind. The one observation of EF_{CO} of 263 g kg⁻¹ was taken during the nonconvective lift stage at 1100 hours (Table VI). We think the weighted EF_{CO} of 100.1 g kg⁻¹ is representative of the emissions for Unit B cross sections 2 to 4. By dividing the CO flux values by the weighted EF_{CO}, fuel consumption rates of 21.8, 15.7, and 55.9 kg s⁻¹ result. These independent calculations of fuel consumption can be compared with Table III values of 23.5, 20.5, and 41.3 kg s⁻¹.

The reasonableness of the calculated emission factor values for TSP, CO, and NO_x with each other; with other work; and the agreement of the calculated rate of fuel consumption with the measured rate tend to validate both the measured fuel consumption and the measured emission fluxes. Our intent was to provide an independent integrated measurement of fuel consumption by back calculation based on the carbon flux. We have only gone the first step in making this independent measurement. Our work this year will concentrate on providing additional plume flux observations and on real-time gas concentration profiling along with acquiring grab samples for gas concentration analysis.

The integrating nephelometer measures the scattering of light resulting from particles in the gas stream. For this study, a nephelometer equipped with a heated inlet tube was used to reduce the effect of relative humidity variations on the mass-to- b_{scat} ratio.⁽¹⁴⁾ Our measured mass-to- b_{scat} ratio of $0.41 \pm 0.12 \text{ g m}^{-2}$ is higher than that determined by Vines et al.⁽⁷⁾ and Ward et al.⁽¹⁴⁾ Both used unheated nephelometers.

A difference in total TSP emissions was measured between Units A and B by multiplying the weighted EF_{TSP} determined from the 4 cross sections (20.0 g kg^{-1}) by total fuel consumed for each unit. A total TSP emissions of 13.0 and 9.0 metric tons was calculated for Units A and B. This demonstrates a 31% reduction in total TSP emissions as a result of decreasing the amount of available fuel from the site through yarding of woody materials with diameters larger than 15.2 cm. This year 2 to 4 additional units will be sampled so that a more definitive relationship can be developed between the level of residue removal and emission production.

Plume Chemistry Discussion

Over the 7-km distance downwind, the ratio of NO_x to O₃ decreased by at least a factor of two; the NO_x to NO ratio remained about constant. Our tests show the NO_x-to-NO ratio to be 4 to 10, or about a factor of 2 larger than reported by Stith et al.⁽⁶⁾ and of comparable magnitude to the report of Westberg et al.⁽¹⁷⁾ It should be noted that our samples were taken from 0800 to 1100 PDT which may have affected the intensity of ultraviolet light and the mixing of emissions through the potentially photochemically active top portion of the plume.

Ratios of heavy elements have been used in a chemical mass balance analysis for allocating the contribution of various sources to the emissions affecting a given receptor site.⁽¹⁸⁾ The ratio between K and Fe is considered significant for forest fires, where the K component represents the impact of vegetative burning and Fe represents the soil component. Our ratio of 8, (calculated by dividing EF_K by EF_{Fe} from Table VII) as measured in the plume close to the source, is compared with ratios ranging from 0.2 to 57 for composite source contribution samples at receptor sites.⁽¹⁹⁾

Conclusions.

Two timber harvest units on the Willamette National Forest in Oregon were yarded to different minimum size specifications for the removal of woody fuels as follows:

Unit A 8" x 10' (20.3 cm x 3m)
 Unit B 6" x 6' (15.2 cm x 1.8 m)

Aircraft and ground sampling measurements enabled the calculation of fuel consumption rates, emission fluxes, and emission factors. By removing an additional 14 tons of woody fuel from each acre burned (3.14 kg m^{-2}), a 31% reduction in TSP emissions was realized. For the unit with the highest amount of woody fuel removed, burnout occurred much more quickly during the smoldering combustion period.

Cross sections of the smoke plumes from the 2 prescribed fires showed source strengths for TSP ranging from 0.42 to 0.77 kg s^{-1} with mean emission factors for TSP, NO_x , and CO of 21.2 ± 4.1 , 1.8 ± 0.6 , and $102 \pm 30 \text{ g kg}^{-1}$, respectively.

The TSP emission factors measured compared favorably when determined using surface-based samplers and aircraft flux methods. The CO emission factor for Unit B was quite high (263 g kg^{-1}), but was measured for the nonconvective lift stage of the fire.

Ozone formation occurred over the 7-km distance of measurement. Our tests show that the NO_x -to-NO ratio increased over the same distance for the conditions of these tests. The NO_x -to- O_3 ratio decreased by at least a factor of 2 over the 7-km distance. Analysis of heavy elements showed a K-to-Fe ratio of 8--the significance of this for source apportionment is not known. Tests will be conducted during the summer of 1982 and 1983 to further examine the effect on emissions production of removing residues.

Acknowledgements

The authors acknowledge the administrative and technical support of Mr. Craig Chase, USDOE. Messrs. James Caswell, Charles Bodie, and David Tjomsland, of the USFS Willamette National Forest, were responsible for the prescribed fire demonstrations. Mr. Hubert Mapes, Willamette National Forest, was instrumental in initiating the research. Ms. Donna Lamb, USFS Region 6, assisted with data collection and analysis.

References

1. R. W. Cooper, "Trade-offs between smoke from wild and prescribed forest fires." In Proceedings of Air quality and smoke from urban and forest fires, Colorado State University, Fort Collins, CO. pp. 27-29. (October 24-26, 1973).
2. D. E. Ward, C. K. McMahon, and R. W. Johansen, "An update on particulate emissions from forest fires." Presented at 69th Annual Meeting of the Air Pollution Control Association, Portland, OR, 15 pp. (June 27-July 1, 1976).
3. GEOMET, Inc., "Impact of forestry burning upon air quality," final report. EPA 910/9-78-052. U.S. Environmental Protection Agency, Region X, Seattle, Washington. 253 pp. (1978).
4. D. V. Sandberg and D. E. Ward, "Air quality considerations in using prescribed fire for weed control." Proceedings: Weed Control in Forest Management, John S. Wright Forestry Conference, Purdue University (1981) pp. 237-247.
5. D. V. Sandberg, "Measurement of particulate emissions from forest residues in open burning experiments." Ph.D. dissertation, University of Washington (1974).
6. J. L. Stith, L. E. Radke, P. V. Hobbs, "Particle emissions and the production of ozone and nitrogen oxides from the burning of forest slash." Atmospheric Environment 15: 73-82. (1981).
7. R. G. Vines, L. Gibson, A. B. Hatch, N. K. King, et al., "On the nature, properties, and behaviour of bush-fire smoke." Div. of Applied Chemistry Tech. Pap. No. 1, Commonwealth Scientific and Industrial Research Organization, Australia (1971) 31 pp.
8. D. V. Sandberg, S. G. Pickford, and E. F. Darley, "Emissions from slash burning and the influence of flame retardant chemicals." APCA Journal 25 (3): 278-281 (1975).
9. P. W. Ryan and C. K. McMahon, "Some chemical and physical characteristics of emissions from forest fires." Presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, OR (June 27-July 1, 1976) 21 pp.
10. R. D. Ottmar and D. V. Sandberg. "Flaming stage fuel consumption." Study plan on file with Forest Residues and Energy Program, Pacific Northwest For. and Range Exp. Stn., Seattle, WA. (1981).
11. S. N. Little, et al. "Duff reduction to prescribed fire on two areas logged to different management intensities." Manuscript in preparation. Pacific Northwest For. and Range Exp. Stn., Portland, OR.

12. R. D. Ottmar and D. V. Sandberg. "Smoldering stage fuel consumption rate." Study plan on file with the Forest Residues and Energy Program, PNW For. and Range Exp. Stn., Seattle, WA. (1982).
13. J. A. Anderson, N. Waters, J. McDonald, et al., "Air quality sampling during the Green Mountain Smoke Characterization Study." Tech. Rep. MRI 82 FR 1854. Meteorology Research, Inc., Altadena, Calif. (1982).
14. D. E. Ward, R. M. Nelson, Jr., and D. F. Adams, "Forest fire smoke plume documentation." Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio (June 24-29, 1979) 24 pp.
15. D. E. Ward and D. V. Sandberg. (1982) Unpublished data on file at PNW, Seattle, WA.
16. H. B. Clements and C. K. McMahon, "Nitrogen oxides from burning forest fuels examined by thermogravimetry and evolved gas analysis." Thermochemica Acta **35** 133-139 (1980).
17. H. Westberg, K. Sexton, and D. Flyckt, "Ozone production and transport in slash burn plumes." Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio (June 24-29, 1979). 16 pp.
18. J. A. Cooper, J. G. Watson, Jr., "Receptor oriented methods of air particulate source apportionment." JAPCA **30** (10): 1116-1125. (1980).
19. J. A. Cooper, L. A. Currie, and G. A. Klouda, "Assessment of contemporary carbon combustion source contributions to urban air particulate levels using Carbon-14 measurements." Environmental Science & Technology **15** (9): 1045-1050 (1981).

List of Figures

- Figure 1. Traverse flight pattern for cross sectioning of smoke plume and for orbiting in smoke plume at two distances downwind from source (2 km and 9 km).
- Figure 2. Queen Air sample inlet lines and external probes.
- Figure 3. "Skyline" apparatus suspension system.
- Figure 4. Typical concentration profiles for B_{scat} , NO_x , NO , O_3 , and CO along one traverse line at 1311 m.
- Figure 5. Isopleth concentration profiles for B_{scat} , NO_x , O_3 , and CO for cross section 3. Ground level at 2 km downwind is approximately 1050 m (msl).
- Figure 6. Summary of the plume excess concentrations.

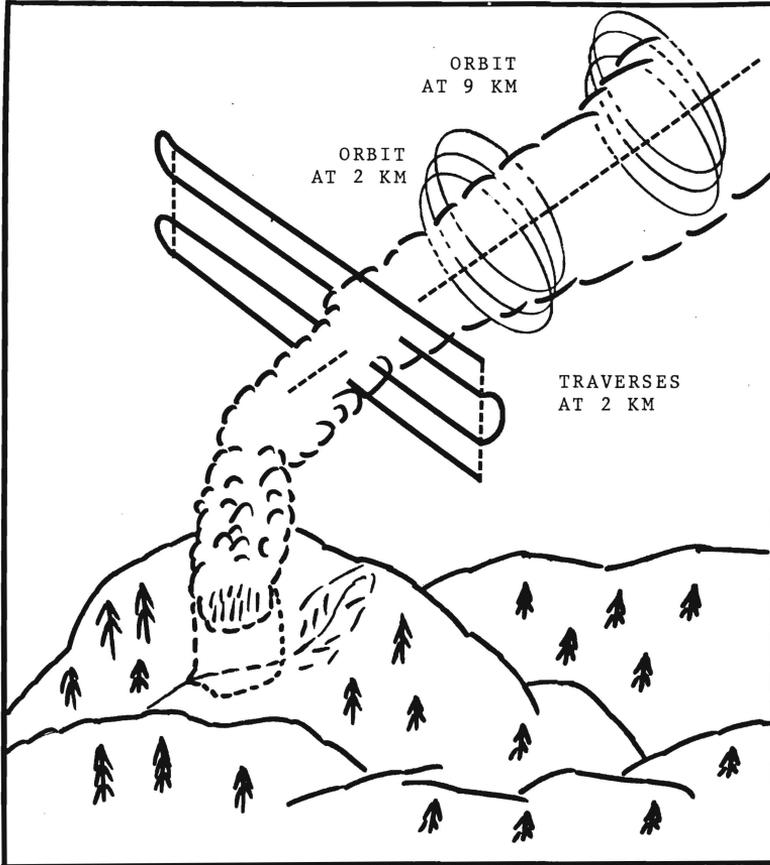


Figure 1. Traverse flight pattern for cross sectioning of smoke plume and for orbiting in smoke plume at two distances downwind from source (2 km and 9 km).

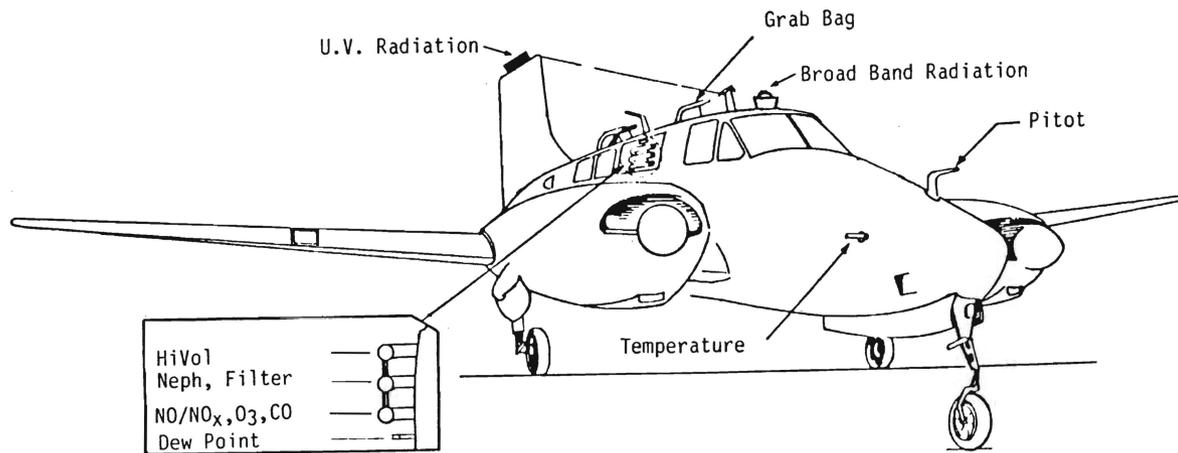


Figure 2. Queen Air Sample Inlet Lines and External Probes

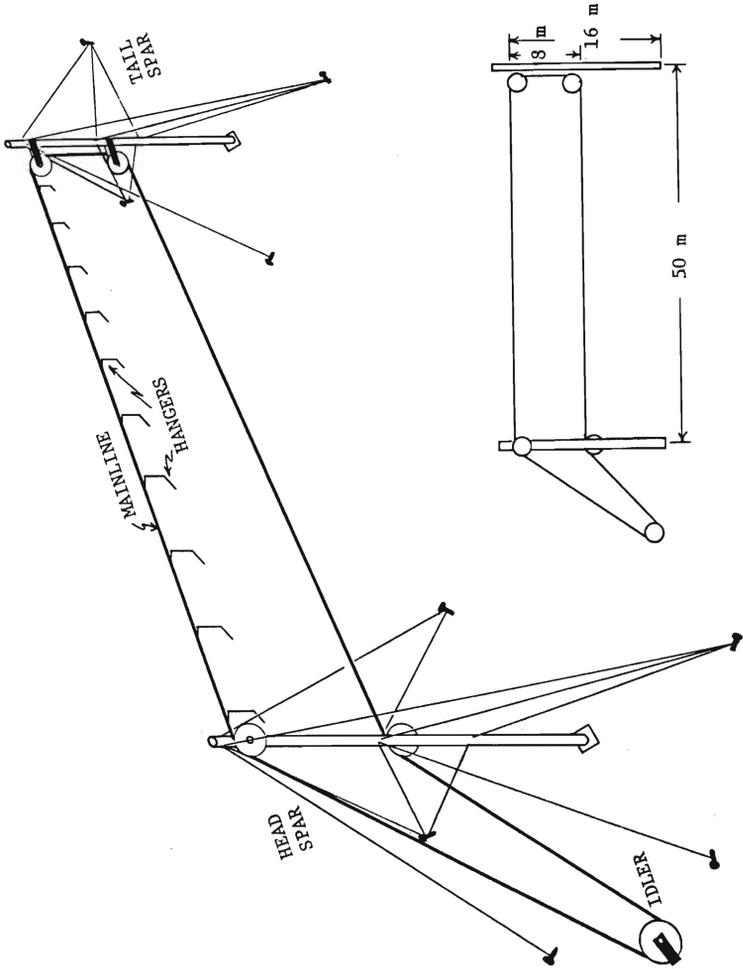


Figure 3.--"Skyline" apparatus suspension system

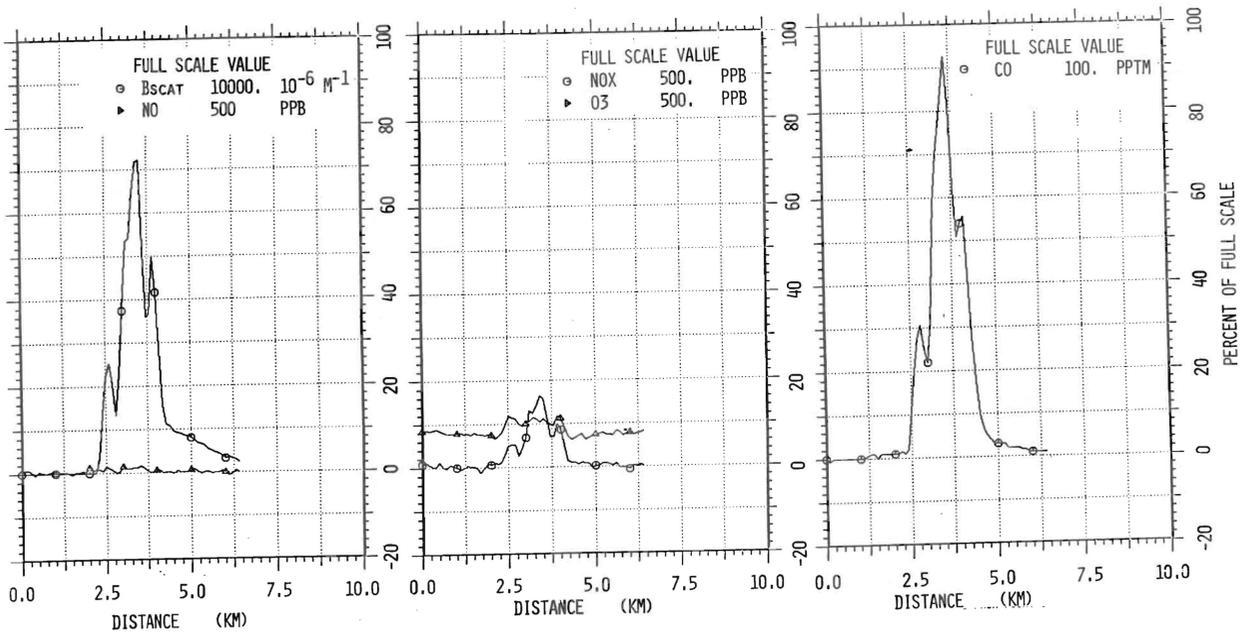


Figure 4. Typical concentration profiles for B_{scat} , NO_x , NO, O_3 , and CO along one traverse line at 1311 m (msl).

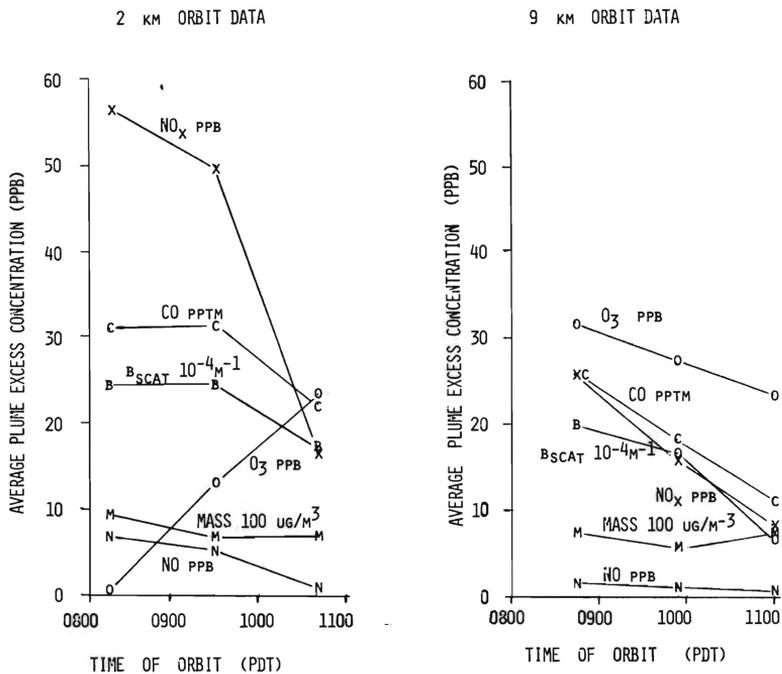


Figure 6. Summary of plume excess concentrations. Filter mass concentrations are in units of 100 ug m^{-3} and b_{scat} in 10^{-4} m^{-1} .