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CHARACTERISTICS OF FOREST FUELS, FIRES AND EMISSIONS

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INTRODUCTION

Forest fires can be divided into two broad classes--wildfires and prescribed fires. Wildfires, whether caused by nature (lightning, etc.) or by the accidental or malicious acts of man, are not planned by forest managers and do not occur under controlled conditions. They can be relatively tame, covering only a few hectares and burning only understory litter, or they can be catastrophic firestorms like the recent one in Australia that covered over 400,000 hectares. Some wildfires cause severe damage to life and property as well as timber, wildlife, soil, water and air resources. Effective fire control and prevention programs have reduced the annual U. S. wildfire loss from 18 million hectares in the early 1930's to less than 1.6 million hectares in the middle 1970's.[1] This reduction represents a significant savings in human and natural resources and one can speculate on the obvious benefits to air quality.

Unlike wildfire, some burning in the nation's forest and range lands takes place according to planned decisions made by land managers. When fire is used to achieve a planned forest or range objective within a defined area under specified conditions of weather, fuel, and ignition techniques, the process is called prescribed burning. Interestingly, a wildfire can become a prescribed fire if brought under control and allowed to continue in a designated area for a specific land management objective. In a broad context some wildfires are beneficial and necessary to preserve the ecology of the forests in which they occur. The increased use of prescribed fire has been partly responsible for the decrease in frequency and acreage of damaging wildfires. The major benefits of prescribed fire include reduction of hazardous fuel accumulations (a form of fire prevention), control of undesirable understory species, preparation of areas for seeding or planting, enhancement of forage, improvement of wildlife habitat, and control of disease.

A number of review articles have been published in recent years which have described the nature and extent of forest burning in the United States[2-5] and summarized its effects on various natural resources[6-10] including the air resource.[11] From a national perspective, prescribed burning does not have a serious impact on our nation's air resources, especially if one accepts prescribed burning as a control technology for reducing damaging wildfires. However, on a local and regional level, the visibility impact of prescribed burning can be substantial and has resulted in a number of smoke management guides[12-17] and a variety of state regulations.[18-19] The guides describe fuel burning techniques, meteorological factors, and prescription scheduling, as well as some alternatives to burning. This paper describes some important properties of forest fuels and of the burning process, as they affect emissions and air quality. It also points to significant gaps in emission data and smoke physical and chemical properties.

FOREST FUELS

The fuels of forest fires consist of understory foliage, small branches, and the upper layers of the forest floor. They can also include the large branches and treetop residues left during land clearing and logging operations.

Wildfires which are often more intense than prescribed fire, may consume the foliage and small limbs of tree crowns, all forest floor layers, and even organic soil layers.

Surface Fuels

Surface fuels include all combustible material lying on or immediately above the ground. Under some conditions, roots and organic soils will burn and should be included in this category. The principal surface fuels are duff, litter, and low-lying vegetative growth.

Duff. Duff is composed of matted layers of partially decomposed organic matter on the forest floor. It is usually divided into a fermentation and humus layer. Duff is normally moist and tightly compressed and has little influence on the forward rate of spread of a fire, supporting instead a slow, smoldering type of combustion. Normally, only the uppermost layer of duff is consumed by a fire. During periods of drought, however, a severe wildfire may consume all of the duff layers, exposing the mineral soil to erosive forces.

Litter. Litter on the forest floor normally consists of fallen leaves or needles, twigs, bark, cones, and small branches that have not decayed sufficiently to lose their identity. Dry, dead leaves and needles ignite easily. Fuel burning characteristics depend on the physical properties of the fuel element and its arrangement with respect to other fuel particles. A litter bed of ponderosa pine needles, for example, burns more rapidly than one of spruce or Douglas-fir needles. Ponderosa pine needles are much larger and are shed in clusters to form a loose, well-aerated mat. In contrast, spruce or Douglas-fir needles are shed singly, are smaller, and form a more compact moisture-retaining mat that ignites and burns more slowly. Leaves or needles attached to fallen branches ignite and burn readily because they are fully exposed to the air and dry quickly. Fine branches, small limbs, bark, and other similar materials strongly influence rate of spread and general fire behavior. Dry twigs and small branches may act as kindling material for larger diameter fuels. In areas where there is a great accumulation of fine dead wood, an extremely hot fire can develop. Large amounts of fine dead wood accumulate on the ground in timber stands, damaged by various agents and in areas containing logging residues. Under dry conditions, such areas burn violently with intense heat.

Heavy fuels, such as logs, stumps, and large limbs, require long periods of hot, dry weather before they can ignite and burn. Usually this material is only partially consumed in rapidly spreading broadcast fires (i.e., fires which burn scattered fuels on a broad front within a delineated area). Managers often pile heavy fuels to obtain more complete fuel consumption. Total consumption of larger sized materials may occur in dry piles because the various fuel components radiate heat to each other very efficiently.

Low-lying Vegetation. These fuels include grasses, low shrubs, ferns, seedlings, and other small herbaceous plants. Propensity to ignite and burn readily varies with plant species, moisture content, weather, and season. For example, early in the growing season succulent new growth will retard fire spread, but as this growth matures and eventually dies, its role changes from one of inhibiting fire spread to promoting fire spread. Open grass and brush types are an important fuel because of their high continuity and their exposure to the drying effects of the sun and wind.

Aerial Fuels

Aerial fuels include all live and dead material not in direct contact with the ground. Ignition probability and burning rate for tree branches and foliage is dependent on type, moisture content, and growth patterns. Volatile oils and resins in coniferous needles make the branches and crowns of these trees important aerial fuels. The live leaves of most hardwood trees will not normally carry fire, but those of mature chaparral and related species do at times when live fuel moisture is low and fine dead twigs are intersperced in the crowns.

Dead branches and bark on trees and snags (dead standing trees) are an important aerial fuel. Concentrations of dead branches and foliage, such as found in insect- or disease-killed stands, can even carry fire from tree to tree. Various species of moss, lichens, and plants hanging on trees are light and flashy aerial fuels. These fuel elements called ladder fuels react quickly to changes in relative humidity and provide a means of spreading fires from ground to aerial fuels, or from one aerial component to another.

Annual United States Fuel Consumption

A 1976 survey[1] estimated that 47 million metric tons of forest fuels were burned annually by wildfire in the United States (including Alaska).

In a 1979 survey,[4] it was estimated that 37 million metric tons were burned by prescribed fire in the United States. This was a 100 percent increase over an earlier estimate,[2] which probably did not include prescribed burning on private lands. However, estimates of acres and tons of fuel burned are subject to much error and are most often experienced judgments rather than physical measurements.[4] New methods are being developed for estimating fuel consumption using photo techniques and algorithms based on fuel moisture content.

A further breakdown of prescribed fire fuels by fuel type and geographic area was also reported. It was found that within the United States, 25 million metric tons are burned annually for timber harvesting and land clearing purposes (slash fuels). Naturally occurring understory vegetation and litter accounts for about 12 million metric tons of fuel burned annually, primarily in the Southeast.

Chemical Properties of Forest Fuels

Elemental Composition. The foliage and woody components of forest fuels contain approximately 50 to 55 percent carbon, 6 percent hydrogen, and 40 to 44 percent oxygen. The high percentage of oxygen in forest fuel is rather unusual when compared to the low amount found in fossil fuels. As a result, the potential for production of oxygenated hydrocarbons in the combustion products is high and gives forest fire smoke one of its most unique characteristics. The high percentage of oxygen also lowers the energy value to approximately 20 MJ kg^{-1} for most wood species.[4] Ash content is under 1 percent for most wood species in the United States. Macronutrients (nitrogen, sulfur, phosphorus, potassium, calcium, magnesium, and iron) and micronutrients (maganese, zinc, copper, boron, to name a few) are found primarily in foliage and bark. Mineral constituents vary greatly between species and between trees within a species.

In general, the amounts of trace minerals are an order of magnitude higher in the bark and foliage than in branch and stemwood components. Fuel nitrogen, sulfur, and chlorine content are of special significance to air quality issues because of the potential contribution to deleterious emissions. In an analysis of 31 foliage, bark, and wood samples from a variety of grass, brush, and tree species, nitrogen content ranged from 0.1 to 2.0 percent, sulfur from below 0.01 to 0.4 percent, and chlorine from 0.005 to 0.7 percent.[21] The higher values were always in the foliage fuels, bark was in the mid-to-low range, while the wood components were always in the low range.

Chemical Compounds in Forest Fuels. The elements found in plants are combined by growth processes into many organic compounds, mainly cellulose, hemicellulose, and lignin. These three polymeric compounds account for over 90 percent of the dry weight of most forest fuels. The minor constituents, often called extractables, consist of several hundred individual organic chemical compounds that vary greatly among tree species, as well as within the various parts of the tree.

The cellulose content of most forest fuel varies between 41 and 53 percent. The chemical composition of cellulose is quite uniform and independent of source; it consists of several hundred glucose-type carbohydrate units linked in a polymeric chain. Hemicellulose is not a specific compound, but is the name given to all noncellulosic polysaccharides as well as to related substances like uronic acids and their derivatives. The hemicellulose content of wood varies between 15 and 25 percent, depending on species. The lignin portion of wood is quite different chemically from cellulose and hemicellulose. It consists of polymeric, aromatic materials characterized by the presence of phenyl propane units with methoxyl, phenolic hydroxyl, and benzyl alcohol functional groups. The term lignin actually refers to a mixture of substances that have similar chemical compositions but may have structural differences. Lignin content normally varies from about 26 to 32 percent in softwoods and 20 to 28 percent in most hardwoods. However, it is much higher (up to 65 percent) in decaying (punky) wood in which the cell wall polysaccharides are partially removed by biological decomposition.

FOREST FIRES

A typical forest fuel complex is composed of many types and sizes of individual fuel elements at varying moisture levels arranged in layers. Thus, the burning process can proceed at different rates throughout the fuel complex. One well known expression of fire intensity for spreading forest fires was described by Byram,[22] and is defined as the rate of energy or heat released per unit time per unit length of fire front, expressed in kilowatts per meter ($kW\ m^{-1}$). Alexander[23] reported that fire line intensity can vary by more than a thousandfold between 15 and 100,000 $kW\ m^{-1}$. However, he noted that wildfire intensities seldom exceed 50,000 $kW\ m^{-1}$ and most crown fires fall within the range of 10,000-30,000 $kW\ m^{-1}$. In contrast, most prescribed fires in understory fuels should be kept below 500 $kW\ m^{-1}$ to minimize damage to trees. When slash fuels are burned after a clearcut timber harvest or land clearing operation, higher intensities are permissible because there is no tree crop to damage.

It is important to emphasize that combustion in forest fires even in the best circumstances, is not a chemically efficient process. One reason is that

the moisture released from the fuels tends to absorb some of the heat energy from the fire, thus limiting combustion temperatures. Another reason is that air movement in and around the fire cannot bring enough oxygen to the combustion zone to mix efficiently with all the flammable gases produced. Air movement also transports partially oxidized gases away from zones of high temperature, releasing products of incomplete combustion to the atmosphere.

The Burning Process

To appreciate how the various components of smoke are generated, we can divide the open burning process of forest fuels into four phases of thermal decomposition.

Preignition Phase (Distillation and Pyrolysis Predominating). In this phase, the fuels ahead of the fire are heated; volatile components move to the surface of the fuel and are released into the surrounding air. Initially, these volatiles contain large amounts of water vapor and some noncombustible organics. As temperatures increase, hemicellulose followed by cellulose and lignin begin decomposing and release a stream of combustible organic products (pyrolysate). Because these gases and vapors are hot they rise, mix with the oxygen in the air, form combustible mixtures, and ignite--usually between 300°C and 600°C--producing the second phase. Above 270°C, thermal decomposition does not require an external heat source because the process becomes exothermic.

Flaming Phase (Gas Phase Oxidation Predominating). In this phase, the temperature rises rapidly from the heat of exothermic reactions. Pyrolysis continues but it is now accompanied by rapid oxidation, or flaming, of the combustible gases being evolved in high concentrations. The products of the flame zone are predominately carbon dioxide and water vapor. The water vapor here is not a result of dehydration as in the preignition phase, but rather a product of the combustion reaction.

Temperatures in this phase range between about 300°C and 1400°C. Some of the pyrolyzed substances cool and condense without passing through the flame zone, others pass through the flames but only partially oxidize, producing a wide range of products. Many compounds of low molecular weight are produced as gases and remain gases as they move downwind; others with higher molecular weights cool and condense to form small tarry liquid droplets and solid soot particles as they move from the combustion zone. These condensing substances, along with the rapidly cooling water vapor that is being evolved in copious amounts, form the smoke that accompanies all forest fires. During this phase, a sufficient number of sooty particles are generated to color the visible smoke plume from black to gray.

Pyrosynthesis also occurs during this phase. Low molecular weight hydrocarbon radicals condense in the reducing region of the flames, leading to the synthesis of relatively large molecules such as the polynuclear aromatic hydrocarbons.

Smoldering Phase (Slow, Flameless Combustion Predominating). In this phase, the overall reaction rate of the fire and the output of pyrolysate vapors has diminished to a point where the temperature and concentration of combustible gases and vapors above the fuel cannot sustain a persistent flame envelope.

Consequently, the vapors condense and are released as visible smoke to the atmosphere. Smoldering often occurs after the flame front moves through a fuel bed in a spreading fire, but also occurs in area fires where logging debris has been piled. Smoke output is usually very high over the entire burned area. The heat release rate from smoldering fires is usually not sufficient to lift the smoke into a well defined convective column. As a result, the smoke stays near the ground in high concentrations, causing potential visibility problems at nearby receptor sites. The smoke evolved during this phase is virtually soot-free and consists of sub-micron tar droplets. When the evolution of pyrolysate vapors ceases, the fuel particle is reduced to a black char and the final phase of combustion can begin.

Glowing Phase (Solid Oxidation Predominating). In this final phase of combustion, all the volatile components of the fuel have been released and oxygen can now migrate to the fuel surface resulting in solid or surface oxidation with its characteristic yellow glow. In prior phases, oxidation was predominately in the gas phase above the fuel. Visible smoke is not present during this final phase; carbon monoxide and carbon dioxide are the principal products of glowing combustion. This phase continues, as long as temperatures remain high enough, until only a small amount of noncombustible minerals remain as gray ash. Many times the arrangement of the fuel and/or the moisture content is such that temperatures cannot be maintained, resulting in a black charred residue instead of the gray ash.

In a forest fire, the four phases just described are difficult to discern because they occur both sequentially and simultaneously. The amount of fuel consumed during flaming and smoldering phases varies widely with fuel, ignition, and weather conditions. Smoke reduction techniques are now aimed at enhancing flaming combustion while minimizing smoldering combustion within the constraints of the land management objectives.

FOREST FIRE EMISSIONS

For many years, national air pollution trends have been compiled by the Environmental Protection Agency and its predecessors. Emission levels were estimated for five major pollutants emitted from six principal source categories. Five of the six categories were considered controllable emissions, whereas one category (miscellaneous emissions) was thought to be uncontrollable. The miscellaneous category included emissions from forest fires, structural burning, and coal refuse burning. The forest fire entry was always footnoted to indicate that it included prescribed fires. Other open-burning sources, such as agricultural burning and municipal solid waste disposal, were considered man-made or man-directed emissions and therefore were included in the controllable source categories. All man-caused emissions were labeled as "anthropogenic" whereas emissions caused by mother nature (i.e. volcanoes, forest fires, wind blown dust, etc.) were given the label "natural" sources. Published estimates by Cavender[24] indicate that forest fires accounted for 16 percent of the total U.S. air pollutants in 1940, but only 1.7 percent in 1970. This dramatic drop is partially caused by a drop in wildfire acreage burned, but could also be due to the uncertainty in emission factors and the techniques used to estimate fuel consumption on the acres burned.

With the passage of the Clean Air Act Amendments of 1970 and 1977, competition for the nation's air resource increased, and prescribed burning began to emerge from the "footnote" category as new efforts were undertaken to improve our national emissions inventory. National totals, averages, and trends were recognized as less than the best guide for estimating the effects produced in a particular locality. This is especially true for an intermittent source such as forest fires. Even though forest fires are not considered to be a significant source on a national level, regional and local surveys sometimes placed prescribed burning programs in competition with other sources for a share of the local airshed. An example is a recent study by Cooper[25] which showed that slash burning contributes approximately 22 percent of the particulate matter loading to the Eugene, Oregon, airshed on the days sampled.

Air quality issues related to prescribed burning began to ease into the federal regulatory process in the late seventies as EPA began to examine and document all potential sources of visibility impairment. In 1979, EPA prepared a comprehensive report to Congress which outlined sources of visibility impairment and proposed methods to evaluate and control adverse impacts.[26] The impacts from prescribed burning, especially slash burning in the Pacific Northwest were carefully noted. In its summary, EPA observed that "some alternatives to forestry burning do exist, especially for disposal of accumulated residues." On the other hand, it was careful to point out that "practical alternatives to the use of fire for improving wildlife habitat and reducing fire hazard in non-harvested areas were not available." Studies are now underway to document emission factors and rates,[27] and to describe methods for reducing emissions from forest residue burning[28] in the Pacific Northwest.

Factors Affecting Emissions

In general, the variables affecting emissions can be grouped into three categories:

1. Fuel conditions--stage of decomposition, moisture content, and physical arrangement.

2. Fire conditions--fire type, fire intensity, ignition technique.

3. Weather conditions--windspeed and relative humidity during a fire and drying conditions before a fire.

A more complete discussion of how these factors affect emissions is in the literature[4,12] and is summarized by Sandberg[28] in another paper in this session.

I have already distinguished prescribed fires from wildfires. Another distinction that should be noted is related to two types of prescribed fire used primarily in understory fuels, namely heading and backing fires. In terms of combustion efficiency, prescribed fires are generally more efficient than large uncontrolled wildfires, and within prescribed fires, backing fires are generally more efficient than heading fires.

Heading Fire. A heading fire moves with the wind. Visualize a fuel complex with a flame front and a surface wind driving the flames. The flame front moves rapidly from fuel element to fuel element. Under these conditions most elements are not consumed completely before the main combustion zone moves ahead. A rather large zone of smoldering fuel is left behind when fuel loadings are substantial.

Backing Fire. A backing fire moves into the wind. The advance of the flaming zone is not nearly as rapid as in the heading fire. Since the flames do not move as rapidly, more of the individual fuel elements are consumed in the flaming zone. Thus, the smoldering time for the fuels is reduced and total combustion efficiency of the fire is increased.

Comparison of Emission Measurement Techniques

Many conventional industrial pollution sources operate under a relatively narrow range of conditions and yield emissions which are relatively easy to measure using conventional stack sampling techniques. Unfortunately, forest fires occur under a very broad set of conditions resulting in emissions that range over several orders of magnitude. In addition to dealing with variability in burning conditions, a new emission measurement technology had to be developed to deal with the open burning phenomena. Both laboratory and field methods were developed and used to acquire the needed information.

In the laboratory, however, fire size and intensity are restricted and fuel beds are often constructed artifically. Thus, the question of whether laboratory experiments are truly representative of what takes place in the real world is often raised. On the other hand, field experiments represent reality but are costly, highly dependent on weather for success, and difficult to replicate. These limitations often mean that few experiments are conducted and that little or no basis for error estimation or statistical analysis is available from the data collected. It seems clear that procedures are needed which use the desirable features of both approaches.

Laboratory Methods. A variety of laboratory methods have been used in emissions studies. Small scale experiments, such as those conducted with thermogravimetric instruments or combustion tube furnaces, are often used to obtain preliminary data upon which to base a larger, more carefully designed experiment. In such experiments, control is precise and there is opportunity to systematically vary heating rate and oxygen level. Thermogravimetric techniques have been used to study nitrogen oxides produced in burning forest fuels.[29] Larger scale laboratory burns are usually patterned after the original design used to measure emissions from agricultural burning.[30] As an experiment begins, smoke from the fire is funneled through an exhaust stack directly above the conditioned fuel bed. Samples of combustion products are withdrawn and filtered to remove particulate matter and moisture and then transferred to gas analyzers. Sloping of the fuel bed permits simulation of backing (downslope) and heading (upslope) fires.

Field Methods. Various field methods have been used to provide emissions estimates for operational use. Ward[31] developed a tower method that was successful with low intensity backing fires. Sampling with towers is usually limited to heights not exceeding 15 meters. In order to overcome the height

limitation, a prototype tethered balloon system was developed by Ryan et al.[32] Sampling packages were suspended at several locations on a vertical instrumentation line which extends downward from the balloon and through the smoke. Control signals and experimental data can be transmitted between the sampling packages and a ground station through the instrumentation line. High cost, difficulty in maintaining the balloon position in a forest environment, and other logistical problems are major drawbacks and precluded its continued development and use. However, many of the basic concepts of sampling from this system have been adapted for use in new ground based sampling systems. For example, a "skyline" tower and cable system for sampling the verticle flux of carbon is now being used on the West coast by Ward[27] to assess the effects of different levels of residue removal, fuel moisture content, and the effect of green fuel on emissions source strength from burning forest residues. It consists of particulate matter and gas sampling apparatus suspended from a 15 meter cable and tower support assembly. For obvious reasons, this system would be limited to fires which would not destroy the sampling complex during the flaming phase. Another means of field sampling is with an instrumented aircraft that flies crossing patterns in the plume at a given distance downwind. This method is most suitable for high intensity operational burns, but requires careful documentation of fuel consumption and fire behavior over a very large area from workers on the ground. Another disadvantage of the aircraft method is that smoke which is not lifted, but remains close to the ground, cannot be sampled. This introduces error into estimates of emission factor and rates during smoldering combustion. Overall, it is very difficult to correlate emissions production with fire and fuel conditions with the aircraft method.

Computation of emission factors, in either laboratory or field experiemnts requires estimates of fuel consumption and mass (or concentration) of the pollutant of interest. In the laboratory, fuel consumption can be accurately measured by direct weighing of the burning fuel with transducers or platform balances. One method used in the field consists of manually sampling the fuel before and after burning. An extension of the lab approach for use in the field with logging debris fuels is to support a flat platform 3 by 3 meters, or larger, with transducers so that fuel consumption rates can be measured directly.[33] One drawback to the platform concept is that fuel layers must be manually constructed, making them artificial to some extent. However, a major advantage is the ability to carry out a systematic experimental design with replication. Thus, functional relationships can be developed, and accuracy of information can be determined.

The latest innovation in field methods makes use of a carbon mass balance technique. This technique makes it possible to estimate fuel consumption and emission factors with a single set of experimental measurements.[27,34] The technique is based on the fact that all forest fuels consist of approximately 50 percent carbon, and that upon burning of the fuel, this carbon appears in the smoke as either carbon dioxide, carbon monoxide, hydrocarbon gases, or particulate matter. If concentrations of these components and verticle velocity of the plum is measured, then the rate of fuel consumption, source strength, and emission factors for four smoke components (carbon dioxide, carbon monoxide, hydrocarbons, and particulate matter) can be computed without the need for tedious manual fuel sampling.

Emissions Data

Forest fire emissions are a complex mixture of soot, tars, and gases. As with open burning of all complex organic fuels, the number of compounds increases as combustion efficiency decreases. Studies have shown that emission factors for some emissions vary over several orders of magnitude depending on fuel and fire conditions. Thus, emission factors often are reported as a range of values and a uniform emission factor cannot be used reliably to represent the diversity of fire and fuel conditions. Summary documents exist to aid in the selection of emission factors for different fuels and types of fires.[3,4,12] However, in each case, users are cautioned about the uncertainty of the values when applied to a specific local situation.

The inherent variability of the fuels and burning process coupled with a hostile, remote sampling environment have made it difficult to obtain representative emission samples in many situations. Thus both researchers and land managers have been frustated when confronted with the question, "What is a good emission factor for forest fire smoke?" For some emissions, it is common to encounter an order of magnitude difference among fuel types, fire types, and between the flaming and smoldering phases of individual fires. As frustrating as this variability may be, it has provided many opportunities to investigate the factors that control emissions output in order to include emission reduction techniques as a smoke management strategy. Current studies are aimed at describing emission reduction techniques[28] and characterizing emissions as a function of time.[35] These efforts should produce tangible improvements in local air quality.

In forest fires, two products of complete oxidation--carbon dioxide (CO_2) and water vapor (H_2O)--make up over 90 percent of the total mass emitted. The other 10 percent include all of the visible smoke and other compounds that fall in the EPA categories of criteria, noncriteria, and hazardous pollutants. I attempt to summarize what is known in each of these areas. All emission factors reported are based on dry fuel weight.

Carbon Dioxide (CO_2). Emission factors range between 1,000 and 1,750 g kg^{-1} of fuel consumed. The higher values are associated with the high combustion efficiency achieved under some flaming conditions while the lower values occur during smoldering and glowing combustion. A theoretical maximum of 1,820 g kg^{-1} is possible from the idealized combustion of wood fuels as shown in the following equation:

$$4\ C_6H_9O_4 + 25\ O_2 \rightarrow 24\ CO_2 + 18\ H_2O + \text{heat}.$$

Carbon dioxide is not an atmospheric pollutant in the usual sense. It is monitored because it can be used to calculate fuel consumption and burning efficiency. It is also of interest to atmospheric scientists interested in the greenhouse effect and global carbon cycles.

Water Vapor (H_2O). Few investigators have reported on the production of water vapor from forest fires. Like CO_2, it is not considered an air pollutant.

Its importance lies in the way it momentarily affects visibility near a fire and the manner in which it interacts with other combustion products. The amount of water vapor produced can range from 250 to 750 g kg^{-1}. It is theoretically possible to produce 860 kg of water from a metric ton of fuel with a moisture content of 30 percent. 300 kg are derived from the distillation of the adsorbed water, and 560 kg from the idealized combustion reaction shown earlier.

Carbon Monoxide (CO). Carbon monoxide is the most abundant criteria air pollutant emitted from forest fires. Reported emission factors for CO generally range between 20 g kg^{-1} and 100 g kg^{-1},[4] with the higher values associated with poor combustion conditions. In smoldering forest residue fuels,[35] burning organic soil,[36] and wood burning stoves,[45] factors above 250 g kg^{-1} have been reported. Unlike urban fires where lethal CO concentrations can develop in a closed fire environment, open burning CO concentrations drop rapidly from approximately 200 ppm very near the fire line to less than 10 ppm within 30 meters of the fire line.[11]

Hydrocarbons. Emission factors for EPA's hydrocarbon criteria pollutant and measured as methane by flame ionization detection (FID) vary from 2 g kg^{-1} to 32 g kg^{-1} in laboratory fires, and from 14 g kg^{-1} to 54 g kg^{-1} in a very limited number of field fires.[4] Methane, ethylene, and acetylene can account for as much as 50 percent of the FID response.[37] Lesser amounts of ethane, propane, propylene, methyl, and ethyl acetylene, butene and butane isomers have also been found. Peak hydrocarbon production is associated with the onset of the smoldering phase of the fire.

Volatile Organic Compounds (VOC). In addition to the low molecular weight, gaseous hydrocarbons just mentioned, there are hundreds, possibly thousands of other organic compounds in forest fire emissions resulting from the incomplete combustion of lignin, cellulose, and other organic substances in the fuel. The VOC fraction contains many of the familiar smoke odors and eye irritants we generally associate with forest fire smoke. Included are many oxygenated species as one might predict from the fuel chemistry. In one limited study, several hundred compounds were identified in smoke samples taken from laboratory fires of pine needles.[38] The sampling system (Tenax GC) was considered useful for compounds in the C_4 - C_{12} range. Gas chromatographic/mass spectrometric analysis showed the major constituents to be toluene, furfural, limonene, p-xylene, and benzene. In addition, many alkanes, alkenes, and oxygenated compounds that are related to furan and phenol were found. Several low molecular weight oxygenated species, especially the carboxylic acids (formic and acetic acids, etc.) and the reactive aldehydes (formaldehydes, acetaldehydes, etc.), were not sampled in this study although they have been reported to be constituents from the smoldering combustion of wood fuels.[72,73] Recent advances in the technology associated with the sampling and analysis of organic air emissions should prove helpful in providing a more complete qualitative and quantitative assessment of VOC's in forest fire smoke. Current studies and recent reports[39,40,45,72,73] of emissions from fireplaces and wood stoves can provide additional insight and information on this largely unknown area. The information from fireplace studies would be more applicable to forest fires than the data from oxygen starved wood stoves.

Nitrogen Oxides (NO_x). Data on NO_x production from forest fuel burning are limited and somewhat inconclusive. For some time, EPA assigned 2 g kg^{-1} as the emission factor based on a laboratory burning of landscape refuse.[41] Benner[42] reported NO_x emission factors in the range 4-10 g kg^{-1} from burning pine needles in a small chamber. Ward[27] recently reported a value of 1.8 g kg^{-1} from burning forest residues in a field study. Recent studies on the use of wood in fireplaces and stoves are reporting average values below 2g kg^{-1}.[39,40] One study[45] found about 4 times as much NO_x from fireplaces (1.9 g kg^{-1}), as for wood stoves (0.5g kg^{-1}).

Combustion processes can form NO_x in three ways:[46]

(1) Reactions of atmospheric nitrogen with oxygen at high temperatures with concentrations peaking above 1,500°C (thermal NO_x).

(2) Reactions of fuel-derived radicals with atmospheric nitrogen (Prompt NO_x).

(3) The oxidation of fuel nitrogen compounds at combustion temperatures below 1,000°C (fuel NO_x).

Temperatures in most prescribed fires, especially in understory fuels, seldom exceed 1,000°C. However, higher temperatures are possible in piled fuels and in some wildfires.

NO_x emissions were reported by Clements and McMahon[29] in a laboratory study which employed thermogravimetric instrumentation with temperatures below 1,000°C. NO_x emission factors for wood, bark, and limbs averaged 1.5 g kg^{-1}, whereas those for samples of pine needles and other forest foliage averaged 7.5 g kg^{-1}. Conversion efficiencies (fuel nitrogen to NO_x) were 16 percent for the woody samples and 21 percent for the foliage samples. Thus, in low temperature fires (below 1,000°C), one can approximate the NO_x emission factor by knowing the percentage of nitrogen in the fuel to be burned. At this time, it is not known if thermal NO_x is produced during the open burning of forest fuels.

Sulfur Oxides (SO_x). Due to the low sulfur content in forest fuels, little data have been reported on emissions of sulfur oxides from forest fires, which are considered a negligible source of SO_x by EPA. Negligible is defined by EPA as a source which produces less than 0.05×10^6 tons of pollutant per year. In a 1978 study, the plumes from five prescribed fires were sampled from an airplane and no significant gaseous sulfur was found.[47] Recent work with the burning of wood bark in industrial boilers suggests a low conversion rate (approximately 5 percent) of bark sulfur to SO_2 with the balance accounted for in the ash.[44] Other studies reported average values of 0.07 g kg^{-1} SO_2 for wood burned in industrial boilers,[48] and 0.2 g kg^{-1} for wood burned in stoves.[45,48] With foliage fuels, higher levels might be expected because of the higher sulfur content. Ward[49] reported 50 to 75 percent sulfur loss from burning pine needles in the laboratory. Only reduced forms of sulfur were measured in the combustion products. Less than 0.2 percent was in the form of carbonyl sulfide and other reduced forms of sulfur.

Particulate Matter. This pollutant has been studied much more extensively than gaseous emissions because of its effects on visibility, and its effects on local concentrations of the criteria pollutant, total suspended particulate matter (TSP). TSP emission factors have been documented for a variety of prescribed fires and been found to range over an order of magnitude (2.5 - 90 g kg^{-1}) depending on conditions of fuel and fire.[4] The higher values occur in fires with a significant smoldering component. TSP emission factors for wildfires have not been published, but have been estimated to be approximately 75 g kg^{-1} based on the extrapolation of laboratory results for head fires in pine litter fuels.[1] Recommended values for a number of understory fuel and fire types and fire stages have been published.[12] Estimates for slash type fuels are now emerging; preliminary results[27] gave an emission factor of 21 g kg^{-1}. Additional studies are planned for 1983 and 1984.

In the West, visibility impact from forest fires is described in terms of plume blight and regional haze factors, and is usually associated with smoke from the flaming combustion phase of logging residue fires. In the South, smoke incidents are more often related to highway visibility problems caused by smoke from the smoldering phase of fires. During this phase of combustion, the fire is often judged to be "out" or "in control." However, smoke often continues to be produced by smoldering of tree snags, logs, stumps, duff layers, or organic soil. Because the heat release rate from smoldering fuels is low, the smoke tends to stay near the ground, creating potential visibility problems in the local area. If the smoldering continues through the night near areas of high moisture (streambeds, etc.), a mixture of smoke and fog may be present in the morning. Stith et al.[50] reports that prescribed burns of slash fuels are prolific sources of cloud condensation nuclei (CCN), producing about 10^{10} - 10^{11} CCN per gram of wood consumed. The CCN resulted in anomalously high concentrations of water droplets <10μm in diameter in the cumulus clouds produced by the burns. Methods to reduce and predict the smoldering potential of forest fuels are now receiving increasing emphasis as new smoke reduction strategies are developed for prescribed burning.

Forestry Smoke Physical Properties. Some early reports on the size of forestry smoke particulate matter erroneously indicated a particle size range from 50 to 100μm in diameter based on examination of microscopic slides placed downwind from the fire.[71] The particles examined were primarily partially consumed fuel fragments and ash particles. These large particles occur primarily in high intensity fires when the turbulent convective activity in the fire zone is sufficient to mechanically generate and entrain large particles in the smoke column. In most cases, they drop out near the fire and are not found in the long range transport of forestry smoke plumes. A number of studies[47,50-55] have now shown that most of the particles formed in forest fires are of submicron size, typical of a combustion aerosol. These studies generally agree on an average particle diameter between 0.1 and 0.5 μm, for mass, number, or volume distributions. Approximately 90 percent of the particle mass was below 1 micrometer diameter from understory burning of pine needles.[52] Laboratory burning of logging slash showed 82 percent of the particle mass below 1 μm.[53] Particle density has not been well documented, Stith[50] reports a range of 0.75 to 1.34 g cc^{-1}, while Foster[57] reported a value of 1.3 g cc^{-1}. However, these data probably do not represent the full range of possible values.

The effect of smoke on visibility depends not only on the concentration of particles emitted, but on the optical properties of the particles as they affect the scattering, absorption, and total extinction of light. A number of studies have reported the relationship between the mass of forest fire particulate matter and light scattering properties. Mass concentration to backscatter ratios (M/b_{scat}) have been reported between 2.0×10^5 and 3.1×10^5 for forest fire plumes as compared to the 3.8×10^5 ratio used for a mixed urban aerosol. Comparison of data is hampered by the use of nephelometers with different spectral responses and/or different methods of analysis. Tangren[56] has recently reviewed this topic and recommends a b_{scat} ratio of 2.8×10^5 for smoke plumes on the ground near the fire and 2.0×10^5 for airborne measurements of aged smoke downwind from the fire. The color of forest fire smoke can vary from dark black, through various shades of grey, to pure white. When smoke particles are collected on a glass fiber filter from different fire phases, the filter will be colored black or grey from flaming combustion, brown during the transition from flaming to smoldering, and bright yellow from the smoldering phase. The black smoke will predominate during vigorous flaming combustion especially in burning foliage fuels containing a high percentage of ether extractable hydrocarbons. These hydrocarbons (terpenes, tannins, resins, oils, etc.,) are somewhat volatile and very flammable. They are also low in oxygen content and thus can form soot precursors more readily than the highly oxygenated lignocellulosic polymers that make up the remaining fuel mass. As flaming combustion diminishes, tarry submicron droplets from smoldering combustion begin to predominate and the smoke color changes from black to white. On a volume, number, and mass basis, the tarry liquid droplets usually predominate over the solid soot particles.

The relative importance of light absorption to light scattering properties for forest fire smoke can be judged from laboratory studies which have measured optical properties and calculated an imaginary refractive index (n_2) for smoke particles from burning pine needles. Nolan[57] reports an $n_2 = 0.05$ for flaming conditions and $n_2 = 0.0004$ for smoldering conditions. Making the same particle density assumptions as Nolan, Patterson and McMahon[58], in a more recent study, estimate n_2 values to be 0.07 for flaming conditions and 0.0026 for smoldering conditions. These values can be compared to a value of pure carbon, $n_2 = 0.66$. In terms of visibility impact, it can be shown from reported optical constants and particle size data that particle absorption and particle scatter are roughly equivalent during periods of vigorous flaming, but that particle absorption is relatively minor or negligible during heavy smoldering conditions.[58]

Chemical Characteristics of Forestry Smoke Particulate Matter. Knowledge of the chemical nature of forest fuels, combined with what is known about pyrolysis and combustion, suggests that particulate matter formed by forest fires would consist primarily of complex organic substances. Analysis of particulate matter from burning forest fuels has been shown to contain between 50 to 60 percent carbon. [21] Similar results were obtained in the analysis of particulate emissions from wood burning fireplaces and stoves[45] with carbon averaging 60 percent and hydrogen 2.0 percent. In this case, the analysis was performed on a methylene chloride extract of the particulate matter. The remainder, or about 40 percent can be assumed to be mostly oxygen because of the low ash content of the fuel. Thus, in general, the carbon analysis of particulate matter compares closely with the amount of carbon in the fuel (50 to 55 percent). The slight difference can be attributed to some loss of hydrogen and oxygen during combustion.

The actual chemical structure of the compounds in the particulate matter, of course, is much different. In a fireplace study, Dasch[59] found the carbon content of the particulate matter was 71 percent from burning softwoods and 54 percent from burning hardwoods. Elemental carbon, as determined by a combustion thermograph technique, was 33 percent for the softwood fire and 8 percent for the hardwood fire. The accuracy of this technique has been questioned because of the tendency of samples to char during the heating process.

The organic characteristics of particulate matter have traditionally been estimated by solvent extractions with benzene. The benzene soluble organic (BSO) fraction of urban particulate matter is usually well below 20 percent. The BSO averages for forestry smoke particulate matter have ranged between 40 and 75 percent.[12] In general, the higher values are found in fires with a large smoldering component. Crude BSO extract has been separated into organic classes for a limited number of samples. The neutral fraction which contains aliphatic and aromatic hydrocarbons, has been found to be approximately 20 percent of the extracted material.[21] Very little detailed chemical characterization of the organic components in forestry particulate matter has been reported in the literature. However, organic emissions are now being studied extensively as a result of environmental issues related to the increased use of wood fuels in stoves and fireplaces. Although some work has been reported and many studies are in progress, over 85 percent of the organic emissions remain uncharacterized.

The organic compounds studied most often are a group known as polycyclic organic matter (POM) and its subgroup, polynuclear aromatic hydrocarbons (PAH). Compilation of an emission inventory for PAH's indicates that residential wood burning may be the largest source of PAH's emitted to the atmosphere. The occurrence of PAH in the combustion products of carbonaceous fuels is well known, and several PAH's are known to be carcinogenic in animals. Benzo(a)pyrene (BaP) is the best known and studied compound in this group. Data on POM/PAH emissions from forest fires are sparse, and in fact there has been only one study[60] performed to measure PAH emissions from prescribed fires. That investigation used simulated backing fires and heading fires in the laboratory with pine needle litter as the fuel. Emissions were channeled through a large stack where particulate matter samples were collected on a glass fiber filter in a modified high volume sampler maintained below 65°C to minimize breakthrough of BaP. Emission factors for PAH species from anthracene to coronene are reported. Heading fires produced substantially more TSP than backing fires (as expected). However, the backing fires produced significantly higher amounts of BaP. Emission factors for BaP ranged from 238 to 3,454 $\mu g\ kg^{-1}$ in backing fires and from 38 to 97 $\mu g\ kg^{-1}$ in heading fires. The ratio of BaP to particulate matter was also much higher in backing fires (169 $\mu g\ g^{-1}$) as compared to heading fires (3 $\mu g\ g^{-1}$). A field study is currently attempting to validate these results and to obtain values from a broader range of forest fuels and fires.

It is common to have BaP and PAH emission factors range over several orders of magnitude. In a recent fireplace study[59], BaP emission factors ranged from 5 to 1,900 $\mu g\ kg^{-1}$. The concentration of BaP in the particulate matter ranged from 3 to 141 $\mu g\ g^{-1}$. Numerous other studies with wood stoves and fireplaces have also demonstrated this wide range. In general, air-tight wood stoves

produced significantly higher levels of PAH than fireplaces.[45] Mode of burning in the wood stoves had a dramatic impact on BaP formation. As shown by Allen,[61] the emission factors were found to be appreciably lower for downdraft and high turbulence burning than from sidedraft and updraft burning.

PAH's can be formed in fires by a complex series of pyrosynthetic steps involving the chemical condensation and cyclization of free radicals in a chemically reducing atmosphere, commonly found in the center of flames. Although PAH can form at 400°C (especially the low molecular weight PAH's), the optimal range for the more complex 5- and 6-ring compounds such as BaP is 700 to 850°C.[60,61] PAH's can be formed in any combustion process involving compounds of carbon and hydrogen; however, it is known that some compounds are more efficient precursors to PAH than others. These findings suggest that carbohydrate structures as found in cellulose and hemicellulose are less efficient precursors to PAH than alkyl-benzene structures as found in lignin.

Forestry Smoke Tracers. A logical development emerging from smoke characterization studies will be the opportunity to identify a unique chemical fingerprint or signature for forest fire emissions which could be used for plume tracking, visibility studies, and source apportionment. Until recently, source oriented dispersion models and subjective visual estimates from aircraft have been the primary means by which air quality specialists have determined the impact of a smoke plume at a receptor site. These methods have been approximations at best, with most dispersion models accurate only within a factor of two. Because of this limitation, there has been increasing interest in receptor model technology; that is, models that assess and separate the individual contributions from mixed pollution sources.[62] Receptor methods have become feasible because of recent improvements in the sampling and analysis of aerosols. Receptor models start with the measurement of a specific feature of the aerosol at the impacted site (receptor). They then calculate the contribution of a specific source type based on a morphological or chemical signature of the source.

Several techniques have already been used in attempting to assess the impact of slash and agricultural burning in Oregon's Willamette Valley.[63] Similar techniques are now being used to assess the impact of wood stove and fireplace emissions.[25,59,62] They include:

(1) Chemical Mass Balance--This technique was first proposed by Friedlander[64] and assumes that the mass of particulate matter deposited on a filter is a linear combination of the mass contributed from each source in an airshed. Watson[65] has used this technique for assessing the sources of particulate matter in Portland, Oregon.

(2) Enrichment Factor Analysis--This method uses data from the elemental concentrations found in ambient air and in the polluting source(s) to estimate the degree to which a tracer element is enriched above normal levels. Both carbon enrichment and fine particle potassium/iron (K/Fe) enrichment techniques have been used to assess agricultural and slash burning impacts in Oregon.[25] The K/Fe ratio technique is a simplified two-component chemical mass balance. Fine particle K is an indicator of vegetation burning while Fe is indicative of the soil component. An important limitation to the use of the K/Fe ratio is its high variability; at present it is only a qualitative indicator of the contribution from burning vegetation.[25]

(3) Carbon-14 Measurements--Newly developed radiocarbon counting techniques have made possible the analysis of ^{14}C isotopes in extremely small samples typically found in aerosol samplers. Using these methods, it is possible to differentiate between modern or contemporary carbon emitted from vegetative burning and fossil carbon emitted from fossil fuel combustion sources. The Carbon-14 content of contemporary carbon is relatively high and roughly comparable to the atmospheric concentration at the time it was formed, while fossil carbon contains essentially no radiocarbon because its age is so much greater than the half-life of Carbon-14. Vegetation burning measured by this technique would include agricultural, forest, and residential wood combustion sources. Thus, it is essential that receptor modeling techniques be used in conjunction with other records of source activities to distinguish between similar sources.

Receptor models are very new and still an emerging technology. At present, methods often only provide qualitative information. However, with expected advances in sampling and analysis methodologies, these techniques can become the primary diagnostic and predictive tool used in air resource management. Perhaps the greatest opportunity for improving receptor models lies in the area of detailed analysis of organic emissions.[66] Most of the models up to now have concentrated on elemental fingerprints. At present, there are no reliable elemental signatures for many combustion sources. Elemental analysis is relatively simple and inexpensive when compared to the techniques needed for organic analysis. However, advances in organic sampling and analysis can be expected and may provide the opportunity for finding compounds or ratios of compounds that will distinguish between two closely related sources. Approaches should consider the type of organic matrix present in the fuels and then focus on expected pyrolysis and combustion products. For forest fuels, specific aldehydes, furans, phenols, or terpenes would be a place to start. Organic group, class, or functional group analysis may also be appropriate, as well as individual constituent analysis, or a combination of both. It is known, for example, that hardwood ligins contain both quaiacyl and syringylpropane units, whereas conifers generally contain exclusively quaiacyl units. Terpene and hemicellulose profiles also vary between species. There are classes of hydrocarbons and polynuclear aromatic hydrocarbons that have different abundance patterns based on fuel chemistry and combustion conditions. For example, forestry smoke contains a high ratio of poly-methylated PAH's compared to fossil fuel sources. It is likely that differences in fuel chemistry and combustion efficiency will show up in the emissions profile.

Photochemical Potential of Forestry Smoke. It has been known for some time that forestry smoke had the necessary ingredients for photochemical reactions that produce ozone and other oxidants. Evans et al.[67] first monitored oxidant concentrations in smoke plumes in Western Australia in 1972. Initial measurements were made with an oxidant monitor which was later judged to give erroneous results in concentrated smoke plumes. In a later report, he used a chemluminescent monitor and found up to 100 ppb ozone in some plumes. The ozone maximum was reached in 1 hour, suggesting that the photochemical reactions in smoke are essentially complete by that time. Reactive aldehydes, terpenes, and free radicals could accelerate the photo-oxidation rate. In a series of chamber studies with smoke from burning pine needles, Benner[42] found that artificial daylight irradiation led to ozone and oxidant formation; he observed typical diurnal type photochemical cycles. Non-ozone oxidant formation always occurred

before ozone was observed. Westberg et al.[69] monitored slash burn plumes in Washington and found a buildup of 40-50 ppb ozone above the ambient background. Hydrocarbon analyses revealed the presence of many photochemically reactive olefins in the plume. Hydrocarbon/NO_x ratios were favorable for photochemical oxidant production. As with the earlier reports, ozone formed rapidly and concentrations were highest 2 miles downwind of the burn. A dilution effect was evident at distances further downwind. However, in another report on ozone from the burning of forest slash, Stith et al.[50] reports one case where the ozone concentration was still increasing at 55.6 km downwind (26 ppb above ambient).

The impact of ozone and oxidants produced in forest fire plumes on downwind air quality depends heavily on meteorological and topographic factors. High-intensity burns, because of their strong convective activity, elevate the smoke plume to altitudes where natural dilution prevents objectional concentrations of ozone reaching ground level. Any problems associated with ozone from forest burning would seem to be vastly overshadowed by the more apparent and potentially serious impact of particulate matter on visibility.

SUMMARY

Emissions from forest fires, although transient in nature, occur in all regions of the country and in all seasons of the year. Approximately 47 million metric tons of forest fuels are burned annually in the United States by wildfire and 37 million tons by prescribed fire. Although forest fires are not considered a major source of criteria air pollutants at the national level, surveys have identified prescribed burning as a significant factor in some local and regional air pollution problems.

There are many different kinds of forest fuels and forest fires, and emissions can vary over one order of magnitude, depending on fuel conditions and fire behavior. Incomplete combustion yields particulate matter, carbon monoxide, gaseous hydrocarbons, and volatile organic compounds. Approximately 20 percent of the fuel nitrogen is converted to nitrogen oxides, but low fuel sulfur and mineral content yields negligible amounts of sulfur oxides and trace elements. Polycyclic organic matter, including polynuclear aromatic hydrocarbons (PAH) have been reported in laboratory fires with pine needles. Additional field studies are now in progress to establish more reliable PAH emission factors. Particulate matter emission factors and emission rates available are for several types of understory fuels and are currently being developed for logging residue fuels. We still do not have adequate emission data for high intensity prescribed fires and wildfires.

Particulate matter emissions cause the most serious impact to air quality related values. Problems vary from plume blight and regional haze visibility problems in the Northwest (from burning logging residues) to highway visibility problems in the South (from smoldering combustion of understory fuels and piled logging debris).

Prediction models for emission factors and emission rates based on fuel conditions and fire behavior are now emerging but require continued development and refinement. Unique chemical fingerprints for forest fire emissions are being identified for use in receptor models and source apportionment studies. When more fully developed, these techniques will become a valuable diagnostic and predictive tool for air quality studies. Air resource management is now an essential part of wildland management plans. Smoke management programs are being used to schedule, dilute, and reduce emissions from prescribed burning.

The physical and chemical properties of forestry smoke particulate matter can vary from flaming and smoldering combustion phases of a fire. In general, the particles consist of complex organic compounds derived from the incomplete combustion of cellulose and lignin polymers. It has been estimated that over 85 percent of the organic emissions remain uncharacterized. The physical properties of forestry particulate matter has been better characterized than its chemical properties. Spherical tar droplets usually predominate over soot particles. Several studies have shown that the average particle diameter is between 0.1 and 0.5 μm. The density of the particles is not well established nor are the sorptive characteristics and behavior of particles under conditions of high humidity.

LITERATURE CITED

1. D. E. Ward, C. K. McMahon, and R. W. Johansen, "An update on particulate emissions from forest fires," Pap. No. 76-2.2 presented at 69th Annual Meeting of the Air Pollution Control Association, Portland, OR (June 1976).
2. G. Yamate, "Development of emission factors for estimating atmospheric emissions from forest fires," EPA-450/3-73-009, U. S. Environmental Protection Agency, Research Triangle Park, NC. 126 pp. (1973).
3. J. D. Cook, J. H. Himel, and R. H. Moyer, "Impact of forestry burning upon air quality: A state-of-the-knowledge characterization in Washington and Oregon," Fin. Report, Contr. No. 68-01-4144, EPA No. 910/9-78-052, NTIS No. PB 290-472/OWP., U. S. Environmental Protection Agency, Reg. X, Seattle, WA, 270 pp. (1978).
4. C. T. Chi, D. A. Horn, R. B. Reznik [and others], "Source assessment: prescribed burning, state of the art." EPA-600/2-79-019h, U. S. Environmental Protection Agency, Research Triangle Park, NC, 107 pp. (November 1979).
5. Society of American Foresters Task Force on Clean Air Act Regulations, "Wildland fires, air quality, and smoke management," J. For. 7: 689-696 (1980).
6. C. G. Wells, R. E. Campbell, L. F. DeBano [and others], "Effects of fire on soil," Forest Service General Technical Report WO-7, U. S. Department of Agriculture, Washington, DC, 34 pp. (March 1979).
7. R. E. Martin, H. E. Anderson, W. D. Boyer [and others], "Effects of fire on fuels," Forest Service General Technical Report WO-13, U. S. Department of Agriculture, Washington, DC, 64 pp. (September 1979).
8. J. E. Lotan, M. E. Alexander, S. F. Arno [and others], "Effects of fire on flora," Forest Service General Technical Report WO-16, U. S. Department of Agriculture, Washington, DC, 71 pp. (March 1981).
9. L. J. Lyon, H. S. Crawford, E. Czuhai [and others], "Effects of fire on fauna," Forest Service General Technical Report WO-6, U. S. Department of Agriculture, Washington, DC, 22 pp. (September 1978).
10. A. R. Tiedemann, C. E. Conrad, J. H. Dieterich [and others], "Effects of fire on water," Forest Service General Technical Report WO-10, U. S. Department of Agriculture, Washington, DC, 28 pp. (September 1979).
11. D. V. Sandberg, J. M. Pierovich, D. G. Fox [and others], "Effects of fire on air," Forest Service General Technical Report WO-9, U. S. Department of Agriculture, Washington, DC, 40 pp. (January 1979).
12. Southern Forest Fire Laboratory Staff, "Southern forestry smoke management guidebook," Forest Service General Technical Report SE-10, U. S. Department of Agriculture, Southeastern Forest Experiment Station, Asheville, NC, 140 pp. (1976).

13. H. E. Mobley, R. S. Jackson, W. E. Balmer [and others], "A guide for prescribed fire in southern forests," Southeastern Area State and Private Forestry, Forest Service, U. S. Department of Agriculture, Atlanta, GA, 40 pp. (1978).
14. R. W. Johansen and R. A. Phernetton, "Smoke management on the Okefenokee National Wildlife Refuge," South. J. Appl. For. 6(4): 200-205 (November 1982).
15. B. L. Cole, "Air quality - prescribed burning, smoke management program," State of Washington Department of Natural Resources, Division of Fire Control, 27 pp. (June 1975).
16. R. B. Geddes, "A guide to smoke management," Virginia Division of Forestry, Department of Conservation and Economic Development, Charlottesville, VA, 22 pp. (March 1981).
17. U. S. Environmental Protection Agency, "Smoke management-a workbook for balancing air quality and land management goals," EPA-450/2-82-001, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 112 pp. (January 10, 1982).
18. J. A. Vance, "Environmental laws and regulations," For. Farmer 39: 92-93 (1980).
19. E. B. Hauenstein and W. C. Siegel, "Air quality laws in southern states: effects on prescribed burning," South. J. Appl. For. 5: 132-145 (1981).
20. P. J. Kramer and T. T. Kozlowski, Physiology of Trees, McGraw-Hill Book Co., Inc., New York, 1960, 642 pp.
21. United States Department of Agriculture, Forest Service, unpublished data related to forest fuels and emissions, on file at the Southern Forest Fire Laboratory, Dry Branch, GA.
22. G. M. Byram, "Combustion of forest fuels," In Forest Fire: Control and Use, K. P. Davis, ed., McGraw-Hill, New York, 1959, pp. 61-89.
23. M. E. Alexander, "Calculating and interpreting forest fire intensities," Can. J. Bot. 60: 349-357 (1982).
24. J. H. Cavender, D. S. Kircher and A. J. Hoffman, "Nationwide air pollutant emission trends 1940-1970," Pub. No. AP-115, U. S. Environmental Protection Agency, Research Triangle Park, NC, 52 pp. (January 1973).
25. 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," Environ. Sci. & Technol. 15(9): 1045-1050 (September 1981).
26. U. S. Environmental Protection Agency, "Protecting visibility, an EPA report to Congress," EPA-450/5-79-008, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 262 pp. (October 1979).
27. D. E. Ward, D. V. Sandberg, R. D. Ottmar [and others], "Measurement of smoke from two prescribed fires in the Pacific Northwest," Pap. No. 82-8.4 presented at 75th Annual Meeting of the Air Pollution Control Association, New Orleans, LA (June 1982).
28. D. V. Sandberg, "Emission reduction from prescribed forest burning," Pap. No. 83-45.2 presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, GA (June 1983).
29. H. B. Clements and C. K. McMahon, "Nitrogen oxides from burning forest fuels examined by thermogravimetry and evolved gas analysis," Thermochimica Acta 35: 133-139 (1980).

30. E. F. Darley, F. R. Burleson, E. H. Mateer [and others], "Contribution of burning of agricultural wastes to photochemical air pollution," J. Air Pollut. Control Assoc. 16: 685-690 (1966).
31. D. E. Ward, E. R. Elliott, C. K. McMahon, and D. D. Wade, "Particulate source strength determination for low-intensity prescribed fires," Proc. control technology of agricultural air pollutants specialty conference, APCA, Pittsburgh, PA, pp. 39-55 (March 1974).
32. P. W. Ryan, C. D. Tangren, C. K. McMahon, "A balloon system for profiling smoke plumes from forest fires," Pap. No. 79-6.1 presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, OH
33. C. K. McMahon, "Slash burning studied," In Forest Fire News, C. B. Lyon, ed., U. S. Department of Agriculture, Forest Service, Washington, DC, 1982, p. 16.
34. R. N. Nelson, Jr., "An evaluation of the carbon balance technique for estimating emission factors and fuel consumption in forest fires," Res. Pap. No. SE-231, U. S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, 9 pp. (1982).
35. D. E. Ward, "Source strength modeling of emissions from forest fires," Pap. No. 83-45.2 presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, GA (June 1983).
36. C. K. McMahon, D. D. Wade, and S. N. Tsoukalas, "Combustion characteristics and emissions from burning organic soils," Pap. No. 80-15.5 presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec (June 1980).
37. D. V. Sandberg, S. G. Pickford, and E. F. Darley, "Emissions from slash burning and the influence of flame retardant chemicals," J. Air Pollut. Control Assoc. 25: 278-281 (1975).
38. E. D. Pellizzari, "The measurement of carcinogenic vapors in ambient atmospheres," EPA-600/7-77-055, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 287 pp. (June 1977).
39. J. A. Cooper and D. Malek, eds., Residential Solid Fuels Environmental Impacts and Solution, Oregon Graduate Center, Beaverton, OR, 1,271 pp. (1982).
40. F. A. Ayer, "Proceedings: Conference on Wood Combustion Environmental Assessment (New Orleans, February 1981)," EPA-600/9-81-029, NTIS No. PB81-248155, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, 323 pp. (1981).
41. R. W. Gerstle and D. A. Kemnitz, "Atmospheric emissions from open burning," J. Air Pollut. Control Assoc. 17: 324-327 (1967).
42. W. H. Benner, "Photochemical reactions of forest fire combustion products," Ph.D. Dissertation, University of Florida, Gainesville, FL (1977).
43. U. S. Environmental Protection Agency, "Compilation of air pollutant emission factors, Second Edition, Part A," Rep. No. AP-42, Office of Air Ouality Planning and Standards, Research Triangle Park, NC (February 1976).
44. H. S. Oglesby and R. O. Blosser, "Information on the sulfur content of bark and its contributions to SO_2 emissions when burned as fuel," Pap. No. 79-6.2, presented at the 72nd Annual meeting of the Air Pollution Control Association, Cincinnati, OH (June 1979).
45. D. G. DeAngelis, D. S. Ruffin, and R. B. Reznik, "Preliminary characterization of emissions from wood-fired residential combustion equipment," EPA-600/7-80-040, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC (1980).

46. N. A. Chigier, Pollution Formation and Destruction in Flames, Vol. 1, Pergamon Press, New York, 1976, 219 pp.
47. L. F. Radke, J. L. Stith, D. A. Hegg, and P. V. Hobbs, "Airborne studies of particles and gases from forest fires," J. Air Pollut. Control Assoc. 28(1):30-34 (1978).
48. K. J. Lim and H. I. Lips, "Overview of emissions from wood combustion," In Proceedings: Conference on Wood Combustion Environmental Assessment, (New Orleans, February 1981), EPA-600/9-81-029, NTIS No. PB81-248155, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, pp. 39-54 (1981).
49. D. E. Ward, C. K. McMahon, and D. F. Adams, "Laboratory measurements of carbonyl sulfide and total sulfur emissions from open burning of forest biomass," Pap. No. 82-51.9 presented at the 75th Annual Meeting of the Air Polluton Control Association, New Orleans, LA, 16 pp. (June 1982).
50. J. L. Stith, L. F. Radke, and P. V. Hobbs, "Particle emissions and the production of ozone and nitrogen oxides from the burning of forest slash," Atmos. Environ. 15: 73-82 (1981).
51. D. A. MacArthur, "Particle sizes in bushfire smoke," Aust. For. 30: 274-278 (1966).
52. P. W. Ryan and C. K. McMahon, "Some chemical and physical characteristics of emissions from forest fires," Pap. No. 76-2.3 presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, OR, 15 pp. (June 1976).
53. D. V. Sandberg and R. E. Martin, Particle sizes in slash fire smoke," Res. Pap. PNW-199, U. S. Department of Agriculture, Forest Service, Pacific Northwest Station, 7 pp., illus. (1975).
54. R. G. Vines, L. Gibson, A. B. Hatch [and others], "On the nature, properties, and behavior of bush-fire smoke," CSIRO Div. Appl. Chem. Tech. Pap. No. 1, 32 pp. (1971).
55. D. R. Packham and R. G. Vines, "Properties of bushfire smoke: the reduction in visibility resulting from prescribed fires in forests," J. Air Pollut. Control Assoc. 28(8): 790-795 (1978).
56. C. D. Tangren, "Scattering coefficient and particulate matter concentration in forest fire smoke," J. Air Pollut. Control Assoc. 32(7): 729-732 (1982).
57. J. L. Nolan, "Measurement of light absorbing aerosols from combustion sources," Masters Thesis, University of Washington, 67 pp. (1977).
58. E. Patterson and C. K. McMahon, "Absorption characteristics of forest fire particulate matter," Final Report, Project FS-SE-2110-8(2), on file at Southern Forest Fire Laboratory, Dry Branch, GA (May 1983).
59. J. M. Dasch, "Particulate and gaseous emissions from wood-burning fireplaces," Environ. Sci. Technol. 16(10): 639-645 (1982).
60. C. K. McMahon and S. N. Tsoukalas, "Polynuclear aromatic hydrocarbons in forest fire smoke," In Carcinogenesis, Vol. 3: Polynuclear Aromatic Hydrocarbons, P. W. Jones and R. I. Freudenthal, eds., Raven Press, New York, 1978, pp. 61-73.
61. J. M. Allen and M. W. Cooke, "Control of emissions from residential wood burning by combustion modification," EPA-600/S7-81-091, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC (December 1981).
62. J. A. Cooper and J. G. Watson, Jr., "Receptor oriented methods of air particulate source apportionment," J. Air Pollut. Control Assoc. 30(10): 1116-1125 (1980).

63. J. E. Core and F. P. Terraglio, "Field and slash burning particulate characterization: the search for unique natural tracers," Pap. No. 78-20 presented at the Pacific Northwest International Section, APCA meeting, Portland, OR (November 1978).
64. S. K. Friedlander, "Chemical element balances and identification of air pollution sources," Environ. Sci. Technol. 7:235 (1973).
65. J. G. Watson, "Chemical element balance receptor model methodology for assessing the source of fine and total suspended particulate matter in Portland, Oregon," Ph.D. Dissertation, Oregon Graduate Center, February 1979.
66. G. E. Gordon, "Receptor models," Environ. Sci. Technol. 14(7): 792-800 (1980).
67. L. F. Evans, N. K. King, D. R. Packham, and E. T. Stephens, "Ozone measurements in smoke from forest fires," Environ. Sci. Technol. 8(1): 75-76 (1974).
68. L. F. Evans, I. A. Weeks, A. J. Eccleston, and D. R. Packham, "Photochemical ozone in smoke from prescribed burning of forests," Environ. Sci. Technol. 11(9): 896-900 (1977).
69. H. Westberg, K. Sexton, and D. Flyckt, "Hydrocarbon production and photochemical ozone formation in forest burn plumes," J. Air Pollut. Control Assoc. 31(6): 661-664 (1981).
70. W. W. Foster, "Attenuation of light by wood smoke," Brit. J. Appl. Phys. 10: 416 (1959).
71. M. S. Feldstein, S. Duckworth, H. C. Wohlers, and B. Linsky, "The contribution of the open burning of land clearing debris to air pollution," J. Air Pollut. Control Assoc. 13: 542-545 (1963).
72. F. W. Lipfert, "A national assessment of the air quality impacts of residential firewood use," In Proceedings: Residential Wood and Coal Combustion Specialty Conference, (Louisville, KY, March 1982), Special Pub. 45, Air Pollution Control Association.
73. D. G. DeAngelis, D. S. Ruffin, J. A. Peters, and R. B. Reznik, "Source assessment: residential combustion of wood," EPA-600/2-80-042b, U. S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC (March 1980).

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