

EMISSIONS FROM PRESCRIBED BURNING OF CHAPARRAL

by

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ABSTRACT

Emissions from Prescribed Burning of Chaparral, D. E. Ward, Intermountain Research Station, USDA Forest Service, Missoula, Montana, 59807, and C. C. Hardy, Pacific Northwest Research Station, USDA Forest Service, Seattle, Washington 98105.

This paper describes emission factors for several gaseous and particulate matter emissions from burning chaparral fuels found primarily in the southwestern United States. Measurements of the smoke were taken for flaming and smoldering combustion phases by suspending sample packages over test fires of about 0.5 hectares in size. The mean emission factor for total particulate matter was 15.2 g/kg, a factor of two greater than the respective value of 7.2 g/kg for particles less than 2.5 micrometers in diameter. Emission factors for carbon monoxide were lower for the burns of chaparral fuels than for logging slash burned in the Pacific Northwest. Concentrations of other trace materials contained with the PM_{2.5} were also much higher in smoke from chaparral-fuel fires. For example, lead made up nearly 0.34 percent of the PM_{2.5} for the chaparral but was less than 0.1 percent for the logging slash fires. Measurements were also taken of temperature, vertical velocity, and carbon mass flux within the convection columns above the burn areas.

INTRODUCTION

Measurements of emissions from prescribed fires in the chaparral fuel type have been very difficult to obtain. Fires in chaparral fuels typically produce flame lengths in excess of 20 meters which complicates the use of surface-based sampling apparatus. The first field measurements of emissions from near full-scale fires in California were made by the Fire and Air Resource Management Project of the Pacific Northwest Research Station during the summer of 1986.

This paper discusses a series of experiments measuring emissions from prescribed fires in three variations of the chaparral fuel type. Similar measurements of smoke characteristics were made earlier for broadcast-prescribed fires of logging slash in the Pacific Northwest by using essentially the same techniques.¹ The experimental area for the chaparral tests was coincident with the large-scale prescribed fires described by others in this session that used airborne sampling techniques.^{2,3} The purpose of the experiments was to provide data on mass fires so that the nuclear winter hypothesis could be evaluated. These first experiments also provided the basis for continuing research intended to improve vegetation-management strategies in consideration of concern for air quality.

Chaparral and associated ecosystems are dominated by deep-rooted, evergreen shrubs, some of which are extremely flammable and have a high content of waxes and oils that increase the rate of heat release substantially when burned. Stands of chaparral older than 30 years often consist of a dead fuel component greater than 50 percent of the total biomass, contributing significantly to the flammability of such stagnating stands. Total above-ground biomass on these sites can exceed 50 tons/hectare, about two-thirds of which may be consumed in a fire. The fire cycle, or periodicity of wildfire, in chaparral fuels is typically 20 to 30 years. The practice of prescribed burning of vegetative materials and manual or mechanical treatment of fuels (felling or crushing) is becoming more prevalent and has been shown to reduce the severity and the frequency of subsequent wildfires.

Pollutants produced by smoke from the fires is one of the major concerns with the use of prescribed fire. Work is being done to characterize emissions from broadcast prescribed fires of different fuel types including Douglas-fir/western hemlock, alder-maple, ponderosa pine, and other mixed conifer species. This provided an excellent opportunity to determine whether similarities existed between the characteristics of smoke from prescribed fires in logging slash and in chaparral. The objectives for this research were as follows:

1. To measure emission factors for fine particles ($EF_{PM2.5}$ -- defined as emission factor for particles with a mean mass cutpoint diameter of $2.5\mu m$) and for particles sampled without regard to size (EF_{PM}).
2. To measure emission factors for combustion gases; that is, CO, CO₂, CH₄, and nonmethane hydrocarbons (NMHC).
3. To measure emission factors for the trace gas CH₃Cl.
4. To measure percent carbon content of PM2.5 and to describe the ratios between organic and graphitic carbon content of PM2.5.
5. To measure the trace element content of PM2.5.
6. To describe the emission factors as functions of fuel and fire behavior descriptors.

EXPERIMENTAL METHODS

Description of Test Areas

Tests were performed in three different mixes of vegetation typical of those burned in vegetation-management projects in the chaparral fuel type. The three adjacent test areas were in Lodi Canyon on the San Dimas Experimental Forest, part of the Angeles National Forest northeast of Los Angeles, California (Figure 1). Each test area was burned separately: the LODI1 test occurred June 30, 1986, and LODI2 and LODI3 occurred September 22 and 23, 1986.

The test areas were about 0.5 hectare each and were situated on three aspects of a narrow ridge top (Figure 1). LODI1 consisted of a fairly evenly distributed mixture of ceanothus (Ceanothus crassifolia) and chamise (Adenostoma fasciculatum), with a southeast aspect. The LODI2 area had a southwest aspect and was dominated by chamise. Unlike the other two areas, all vegetation on the LODI3 area was felled and cured before burning. Having a northeast aspect, the composition of vegetation was also different than the others; it had a mixture of ceanothus, scrub oak (Quercus dumosa), toyon (Heteromeles arbutifolia), and western mountain-mahogany (Cercocarpus betuloides).

Statistical significance of differences in emissions attributable to vegetation type as an independent variable would not be proveable; however, the present design of continuing research in 1989 in the chaparral fuel types is relying on data from these three tests as a preliminary baseline. New research will use similar treatment methods in similar vegetation mixes to build on what has been learned

from the LODI tests. Work is also underway to model emissions production from laboratory fires of chaparral fuels. These field observations will be important for calibrating the models.

Fires in the chaparral fuels tend to involve two combustion phases: 1. flaming combustion lasting from 4 to 10 minutes; and 2. smoldering combustion, lasting an additional 10 to 20 minutes. Emissions were sampled and are described here for each respective combustion phase.

Sampling System

The sampling system was designed to obtain continuous, real time measurements of the flux of emissions and to collect grab samples of emissions during specific periods of time from the prescribed fires. A twenty-five-meter boom was used on two of the tests to suspend five identical sampling packages along the boom at nearly right angles from the slope (Figure 2). Each sampling package was attached to a wiring-and-hose umbilical providing vacuum and electrical connections.

Grab Sampling System for Particulate Matter and Gases. The packages were designed to collect simultaneously grab samples of particulate matter and gases from the same sample space and were aligned to cross-section the plume. Discrete samples were collected for two combustion phases--flaming and smoldering.

The particulate matter samples were stratified into total particulate matter (PM) and particulate matter with particle diameters of less than $2.5\mu\text{m}$ mean mass cutpoint diameter (PM_{2.5}). The PM samples were collected by open-faced filters, and the PM_{2.5} samples were collected with a cyclone presampler to provide the size separation. Type of filter, size of filter, rate of flow of sample gas, and type of analyses are listed in Table I. Concurrent with the particulate matter samples, grab samples of the gases were collected at a constant volume flow rate in sample bags made of aluminized mylar and later transferred to stainless steel cylinders for trace gas analyses. The gas and particulate matter samplers were operated for discrete time periods ranging from 10 minutes for the flaming phase to 60 minutes for the smoldering combustion phase.

Real Time System. The real time components of the system were configured to measure the concentrations of CO and CO₂ sequentially from each of the five sampling packages. A scanning sample valve was used to direct the gas streams from each sample package sequentially (25 seconds per package) through the gas analyzers. In addition, the temperature and vertical velocity of the combustion gases were measured continuously at each of the sampling packages. All real time

measurements as well as several system-status parameters were recorded at 2-second intervals by a Fluke 2280A data logger system and were afterwards reduced to appropriate engineering units using IBM-compatible microcomputers. (Mention of a commercial or proprietary product does not constitute endorsement by the USDA.)

Analytical Procedures

Filter weighing was done by using a Cahn Model 28 electrobalance to weigh all 37-mm and 47-mm filters before and after exposure ($\pm 10\mu\text{g}$ in the 1- to 200-mg range). Standardized weighing procedures were followed when both field-control blanks and standard check weights were weighed with the exposed filters. A carefully controlled, NBS-traceable calibration weight was maintained and weighed periodically to check and control drift of the electrobalance. This strict weighing protocol included the equilibration of all filter media for 24 hours in a laboratory atmosphere regulated at a relative humidity of 50 percent and at a constant temperature of 72 to 76 degrees Fahrenheit. Additionally, an industry-standard ionization source was used for static control.

Nondispersive infrared gas analyzers were used to measure the concentrations of CO and CO₂ to accuracies of ± 0.3 and ± 0.4 percent, respectively. The CH₄ and NMHC fractions were determined by using a Baseline Industries gas chromatograph. Before and after each period of use of the analytical instruments, a series of carefully diluted, multicomponent gas standards was used for calibrating each analyzer.

Temperature measurements were taken of combustion gases in the convection column by using type K thermocouples electronically referenced to zero degrees Celsius within each thermally protected sampling package.

The vertical velocity of the combustion plume was measured at each of the five sampling packages by using (at alternate packages) either a Kurz Model 455-2 mass-flow anemometer (designed for dirty atmospheres and temperature-compensated) or a vane anemometer made by Qualimetrics, Model 24201. These instruments were calibrated periodically at a low-speed wind tunnel maintained to NBS standards by the National Oceanic and Atmospheric Administration, Seattle, Washington.

Calculation of Emission Factors

The carbon-mass balance method was used to assess the mass of fuel consumed that produced the emissions. The technique was first used successfully under field conditions and reported by Ward and others (1982); all the emission factors described in

this report were similarly calculated.⁴ The method is based on the stoichiometric partial oxidation of fuel ($C_6H_9O_4$) to products of CO_2 and incomplete combustion. The carbon contained in the fuel is about 50 percent of the mass of the fuel. The measured carbon contained with the combustion products is multiplied by two to calculate the mass of fuel consumed in producing the combustion products. Emission factors for specific emission components are calculated by dividing the mass of the emission by the fuel consumed and are expressed in units of grams of emission per kilogram of fuel consumed (g/kg).

Calculation of Rate of Fuel Consumption

The rate of fuel consumption during the fire was measured by the carbon-flux technique. The concentration of carbon on a mass-per-cubic-meter basis is multiplied by the measured velocity (in meters per second) to compute the mass of carbon released per square meter of area per unit of time (second).

Calculation of Rate of Energy Release

A measurement of the energy yield of the fires was made by measuring the temperature concurrently with the velocity. The specific heat of the gases was used to compute a flux of heat from the fire. This flux of heat was computed on a per-meter-of-fireline basis (fireline intensity) and on a square meter of area burned (reaction intensity) and was expressed in units of kW/m or kW/m^2 , respectively.

RESULTS AND DISCUSSION

Emission Factors

Emission factors for particulate matter, carbon monoxide, carbon dioxide, methane, and nonmethane hydrocarbons (in propane equivalents) are listed in Table II. The EF_{PM} values were highest for the most intense test fire (21.1 g/kg) with the difference between EF_{PM} and $EF_{PM2.5}$ being greatest for the same test fire (LODI2). This result is consistent with observations made for broadcast burns of logging slash in the Pacific Northwest where the difference between EF_{PM} and $EF_{PM2.5}$ has been shown to be proportional to the rate of heat release for the fire.⁵

The differences in emission factors for particulate matter as a function of species and aspect were not evident from the data collected for the three tests in Lodi Canyon. However, emission factors for particulate matter from fires in Pacific Northwest fuels have been shown to be affected by the two distinct phases of combustion.⁶ Discrete samples of

particulate matter for each phase of combustion in the chaparral tests were obtained only from LODI3. This is partly the result of difficulties encountered in identifying the transition from flaming to smoldering combustion and the short smoldering combustion period noted for the chaparral test area fires. Only a small difference was measured for either EF_{PM} or $EF_{PM2.5}$ between the flaming and smoldering combustion phases of LODI3, where EF_{PM} and $EF_{PM2.5}$ were, respectively, 20 and 30 percent higher in the smoldering phase. Samples of particulate matter were composited in some cases. These composite samples are identified in Table II by indicating the two combustion phases sampled; that is, FS1 or F1F2 represent composite samples for the flaming phase and smoldering phase or first flaming phase and second flaming phase, respectively.

Emission factors for gases were defined more precisely for each phase of combustion through the system of switching sample bags at appropriate times during the tests. It was thereby possible to obtain separate gas samples by phase of combustion. Hence, the emission factors for the gases shown in Table II (EF_{CO} , EF_{CO2} , EF_{CH4} , and EF_{NMHC}) have a greater range of variability than noted for the particulate matter. The measurements of EF_{CO} ranged from a low of 34.4 g/kg for the flaming phase of the test involving slashed chaparral (LODI3) to a high of 102.0 g/kg for the smoldering phase of the same test. LODI2, the test with the highest rate of energy release, yielded EF_{CO} values for the flaming phase 27 percent lower than the respective value for LODI1--the comparable test in standing live chaparral conducted earlier in the summer. It is not known whether seasonal effects or energy-release/combustion-efficiency effects resulted in the slight difference.

EF_{CH4} values (Table II) ranged from a high of 6.2 g/kg for the smoldering phase of the slashed chaparral (LODI3) to a low of 0.6 g/kg for the flaming phase of the highest heat release fire, LODI2. This is consistent with other measurements of emission factors for CH_4 made in the Pacific Northwest for logging slash fires. Both EF_{CO2} and EF_{NMHC} values are similar to most measurements made for fires in the Pacific Northwest. The EF_{NMHC} values may be an artifact of the sampling system because of the difficulty in moving high molecular weight species of hydrocarbons through the unheated umbilical tubes and the storage of these gases in bags prior to analysis.

Trace Element Content of PM2.5

Knowledge of the trace element content of fine particles is important for developing profiles of materials that can be used for receptor modeling--for apportioning the impact of smoke from vegetative burning at air quality monitoring sites. Profiles of several of the trace metals were developed for each of the tests by combustion phase. The

percent of PM_{2.5} that consisted of specific materials is summarized in Table III with the average, standard deviation, and coefficient of variation. The average values for the trace materials produced with the PM_{2.5} during the flaming phase were generally higher for the chaparral tests than for slash-fire smoke in the Pacific Northwest, as shown in Figure 3. For broadcast burns of conifer species logging slash in the Pacific Northwest, the effect of fire intensity on the content of the fine particles was pronounced. For example, it was found that the sum of the percent composition of S, Cl, and K differed as a function of fire intensity ($r=0.92$).⁸ For the flaming phases of the LODI tests, the S, Cl, and K content was nearly an order of magnitude larger than for tests in the Pacific Northwest (flaming phase) (Figure 3).

The total carbon content of the particles was similar for the LODI tests and for test fires in the Pacific Northwest (Figure 3), but for the same LODI tests the concentration of most trace elements was higher. Potentially, the higher intensity fires of the LODI experiments could have consumed more of the carbon than do slash fires of the Pacific Northwest. Another hypothesis is that the trace-element content of the vegetative materials consumed by the fires was greater for the LODI tests than for tests in the Pacific Northwest. Material from the Los Angeles basin could be deposited in the surrounding mountainous area thus increasing the concentration of materials such as lead, S, Cl, and K. The materials might be resuspended in the atmosphere because of the heat and turbulence of the fire. More work is needed to adequately explain these effects.

The graphitic carbon content of the PM_{2.5} (EC) from fires in the chaparral-fuel type was 50 percent less as compared to fires in logging slash fuels of the Pacific Northwest (Figure 3). Only one sample of PM_{2.5} from the LODI tests was similar to the respective flaming phase value for logging slash, containing 15 percent graphitic carbon (Table IV). This sample was from the felled and cured chaparral test, LODI3.

Trace Gas Emissions

The results will be confined to the emissions of methyl chloride. Ratios of CH₃Cl to PM_{2.5} were found to be reasonably consistent and stable over the range of measured combustion conditions. The low to high values were different by a factor of 2 (Table V) with a coefficient variation of 31 percent. Methyl chloride is used as a tracer material for the burning of vegetative materials in residential wood-combustion ambient air quality studies because: 1. the background concentration of CH₃Cl is low; 2. the stability in the atmosphere is high; and, 3. it is produced specifically from the combustion of vegetative materials. Reinhardt and

Ward found CH_3Cl to be produced proportional to the chlorine content of the wood and inversely proportional to the intensity of the fire and combustion efficiency.⁹ The data for wildland fuels burned in the open environment do not totally support the desirability of using CH_3Cl alone as a conservative tracer.

Real Time Measurements

Real time measurements of carbon dioxide concentrations were taken sequentially (by sampling package) during the course of the experiment; repeat measurements were made at each of the package locations at about a 2.2-minute cycle. The concentration ranged to nearly 1 percent by volume above background for the peak concentration recorded during LODI2 (Figure 4). Carbon monoxide concentrations were measured simultaneously with CO_2 (Figure 5) which then allowed the calculation of combustion efficiency because about 90 to 95 percent of the carbon of the fuel is converted to either CO_2 or CO . Combustion efficiency can be calculated by considering the percent of carbon that is completely oxidized to carbon dioxide relative to that which theoretically could have been oxidized. Hence, ratios of the emission factor for CO_2 measured for the fire divided by the theoretical emission factor for CO_2 provides a good approximation of combustion efficiency. For example, during the LODI2 test, the combustion efficiency calculated for the period of highest CO_2 concentrations shown in Figure 4 ranged from 87 to 97 percent. This is consistent with the low emission factors for carbon monoxide noted in Table II.

During the same period of time for which combustion efficiency was calculated (starting at 2:21 PM), the temperature of the combustion gases from LODI2 increased to 265 degrees Celsius for one brief pulse. The temperature exceeded 100 degrees Celsius for less than 1 minute at three package locations (Figure 6). Concurrent with the observed peak in temperature was a peak in the velocity of the combustion gases at nearly 13 m/s (Figure 7).

Rate of energy release for LODI2 was calculated from the velocity and temperature measurements and other thermodynamic considerations regarding the specific heat of air. The cross section of energy release (fireline intensity), from the leading edge of the fire to the trailing edge, showed an integrated energy release in excess of 20 megawatts per meter of fire front for a brief period coincident with the highest velocity and temperature measurements (Figure 8). The energy release on a unit-area basis (reaction intensity) peaked at nearly 3 megawatts per square meter and is plotted in Figure 9 for three packages.

Derivation of energy-release rates was not possible for the other tests because of the noncontainment of the plume by the 25-meter boom used to support the sample packages. Few comparisons can be made among tests based on an intensity criteria. Visually, LODI2 was the most intense fire of the series, and the duration of the intense burning period was relatively short in comparison to fires in the heavier logging slash of the Pacific Northwest.

CONCLUSIONS

1. Successful measurements of particulate matter and gaseous emissions were made from the same sample space by using a surface-based sampling system. These measurements and concurrent real time measurements of temperatures and velocities have provided for carbon-mass balance and carbon-flux calculations of emission factors and fuel consumption.
2. Emission factors for total particulate matter (EF_{PM}) were largest for the highest intensity fire (21.1 g/kg) and emission factors for the fine particles ($EF_{PM2.5}$) ranged from 5.5 to 7.7 g/kg. Both EF_{PM} and $EF_{PM2.5}$ compare well with respective flaming emission factors from Pacific Northwest logging slash.
3. Carbon monoxide emission factors, EF_{CO} , were observed to range from 34 to 102 g/kg for flaming and smoldering combustion, respectively. These values are 50 percent of EF_{CO} values for logging slash.
4. Lead emissions for the flaming phase are higher by a factor of 3 for the chaparral fires in the area of the test fires than for sample locations measured in the Pacific Northwest for logging slash fuels.
5. The profiles of trace elements from the chaparral tests are quite different than those from logging slash. The PM2.5 content of several of the elements was nearly an order of magnitude greater than for the same elements in smoke from logging slash. It is essential that profiles are developed for wildland fires in the California area for receptor modeling to be effective.
6. Graphitic carbon emissions (presented as a percent of PM2.5) were lower, while the concentration of heavy metals was higher for the fires in California compared to tests in the Pacific Northwest.
7. Improvements to strategies for management of southern-California chaparral are now dependent on reliable source-emissions information. As a result of continuation of the research presented here and through detailed

characterizations of modeled fuels, it is expected that air resource managers and land managers will benefit from information needed to provide the appropriate management of the two resources.

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REFERENCES

1. D. E. Ward and C. C. Hardy, Advances in the characterization and control of emissions from prescribed fires, Paper No. 84-36.3, presented at the 78th annual meeting of the Air Pollution Control Association; 1984 June 24-29; San Francisco, CA, Air Pollution Control Association, Pittsburgh, PA, 1984.
2. Lawrence Radke, Jamie H. Lyons, Dean A. Hegg, David V. Sandberg and Darold E. Ward, Airborne monitoring and smoke characterization of prescribed fires on forest lands in western Washington and Oregon, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. [In press].
3. W. Einfeld, Particle and trace element production from fires in the chaparral fuel type, Paper No. 89-025.002, in: Proceedings of the 1989 National Air and Waste Management Association Meeting; 1989 June 25-30; Anaheim, CA, Air and Waste Management Association: Pittsburgh, PA.
4. D. E. Ward, C. C. Hardy, R. D. Ottmar and D. V. Sandberg, A sampling system for measuring emissions from West Coast prescribed fires, Paper 4B-3.1, in: Proceedings of the 1982 Annual General Meeting of the Pacific Northwest International Section, Air Pollution Control Association; 1982 November 15-17; Vancouver, B. CC., Canada, Air Pollution Control Association, Portland, OR, 1982.
5. D. E. Ward, D. C. Hardy and D. V. Sandberg, Emission factors for particles from prescribed fires by region in the United States, in: Transactions PM-10 implementation of standards: an APCA/EPA International specialty conference; 1988 February 23-24; San Francisco, CA, Air Pollution Control Association, Pittsburgh, PA, 1988, pp. 372-386.
6. C. C. Hardy and D. E. Ward, Emissions factors for particulate matter by phase of combustion from prescribed burning, in: Proceedings of the 1986 annual meeting of the Pacific Northwest International Section, Pollution Control Association; 1986 November 19-21; Eugene OR, 1986.

7. D. E. Ward and J. E. Core, Source emission profiles for Douglas-fir and hemlock slash burning, Paper No. 84-19, presented at 78th annual meeting of the Air pollution Control Association; 1984 June 24-29; San Francisco, CA, Air Pollution Control Association, Pittsburgh, PA, 1984.
8. D. E. Ward and C. C. Hardy, Organic and elemental profiles for smoke from prescribed fires, in: Transaction of an APCA specialty conference, receptor models in air resources management; 1988 February; San Francisco, CA, Air Pollution Control Association [In press].
9. T. E. Reinhardt and D. E. Ward, Factors affecting methyl chloride emissions from burning forest biomass, unpublished manuscript on file at U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle, WA.

Table I. Matrix of filters used in collecting the particulate matter by combustion phase and the specific analyses.

Type of filter	Particle size	Filter size	Sample rate	Analytical procedure
Glass fiber	<2.5 μ m	37-mm	2 lpm	Carbon analysis. Gravimetry.
Teflon	<2.5 μ m	37-mm	2 lpm	Trace element analysis by using X-ray fluorescence. Gravimetry.
Glass fiber	Total PM	47-mm	4-7 lpm	Total particulate matter. Gravimetry.

Table II. Emission factors for primary combustion products including total particulate matter, particulate matter with particle diameters less than 2.5 μ m, carbon monoxide, carbon dioxide, methane, and nonmethane hydrocarbons.

Fire	Combustion phase	Emission Factors					
		PM	PM2.5	CO	CO ₂	CH ₄	NMHC
		(g/kg)					
LODI1	F	12.4	7.7	66.2	1654	2.7	3.6
LODI2	F1			48.0	1681	0.6	2.1
LODI2	F2			60.4	1650	2.3	4.2
LODI2	F1F2	21.1	7.7	55.8	1690	1.8	3.8
LODI3	F	12.2	5.5	34.4	1715	1.2	2.0
LODI3	S1	15.0	7.7	102.0	1600	6.2	5.1

Table III. Percent trace element content of particles less than 2.5 μ m diameter (PM2.5). Statistics shown include the mean, standard deviation (s.d.), and coefficient of variation (c.v.) for each phase and for the total fire.

Fire	Phase	Al	Si	P	S	Cl	K	Ca	Mn	Fe	Ni	Cu	Zn	Pb
----- (Percent of PM2.5) -----														
LOD11	F	0.11	0.33	0.14	1.39	2.45	5.87	0.28	0.01	0.04	0.00	0.00	0.12	0.30
LOD12	FlF2	0.15	0.67	0.23	2.43	4.80	11.0	0.90	0.01	0.17	0.00	0.01	0.22	0.60
LOD13	F	0.52	1.09	0.25	3.06	5.71	12.70	0.56	0.03	0.15	0.00	0.01	0.21	0.37
LOD13	S1	0.08	0.24	0.10	0.84	1.55	3.99	0.27	0.01	0.02	0.00		0.04	0.08
LOD1 Statistics (flaming phase)														
Mean	Flame	0.26	0.70	0.21	2.29	4.32	9.86	0.58	0.02	0.12	0.00	0.01	0.18	0.42
S.d.	Flame	0.23	0.38	0.06	0.84	1.68	3.56	0.31	0.01	0.07	0.00	0.01	0.06	0.16
C.V.	Flame	86.94	54.65	28.35	36.77	38.94	36.07	53.53	69.28	58.33		86.60	30.04	37.07
LOD1 Statistics (total fire)														
Mean	Fire	0.22	0.58	0.18	1.93	3.63	8.39	0.50	0.02	0.10	0.00	0.01	0.15	0.34
S.d.	Fire	0.19	0.41	0.07	1.16	2.25	4.90	0.30	0.01	0.07	0.00	0.01	0.08	0.21
C.V.	Fire	87.83	70.94	39.80	60.00	61.96	58.38	60.63	97.37	73.49		75.00	52.02	62.30

Table IV. Percent carbon content of PM2.5 contained with organic carbon and graphitic (elemental) carbon fractions. Total carbon is the sum of the organic and graphitic carbon fractions.

Fire	Combustion Phase	Organic -----	Elemental (Percent of PM2.5)	Total -----
LODI1	F1F2	45.3	7.5	52.8
LODI2	F1F2	44.9	5.9	50.7
LODI3	F	51.4	14.7	66.1
LODI3	S1	63.9	7.8	71.6

Table V. Emission factors for methyl chloride and ratios of methyl chloride to PM2.5 emission factors.

Fire	Combustion Phase	Emission Factors CH ₃ Cl -----	PM2.5 (g/kg)	Ratio of CH ₃ Cl to PM2.5 (dimensionless)
LODI1	F	0.026	7.7	0.003
LODI2	F1F2	0.047	7.7	0.006
LODI3	F	0.016	5.5	0.003
LODI3	S1	0.030	7.7	0.004

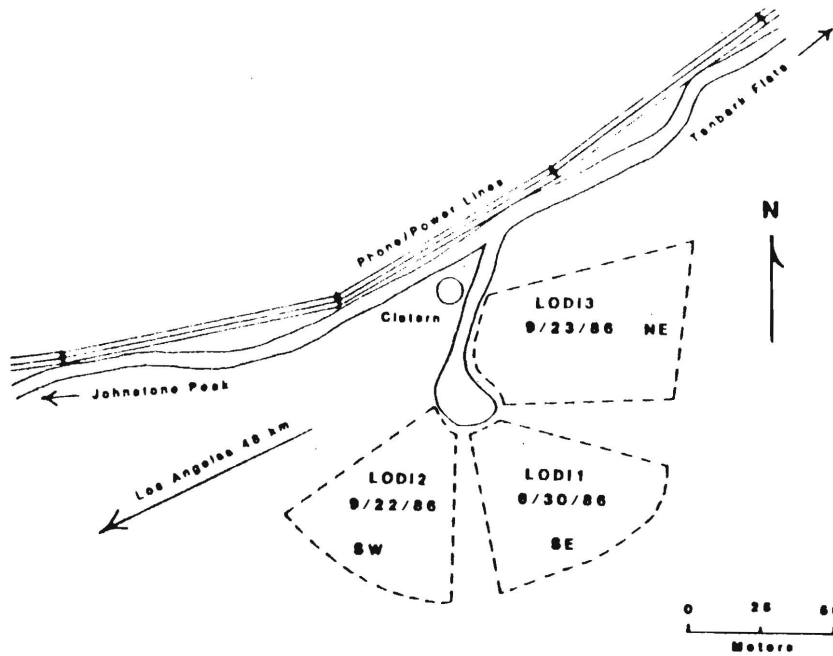


Figure 1. Location of the three small test areas on the San Dimas Experimental Forest, 48 kilometers northeast of Los Angeles; part of the Angeles National Forest.

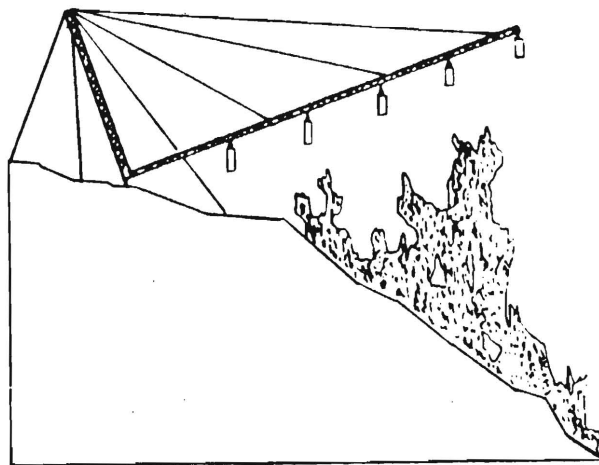


Figure 2. General schematic of 25-meter boom used to position sample packages in the convection column from prescribed-fire test fires.

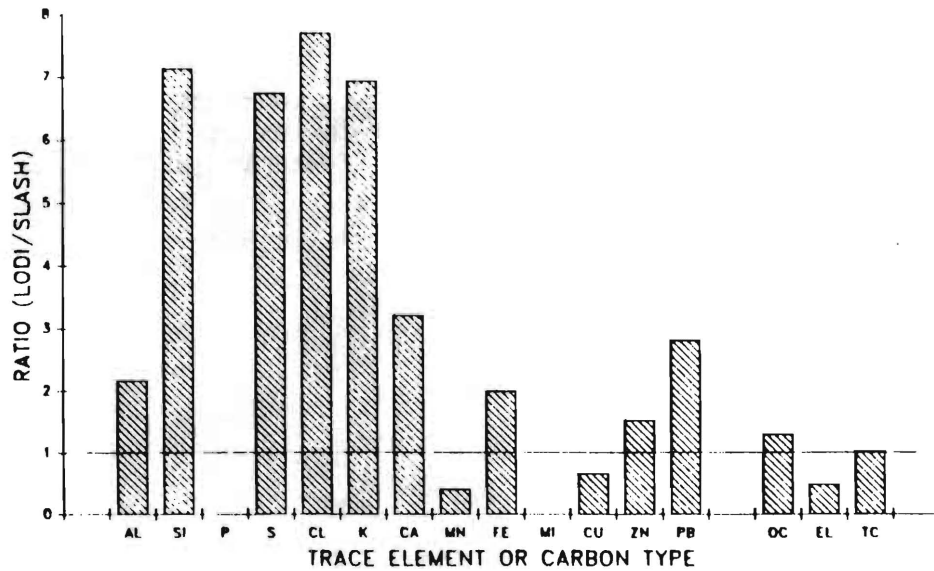


Figure 3. Percent content of PM_{2.5} that is a specific trace element or carbon fraction divided by the same material for the Pacific Northwest logging slash fires. The Lodi data is an average for the flaming phase (Table III), and the data for logging slash is an average for the flaming phase from tests by Ward and Hardy in the conifer fuel types.⁸

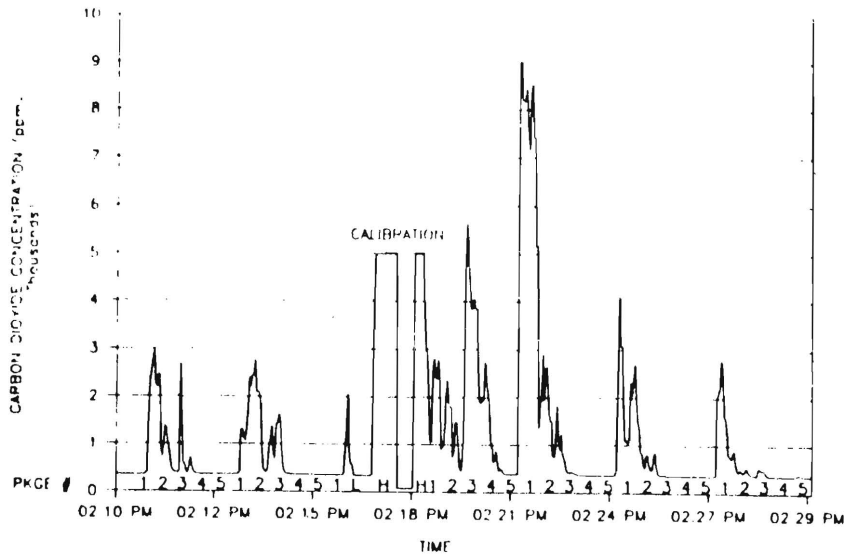


Figure 4. Carbon dioxide concentrations during sequential real time sampling of gases in the convection column for LODI2. The numbers (1-5) above the x-axis indicate the package being sampled.

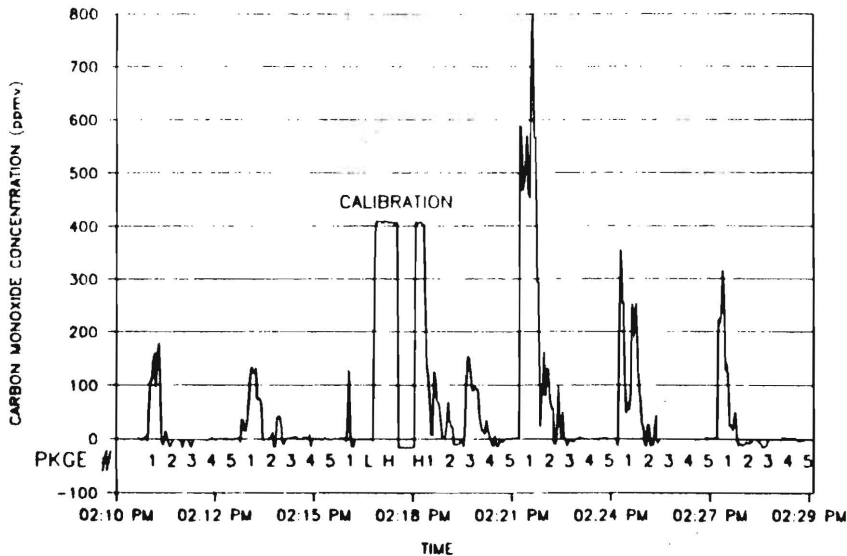


Figure 5. Carbon monoxide concentrations during sequential real time sampling of gases in the convection column for LODI2. The numbers (1-5) above the x-axis indicate the package being sampled.

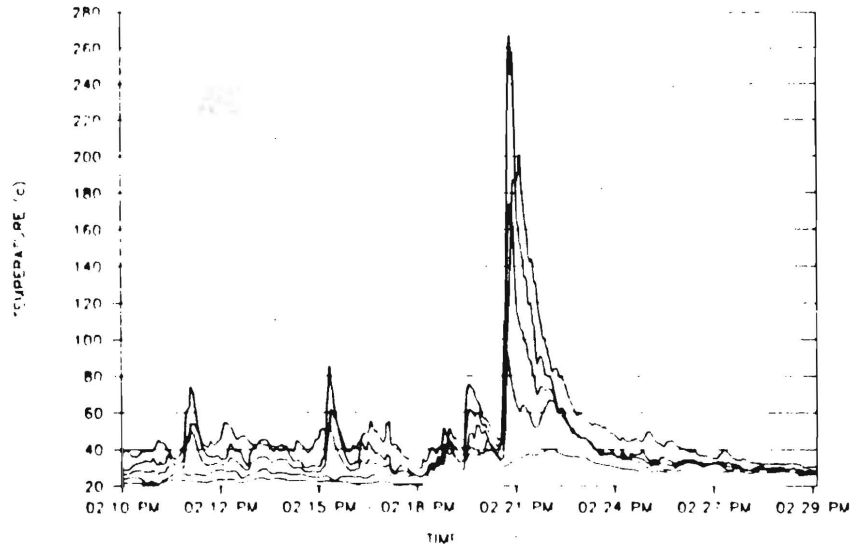


Figure 6. Temperature at each of the five sample points during the time of maximum heat release by the fire for LODI2.

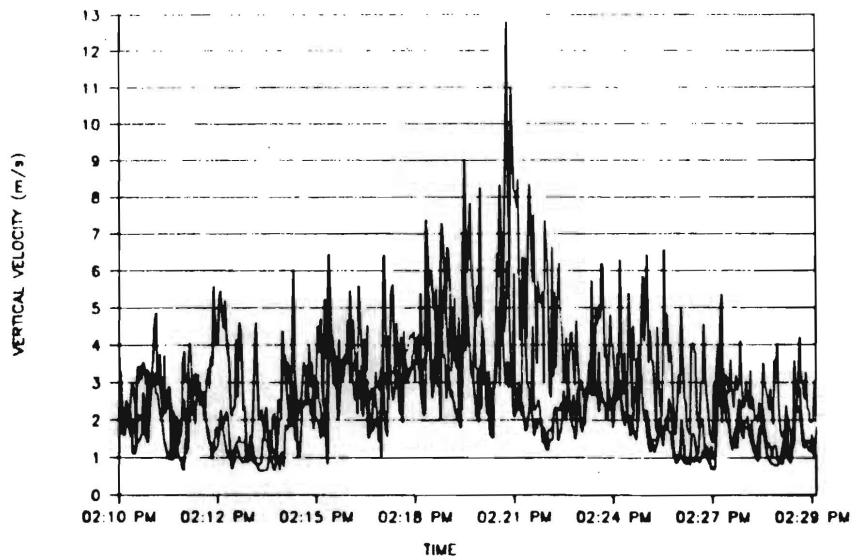


Figure 7. Vertical velocity of convection column in meters per second for sample packages 1,3, and 5, along the 25-meter boom during the time of maximum heat release by the fire for LODI2.

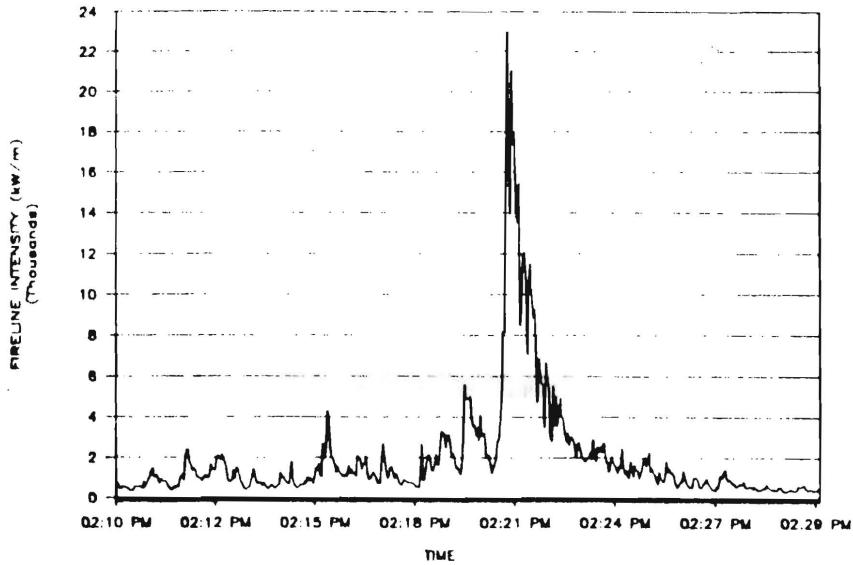


Figure 8. Rate of energy release for the entire cross section through the flame front (fireline intensity), integrated for all packages.

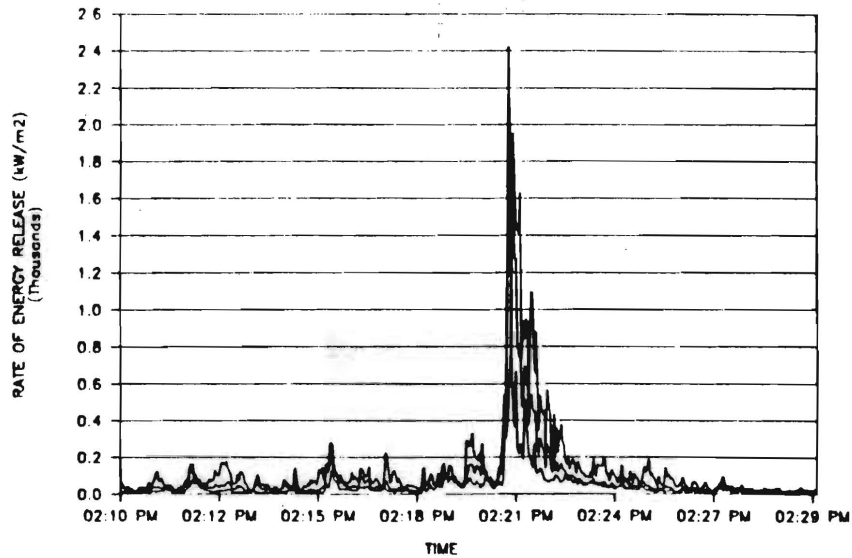


Figure 9. The rate of energy release per unit area (reaction intensity) for the LODI2 test fire, shown for packages 1, 2, and 3.