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MEASUREMENT OF SMOKE FROM PRESCRIBED FIRES IN THE PACIFIC NORTHWEST: A PROGRESS REPORT

By

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Introduction

To meet forest management objectives, it is necessary to burn unutilized residues (slash) left after timber harvest. Burning is required even though there is an increasing demand for slash as a source of biomass for energy. If the trend continues, there will be a resultant decrease in emissions from slash burning. The current use of fire for forest management purposes produces a significant quantity of air pollutant emissions. This paper reports on the progress of the interagency research program of the USDA Forest Service, Environmental Protection Agency, Department of Energy, Bonneville Power Administration, and Oregon State Department of Environmental Quality. Our goal is to encourage utilization of residues and other measures that improve air quality. The agencies are cooperating in an effort to demonstrate the effectiveness of emissions-reduction strategies through a series of plume-sampling experiments using instrumented aircraft. This combined effort complements the research program of the USDA Forest Service research team which is producing an emissions-source-strength model to evaluate a wide range of emission-reduction strategies.

This paper provides an update of our sampling program and outlines the technology emerging from the application of these data. During the past year, 90% of the objectives were satisfied for sampling emissions in plumes from prescribed fires at downwind locations by using instrumented fixed-wing aircraft. The data collected is being used to evaluate emission factors and source strength for criteria pollutants as a function of the level of removal of residues from the units burned.

Objective

The sampling program using instrumented aircraft involved three phases. The first two phases included sampling of emissions from the Green Mountain (Phase I) and Joule (Phase II) units on the Willamette National Forest as part of the Wood Residue Utilization Study. Essentially, research conducted in Phases I and II was for the purpose of examining the effect of wood utilization on emissions reduction. The main objective of Phase III was to determine the effect of rapid area ignition on emission factors for particulate matter and on the total emissions produced. Superimposed upon the three phases of our cooperative program were a number of other objectives:

1. Compare concurrently measured pollutant flux and total emission measurements from an instrumented aircraft with independent estimates made from ground-based sampling (Phases I and II).
2. Measure emission factors for criteria pollutants (Phases I, II, and III).
3. Measure NO_x, O_3, and hydrocarbon concentrations and assess plume chemistry (Phases I, II, and III).
4. Measure particulate matter concentration to scattering-coefficient ratios for the integrating nephelometer (Phases I, II, and III).
5. Determine the relative elemental composition of the heavy elements in smoke (particulate matter) for "fingerprinting" purposes (Phases I, II, III).
6. Measure differences in composite convective-lift emission factors and differences in total mass of convective-lift emissions attributable to mass-ignition techniques (Phase III).

Phase I was reported in detail[1,2] and provided an assessment of sampling techniques which have been improved to accomplish Phases II and III. A summary of the results from Phase I is followed by an overview of the data collected during Phase II. Phase III addresses other emissions-reduction techniques.

Residue Removal as an Emissions-Reduction Technique

Increased residue utilization is the most attractive emissions-reduction technique because it also provides wood for energy or fiber production. Consequently, this technique has received the bulk of our attention to date.

Verification of Ground-Based Emissions Modeling--Phase I

Two timber harvest clearcut units approximately 90 km east of Eugene, Oregon, on the Blue River District of the Willamette National Forest, were selected. The units were part of the Green Mountain Timber Sale Wood Utilization Study which investigated costs and utilization potential on paired units logged to different minimum size removal requirements.

The units were similar except for the amount of woody material removed. Unit A was YUM-yarded (Yarding Unmerchantable Material) to a minimum 8-inch diameter by 10-foot length (20.3-cm x 3-m) piece size. Unit B was YUM'ed to a 6-inch x 6-foot (15.2-cm x 1.8-m) piece size with pieces larger than 16 inches x 2 feet (40 cm x 0.6 m) also being removed. Similar volumes (±10%) of merchantable and utility logs were removed from the units. The removal of lower quality per-acre material was 45% greater on unit B. Differences in preburn slash loadings were significant only in the greater-than-6-inch (15.2-cm) diameter size class. Fourteen tons per acre (31.4 metric tons/hectare) of this size material was left on Unit A; only 1 ton per acre (2.24 metric tons/hectare) was left on Unit B.

The units were burned on successive days in July 1981. Emission rates for total suspended particulate matter were measured in two ways. First, in accordance with methods developed for other studies,[3] the rate of fuel consumption was measured in 10-minute intervals during both burns. Fuel consumption rates were multiplied by particulate emission factors of 12 g kg^{-1} (flaming stage) and 27 g kg^{-1} (smoldering stage) to obtain ground-based estimates of pollutant flux for each unit. Second, emissions were sampled directly from an aircraft sampling system[1] by measuring pollutant concentrations and multiplying them by the wind speed. One objective of our study was to compare results from the two independent methods.

The estimate of pollutant flux was generated continuously for the duration of each fire (Figure 1) from measurements made from ground locations. Particulate emission rates from Unit A averaged 705 g s^{-1} for the first 4 hours, compared to an average rate of 487 g s^{-1} on Unit B; a 31% reduction. Peak emission rates were 1162 and 851 g s^{-1}, respectively, for a 27% difference. After 4 hours, the differences became even greater. Emissions during this period of inefficient residual smoke production were reduced by more than 50% owing to the absence of large and defective pieces which normally prolong the smoldering period.

Attempts to verify the ground-based estimates from the aircraft were encouraging. Given the uncertainties in both techniques, we would have been happy with anything less than a 50% difference in the two measurements. All four verification points (aircraft cross-section times) were well within that accuracy. (See Figure 1.)

Utilization and Emissions Reduction--Phase II

On the strength of the results from Phase I, a more extensive program was scheduled for our ground-based emissions estimates and aerial verifications. Successful verification will allow us to develop a simulation model to predict emission reduction possible at any level of utilization. This is important because, obviously, we can never collect enough empirical data to test every possibility.

Experiments were performed during July 1982 on the Joule Timber Sale on the Lowell District of the Willamette National Forest. The sale consists of 5 harvest units logged to a variety of minimum piece-size specifications ranging from 4 inches x 4 feet (10.2 cm x 1.2 m) to 8 inches x 10 feet (20.3 cm x 3.0 m). The paired-unit configuration was ideal for testing the change in emissions production as a function of the level of utilization.

The units were burned on 4 successive days in July 1982, much the same as the previous year. Emissions were sampled using the University of Washington's (UW) instrumented aircraft (B-23). Surface sampling was done by the USDA Forest Service (PNW) and the Oregon State Department of Environmental Quality (DEQ). For one fire, Battelle Northwest Laboratories (BNW) sampled from their instrumented aircraft at distances greater than 10 km from the source. Fuel consumption and fire behavior were measured and PIBAL soundings were taken coincidentally with emission measurements made from the instrumented aircraft while cross-sectioning the smoke plumes. The gaseous and particulate matter samples collected and the analyses performed are summarized by cooperator in Table I.

Table I. Classification of data by cooperator for the Phase II research project, Joule units, Willamette National Forest.

COOPERATOR	GAS ANALYSIS					PARTICULATE MATTER ANALYSIS			
	CO_2	CO	NMHC	CH_4	Trace gases	TSP	Heavy elements	TSP carbon	Size dist.
PNW Station, USDA Forest Service	X	X	X	X		X			
Department of Environmental Quality State of Oregon							X	X	
Battelle Northwest Laboratories		X				X			
University of Washington Department of Cloud Physics	X	X	X	X		X			X
University of California, Davis						X	X	X	
Lockheed-EMSCO	X	X	X	X					
Oregon Graduate Center	X	X	X	X	X				

It was learned during Phase I that greater analytical sensitivity and sampling finesse would be required to independently estimate emission factors from samples collected from aircraft platforms. Although the carbon-mass balance method provided reliable emission factors based on samples taken from a tower system during Phase I, samples of CO_2 collected from the aircraft platform were not resolvable from background concentration levels, or else the samples of gases were not well correlated with TSP measurements.[1] Other research efforts have been fraught with similar difficulties.[4,5]

We analyzed very carefully the results from previous work and concluded that successful measurements were possible using canister grab-sampling techniques coupled with state-of-the-art analytical procedures. The University of Washington B-23 aircraft is equipped with a grab-sampling system for collecting 500 liters of gas in a period of about 5 seconds. This system was used for purging with 5-6 volumes, 6-liter capacity stainless steel canisters and for collecting a sample of particulate matter on 37-mm stretched-teflon filter mats. The canister samples were analyzed by personnel from Lockheed-EMSCO using a Byron 401 gas chromatography system.[6]

Data analysis is only 20% complete, but we have spot checked the data for accuracy and are confident of obtaining reliable results. For example, based on 14 canister grab samples taken from the plume during flight 1, integrated emission factors for CO ranged from 52 to 110 g kg^{-1}. This can be compared to an emission factor for CO of 106 g kg^{-1} for Phase I. Similar results have been reported for samples collected from our tower and cable system over broadcast-burned units. (The system used is described in detail by a companion paper.[7])

Figure 2 is a block diagram which illustrates the interdependency of the fire behavior, fuels, weather, and emissions data. Although some of the data stand alone (e.g., fuel consumption), other data (e.g., those required for computing source strength) have real significance only when considered in their entirety. By applying fire-specific emission factors for the various combustion phases to the fuel consumption for those phases, the source strength can be calculated, as was done in Phase I. These values can be compared with the integrated measurements and calculations made using the aircraft and PIBAL data. Eventually, the combined source strength, heat release, and weather sounding data can be used for validating or further refining models for predicting downwind impacts at receptor sites.

Mass Ignition as an Emissions-Reduction Technique--Phase III Research

Experiments were conducted in September and October of 1982 in cooperation with Weyerhaeuser Timber Co., near Cosmopolis, Washington. Our principal objective for these tests was to measure differences in composite convective-lift emission factors and differences in their total mass attributable to mass-ignition techniques. The results from this set of experiments will be compared with the data generated from the tests on the Willamette National Forest (Phases I and II). We hypothesize mass-ignition could reduce total emissions by 15 to 35% by reducing the composite emission factor and by limiting the smoldering period. Two of the three proposed test flights have been performed. We have not begun the data reduction and analysis process for Phase III.

Expected Results from Research

Results from the research completed during Phase I demonstrated a 31% reduction in particulate matter emissions over the first 4 hours of the burn. Emissions were reduced by over 50% during the residual-smoke phase as a result of removing material from the burn unit. Refinements will result from Phases II and III. These data will contribute substantially to a simulation model for defining the reduction in emissions over a wide range of environmental, site, and man-controlled variables. They will also provide an independent demonstration of the effectiveness of residue removal and mass ignition for reducing emissions source strength.

The aircraft sampling program is providing a verification test of techniques to estimate source strength from ground samples of fuel consumption, emission factors, and fire behavior. We expect a major publication dealing with emission factors for different fire intensity conditions and with fuel consumption as measured by direct ground methods in comparison to the carbon flux measured during aircraft cross sectioning of the smoke plumes. Phases II and III data should be well suited to making these verification measurements and should contribute substantially to that which was learned during Phase I.[1,2]

The science of "fingerprinting" of emissions from prescribed burning of forest fuels is in its infancy. The variance encountered between samples is still too great to make this a reliable method for assessing impacts. It is hoped this year's cooperative effort between the USDA Forest Service, Oregon State Department of Environmental Quality, the University of California at Davis, the Oregon Graduate Center, and others will provide information that can be used for assessing the impact of forest burning at receptor sites. From the multiple samples collected both at the surface and at downwind locations in the plume, the reliability and comparability from a spatial and time standpoint should be more fully understood. This area of research should be accelerated.

Plume chemistry should be much better understood through the data collected. Battelle Northwest Laboratories, the University of Washington, the USDA Forest Service, the Oregon Graduate Center, Oregon State Department of Environmental Quality, and Lockheed-EMSCO have all contributed concentration data of combustion products sampled in different spatial locations from immediately above the fire (7-15 m) to several 10's of kilometers downwind (Table I). This is a unique set of data which far exceeded our expectations. These plumes have probably been sampled more intensively than any other forest fire plumes. Results are expected regarding transformations of materials in transport, especially regarding the NO_x-O_3-hydrocarbon chemical equilibriums. Dr. Rasmussen, at the Oregon Graduate Center, has analyzed a number of samples for trace gases. So far, Ch_3Cl and CH_3I are thought to be quite specific tracers of low-temperature combustion of woody fuels.[8]

Localized winds, the onset of downcanyon flow, the effect of windspeed with height related to the release rate of fire heat, and other factors affecting the plume trajectory and smoke concentrations are being studied. The work is being performed in cooperation with Oregon State University, the USDA Forest Service Rocky Mountain Forest and Range Experiment Station, Oregon State Department of Environmental Quality, and others.

Data reduction and analysis from a smoke-characterization study of this magnitude will take years to complete. Already, there are at least 10 papers directly or indirectly benefiting from data generated during this study. We look forward to making a substantial contribution to knowledge about the character of fire smoke and how to reduce or prevent the production of undesirable constituents.

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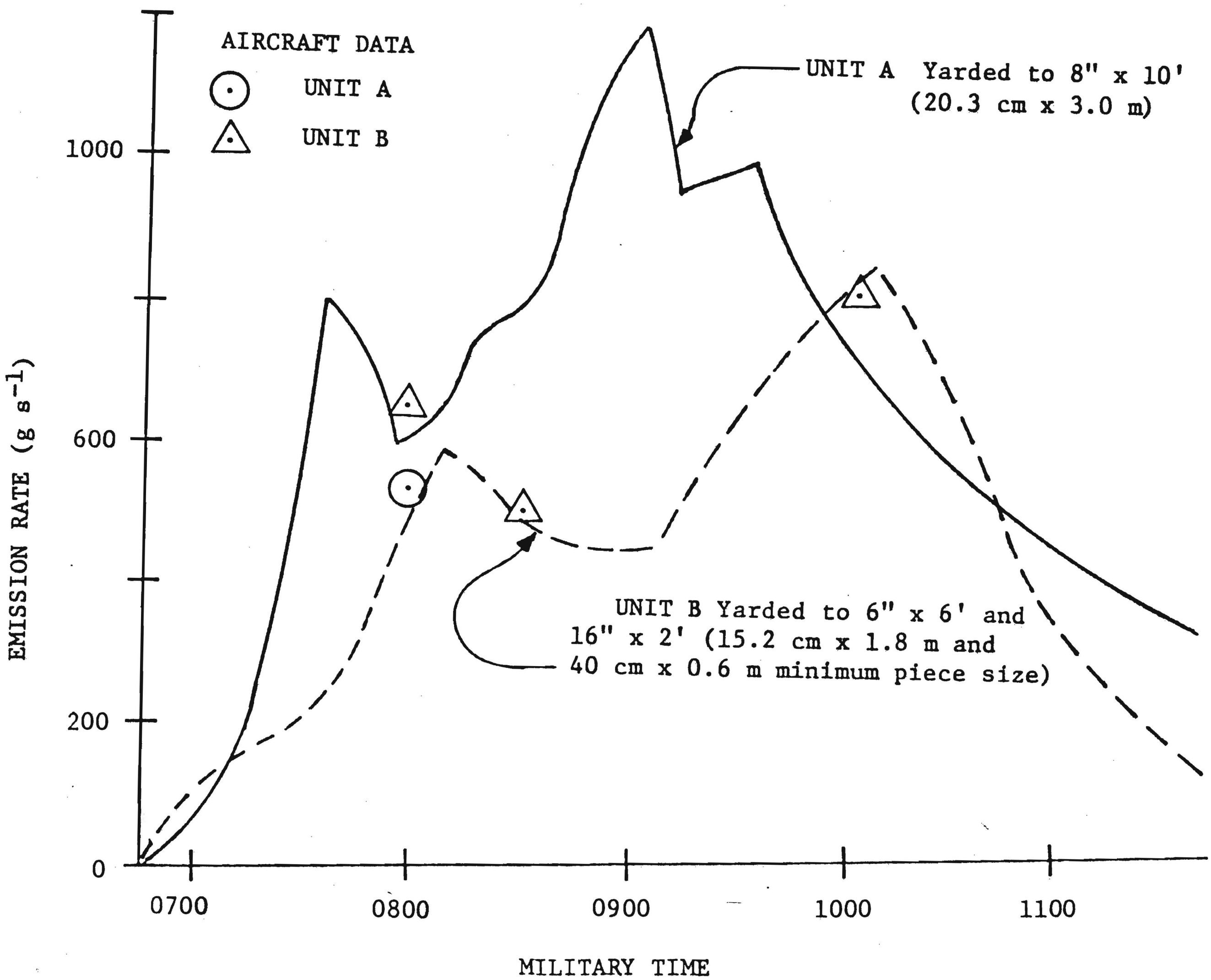
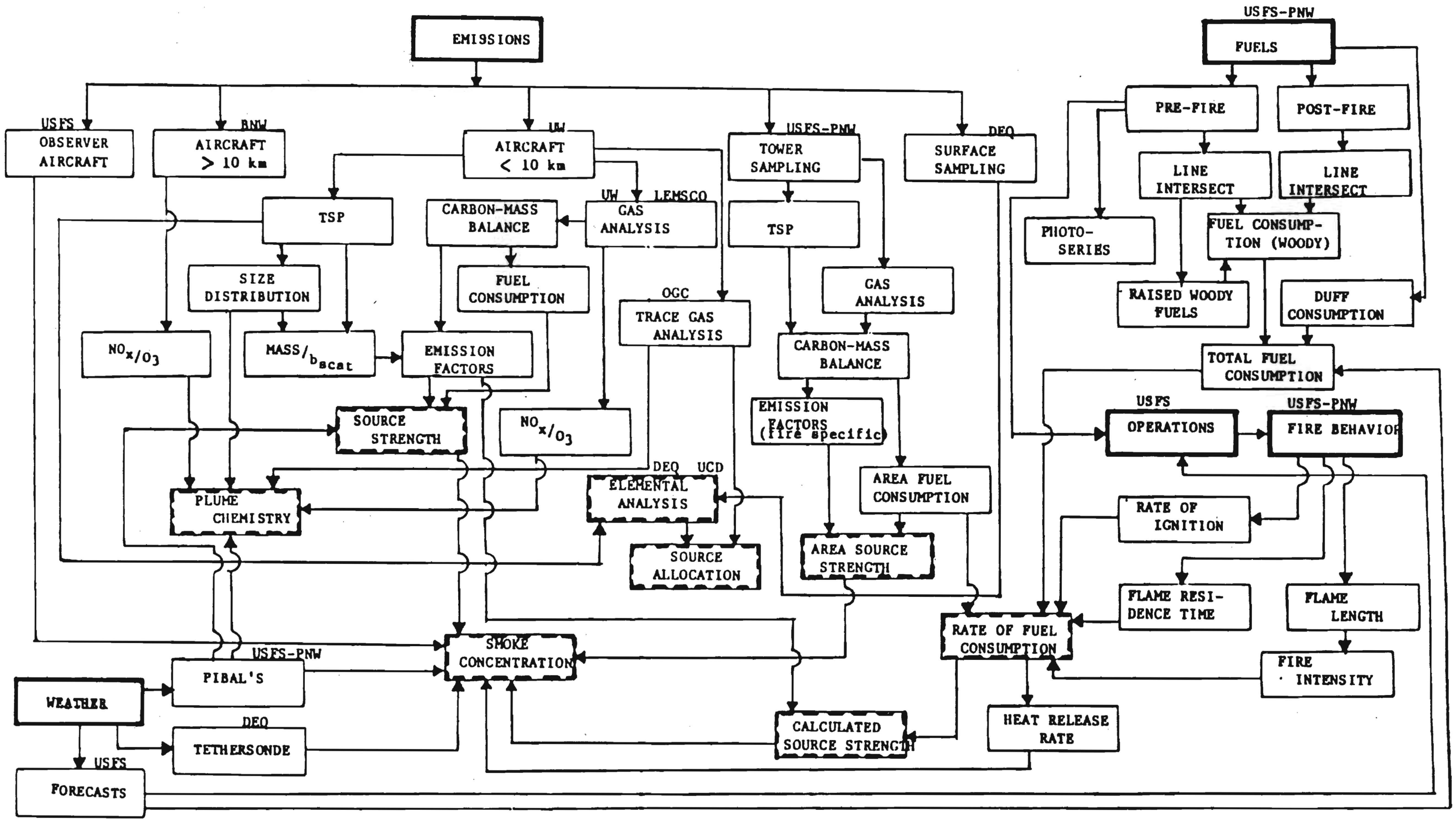


Figure 1. Particulate matter emission rate from two prescribed fires on the Willamette National Forest. Lines are plotted from ground-based measurements of fuel consumption and emission factors. Plotted symbols are aircraft measurements of pollutant flux.



KEY TO COOPERATORS: USDA Forest Service, Willamette National Forest (USFS); USDA Forest Service, Pacific Northwest Forest and Range Experiment Station (USFS-PNW); Battelle Northwest Laboratories (BNW); University of Washington (UW); Oregon State Department of Environmental Quality (DEQ); Lockheed Engineering Management Services Company (LEMSCO); Oregon Graduate Center (OGC); and University of California, Davis (UCD).

Figure 2. Block diagram of major classes of data (dark outlined boxes) and the pathways for integrating the data into research results (dashed outlined boxes).