SOUTHERN FORESTRY SMOKE MANAGEMENT GUIDEBOOK

DEDICATION

The staff of the Southern Forest Fire Laboratory respectfully dedicates this work to the memory of Robert W. Cooper whose guidance and inspiration long helped to bring science to the art of prescribed burning in the South.

HOW THIS BOOK WAS WRITTEN

Contributions from many scientists were required to complete this Guidebook. These contributors are listed as authors of the individual Chapters, and they take sole responsibility for technical content. Advice on overall content and applicability for users was provided by a group of compilers. The senior compiler worked directly with the authors to achieve a team product.

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USDA Forest Service General Technical Report SE-10

December 1976

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by

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ABSTRACT

A system for predicting and modifying smoke concentrations from prescription fires is introduced. While limited to particulate matter and the more typical southern fuels, the system is for both simple and complex applications. Forestry smoke constituents, variables affecting smoke production and dispersion, and new methods for estimating available fuel are presented.

KEYWORDS: Air quality, pollution, prescribed burning, smoke management, particulate matter, smoke concentrations, emission factors, components of forestry smoke, fuel loading.

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PERSPECTIVES

The air we breathe is essential to our lives and well-being. Forests are also important to our well-being. This Guidebook was prepared because the fires used in forest management can temporarily reduce air quality. Possible air quality impacts are discussed in detail, and ways are suggested to minimize unwanted atmospheric consequences when using fire in the forests. Procedures and suggestions to follow should be viewed as an opportunity to apply the best available knowledge, consistent with current need. In some locales, this need may be for use of only the more simple procedures. Complex air quality problems in other locales are likely to call for application of complex procedures. We have attempted to provide for both needs.

When compared with other sources of emissions, smoke from forestry burning has been regarded by regulatory agencies as only locally important. Its components are thought of as natural, occur from other sources as well, and may even be deemed inevitable if we accept prescribed fire as merely a practical substitute for wildfire. The ecological necessity for fire in some forests and the use of controlled fire to avoid the devastation of wildfires are strong arguments for its prescription. Forest pathologists recognize fire as a needed sanitation measure in some situations. On the other hand, because some smoke components are toxic, because they may interact unfavorably with one another and with other chemicals in the atmosphere, and because they can also impair safe or esthetic visibility, alternatives to open burning are sometimes strongly advocated. Also, burning forest fuels, like all carbonaceous fuels, produce traces of such implicated carcinogens as benzo(a)pyrene. Because not all health-related threshold levels have been established, a first reaction could be to avoid all open burning.

In truth, knowledge of interrelating synergistic effects and of general human susceptibility to airborne toxins is still too imperfect to suggest elimination of all smoke as attainable, or even necessary. And while heavy debate continues over *safe* or *no-effect* proposals, a seemingly rational control approach may emerge. Rather than attempt to regulate emissions merely on the basis of our rapidly improving detection (i.e., analytical) capability, it is suggested that acceptable levels for naturally occurring, physiologically active pollutants be related to their ambient (or background) levels.

This is not to say alternatives to open burning are not preferred when possible. Neither is it intended as anything but a strong message to apply a meaningful principle:

AVOID OVERLOADING NATURAL CLEARANCE MECHANISMS— BOTH PULMONARY AND ENVIRONMENTAL

By applying this principle, prolonged toxic contact and possibly increased physiologic effect on humans can be avoided. We believe that some smoke from forest management can be accepted in trade for benefits to the forest and for prevention of uncontrolled and overloading emissions from wildfire.

This Guidebook provides for the needs of both air and forest resource stewardship, and it is offered for local interpretation and use. It is offered, too, in the expectation that the health and well-being of the populace will be a primary concern of forestry smoke managers.

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CHAPTER I

SMOKE MANAGEMENT — WHAT IS IT?

by

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PURPOSE OF THESE GUIDELINES

This Guidebook is designed to help you determine in advance:

WHAT YOUR FIRE WILL PUT INTO THE AIR
WHERE THIS MATERIAL WILL GO
WHAT WILL HAPPEN TO IT
WHAT EFFECT IT WILL HAVE
WHAT YOU CAN DO ABOUT IT

. . .and doing something about it to minimize environmental impact is *smoke management.*

Fire in the forest—natural, accidental, or deliberate—has been an important process in the ecology of the South for thousands of years, especially in the fire subclimax pine stands of the Coastal Plains. The use of prescribed fire to accomplish specific forest management objectives is now regarded as an indispensable tool of the forest manager (Mobley and others 1973). Today, nearly 3 million acres a year are burned by prescription in the Southern United States. In the past, the forest manager had only a minimum of information to help him determine what smoke from a prescription fire would do to visibility or to the atmosphere.

This Guidebook was developed for southern forest-land managers who prescribe fires, and for public agencies that are responsible for maintaining air quality in southern rural areas where forests are burned. What is presented is based upon the best available technology. Because knowledge is presently incomplete, the scope is limited to:

A broad breakdown of important southern fuels

Single prescription fires

Predictions of particulate matter emissions only.

A SOURCE OF MORE INFORMATION

As this Guidebook is being written, a parallel *Forestry Smoke Management Sourcebook* is also being developed. This Guidebook provides a great deal of information to practitioners in condensed form, while the *Sourcebook* will provide much additional information to key specialists. Any references made to the *Sourcebook* are intended to let you know that additional information is already available—at least in manuscript form. The first edition of the *Sourcebook* will probably be distributed in 1977 to regional and areal levels of the Forest Service and to State Foresters in a looseleaf format.

WHAT'S IN THIS GUIDEBOOK

A lot of information is presented for the first time in this Guidebook. Much is based on limited data and will be subject to updating. New information includes:

A system for estimating total fuel loading

A system for estimating available fuel

Particulate matter emission factors for major fuel types and burning techniques

A procedure for determining particulate matter production rate

A procedure for predicting smoke concentrations at any target area.

All are described in Chapters IV and V. This information is put together in a step-by-step decision-logic framework in Chapter VI that can be used to predict what smoke from a planned burn will do to the immediate airshed, and how it will affect visibility at any point downwind.

Although much more information can be found in the *Sourcebook* that is being developed, Chapter II summarizes what is presently known about the components of smoke plumes and their effects. Chapter III briefly reviews the Clean Air Acts and resulting Federal standards, State regulations that pertain to forestry burning, and a proposed method for determining a voluntary limit on emissions.

THERE ARE ALTERNATIVES

When land managers want to reduce competing vegetation or debris, they have various treatment alternatives: open burning, mechanical treatment, chemical application, close utilization, and doing nothing. No one system or type of treatment will meet *all* needs. The common treatments and considerations affecting their choices are summarized in table 1.

Three special categories of alternatives need further discussion: fire, utilization, and no treatment.

FIRE

Burning may be for more than one purpose; but because reasons vary by treatment, the discussions that follow are categorized by specific treatment objectives. In each of the following sections, a brief discussion of the need to meet the objective is also provided.

Reduction of Hazardous Fuels

Flammable vegetation and litter accumulate rapidly in pine forests. This material is fuel for wildfires, and excessive accumulation must be controlled to minimize losses and damages. When fire is prescribed to reduce hazardous fuel accumulations, the stand is virtually fireproofed for the next year or two. Fuel begins to accumulate immediately, but wildfires that do occur are of lower intensity and much easier to control; they burn less area and cause less damage to the forest. In the South, prescribed fire is used primarily for this purpose.

Figure 1. — Natural accumulations of understory vegetation are burned by prescription to reduce fire hazard.

Table 1.--Considerations in reducing forest debris by different treatments[1]

Considerations	Prescription burning	Chemicals	Forced-air burners
Adverse effect on air	Produces smoke	Chemical drift in foliar application	Very little visible emissions
Adverse effect on water	None[2]	May contaminate[3]	Negligible[2]
Adverse effect on soil	Negligible[2]	Negligible[2]	Some compaction[4]
Erosion	Possibly on steep slopes[5]	Negligible[2]	Possibly on steep slopes[4, 5]
Overstory	Negligible[2]	Negligible[2]	Skin trees[4]
Energy use	None	None to very little	Very high
Portability at site	Yes	Yes	None
Transportation requirements	Crew truck	Crew truck &/or tank truck Spray unit if used	Lowboy & tractor (2 units)
Costs[6]	20¢ to $2.50/acre (avg. $1) Site preparation up to $6/acre	$20 to $45/acre (avg. $25)	$5 to $10/ton of material treated
Effectiveness under stands	Effective	Effective on all sizes (live vegetation only)	Not effective
Effectiveness in the open	Effective only on small material	Not effective on dead material	Effective
Advantages	Inexpensive Fast Multiple benefits	Versatile Can treat any size material	Can handle large boles
Disadvantages	Air pollution Usable days are limited Not effective on large material	Public disapproval Regulated Possible offsite effects Volume not reduced Increased fire hazard	Need support equipment Costly Cannot treat understory
Best use	Hazardous fuel reduction Wildlife habitat improvement Grazing improvement	Timber stand improvement or conversion	Change in land use Site preparation Right-of-way clearing

continued

Table 1.--Considerations in reducing forest debris by different treatments[1] (continued)

Considerations	Drum choppers	Rotary-blade choppers	Dozing or shearing and root raking	Total-tree chippers
Adverse effect on air	Only exhaust emissions	Only exhaust emissions	Only exhaust emissions	Only exhaust emissions
Adverse effect on water	Negligible[2]	Negligible[2]	Sedimentation if on slope	Negligible[2]
Adverse effect on soil	Possible compaction	Some compaction	Compaction and removal of topsoil	Some compaction
Erosion	Moderate to steep slopes[5]	Possibly on steep slopes[5]	Very susceptible[5]	Possibly on steep slopes[4, 5]
Overstory	Skin tree boles & damage roots	None	Excessive damage	Skin trees[4]
Energy use	High	High	High	Very high
Portability at site	Limited in stands	Limited in stands	Limited in stands	None
Transportation requirements	Lowboy & tractor	Lowboy & tractor	Lowboy & tractor	Lowboy & tractor (2 units)
Costs[6]	\$30 to \$50/acre	\$10 to \$20/acre	\$50 to \$125/acre	About \$10/ton of material treated
Effectiveness under stands	Very limited Damage overstory	Limited	Cannot be used	Not effective
Effectiveness in the open	Effective	Effective on small material	Effective	Effective
Advantages	Effective in logging residue	Effective on small standing material Thorough treatment	Leaves ground clean	Salable product Can handle large boles
Disadvantages	Damages leave trees Blades tend to break on rocky ground	Limited where can be used	Debris left Erosion Costly Cannot treat understory	Need support equipment Initial investment Cannot treat understory
Best use	Site preparation	Maintenance of openings and rights-of-way	Change in land use Site preparation	Pulpwood logging Change in land use

[1]Adapted from Harrison (1975).

[2]Improper use could cause some adverse effects.

[3]If long-term chemicals are used or if treatment is close to stream or reservoir.

[4]Support equipment.

[5]These treatments are not feasible on steep slopes due to erosion and/or excessive cost--and generally not needed.

[6]Costs are usually higher in Piedmont areas.

Figure 2. — Wildlife favor the newly sprouting vegetation that appears after a prescribed burn.

Wildlife Habitat Improvement

As shrubs mature, the amount of food available to wildlife declines. Fires are often prescribed by wildlife biologists to improve wildlife habitat. Unpalatable brush and litter are removed, allowing production of palatable new plants and sprouts. Seeds and insects are also more plentiful on burned areas.

Site Preparation

Litter and debris must be removed to reduce competition and prepare a proper site for tree seeding or planting. Mechanical treatments alone may create large, unmanageable accumulations of debris that occupy space needed for growing trees. This debris can tie up nitrogen needed by the new stand for a prolonged period. Furthermore, mechanical treatment alone often fails to expose the soil properly. On the other hand, burning alone is not very effective either—except when the volume of debris is very low. Where the volume of logging debris is large, fire is often used in conjunction with mechanical treatment.

Figure 3. — Logging debris is burned by prescription to prepare sites for new crops of trees.

Control of Undesirable Species

In the absence of fire, most pine sites in the South tend to succeed to a climax type of scrub hardwoods. If these species are permitted to invade and compete with overstory pine, production is impaired and regeneration is very difficult.

Complete elimination of understory brush is not ecologically desirable or economically practical. It can be controlled with fire, however, if done while the understory is small. The resulting sprouts and growth of annuals provide good food and improved habitat for wildlife as well.

Disease Control

To control brownspot needle blight *(Scirrhia acicola* [Dearn.] Siggers) in longleaf pine *(Pinus palustris* Mill.) seedlings, the infected needles must be removed without damaging the bud. Fire is the only known practical way to properly remove the brownspot-infected needles of longleaf pines. Long experience with fire for this purpose has made it possible to do so without killing the bud.

Improve Forage for Grazing

Cattlemen produce beef on forested ranges. However, native grasses in the timber understory are smothered by shrubs and inferior hardwoods. Periodic, low-intensity fires control competition and maintain the grass species. In addition, the grass produced after such burning is especially nutritious and palatable for cattle.

Other Objectives

Other treatment objectives are to fireproof stands before initiating naval stores operations, to enhance esthetic appearance, and to improve accessibility for timber operators and hunters.

UTILIZATION

After allocating sufficient woody material to protect the soil from erosion, moisture loss, and unwanted loss of nutrients, most managers of commercial woodland would like to utilize all the remaining woody material for production of energy or as a raw material. Progress is being made in this

Figure 4. — Whole-tree chipping may be a practical alternative to burning in some places.

direction. In the South, merchantable pine trees are often utilized down to diameters of 2 to 4 inches. This is not usually the case, however, with hardwoods or forest areas being cleared for other uses.

One utilization system that looks promising is total-tree chipping. This system employs large, transportable chippers mounted on semitrailers. These will accept whole trees (limbs, leaves, and bark), cutting them into chips which can be blown into a truck and hauled to a pulpmill. No appreciable logging debris is left on areas logged in this manner. The investment cost and use of energy are high, but these disadvantages are offset where there is a market for such chips that contain bark and leaves. Some southern pulpmills can now accept substantial amounts of this type chipped material. Where such markets exist, total-tree chipping may be a better alternative than prescription burning. To meet energy needs, total-tree chippers can also be used to produce fuel for boilers. Studies and limited use are already underway.

Utilization of the small shrubs, brush, litter, and leaves within timber stands does not look promising. Volumes are too low and scattered to justify the cost of harvesting the material from among tree stems. Neither is there a developed market for most of this material. Pine needles can be sold for mulch when located close to metropolitan areas or nurseries.

NO TREATMENT

Choosing no treatment as an alternative—letting nature take its course—certainly has no immediate adverse effects on the quality of air, soil, or water. However, there can be other consequences:

Competition of unwanted plant species reduces timber growth.

Failure to prepare a site may make establishment of a new commercial timber stand difficult or impossible.

Wildlife habitat and food sources may disappear.

Palatable grass for cattle will be reduced or eliminated.

In stands of longleaf pine seedlings, mortality from brownspot disease will be increased.

Accessibility for hunting, timber management, and naval stores activites will be reduced.

Damage, as well as pollution of air and water, from wildfires will probably increase drastically—especially in areas of high fire occurence.

LITERATURE CITED

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1973. A guide for prescribed fire in southern forests. Southeast. Area, State & Priv. For.-2, 40 p. USDA For. Serv., Southeast. Area, State & Priv. For., Atlanta, Ga.

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Figure 5. — Unless its growth is controlled in some manner, understory vegetation will take over desirable pine sites.

CHAPTER II

CONTENTS AND EFFECTS OF FOREST FIRE SMOKE

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The components of smoke are determined by the fuel and the process that converts this fuel to smoke. We therefore begin this Chapter with a description of the chemical elements of wood and the fuel. We then describe the process that first separates, and then recombines, these elements into the constituents of smoke. Although there are only a few major chemical elements in wood, the complex burning process results in numerous combinations and thereby generates a large number of chemical compounds.

We will then describe the products emitted from forest fires and their effects. Most investigators have measured only the major combustion products: carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (HC), and particulate matter. A few have measured nitrogen oxides (NO_x), organic acids, and aldehydes. The effects of forest fire smoke on man and his environment have not been measured directly. However, since the components of this smoke are similar to those of smoke from other combustion sources, we will draw information on effects from studies of individual components.

In the last section, we discuss particulate matter at some length. We provide detail on polycyclic organic matter (POM) and on physical characteristics. Size is perhaps the most important physical property of particulate matter. This size distribution is a good indicator of the potential for causing both health and visibility problems.

FUEL

The fuels of prescribed fires in the South, described in greater detail in Chapter IV, are mostly understory foliage, small branches, and the upper layers of ground litter. To a lesser extent, fuels also include the large branches and treetops left during land clearing and logging. Wildfires, which are often more intense than prescribed fires, may consume the foliage and small limbs of tree crowns, all litter layers, and organic soil. When burned, these fuel elements emit smoke with a chemical character that is basically determined by the chemical character of the fuel. Therefore, our discussion will start with an examination of the chemical character of forest vegetation.

CHEMICAL ELEMENTS OF WOOD

Chemical analysis of wood shows that it is composed of about 50 percent carbon, 6 percent hydrogen, 44 percent oxygen, and a fractional percent of what are called trace inorganic components. Surprisingly, there is only a minor difference in the major components between various wood species. The variability among trace components such as ash and nitrogen is greater. Ash content varies from 0.2 to over 0.9 percent for wood species in the United States. For nitrogen, the variation can be tenfold; for example, ponderosa pine *(Pinus ponderosa* Laws.) ranges from 0.13 percent nitrogen in boles to 1.04 percent nitrogen in growing needles.

More than half of the elements in the periodic table have been found in plants. At least 27 elements were identified in certain samples of white pine *(Pinus strobus* L.) wood and others doubtless occur in very small quantities.

Many of these elements are commonly recognized growth nutrients. Those occurring in fairly large quantities are called the major or macronutrients: nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Elements required in smaller quantities are the minor or micronutrients: iron, manganese, zinc, copper, boron, and molybdenum. This list may be expanded further as more is learned about plants. Table 2 shows an example of the type and concentration of trace elements.

Table 2. — Relative amounts of various elements found in dried leaf tissue of healthy plants[1/]

Element	Content	Content percentage
	Ppm	Percent
Nitrogen	20,000	2.0
Potassium	15,000	1.5
Calcium	15,000	1.5
Magnesium	3,000	0.3
Phosphorus	2,500	0.25
Sulfur	2,000	0.2
Iron	100	0.01
Boron	40	0.004
Manganese	40	0.004
Zinc	40	0.004
Copper	25	0.0025
Molybdenum	1	0.0001

1/ From Kramer and Kozlowski (1960).

Consideration of the trace components may seem trivial and unnecessary at first glance. Trace components, however, can cause major environmental problems. For example, the emission of sulfur oxides (regarded as a major pollutant) results from relatively minor amounts of sulfur in coal, oil, and other fossil fuels.

CHEMICAL COMPOUNDS IN WOOD

Ninety to ninety-five percent of the dry weight of wood is composed of three polymeric cell-wall constituents: cellulose, hemicellulose, and lignin. The other 5 to 10 percent includes constituents often listed as extractables or extraneous components. The extraneous components consist of several hundred individual chemical compounds that vary greatly between species, within species, and even within parts of the tree. In this group we find terpenes, tannins, resins, oils, pectins, gums, free organic acids, and minerals.

Wood contains between 41 and 53 percent cellulose. The 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 includes all noncellulosic polysaccharides such as the xylans, mannans, and glactans—plus related substances such as the uronic acids and their derivatives. No single, structural formula can be presented for this group; in fact, objections are often raised to the use of the collective term hemicellulose. The hemicellulose content of wood varies from 15 to 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 phenolic hydroxyl groups. Lignin includes a variety of substances that have similar chemical compositions, but may have structural differences. The basic building block of lignin is the phenyl propane unit. The lignin content varies from about 23 to 33 percent in softwoods, and from about 16 to 25 percent in hardwoods.

BURNING PROCESS

How the components of smoke are generated from burning forest vegetation is best understood by recognizing that fire is a two-stage process of pyrolysis and combustion. Although both stages occur simultaneously, pyrolysis occurs first; it is the initiating stage of chemical decomposition at elevated temperatures. It is most often viewed as a heat-absorbing (endothermic) reaction that converts large molecules into smaller ones. Fuel elements are separated into char, vapors, and high-molecular-weight hydrocarbons and particulate matter.

Combustion is the burning or rapid oxidation of the pyrolysate vapors escaping from the surface of the fuel. Defined in the most rigorous sense, combustion is a relatively fast, heat-releasing (exothermic), chemical reaction among pyrolysate vapors and oxygen.

Pyrosynthesis is a third activity that is a part of both the pyrolysis and combustion stages. It forms large and complex organic compounds from smaller free-radical hydrocarbons in the high-temperature and low-oxygen regions of the fuel and combustion zone. The formation of these compounds occurs in any combustion of carbonaceous fuel, and is due more to combustion characteristics than fuel characteristics.

Brown and Davis (1973), Browne (1963), and Murty Kanury (1972) have described what takes place during combustion of forest fuels. Combining their views, we can recognize three distinct phases of decomposition within fuel particles that are consumed. These phases—pre-ignition, flaming, and glowing—occur both sequentially and simultaneously in a moving fire front.

PRE-IGNITION PHASE (PYROLYSIS PREDOMINATING)

In this phase, the fuel is heated; volatile components move to the surface of the fuel and are expelled in the surrounding air. Initially, these volatiles contain large amounts of water vapor and some noncombustible organic compounds. As temperatures increase, hemicellulose, followed by cellulose and lignin, begin to decompose and release a stream of combustible organic products (pyrolysates). Because these gases and vapors are hot they rise, mix with the oxygen in the air, and ignite—producing the second phase.

FLAMING PHASE (GAS-PHASE OXIDATION PREDOMINATING)

In the second 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. Carbon monoxide, methane, formaldehyde, organic acids, methanol, and other highly combustible hydrocarbon species are being fed into the flame zone. The products of the flame zone are predominantly carbon dioxide and water vapor. The water vapor here is not a result of dehydration as in the pre-ignition phase, but rather a major product of the oxidation of the fuel constituents.

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 products of low molecular weight (methane, propane, etc.) remain as gases after cooling. 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.

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.

GLOWING PHASE (SOLID OXIDATION PREDOMINATING)

In the final phase of combustion, the exposed surface of the char left from the flaming phase is oxidized, producing a characteristic glow. This continues, as long as temperatures remain high enough, until only small amounts of noncombustible minerals remain as gray ash. Many times the arrangement of the burning material is such that temperatures cannot be maintained, and black char is left instead of gray ash.

Fuel particles are not always consumed in a moving fire front. Because of the size, condition, or arrangement of these particles, some are pyrolyzed but not oxidized and others are only partially consumed before the flame is extinguished. From the heat still available after the flaming phase, these particles emit large amounts of smoke. Still other particles continue in flaming combustion after the flaming phase has ended. As a result dehydration, pyrolysis, solid oxidation, and scattered flaming often occur simultaneously during this last phase. Where this condition exists, this last phase is called smoldering.

In subsequent Chapters, two fire phases are described: one with convective lift and one without. These phases are related to the activity of the convection column and not to the pre-ignition, flaming, glowing, and smoldering phases just described. In the convective-lift phase most emissions are entrained into a definite convection column. In the no-convective-lift phase, most emissions are not entrained into a definite convection column. The smoldering phase described in this Chapter occurs in both the convective-lift and no-convective-lift phases.

The discussion that follows covers the gases, vapors, and suspended particulate matter found in forestry smoke. Because of the special importance of particulate matter, a separate section will follow the more general discussions of primary and secondary emissions.

PRIMARY PRODUCTS

The burning of forest fuels emits hundreds, if not thousands, of chemical compounds into the atmosphere. An appreciation of the complexity of smoke can be obtained by a quick glance at research on the chemical characterization of tobacco smoke. As of 1968, over 10,000 publications had reported the identification of over 1,200 chemical compounds. To date, over 200 compounds have been identified in woods smoke.

Amounts of carbon dioxide and water vapor emitted are indicators of burning efficiency. The more efficient the combustion, the more CO_2 and water vapor produced. As combustion efficiency decreases, the proportion of undesirable emissions increases. Efficiency varies with the fuel moisture, fuel loading, type of fire (heading versus backing), and to a lesser extent, weather conditions. Perhaps the most dramatic finding to date is that heading fires produce approximately three times more particulate matter than backing fires. Wet fuels produce substantially more particulate matter than dry fuels.

Scientists have shown that amounts of emissions per ton of fuel consumed (emission factors) vary widely (table 3). In most cases, investigators

Table 3. — Range of emission factors for components of forest fire smoke, with effect potentials

Components	Range of emission factors (pounds produced per ton of fuel consumed)	Effect potentials
Carbon dioxide	1/ 2,000-3,500	No direct
Water vapor	500-1,500	Visibility
Carbon monoxide	20-500	Health
Total suspended particulate matter	20-180	Visibility & health
Total hydrocarbons	10-40	Visibility & health 2/
Other organics	Unknown	Visibility & health 2/
Nitrogen oxides	1-9	Visibility & health 2/
Sulfur oxides	Negligible 3/	Health

1/ Values higher than 1 ton occur because of the chemical combination of carbonaceous constituents with oxygen in air to produce carbon dioxide.
2/ Includes effects from secondary photochemical products.
3/ A possible exception in the high-sulfur peat or "muck" soils.

measured only CO_2, CO, total hydrocarbons (HC), and particulate matter. In a very few instances they measured nitrogen oxides, aldehydes, and organic acids. Data on the latter groups are insufficient to estimate their emission factors with reasonable accuracy. Most studies have been limited to those emissions that are currently covered by the National Ambient Air Quality Standards.

In forest fires, the two products of complete oxidation—carbon dioxide (CO_2) and water vapor—make up over 90 percent of the mass emitted. The other 10 percent includes virtually all of the smoke and potential problem compounds. Products of major concern are carbon monoxide, particulate matter, gaseous hydrocarbons, other organic compounds, and the nitrogen oxides.

The effects of smoke from forest fires on man and his environment cannot yet be directly measured. We can only consider the potential effects of components known to exist in this smoke. The components that are potentially most harmful to humans are the volatile organic compounds and the particles. Both temporary and lasting effects must be considered. The potential for a lasting effect is reduced by the detoxification capability of the body organs. Even compounds that can act synergistically to cause cell damage at levels below the threshold effect of each compound alone are a threat only in dosages above the body's capacity for detoxification.

CARBON DIOXIDE (CO_2)

Carbon dioxide is an odorless and colorless nontoxic gas formed abundantly in nature by the decomposition of organic substances. It is exhaled by man and animals during breathing and absorbed from the air by plants for use in photosynthesis. Its only potential as a pollutant is as a contributor to the overall greenhouse effect that may be causing a rise in the Earth's air temperatures.

WATER VAPOR (H_2O)

Water vapor is important because it can affect visibility near a fire, and because it interacts with the other combustion products to reduce combustion efficiency. It is theoretically possible to produce 1,720 pounds of water from a ton of fuel at a moisture content of 30 percent. Six hundred pounds are unbound, or free water, and 1,120 pounds are from the combustion reaction.

CARBON MONOXIDE (CO)

Carbon monoxide is a colorless and odorless toxic gas. Although concentrations of this gas can be quite high (100 to 200 ppm) right at the fireline, measurements on low-intensity prescribed fires show that normal atmospheric dilution processes are quite rapid—reducing this level to below 10 ppm approximately 100 feet downwind. Although the subject has been studied in depth and is still debated, reviews of the literature by Hueter and others (1972), Bartlett (1973), and Horvath (1973) indicate that the concentrations would probably have to exceed 10 ppm for a lengthy period to produce serious effects.

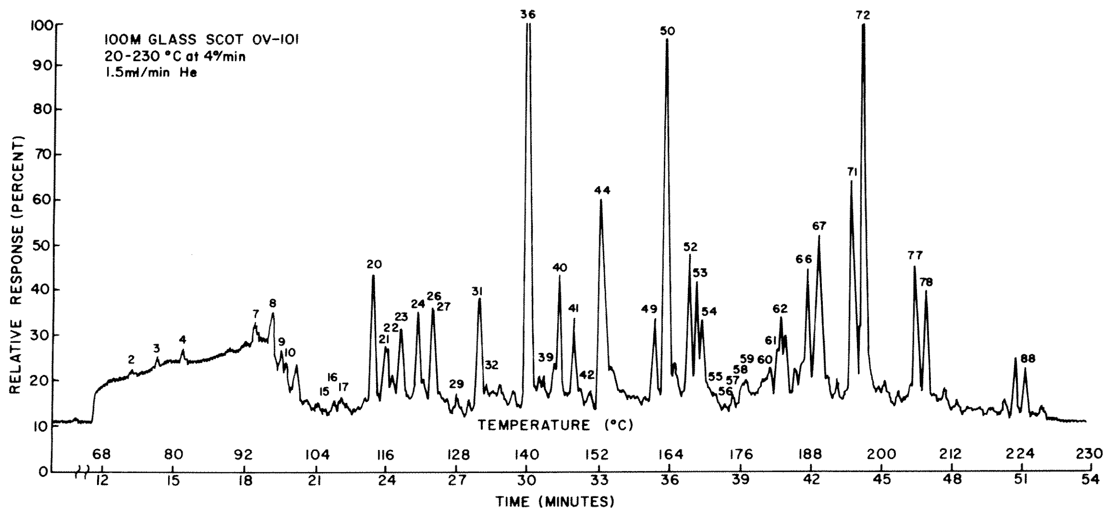
HYDROCARBONS (HC)

Hydrocarbons are organic compounds containing only carbon and hydrogen in the molecule. Two groups of hydrocarbons are particularly important potential pollutants: the low-molecular-weight olefins or unsaturated hydrocarbons and the high-molecular-weight, aromatic-type hydrocarbons. Methane, ethylene, and acetylene are the predominant low-molecular-weight hydrocarbons in forest fire smoke, comprising as much as 50 percent of the total. Lesser amounts of ethane, propane, propylene, methyl and ethyl acetylene, and butene and butane isomers have also been found. Characterization of the high-molecular-weight hydrocarbons to date is too fragmented and incomplete to draw any meaningful conclusions.

Hueter and others (1974) report that the hydrocarbons propylene, acetylene, and ethylene are known to affect plants. However, the amount of propylene in smoke is too small to be of direct concern, and both propylene and acetylene are considerably less phytotoxic than ethylene. Also, exposure from forest fire smoke is believed likely to be of too short a duration for any appreciable direct adverse effect from ethylene.

OTHER ORGANIC COMPOUNDS

In addition to the hydrocarbon organic compounds, there are literally hundreds of other organic gases and vapors in forest fire smoke. Figure 6 is a chromatogram of organic vapors



PEAK	COMPOUND
2	isopentane
2B	1-pentene
2C	furan
3	n-pentane
3A	isoprene
3B	acetone
4A	isopropanol
4B	cyclopentadiene
7	diacetyl
8	1-hexene
8A	methyl vinyl ketone
9	2-methylfuran
10	n-hexane
15	2,4-hexadiene
16	1,3,5-hexatriene
17	3-methylbutanal
20	benzene
21	cyclohexane
22	4-methylpentene
23	2,4-dimethylpentane
24	1-trans-2-dimethyl-cyclopentane
24A	sorbaldehyde (tent.)
26	2,5-dimethylfuran
26A	n-heptane
27	cis-2-heptane
29	2-vinylfuran
31	2,3-dimethyl-2-pentane
32	2,4-dimethylhexane
36	toluene
39	1-octene
40	2,3-dimethylhexa-1,4-diene
41	n-octane
42	2,3,5-trimethylfuran
44	furfural
49	ethyl benzene
50	p-xylene
50A	2-propionylfuran (tent.)
52	styrene
53	o-xylene
54	n-nonane
54A	2-isopropylfuran
55	anisole
56	2-methyl-5-isopropenylfuran
57	cumene
58	n-decane
59	camphene (tent.)
60	n-propylbenzene
61	m-ethyltoluene
62	p-ethyltoluene
66	1-decene
67	benzofuran
71	m-diethylbenzene
72	limonene
77	p-α-dimethylstyrene
78	n-undecane
88	n-dodecane

Figure 6. — Chromatogram of organic vapors in loblolly pine smoke. Each peak represents a separate compound.

sampled from a laboratory fire of loblolly pine *(Pinus taeda* L.) needles. Each peak represents a separate compound. This display includes only some of the organic compounds in smoke—principally those with 4 to 12 carbon atoms. Included in this fraction are many oxygenated compounds—mostly organic acids, aldehydes, and furans—plus many high-molecular-weight aliphatic and aromatic hydrocarbons. Several low-molecular-weight and oxygenated species, especially the carboxylic acids (formic and acetic acids, etc.) and the reactive aldehydes (formaldehyde, acetaldehyde, acrolein, etc.) have been reported as minor, but significant, constituents of woods smoke.

In extensive reviews of the health effects of volatile organic compounds, Balchum (1973) and Hueter and others (1974) point to the lower molecular-weight and more soluble aldehydes—such as formaldehyde—as irritants to the mucous membranes of the eyes and upper respiratory tract. Formaldehyde irritates the eyes, nose, and throat at levels of 0.01 to 1.0 ppm, causes discomfort at 2.0 to 3.0 ppm, and can only be tolerated for 10 to 30 minutes at 4.0 to 5.0 ppm. The higher molecular-weight and less soluble aldehydes are deep-lung irritants.

Balchum (1973) and Hueter and others (1974) have found that the unsaturated aldehydes are several times more irritating and toxic than the saturated aliphatic aldehydes. Within the saturated and unsaturated aldehydes, toxicity increases with decreasing molecular weight. For example, unsaturated acrolein can cause moderate irritation of the eyes and nose within 5 minutes at levels as low as 0.25 ppm and becomes intolerable at 5.0 ppm within this same time. In contrast, saturated acetaldehyde does not become an irritant until it reaches a concentration of 50 ppm, far above anticipated levels.

OXIDES OF NITROGEN (NO_x)

Oxides of nitrogen (NO_x) include both nitric oxide (NO) and nitrogen oxide (NO_2). NO is a colorless gas that, in contact with air, forms NO_2, a reddish-brown gas. The normal mechanism for the formation of oxides of nitrogen in combustion is through fixation of atmospheric nitrogen and oxygen in the burning zone, principally at temperatures above 1,600° C. This is above temperatures normally occurring in prescribed forest fires. However, these temperatures could be achieved in piled slash or wildfires.

Nitric oxide can also be formed at lower temperatures in the presence of hydrocarbon-free radicals (Ay and Sichel 1976). Significant amounts of nitric oxide may be formed in this way in forest fires. Nitrogenous compounds in forest fuels are another potential source of oxides of nitrogen in emissions. Information on nitrogen oxide emission rates from forest fires is scanty and inconclusive.

NO_2 is about four times more toxic than NO and exerts its primary effect on the lungs. However, based on the reviews of Hueter and others (1973) and Shy (1973), concentrations far exceeding those expected of a forest fire are required for direct effects on man. The real importance is in the formation of a whole train of secondary products.

SULFUR OXIDES (SO_x)

Sulfur oxides are probably produced only in negligible quantities because most forest fuels contain less than 0.2 percent sulfur. Sulfur oxides have not yet been detected in forest fire smoke. A notable exception is certain organic soils in Florida which have a sulfur content of about 4 percent and are under current investigation.

SECONDARY PRODUCTS

We have briefly reviewed the major findings on primary or fire-produced emissions and their effects. As smoke plumes travel through the atmosphere, secondary products can be generated through mixing of primary effluents or photochemical activity. Evans and others (1974), for example, reported formation of ozone in the upper layer of a smoke plume when it was irradiated with sunlight. Some secondary products are more harmful than the primary products, and some are harmless.

Health effects due to the interaction of particulate matter and sulfur dioxide have been found in numerous air pollution studies (Engel and others 1971, National Academy of Sciences 1973 and 1975). Our current studies, while only yielding tentative results, tend to confirm that these and other secondary reactions will take place.

PARTICULATE MATTER

In this Guidebook, particulate matter is defined as any dispersed aggregate matter, solid or liquid (other than water), that for practical purposes is larger than about 0.002 micron in diameter, but smaller than 500 microns in diameter. The size, shape, porosity, density, and other physical properties of particulate matter are highly variable. Aerosol, another often-used term, is considered here to mean small, airborne particulate matter.

Particulate matter remains suspended in the atmosphere for periods of a few seconds to several months. Suspended particulate matter is that portion which, because of its small size (below 5 to 10 microns in diameter), is transported long distances in the atmosphere and has the greatest potential for environmental impact. Suspended particles are of greatest concern in smoke management.

The most obvious environmental effect of smoke from prescribed forest fires is a reduction in visibility. This effect is caused by the particles that absorb and scatter light, washing out the contrast that exists between the source and its background. These particles can also scatter the sunlight that illuminates the air between the source and the receiver, again washing out the contrast as distance increases. This temporary reduction in visibility can hinder safe operation of aircraft and automobiles or the enjoyment of scenic vistas.

The soiling ability of larger carbon-type particles is another environmental effect of forest fires; but in prescription burning, these particles tend to fall out of the smoke column close to the fire rather than adding to the general pollution level.

Figure 7. — A reduction in visibility is the most obvious adverse effect of smoke on the environment.

A term that is increasing in popularity and significance is fine particulate matter (or sometimes, respirable suspended particulate [RSP]) which comprises particles below 2 to 3 microns. These have an especially long residence time in the atmosphere, contribute to smog formation, and penetrate deeply into the lungs. Also, they may act synergistically with gases or other particles.

According to the review of Engel and others (1971), particulate matter may contribute to accelerated corrosion of metals upon which they are deposited by sorbing corrosive chemicals from the atmosphere. Almost all of this information comes from studies of urban versus rural areas where gaseous pollutants in the urban areas are adding to the corrosion.

Health effects of particulate matter are determined by three properties: size, sorption, and chemical composition. Sizes of particles are important because of their relation to different parts of the respiratory system. The three main parts of the respiratory system are the nasopharyngeal, tracheobronchial, and pulmonary. Of these, the upper two contain cellular tissue with hairlike outgrowths (cilia) covered with mucus, and the lower one contains moist cellular tissue covered by a surface-active material to prevent the collapse of the air sacs at the end of respiration. Through inertial impaction and gravitational settling, the larger particles are deposited in the upper two parts of the system and then expelled. As the size decreases below 5.0 microns in diameter, increasing numbers are deposited in the lower respiratory tract—including over 50 percent of those between 0.01 and 0.1 micron that penetrate this far. Many forest fire smoke particles, as shown in the physical properties subsection, have a potential for being deposited deep in the lungs.

Sorptive properties of particles make them potential carriers of toxic material. In a review of the effects of particles on health, Engel and others (1971) found that formaldehyde, which does not itself readily penetrate the upper respiratory tract, is carried to the lungs by adsorption to small particles—causing increased toxic effect. In their review of hydrocarbons, Hueter and others (1974) found that the toxicity of acrolein and formaldehyde (both constituents of forestry smoke), when in the presence of certain inert aerosols, appeared more toxic to mice.

Particulate matter can consist of just a few easily analyzed solid inorganic compounds as in some industrial smoke, or it can consist of several hundred liquid and solid compounds in a complex organic/inorganic matrix as in certain natural aerosols. Examples of natural particulate matter are: (1) the coarse, inorganic mineral dust particles derived from windblown soil, (2) the inorganic sea-salt particles emitted from the oceans, (3) the powderlike, organic pollens from plants, and (4) the organic aerosols produced by forest fires.

Solvent extractions with benzene have traditionally been used to estimate the amount of organic compounds in particulate matter. The benzene soluble organic (BSO) fraction of particulate matter from fires in various southern fuels has been found to range from 40 to 75 percent. Some of this variation is due to the type of fire. In comparison, the average BSO fraction of ambient air particulate matter is about 8 percent.

The BSO percentage, while a measure of the organic content of particles, gives no information about the individual organic compounds. Very little of the chemical analysis required for this has been accomplished for forest fire particles. However, a considerable amount of analysis of the smoke in flavoring food, from tobacco, and from burning building materials has been completed. Those analyses that covered the burning of cellulose, hemicellulose, and lignin have identified several hundred organic compounds in the particulate matter. These compounds, expected to be a part of forest fire smoke, are categorized in the general classes: organic acids, alcohols, aldehydes, furans, ketones, and aromatic compounds. The aromatic compounds include the esters, phenols, and polycyclic organic matter.

POLYCYCLIC ORGANIC MATTER

Polycyclic organic matter (POM) is of special interest in smoke management because it is a class of compounds containing many physiologically active substances. Benzo(a)pyrene (BaP) and other implicated carcinogens are usually found in POM.

POM is formed by the pyrosynthesis of small carbon fragments into large hydrocarbon molecules in the low-oxygen region of combustion processes. It is found in virtually all burning which involves carbonaceous fuels. Production of POM is more dependent on the conditions of the fire than the type of carbonaceous fuel. For example, inefficient, residential coal furnaces produce substantially more benzo(a)pyrene per unit of fuel consumed than do more efficient coal furnaces in power plants (National Academy of Sciences 1972).

In recent laboratory experiments, BaP concentrations were measured in the smoke from burning slash pine (*Pinus elliottii* Engelm.) needles. With the laboratory burning tray on a slope of 50 percent, heading and backing fires (two replicates) were set at three loadings (pounds per square foot) each.

Heading fires, as expected, usually produced more particulate matter per ton of fuel at a given fuel loading (table 4). Backing fires, however, produced substantially more benzo(a)pyrene, especially at light loadings.

Within heading fires, the smoldering phase produces higher amounts of both BaP and particulate matter than the corresponding flaming phase (table 5).

The differences in BaP production can be explained partly by the conditions required for its formation—moderately high temperatures, low oxygen, and long residence times in the reaction zone. Carbon fragments in the slow-moving, backing fires (especially the light loadings) remained under these optimum formation conditions substantially longer than in the heading fires. Within heading fires the carbon fragments in the

Table 4. — Benzo(a) pyrene (BaP) and total suspended particulate matter (TSP) from burning pine needles 1/

Type of fire and fuel loading (pounds per square foot)	Emissions	
	Benzo(a)pyrene	Total suspended particulate matter
	ng/g 2/	Pounds per ton 3/
Backing:		
Light (0.1)	3,500	22
Medium (0.3)	560	8
Heavy (0.5)	240	5
Heading:		
Light (0.1)	38	22
Medium (0.3)	40	88
Heavy (0.5)	100	129

1/ Fuel moisture content for all fires ranged from 18 to 27 percent.

2/ Nanograms of benzo(a)pyrene per gram of fuel burned. A nanogram is 0.000000001 gram.

3/ Pounds of total suspended particulate matter per ton of fuel burned.

smoldering phase, even though at less than optimum BaP formation temperatures, are subject to these conditions for substantially longer periods than in the corresponding flaming phase.

The benzo(a)pyrene levels shown in tables 4 and 5 are generally in the ranges reported elsewhere for open burning of landscape refuse, grass clippings, leaves and branches (National Academy of Sciences 1972), and hardwood leaves (Jones 1975). The one exception is the value we observed for lightly loaded backing fires. That value is about 10 times what we might have expected from reading earlier study results.

Table 5. — Benzo(a)pyrene (BaP) and total suspended particulate matter (TSP) from flaming and smoldering phases of burning pine needles 1/

Fire phase and fuel loading (pounds per square foot)	Emissions: Benzo(a)pyrene	Emissions: Total suspended particulate matter
	ng/g 2/	Pounds per ton 3/
Flaming:		
Light (0.1)	33	14
Medium (0.3)	17	17
Heavy (0.5)	36	40
Smoldering:		
Light (0.1)	100	59
Medium (0.3)	55	143
Heavy (0.5)	140	192

1/ Fuel moisture content for all fires ranged from 18 to 27 percent.
2/ Nanograms of benzo(a)pyrene per gram of fuel burned. A nanogram is 0.000000001 gram.
3/ Pounds of total suspended particulate matter per ton of fuel burned.

General conclusions about benzo(a)pyrene in forestry smoke cannot be drawn at this time. The levels we found in our limited number of laboratory fires were very low to moderate. Our data may indicate, however, that one should be cautious in declaring backing fires to be the cleanest. It is true that backing fires can be expected to produce a lower volume of all particulate matter than heading fires. But, it appears that some backing fires can be expected to produce more BaP than heading fires.

PHYSICAL PROPERTIES

The particulate fraction of forest fire smoke is highly variable. As we have shown, this high variability is not only in the mass produced but also in the size, shape, porosity, density, and other physical properties of individual particles. Particles are responsible for two major smoke problems: respiratory effects and visibility reduction. Respiratory effects have been discussed previously.

Visibility reduction is caused by the scattering of light by the particles. All particles do not scatter light to the same degree. Those having diameters within the wavelength of visible light, between 0.3 and 0.8 micron, cause the maximum scattering. Unfortunately, these sizes of particles remain suspended in the air the longest.

Particle Formation

The majority of particles in forest fire smoke are formed from the gaseous organic compounds produced by pyrolysis and combustion. Nucleation, condensation, and coagulation form both liquid and solid particles ranging upward in size from about 0.002 micron. From 60 to 70 percent of the total particles produced are liquid. These are formed into a spherical shape by the condensation of organic vapors and range from the highly volatile and short lived to the long lived, tarry, and viscous. Figure 8 is a photomicrograph that shows both the spherical liquid particles and the irregular solid particles.

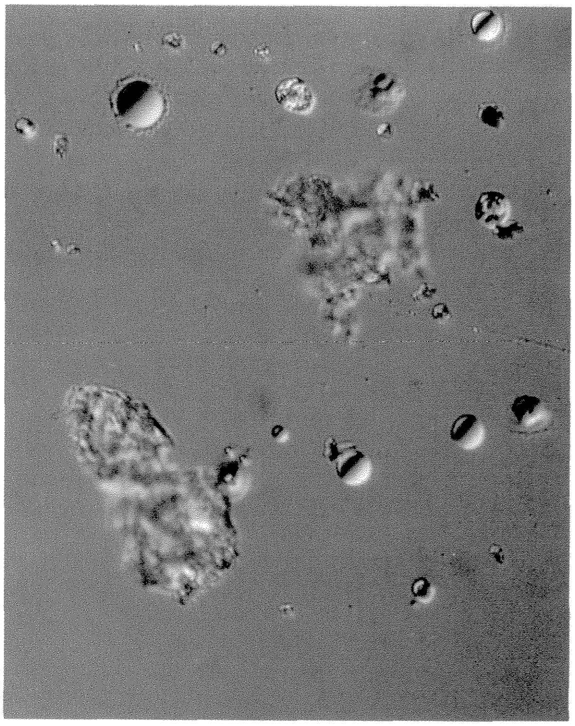


Figure 8. — Liquid particles are spherical, whereas solid particles are irregularly shaped. Characterizing particle shapes often helps in evaluating environmental effects.

Solid particles created by the combustion process, particularly the smaller ones, can also assume a spherical shape. More commonly, however, they assume other forms that approximate flattened discs, angular cubes, and long, chainlike agglomerates. Sizes of the solid particles range from 0.01 micron to 5 microns in diameter. Frequently, the small particles will bind together to produce larger agglomerates that vary in shape from roughly circular to long, slender, chainlike masses. Figure 9 is a scanning electron micrograph illustrating these agglomerated particles.

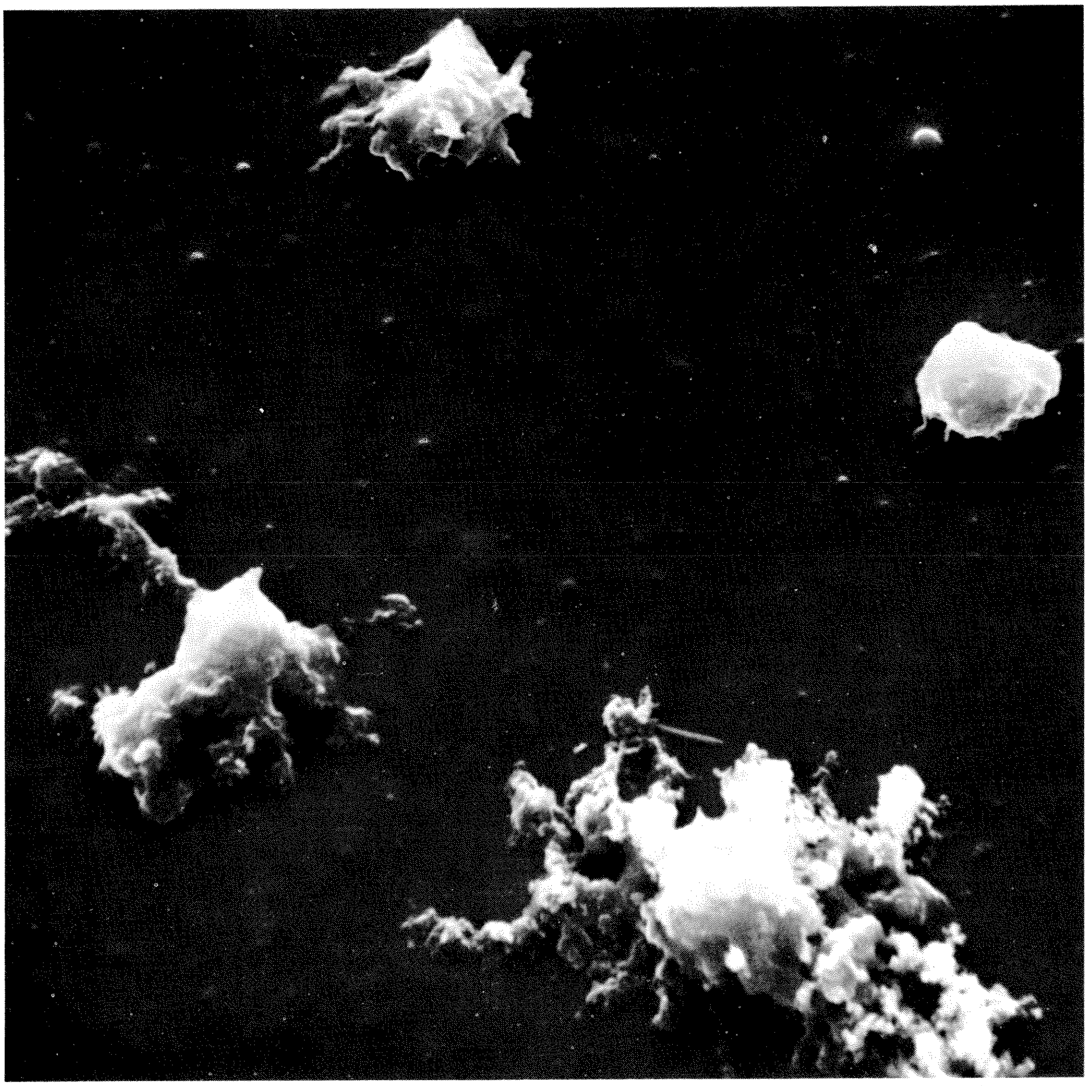


Figure 9. — A scanning electron micrograph shows angular nature of solid primary particles and the aggregation of small particles into long, chainlike masses.

Particles are also formed by the mechanical action of turbulent forces present in the fire zone. These forces simply break up the fire-weakened fuel and lift small pieces into the heated air column over the fire. Initially, mechanically formed particles are fewer in number but usually are larger and have more mass than the chemically produced ones. Figure 10 shows this type of particle.

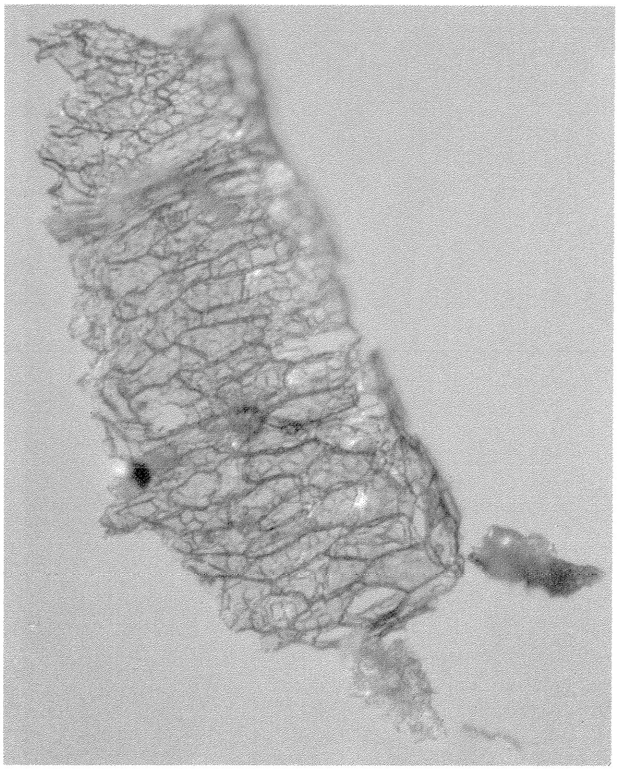


Figure 10. — A large, mechanically formed particle. Notice that plant structures can still be identified.

Mass Distribution

Particles are produced in a wide range of sizes. The amount of particulate matter in each size category is called the size distribution, which can be expressed as mass or number of particles. We report both mass and number distributions because some effects are more closely related to mass distribution and others to number distribution. In addition, no existing instrument can measure the full range of sizes. Expensive instruments are available to measure very small particles; they usually record number distributions. Commonly available instruments for measuring larger particles usually record mass distributions.

A particle's mass, in combination with its size and shape, determines its aerodynamic size. Aerodynamic size equates an irregular shape to a sphere and can be much different than physical size. The solid and liquid particles in figure 8, although of obviously different physical sizes, are the same aerodynamic size. Aerodynamic size is more closely related to particulate matter dispersion and respiratory effects, while physical size is more related to visibility effects.

We sampled the aerodynamic mass size distribution of particulate matter from several experimental backing fires in slash pine and palmetto-gallberry fuels of Georgia and Florida. About 70 percent of the particle mass from the slash pine fires was less than 0.4 micron in diameter, and 95 percent was less than 1 micron. Similar results have been reported from other studies in the United States and elsewhere. In the smoke from Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco) fires in the Northwest, 69 percent of the particle mass was found to be less than 0.3 micron and 82 percent less than 1 micron (Sandberg and Martin 1975). Additional information collected with a scanning electron microscope showed that most single, spherical particles were about 0.1 micron in diameter. Particulate matter in the smoke from burning rice residue was found to have mass median diameters that range from 0.1 to 0.3 micron (Goss and Miller 1973). Reports from Australia and England show that woods smoke particles are about 0.1 micron in diameter (MacArthur 1966 and Foster 1960).

Number Distribution

A recently developed instrument has given us the opportunity to measure the lower range of particle distribution. It was used in field experiments during the 1974-75 fire season. These distributions (fig. 11) are from fires in longleaf-slash pine needles in Louisiana, a sawgrass stand in the Everglades of Florida, light brush under a loblolly pine stand in Georgia, and light brush under a loblolly pine stand in North Carolina. Samples were collected at distances from the fire site of 0.3 mile to 3.5 miles, except in Florida where the distance was 12 miles.

Certain properties of the size distributions of particles can be discovered by comparing the number distributions (fig. 11) with the mass distributions (fig. 12). Merging values from the two distributions, we found that the average diameter of particles in forest fire smoke is approximately 0.1 micron, and that this average is approximately the same for fires in all fuel types.

In general, only particles smaller than 10 microns can be expected to pose problems at distances greater than ½ to 1 mile from the source of production. Particles larger than 10 or 20 microns will usually be removed from the atmosphere by gravitational forces within this distance. There are, of course, exceptions caused by extreme

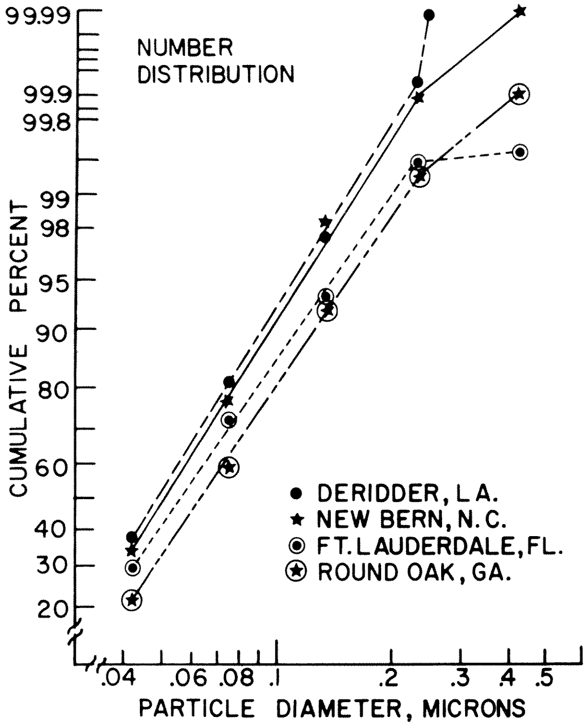


Figure 11. — Size distribution for particles smaller than about 0.5 micron. Distribution is based on numbers of particles.

windspeeds or by specialized particle growth conditions high in the atmosphere. Particles found by aircraft samplings of forest fire smoke plumes are rarely larger than 10 microns.

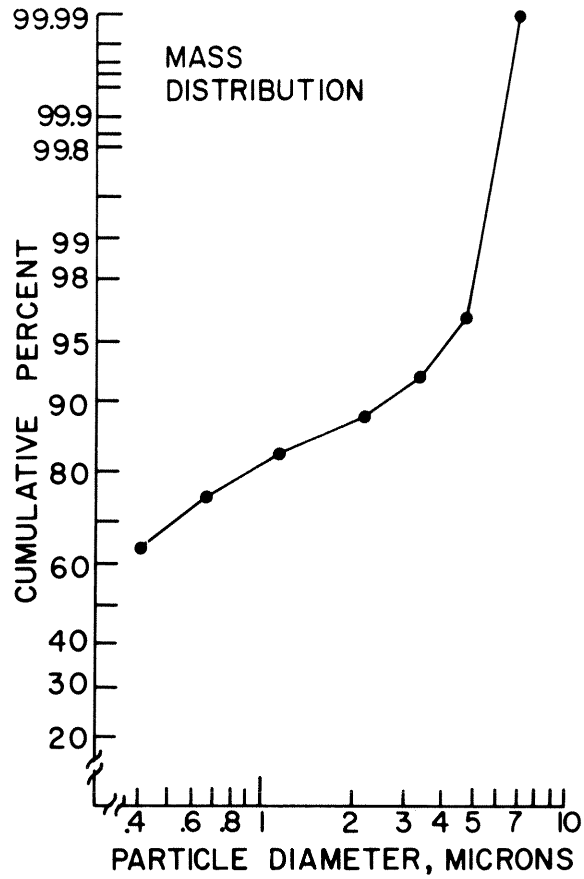


Figure 12. — Distribution of particles larger than 0.4 micron. Distribution is based on mass.

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CHAPTER III

AIR QUALITY ADMINISTRATION

by

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This Chapter reviews the legislation and regulations passed to maintain air quality. It also introduces a voluntary decision procedure proposed for forestry smoke management.

THE FEDERAL CLEAN AIR ACTS

Interest in Federal clean air legislation began to accelerate in 1955 when Congress provided for investigations into the nature and extent of the Nation's air pollution problems. With the passage of the Clean Air Act of 1963 (PL 88-206), Congress encouraged the first air pollution abatement programs by providing Federal funds to assist in State and local control efforts and by establishing limited authority to abate interstate air pollution. Amendments to the 1963 Act in July 1967 increased the powers of the Secretary of the Department of Health, Education, and Welfare to implement air pollution abatement programs anywhere in the United States. The amendments included provisions to:

Request injunctions to abate emissions

Designate air quality control regions

Establish air quality standards for the above regions in the absence of effective State action

Enforce the above standards

Establish interstate air quality planning commissions; in lieu of action by the affected States (Stern 1971).

The Clean Air Act of 1970 greatly increased Federal powers and responsibilities. Section 101, paragraph (b) of the 1970 Clean Air Act lists as its purpose:

"To protect and enhance the quality of the Nation's air resources so as to promote the public health and welfare and the productive capacity of its population" (U.S. Code: 42 U.S.C. S. 1857), while at the same time encouraging additional State and local regulations.

A REVIEW OF KEY SECTIONS OF THE 1970 CLEAN AIR ACT (PL 91-604) APPLICABLE TO FORESTRY PRESCRIBED BURNING

SECTION 108: AIR QUALITY CRITERIA AND CONTROL TECHNIQUES

The Environmental Protection Agency Administrator is directed to identify and publish a list of air pollutants. Included in this list is particulate matter.

SECTION 109: NATIONAL AMBIENT AIR QUALITY STANDARDS

The EPA Administrator is required to establish national primary and secondary ambient air quality standards for the pollutants identified in Section 108. The primary standard is set at a level necessary to protect the public health, while the secondary standard is set at a level to protect the public welfare from any known or anticipated adverse effects of a pollutant. Table 6 lists the levels of pollutants thus far identified by the standards as being adequate to protect the public health and welfare.

Table 6. — National primary and secondary ambient air quality standards 1/

Pollutant	Type of standard	Averaging time	Frequency parameter	Concentration	
				μg/m³	Ppm
Carbon monoxide	Primary and secondary	1 hr	Annual maximum 2/	40,000	35.0
		8 hr	Annual maximum 2/	10,000	9.0
Hydrocarbons (nonmethane)	Primary and secondary	3 hr (6 to 9 a.m.)	Annual maximum 2/	3/ 160	3/ 0.24
Nitrogen dioxide	Primary and secondary	1 yr	Annual arithmetic mean	100	0.05
Photochemical oxidants	Primary and secondary	1 hr	Annual maximum 2/	160	0.08
Particulate matter	Primary	24 hr	Annual maximum 2/	260	—
		1 yr	Annual geometric mean	75	—
	Secondary	24 hr	Annual maximum 2/	150	—
		1 yr	Annual geometric mean	4/ 60	—
Sulfur dioxide	Primary	24 hr	Annual maximum 2/	365	0.14
		1 yr	Annual arithmetic mean	80	0.03
	Secondary	3 hr	Annual maximum 2/	1,300	0.05

1/ Adapted from Federal Register (1971).
2/ Not to be exceeded more than once per year.
3/ As a guide in devising implementation plans for achieving oxidant standards.
4/ As a guide to be used in assessing implementation plans for achieving the annual maximum 24-hour standard.

SECTION 110: IMPLEMENTATION PLANS

Each State must develop and submit for Federal approval a comprehensive plan identifying the strategy that the State intends to follow in order to attain and maintain the National Ambient Air Quality Standards. A State may revise its State Implementation Plan (SIP) at any time and, in turn, may be required to revise its plan by the Environmental Protection Agency (EPA) if it is found to be substantially inadequate.

SECTION 113: FEDERAL ENFORCEMENT

This Section also provides for Federal enforcement of an SIP where violations appear to be caused by a State's failure to enforce its own SIP. The EPA can initiate court actions against polluters violating an applicable provision of an SIP.

SECTION 114: INSPECTIONS, MONITORING, AND ENTRY

Onsite inspection of emission sources is authorized (U.S. Environmental Protection Agency 1970).

STATE AND LOCAL AIR QUALITY REGULATIONS 1/

Most States have granted variances from air pollution control rules to valid forestry burning practices. This could be done under the provisions of the Clean Air Act because these operations have not been identified as a *major* source of particulate matter.

1/ Portions of this Section were contributed by Joan B. Boilen, Attorney, Legal Support Branch, U. S. Environ. Prot. Agency, Reg. IV, Atlanta, Ga., 1975.

When emissions from major sources are reduced, lesser sources may be expected to receive more attention. Control of major sources alone may not be sufficient to achieve local ambient standards. Then, reduction of emissions from minor sources may be required. Some southern States are bringing prescription burning under control by requiring permits, and some have specified certain conditions limiting open burning. A few counties have curtailed all open burning.

The following are examples of some of the more stringent State regulations affecting forestry prescription burning in the South:

> In Arkansas, open burning is prohibited within specified distances of certain population centers except for fires used for purposes of forestry management, provided fires are set and burned when winds are blowing away from populated areas.
>
> In Florida, open burning is allowed between 9:00 a.m. and 1 hour before sunset with permission of the State Division of Forestry, or at other times when allowed by the Division and when dispersion of air pollutants is reasonably assured.
>
> In Georgia, counties with populations exceeding 65,000 allow open burning only if adequate disposal facilities are not reasonably available. In all counties, no smoke of a shade darker than a No. 2 on a Ringelmann chart (a means by which opacity of smoke plumes is judged by visual observation) is permitted—except for a reasonable period to get the fire started.
>
> In South Carolina, open burning specifically for forestry management is excepted from a general ban when practices acceptable to the State Board of Health and Environmental Control are followed, and when no undersirable levels of pollutants are or will be created.
>
> In Tennessee, forestry prescription burning exceptions include provisions that no public nuisance is created, and that no land, air, or water traffic hazard is created. Distances from certain specified land-use areas (e.g., 1/2 mile from a secondary highway) are also imposed as restrictions on burning.

The importance of having an up-to-date knowledge of traditional State and local air quality regulatory requirements is evident from these examples. In addition, the forestry smoke manager needs firsthand knowledge of specific concerns in each Air Quality Control Region (AQCR) and in any Air Quality Maintenance Area (AQMA) where he works.

AIR QUALITY CONTROL REGIONS AND MAINTENANCE AREAS [2/]

The primary air quality administrative area is the Air Quality Control Region (AQCR). These areas were designated on the basis of geographical and meteorological considerations, as well as political boundaries. For this reason, they may transcend State or county borders.

Initially, in 1971 these AQCR's were classified Priority I, II, or III based upon existing air quality to assist States in planning. In each AQCR the sources of air pollution were identified and control measures adopted that, after analysis, were felt to be sufficient to provide for attainment of the National Ambient Standards upon implementation.

In 1973, a court decision required EPA to disapprove all State Implementation Plans (SIP's) for not providing for maintenance of the ambient standards beyond the attainment date of mid-1975. The court held that SIP's had addressed the growth of pollution sources and their related air emissions only until the time when standards would be attained, and not beyond. Further, the court made clear the Clean Air Act required the development of a plan that included provisions for continuing attainment and maintenance of the ambient standards well beyond the attainment date. In response to the court's decision, EPA developed procedures for each State to use in assessing the maintenance issue. Each State was asked to review the air quality within its jurisdiction and identify those areas (usually counties) that, due to anticipated growth, had the potential to violate the ambient standards during the forthcoming 10-year period. These areas were identified as Air Quality Maintenance Areas (AQMA's).

In most cases, the area designated as an AQMA is only a portion of an AQCR. Usually the AQMA is urban as well as the surrounding area expected to be affected by the same growth potential. Designation of the AQMA's was completed in September 1975. Much emphasis has been placed on these AQMA's by each State in their reviews of growth and its impact on air pollution. The States are assessing strategies that, upon application, will provide continuous maintenance of the ambient standards.

2/ Portions of this Section were contributed by William M. Burch, Chief, Air Strategy Dev. Sect., Air Programs Branch, Air and Hazardous Mater. Div., U.S. Environ. Prot. Agency, Reg. IV, Atlanta, Ga., 1975.

PREVENTION OF SIGNIFICANT DETERIORATION

Additional court decisions involving interpretation of the Clean Air Act resulted in the development of the EPA program to prevent significant deterioration (PSD) of air quality. The Administrator put this program into effect on December 5, 1974 (Federal Register 1974).

These PSD regulations combined the concept of area classification with new source review procedures and the application of best available control technology. The preconstruction review of all new and modified sources now including 19 major categories (but not forestry burning) is designed to prevent their violating allowable increments of deterioration and to assure the employment of best available control technology (Federal Register 1975). States are being encouraged to accept a delegation of authority to implement this review process fully.

While the regulations are directed to specifically named stationary sources, their importance to other sources lies in area classification by classes.

The regulations stated that, effective January 6, 1975, all areas are designated Class II and restrict deterioration to that associated with normal, well-controlled growth. With the 1974 air quality regulations as a baseline, States may decide if areas should remain Class II or should be either Class I that restricts deterioration to a minimum, or Class III that levies no additional restrictions beyond State plan requirements and considers any deterioration as insignificant as long as no national standards are violated. These class designations differ from the priority classification discussed earlier in that they indicate levels of air quality to be maintained, whereas the priority classifications indicate the urgency to apply pollution abatement measures to the areas so designated.

A VOLUNTARY DECISION PROCEDURE PROPOSED FOR FORESTRY SMOKE MANAGEMENT [3/]

Even though the main focus of air quality regulations has been on stationary and automotive sources of emissions, southern forest managers have sought a method by which they may voluntarily help to avoid unwanted environmental consequences from prescription burning. In the preceding sections of this Chapter, we have reviewed an evolving framework of air quality administration. In Chapter I we discussed alternatives to burning, and in Chapter II we examined the characteristics of forestry smoke likely to bear on future increased regulatory interest, locale by locale.

A single forestry burn will seldom be an important emitter more than a few hours on 1 day every 3 or 4 years. It may, however, contribute emissions of consequence to a given atmosphere when the pollution load is already high, or when concentrations temporarily exceed locally acceptable levels. Because they are based on long-term health studies, regulations and standards established for stationary and mobile sources of emissions do not lend themselves well to decision procedures for these transitory forestry sources. For example, standards are usually expressed as concentrations averaged over times longer than a forestry burn would last. Because of this, a time/concentration adjustment could be made which would still be within established standards; the adjusted concentration could, however, be intolerable when judged by other criteria such as highway safety or personal respiratory difficulties.

In some areas of the United States, carrying capacity of the atmosphere is estimated within certain boundaries. This approach is called the "Tank Concept" in that this supposed finite atmosphere is regarded as having limiting "walls" and a "lid." We have rejected this concept because it does not adequately represent actual dispersion, particularly in the initial stages.

Our proposal will be fully presented in Chapter VI, after discussions in Chapters IV and V on the important variables affecting the procedure. We believe the proposal will lend itself well to self-regulation or to agency administration. It emphasizes decisions for the single forestry burn, but also recognizes multiple contributions from other forestry burning or fixed sources. A major gain in air quality will be achieved in some locales if the procedures for multiple-source forestry burns are applied by mutual agreement between burners.

Currently the best available control technology (also used in many similar instances) is to limit the escape of particulate matter into the atmosphere, regardless of the size or chemical composition of the particulate matter. We have

3/ Contributed by Southern Forest Fire Laboratory personnel who developed the Decision-Logic presented in Chapter VI.

adapted this control technology to short-term or instantaneous concentrations.

Very small chemically reactive particles have a greater potential to impair health than large chemically inert particles. Regulatory agencies are placing increased emphasis on controlling more harmful components. Limiting strategies under development will thus likely be more specific.

While many tedious operations are needed for decisions in complex situations, the basic procedure involves just five main steps:

1. Predicting a smoke plume trajectory

2. Identifying key targets along this trajectory (in this text, targets denote locations where smoke concentrations are more likely to have unwanted effects; e.g.: an AQMA, a "sensitive" community, an airport, a road, a highway, a townsite, etc.)

3. Selecting a maximum acceptable particulate matter concentration for each key target identified

4. Determining the "background" pollutant level within the target area, then adding this to the prescribed fire concentration predicted to reach the zone where the target is identified

5. Comparing the maximum acceptable concentration in No. 3 with the total concentration in No. 4.

Selection of a maximum acceptable concentration in No. 3 above can be either as determined by a special ambient air quality requirement in effect or desired, or as dictated by a need to maintain a certain level of visibility. In the procedure described in Chapter VI, either type of value can be selected by the decisionmaker. There is an implication in the literature that public complaints are more closely associated with visibility reductions and with effects of visibility impairment on highway and air traffic safety. Decisionmakers arriving at acceptable concentrations may also be influenced by the current indication that visibility-determined concentrations for total suspended particulate matter are more stringent than those suggested by published human health effects (U.S. Department of Health, Education, and Welfare 1969).

Figure 13. — A first step in smoke management is to identify potential targets — areas that might be adversely affected by the smoke from a prescribed burn.

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CHAPTER IV
FUELS, FIRE BEHAVIOR, AND EMISSIONS

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This Chapter prepares you to predict the amount of particulate matter emitted and the rate of heat release from deliberate burning of forest fuel. Making these predictions requires estimates of the amount of fuel that will burn, the rate at which fire will spread, the amount of particulate matter that evolves per ton of fuel burned (called emission factor), and the heat yield of the fuel.

The material presented is organized as follows: variables affecting emissions and fire phases, heat release rate, emission rate, specific information by fuel types, and a conclusion. Although many fuel complexes are present in the Southeast, only the major types in which most of the prescription burning is done will be discussed. The identification of each fuel type is generally based on its vegetative cover and, to some extent, on the ecological province it occupies. The major fuel types discussed in separate sections are: grasses, pine needle litter, palmetto-gallberry, light brush, and pine logging debris.

VARIABLES AFFECTING EMISSIONS AND FIRE PHASES

Emissions of particulate matter are influenced by many variables as are fire phases. These are reflected in fuel loading, rate of spread, burning method, and combustion stage.

FUEL LOADING

It is important to understand the difference between *total* fuel and *available* fuel. *Total* fuel is the entire accumulation of vegetative matter, living or dead, that could possibly burn if properly conditioned. *Available* fuel is that portion of the total fuel that will be consumed by a fire during the burning period following ignition. While available fuel is needed in the emission rate and heat release rate equations, total fuel must be estimated before the available value can be calculated.

Three layers of litter will eventually develop on an undisturbed forest floor: a top litter layer (L), a fermentation layer (F), and a humus layer (H). When sampling, the two upper litter layers (L + F) can be grouped. These L + F layers account for most of the fuel consumed during prescription burns (Hough 1968). During droughts, considerable humus can also burn. Live vegetation in the understory must also be accounted for since it will be consumed in varying degrees, depending on the burning conditions.

RATE OF SPREAD

Rate of fire spread must be known to compute *particulate matter emission rate* and *heat release rate to the atmosphere* from prescribed fire.

The rate at which fire advances through a forest fuel usually depends on windspeed and on size, arrangement, and moisture content of the surface litter and understory fuel. An exception is when the fire is backing against the wind. In that case differences in windspeed have a negligible effect on spread rate, and a windspeed of zero should be used when entering the rate of spread tables.

Fire spread rates vary by fuel type because of differences in fuel type and arrangement. They are, therefore, discussed individually in the Guidebook.

BURNING METHOD

The burning method employed will depend upon the kind of area to be burned and the burning conditions. There are four main categories of burning method:

Backing fires are those that are ignited on the downwind side of an area and permitted to spread (or "back") against the wind.

Heading fires are ignited on the upwind side of an area and permitted to spread (or "head") with the wind.

Sometimes, *backing* or *heading fires* are ignited in strips and allowed to burn together.

Ring fires are ignited on all sides of an area to be burned.

Area-ignited fires or *simultaneous-ignition fires* are those that are ignited in many places at about the same time to result in many small fires burning together.

Often, combinations of these categories are used.

Burning is generally done in two kinds of areas. In the first, a tree overstory exists and considerable understory and/or litter are to be removed. The fuel is generally natural plant accumulations that increase with time, although logging residue from thinnings may also be present. In the second kind of area a tree overstory no longer exists, but there is fuel on the ground. This fuel results from clearcut logging or brush clearing.

When burning under a tree overstory, timber managers must be sure their fires do not seriously damage or destroy crop trees. A manager usually waits for those days when winds are likely to remain steady for the burning period. He can then ignite the downwind side of his area and allow the fire to back slowly against the wind. If fuel loading is not excessive, intensity of a heading fire may be acceptably low.

When burning areas free of an overstory, there is obviously no need for concern about damage to an overstory. The main purpose of such burns is to consume as much fuel as possible on the area. Only precautions to prevent fire escape, to minimize air pollution downwind, to avoid soil damage and unwanted runoff of ash, etc., need be considered. High-intensity heading fires are generally used when the fuel is dispersed over the area. Such fires will usually jump gaps in fuel continuity.

There are times, especially in land-clearing operations, when much of the fuel exceeds 2 inches in diameter. If disposal of the large material by burning is desired, some form of piling is necessary. Concentrating the fine fuel with the large, allowing the entire mass to dry, and igniting the pile perimeters quickly to get rapid heat buildup will permit the large fuel elements to be ignited and eventually consumed.

Burning method affects rate of fire spread, rate of particulate matter emission, and amount of fuel consumed. In heading fires, a relatively large amount of fuel is consumed during the residual combustion stage, and more particulate matter is produced per unit of fuel burned.

COMBUSTION STAGES

We will discuss combustion in two main stages: *advancing-front stage* and *residual stage.* These stages may be broken down into substages to further characterize the fire behavior. For example, the *advancing-front stage* is usually a *flaming front,* but can also be a *smoldering front.* For the burning situations covered in this Guidebook, only the two main stages are important to determining separate emission factors (EF) and emission rates (ER) due to marked differences in quantities of particulate matter emitted in these stages.

FIRE PHASES

For convenience, we have separated fires into two phases: *convective-lift phase* and *no-convective-lift phase.* The *convective-lift phase* is when most emissions are entrained into a definite convection column because of heat being released from the fire. The *no-convective-lift phase* is when most emissions are not entrained into a definite convection column. Heat release rate will be of consequence to the plume rise of the *convective-lift phase,* but of no consequence to the *no-convective-lift phase.*

MINIMIZING DURATION OF THE NO-CONVECTIVE-LIFT FIRE PHASE

Long-duration residual combustion involves humus, organic soil, and large fuel elements such as stumps, snags, and logs. Decaying stumps and snags exceeding 10 inches in diameter contribute most to long-duration residual combustion. Large pieces of sound wood are not easily ignited during the relatively brief exposure to the flaming front of a prescribed fire. When ignition does occur, the rapid departure of reinforcing heat from surrounding sources causes quick flameout, and smoldering in sound wood is short lived. This Guidebook does not address the problem of long-duration residual combustion in detail because the great variability does not now permit a standard handling procedure. There are, however, some safeguards that can be observed to minimize troublesome emissions during the associated no-convective-lift phase of fires.

Rate of stump deterioration following timber cutting was observed in the Coastal Plains of Georgia (unpublished data, Southeastern Forest Experiment Station). Data from this study permit estimation of the extent of rot in stumps if the time of cutting is known:

Year after cutting	Depth of decay (Inches)
1	0.5
2	1.5 - 2.5
3	4.0 - 5.0
4	6.0

To minimize the amount and duration of residual combustion, take these actions:

Fell dead snags.

In cutting operations, keep stump height as low as possible to maximize moisture content of decaying stumpwood and speed decay.

Burn only when stump moisture content is high, as soon after a heavy rainfall as possible.

Scatter large, sound wood material.

As necessary, provide for mopup.

TOTAL LITTER LAYER MOISTURE CONTENT

Fuel moisture is constantly changing, and the changes must be monitored. Both wetting and drying moisture curves for 10-hour timelag fuels are contained in the National Fire-Danger Rating System (NFDRS) (Deeming and others 1972), but they do not apply to pine needle litter. The *wetting curves* are based on moisture absorbed by wood dowels that respond much slower than does pine needle litter. The *drying curves* approach 10 to 15 percent moisture content in about 7 days—lower than measured moisture contents in heavy slash pine litter layers 7 days after a rain. Palmetto-gallberry, grass, and pine needle litter types all need more accurate litter moisture estimates. More appropriate curves were, therefore, developed using data from experimentally burned plots in the South.

Multiple-regression analysis showed that total litter layer moisture content could be predicted with acceptable accuracy from days since rain and total litter layer dry weight (Hough 1976). In the presence of these variables, relative humidity did not improve predictions. Using Hough's (1976) equations, table 7 was developed to show rates of drying for litter. To enter the table, one must know the age of rough and yesterday's total litter layer moisture content. The value shown in the table is subtracted from yesterday's value to estimate today's total litter layer moisture content.

During wet, rainy periods forest litter moisture content increases. Moisture retention capacity of total forest litter layers has been found to be up to 300 percent of dry weight (Swank and others 1972, Metz 1958, Helvey 1964, Van Wagner 1970). Metz found this maximum moisture content only after prolonged rainfall, indicating the importance of rainfall duration. This need was also shown by Paul,[4/] who found that maximum water uptake for pine litter occurs in 10 to 12 hours. A single curve of total litter layer moisture content versus duration of precipitation was used to construct a table that gives a reasonable estimate of moisture content *increases* in the litter fuel bed (table 8).

4/ Paul, James T. 1967. Influence of rate of rainfall on pine litter moisture content. Unpublished report. Southeast. For. Exp. Stn., Macon, Ga.

Table 7. — Daily correction to the total litter layer moisture content for drying

Age of rough (years)	Yesterday's total litter layer moisture content (percent)																
	1-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-55	56-65	66-89	90-109	110-129	130-164	165-199	200-200+
	Percent																
1 to 2	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-13	-18	-25	-40	-60	-75	-80
3 to 10			0	-1	-2	-3	-4	-5	-6	-7	- 9	-12	-16	-25	-50	-70	-75
11 to 25					0	-1	-2	-3	-4	-5	- 6	- 9	-12	-17	-40	-65	-70

Table 8. — Correction to total litter layer moisture content for wetting due to precipitation

Precipitation duration (hours)	Yesterday's total litter layer moisture content (percent) [1/]				
	10-30	31-50	51-70	71-90	91+
	Percent				
1	+ 75	+ 55	+ 35	+ 15	0
2	+100	+ 80	+ 60	+ 40	+ 25
3	+120	+100	+ 80	+ 60	+ 45
4-5	+135	+115	+ 95	+ 75	+ 60
6-8	+150	+130	+110	+ 90	+ 75
9-12	+165	+145	+125	+105	+ 90
12-24	+220	+200	+180	+160	+145

1/ A value of 250 percent is the practical maximum that should be used. If yesterday's total litter moisture content, plus the correction for precipitation exceeds 250, enter 250 on records.

To use table 8, all that is needed is duration of rainfall and a value for yesterday's total litter layer moisture content. The value taken from the table is added to yesterday's total litter layer moisture content to give the moisture content of the layer today. Rainfall duration should be obtained from nearby weather stations, or from fire-danger rating stations that maintain rainfall duration records. A form (table 9) was designed to keep track of daily changes in total litter layer moisture content. This record should be started when there has been abundant rainfall for 8 or more hours so that an initial value of 250 percent for today's litter moisture can be assigned opposite the appropriate date and fuel loading class. Should a time of year be selected for beginning to track the total litter layer moisture when the chance for having 8 hours of continuous rain is remote, pick a day when at least 0.25 inch of rainfall occurs and assign a litter moisture value of 100 for that day.

If a number of stands have different ages of rough and are being considered for prescription

Table 9. — Daily record of total litter layer moisture content

Day of month	Age of needle rough	Correction for daily drying	Precipitation			Correction due to rain duration	Yesterday's litter moisture content	Today's total litter moisture content
			Begin	End	Duration			
	Years	Percent	Time	Time	Hours	Percent	Percent	Percent
1	1- 2	—				+		
	3-10	—				+		
	11-25	—				+		
2	1- 2	—				+		
	3-10	—				+		
	11-25	—				+		
3	1- 2	—				+		
	3-10	—				+		
	11-25	—				+		
4	1- 2	—				+		
	3-10	—				+		
	11-25	—				+		
Daily record continues to end of month								

burning, the daily drying rates will have to be maintained for each age class.

Steps and tables needed to determine total litter layer moisture content are:

1. Obtain records of daily rainfall duration from the nearest weather station or fire-danger rating station.

2. Beginning with the day of interest (today), search the records backward until a day is found on which rainfall duration exceeded 8 hours or at least ¼ inch of rain fell.

3. Locate that date on table 9 and enter 250 or 100 in the "Today's" column for that day's litter moisture.

4. Compute daily change in fuel moisture using instructions found on that form until today's date is reached. After these initial calculations are completed, it is suggested that daily calculations of total fuel moisture be made to maintain a current record.

5. When rain has fallen in the past 24 hours, go directly to Step 7. When it has not, go to Step 6.

6a. Record age of rough: ______ years.

b. Obtain yesterday's total litter layer moisture content from table 9.

c. Read correction factor due to drying from table 7.

d. Record factor in correction for daily drying column opposite today's date on table 9.

e. Subtract drying correction from yesterday's litter moisture.

f. Record answer in today's total litter moisture content column on table 9.

7. To increase yesterday's total litter moisture content by a correction factor for rain:

a. Record rain duration for past 24 hours: ______ hours.

b. Obtain yesterday's litter layer moisture content from table 9: ______ percent.

c. Read correction for rain in table 8.

d. Record correction due to rain duration opposite today's date and proper age of rough on table 9.

e. Add rain correction to yesterday's litter moisture.

f. Record answer in today's total litter moisture content column on table 9.

HEAT RELEASE RATE TO THE ATMOSPHERE

The rate of heat released to the atmosphere (HRR) by flames in an advancing-front combustion stage is needed to determine how high a smoke plume will rise during the convective-lift phase of the fire. Heat released from the residual stage of combustion is expected to be of importance in some situations, but is only negligible for those situations covered in this Guidebook.

The total heat of combustion of ovendry forest fuel burned in a bomb calorimeter averages 8,600 British thermal units (Btu) per pound and is a maximum value. Considerable heat is lost when these fuels are burned in the forest in their natural state. There, heat yield varies from 5,000 to 7,000 Btu. Losses are due to such phenomena as incomplete combustion, radiation, and the presence of moisture in the fuel. Brown and Davis (1973) report that 6,300 Btu is a good average for fuel conditions and types of fire encountered when prescription burning southern fuels. Further details will be covered in the *Forestry Smoke Management Sourcebook.*

The calculations for heat release rate (HRR) are:

1. To simplify the heat release rate equation and provide the dimensional units used in Chapters V and VI, we have determined a factor that includes the heat yield constant and converts from English to metric units—0.0012.

2. The heat release rate equation with this conversion factor is:

$$HRR = 0.0012\, y_A\, wrL \qquad (1)$$

where HRR = heat release rate to the atmosphere in megacalories per second

y_A = fractional part of available fuel involved in the advancing-front combustion stage (range 0.01 to 1.00)

w = weight of available fuel in tons per acre

r = rate of spread in feet per minute

L = length of fire front in feet.

PARTICULATE MATTER EMISSION RATE

The particulate matter emission rate (ER) is the weight of suspended particulate matter produced per unit length of line per unit of time. This rate is needed to determine how much will be transported and dispersed to targets downwind from a burn. An emission factor (EF) will be used in this calculation. Each fuel type has been assigned a constant emission factor that reflects its unique characteristics. Within fuel types, fuel arrangement and moisture patterns are known to influence the EF. We do not have sufficient data to calculate such variations precisely, and the calculations would be cumbersome.

The manner in which particulate matter evolves from a prescription burn can differ measurably, depending upon available fuel and the manner of burning. All backing fires, and those heading fires burning on areas having low fuel loadings (1- to 2-year-old roughs), consume most of the fuel in the advancing-front combustion stage. However, heading fires in older roughs or in broadcast logging debris consume only 50 to 80 percent of the fuel during the advancing-front combustion stage. The available fuel remaining in heading fires is consumed in the residual combustion stage. In the case of heading fires in older roughs and logging debris, there is enough heat in the advancing-front combustion stage to entrain part of the residual stage emissions into a convection column; after the heat diminishes, emissions from the residual combustion stage become associated only with the no-convective-lift fire phase.

Contributions of emissions from the two combustion stages to the convective-lift fire phase and to the no-convective-lift fire phase are summarized by fuel type and burning method (table 10). More detailed information on emission factors (EF) is in separate sections to follow for each fuel type.

Table 10. — Contribution of emissions from combustion stages to fire phases

Fuel type and burning method	Fire phases	
	Convective-lift (CL) phase	**No-convective-lift (NCL) phase**
Grass with pine overstory:		
all burning methods	Advancing-front stage EF = 15 lb/ton	None
Pine needle litter and/or light brush with age of rough 2 years and less:		
all burning methods	Advancing-front stage EF = 50 lb/ton	None
Pine needle litter and/or light brush with age of rough more than 2 years:		
backing fires	Advancing-front stage EF = 50 lb/ton	None
heading fires	Advancing-front stage EF = 50 lb/ton and Residual stage EF = 180 lb/ton	Residual stage EF = 180 lb/ton
Palmetto-gallberry with age of rough 2 years and less:		
all burning methods	Advancing-front stage EF = 25 lb/ton	None
Palmetto-gallberry with age of rough more than 2 years:		
backing fires	Advancing-front stage EF = 25 lb/ton	None
heading fires	Advancing-front stage EF = 25 lb/ton and Residual stage EF = 125 lb/ton	Residual stage EF = 125 lb/ton
Unpiled logging debris:		
all burning methods	Advancing-front stage EF = 35 lb/ton and Residual stage EF = 180 lb/ton	Residual stage EF = 180 lb/ton

A factor of 570 is needed to convert from the familiar English units (pounds, acres, feet) used to describe our fuel, fire movement, and emission factor (EF) to the metric units needed in the emission rate (ER) dispersion equation in Chapters V and VI.

The equation for the advancing-front combustion stage particulate matter emission rate (ER_A) is:

$$ER_A = 570\, y_A w r EF_A \qquad (2)$$

where ER_A = particulate matter emission rate in micrograms per meter-second

y_A = fractional part of available fuel involved in the advancing-front combustion stage (range 0.01 to 1.00)

w = weight of available fuel in tons per acre

r = rate of fire spread in feet per minute

EF_A = emission factor in pounds per ton for the advancing-front combustion stage.

The particulate matter emission rate (ER_R) for the residual combustion stage can be calculated in the same manner as for the advancing-front stage of combustion:

$$ER_R = 570\, y_R w r EF_R \qquad (3)$$

where ER_R = particulate matter emission rate in micrograms per meter-second

y_R = fractional part of available fuel remaining to be involved in the residual combustion stage (or $1 - y_A$)

w = weight of available fuel in tons per acre

r = rate of fire spread in feet per minute

EF_R = emission factor in pounds per ton for the residual combustion stage.

For the convective-lift phase of heading fires where the total emissions must include those from both the advancing-front stage and the residual stage of combustion, a total emission rate is calculated as follows:

$$ER_{A+R} = ER_A + ER_R \qquad (4)$$

Fuel types are discussed individually in the following sections. Since all of the referenced tables must be used in Chapter VI, they are presented therein for convenience of users, and will only be cited here to avoid repetition and save space.

GRASS WITH PINE OVERSTORY FUEL TYPE

DESCRIPTION

Loblolly, slash, and longleaf pines in the South are normally associated with various grasses, most of which form bunches rather than turf.

Figure 14. — Grass with pine overstory fuel type.

Grasses of the genus *Andropogon*—including broomsedge (A. *virginicus* L.), little bluestem (A. *scoparius* Michx.), and slender bluestem (A. *tener* Muhl.)—are dominant on all of the moist sites where longleaf has been succeeded by slash and loblolly pines, or where sites have been extensively disturbed by cultivation or site preparation such as disking, chopping, and bedding (Grelen 1962). On drier, sandy sites where longleaf pines predominate, wiregrass (*Aristida* spp.) dominates the site.

Where grass makes up a significant portion of the total fuel loading (estimated to exceed 50 percent by weight), and the presence of shrubs is insignificant, the fuel type will be designated "grass." Where a dense pine overstory exists, the fuel type is considered the same as a "pine needle litter type" after age of rough is more than 1 year.

FUEL LOADING

Grass fuels in forested stands are unique. The greatest accumulation occurs after the first growing season following a fire and continues to decrease thereafter. The decrease is due to the smothering effect of accumulating needles shed from a pine overstory and the shading effect of a developing brush understory. Total grass accumulation in tons per acre is presented in table VI-F-1, page 105, for easy use. For grass, available fuel will be considered equal to total fuel. The available fuel in any pine needle accumulation must also be estimated (table VI-F-5, page 109; or table VI-F-6, page 110; and table VI-F-7, page 111).

EMISSION FACTOR

Evidence available from the experimental burning of many grass species suggests an emission factor of 15 (pounds of particulate matter per ton of fuel) for prescribed burning with heading or backing fires. We are assuming that most of this burning will take place when fuel moisture is between 4 and 15 percent (dry basis), and that all fuel is consumed during the advancing-front combustion stage.

RATE OF SPREAD

The estimating system that best represents measured rate-of-spread values in grass fuel was calculated from the Rothermel rate-of-spread equation using typical grass fuel characteristics (Rothermel 1972). Calculated values have been converted to tabular form so that the only variables needed to determine the rate of spread are fine fuel moisture and windspeed (table VI-F-4, page 108). Actual fuel moisture can be derived from table VI-F-2 (page 106) where the fuel moisture is shown to be a function of ambient temperature, relative humidity, and cloud cover. The windspeed used should be that at midflame height. This value can be approximated by obtaining the value reported from a 20-foot tower at the nearest fire-danger rating station and dividing that value by 4.

Data from table VI-F-4 (page 108) should be used only for sites with slopes of 20 percent or less. The table is suitable for the Coastal Plains of the South where most prescription burning is done.

Fire travel in feet per minute from the table can be converted to miles per hour as follows:

$$\text{mph} = \frac{\text{feet per minute}}{88}$$

PINE NEEDLE LITTER AND LIGHT BRUSH FUEL TYPES

The forest floor of pine stands having light brush understories may appear quite different from that of a pine stand without an understory, but knowledge gained from studying fuel buildup and fire behavior in these stands shows them to be very similar. They will, therefore, be treated as a single fuel complex.

DESCRIPTION

Pine Needle Litter

In well-stocked pine stands, understory grasses and shrubs are drastically reduced after crowns close due to overhead shading from the pine canopy, competition from pine roots, and the blanketing effect of the shedding pine needles. The areas are generally parklike with a blanket of pine needles covering the soil surface. Understory shrubs that are present are sparsely scattered, and grass is found mainly in stand openings.

This type usually develops where previously cultivated land has reverted to pine forest, and where sites have been carefully prepared by plowing, disking, or bedding prior to pine regeneration.

Light Brush

This type is found throughout the Piedmont and Upper Coastal Plain regions of the Southern States. The fuel mixture consists of grasses, forbs, pine needle litter (usually loblolly pine), deciduous shrubs, and small deciduous trees such as blackgum (*Nyssa sylvatica* Marsh.), sweetgum (*Liquidambar styraciflua* L.), red maple (*Acer rubrum* L.), oaks (*Quercus* spp.), etc. There may also be some scattered nondeciduous shrubs, such as wax myrtle (*Myrica cerifera* L.) or holly (*Ilex opaca* Ait.).

Figure 15. — Backing fire in pine needle litter fuel type.

During the winter and early spring when prescription burning is usually done, only the naked stems of the shrubs are standing. All the leaves have fallen and become part of the litter layer—together with the grass, forbs, and pine needles. Most of the available fuel is in this layer.

FUEL LOADING

Because rate of pine needle accumulation under slash pine stands differs considerably from accumulations under loblolly or loblolly-longleaf stands, separate tables for predicting fuel loading will be presented for each.

Litter accumulation is the same whether an understory does or does not exist. In stands where no understory exists, only the litter fuel need be considered as total fuel for the area. Where understory fuels will be consumed by a prescribed burn, the two fuel fractions must be summed to estimate total fuel.

Slash Pine Litter Total Fuel Estimate

Equations describing the relationships between litter accumulation on the forest floor, basal area, and age of rough have been reported by McNab and Edwards (1976). For field use, the ovendry values are presented in table VI-F-5 (page 109). This table shows, for example, that in a 5-year-old rough where the stand basal area is 70 square feet, there would be a *total* litter accumulation of 6.1 tons.

Slash Pine Litter Available Fuel Estimate

The portion of total fuel that is *available* for consumption by a prescribed fire is directly correlated with the moisture content of the fuel. By estimating *total* loading from table VI-F-5 (page 109) and deriving the total litter layer moisture content (percent), the amount of fuel *available* for burning can be read from the center of table VI-F-7 (page 111). To use the table you must know the total litter layer moisture content, discussed under VARIABLES AFFECTING EMISSIONS AND FIRE PHASES.

Loblolly Pine Litter And Light Brush Total Fuel Estimate

The primary fuel consumed during a prescribed burn in this fuel type is loblolly pine needles, or a mixture of loblolly and longleaf or loblolly and shortleaf needles—possibly with some hardwood brush leaves.

High densities of young hardwood and brush stems are present in this type. During the growing season, the brush is very evident due to the presence of their green leaves; but during dormancy, when all the leaves have been shed, only naked stems are evident. Although they are usually killed by the heat, the stems are not generally consumed in prescribed burns.

An insufficient number of loblolly pine plots were sampled to develop a *total* litter prediction equation as was done with slash pine litter. The slash pine litter model was tried for estimating loblolly litter accumulations using the loblolly stand parameters of basal area and age of rough. In every case, the slash pine model overestimated the actual loblolly weights. We decided to use the model and calculate an error factor by regression:

$$\text{Error factor} = 1 + \left[\frac{3.74 + 4.49\ (\text{age of rough})}{100}\right]$$

Then,

$$\text{Loblolly litter weight} = \frac{\text{Slash pine litter weight}}{\text{Error factor}}$$

Using values from slash pine litter data and the error factor equation, loblolly pine litter accumulations were computed and listed in table VI-F-6 (page 110). Considerable estimation error may occur when using values in excess of 5 tons per acre because those values are extrapolated well beyond the weights actually measured on our limited sample plots.

Loblolly Pine Litter and Light Brush Available Fuel Estimates

Loblolly litter can now be determined from table VI-F-7 (page 111) using the total weight values derived from table VI-F-6 (page 110) and total litter layer moisture content as earlier discussed under VARIABLES AFFECTING EMISSIONS AND FIRE PHASES.

EMISSION FACTOR FOR SLASH AND LOBLOLLY PINE LITTER AND LIGHT BRUSH FUEL TYPES

Particulate matter emissions from burning pine needle litter were derived from laboratory and field experiments by Southern Forest Fire Laboratory personnel.

Backing Fires

As fuel moisture increases, so does emission of particulate matter. Backing fires in laboratory-burned loblolly needle beds at a moisture content of 6 to 10 percent had an emission factor of 17 pounds per ton of fuel consumed; but at a 19 percent moisture content, the value was 28 pounds.

Particulate matter emissions measured on several backing fires in slash pine plantations averaged approximately 50 pounds per ton of consumed fuel. This higher emission factor is thought to be due to differences in moisture content of different litter layers.

Until further knowledge is gained to reconcile the differences in particulate matter emissions between laboratory and field burns, and to account for the effect of fuel moisture, an emission factor of 50 pounds of particulate matter per ton of needles consumed should be used. Most emissions are from the slow-moving flaming portion of the fire.

Heading Fires

Emissions from heading fires moving through pine needle fuel (ER_{A+R}) usually come from both the advancing-front combustion stage and the residual combustion stage that take place immediately after passage of the advancing front. Thus, $ER_{A+R} = ER_A + ER_R$.

In the advancing-front stage the emission factor would be identical to that of backing fires, 50 pounds per ton of fuel consumed; but the emission factor in the residual combustion stage could be up to 180 pounds. These data are based on the burning of small fuel beds in a laboratory, but are the best available.

Where litter buildup is low, as in a 1- to 2-year-old rough, emissions from residual combustion are negligible and only advancing-front combustion need be considered. Such burns would have an emission factor of 50.

RATE OF SPREAD

Pine needle and low-brush fuel types are similar in fuel makeup and arrangement. Fire behavior will, therefore, be considered the same for identical fuel moisture and wind conditions.

The best estimate of rate of fire spread in this fuel type was calculated with the Rothermel spread model (Rothermel 1972). Rates of fire spread are shown in table VI-F-8 (page 112).

As in the grass model, rate of fire spread can be predicted by knowing only midflame windspeed and fine fuel moisture (1-hour timelag) values. This windspeed can be estimated by obtaining a value from a 20-foot, open-tower installation at a nearby fire-danger rating station and dividing that value by 4. Fine fuel moisture can be read from table VI-F-3 (page 107) as a function of only relative humidity. Rate of spread in feet per minute is read from table VI-F-8 (page 112). If desired, the rate of spread in feet per minute can be converted to miles per hour:

$$\text{mph} = \frac{\text{feet per minute}}{88}$$

PALMETTO-GALLBERRY WITH PINE OVERSTORY FUEL TYPE

DESCRIPTION

The vegetation commonly referred to by southern forest fire control personnel as the palmetto-gallberry fuel type can vary widely in amount of vegetation and plant composition throughout its range. Saw-palmetto (*Serenoa repens* [Bartr.] Small) is native to the Lower Coastal Plain, extending south from Charleston, South Carolina, into the whole of Florida and west into southeastern Louisiana (Hilmon 1968).

The gallberry (*Ilex glabra* [L.] Gray) range overlaps the palmetto range, but is considerably more extensive, stretching from Nova Scotia to Louisiana (Gleason 1968). Within the fuel type both shrub species are generally associated and predominate, although in south Florida the gallberry may be totally absent.

Other shrub associates include blueberry (*Vaccinium myrsinites* Lam.), dwarf pawpaw (*Asimina parviflora* [Michx.] Dunal.), titi (*Cyrilla racemiflora* L.), dwarf candleberry (*Myrica cerifera* var. *pumila* Michx.), tar-flower (*Befaria racemosa* Vent.), running oak (*Quercus pumila* Walter.), huckleberry (*Gaylussacia* spp.), fetterbush (*Lyonia lucida* [Lam.] K. Koch), pepperbush (*Clethra acuminata* var. *tomentosa* [Lam.] Michx.), etc.

The herbaceous stratum is made up primarily of grasses and dominated by wiregrass and broomsedge.

The genera *Aristida, Andropogon, Panicum,* and *Rhynchospora* comprise a major portion of the herbaceous weight on sites that are frequently burned. In parts of South Carolina, brackenfern

Figure 16. — Palmetto-gallberry fuel type.

(*Pteridium aquilinum* [L.] Kuhn.) is the predominant herb, while tropical shrubs predominate in the south Florida Everglades.

This fuel type is usually found under an overstory of loblolly, slash, or longleaf pine, and considerable quantities of pine needles are mixed with dead grass and other vegetative debris in the ground litter. All estimates of fuel buildup for this type assume the presence of a pine overstory.

FUEL LOADING

The palmetto-gallberry type has two levels of fuel: (1) the understory living vegetation and standing or logged debris and (2) dead material on the forest floor. Separate computations must be made for each level.

Understory

Weight of understory vegetation is related to time since last disturbance (age of rough) and vegetative height. Table VI-F-9 (page 113) shows weights of understory vegetation; but to use it, average height of representative understory vegetation must first be estimated. If, for example, understory height averages 4 feet and age of rough is 3 years, the weight of understory material would be 4.6 tons per acre.

Available Litter Fuel Estimate

The litter buildup in a palmetto-gallberry fuel type is primarily influenced by the pine overstory and should be predicted from table VI-F-5 (page 109) or VI-F-6 (page 110) using basal area of the stand and age of rough as inputs.

Data from prescription-burned experimental plots containing aerial fuel in addition to pine litter were analyzed for fuel consumption. Differences between backing and low-intensity heading fires were not great, so all the data were combined. Data needed to estimate available fuel are:

1. Total standing understory vegetation (table VI-F-9, page 113)
2. Total litter fuel (table VI-F-5, page 109) or VI-F-6 (page 110)
3. Moisture content of the total litter layer from a worksheet (table 9) as shown in this Chapter.

Tables 7 and 8 are used to determine the changes in moisture content of the total litter from normal drying, or from wetting by rain. Their use is explained on pages 31 and 32.

The amount of available fuel consumed from the entire understory fuel bed (includes litter) is presented in table VI-F-10 (page 114). This table has six sections (10, 20, 40, 80, 120, and 160 percent) that represent the range of litter fuel moisture that would be expected when prescribed burning would be considered. The moisture interval is smaller at the lower moisture contents because the change in available fuel consumed is greatest at these lower moisture contents. Should the predicted moisture level not correspond to one of the moisture content sections listed (e.g., 50 percent instead of 40 or 80 percent), choose the section with the closest value (the 40-percent moisture content in this case). Limitations on the accuracy of estimates in the palmetto-gallberry fuel type depend primarily upon the accuracy of the litter and moisture content estimates. These estimates should, therefore, be made with care.

EMISSION FACTOR

The calculated emission factors from experimental field burns in Georgia ranged from 11.8 (pounds of particulate matter per ton of consumed fuel) to 41.2. Based on these field experiments, an advancing-front particulate matter emission factor (EF_A) of 25 pounds per ton of palmetto-gallberry fuel burned is suggested for use with backing fires. This value is believed to be less than emissions from pine needle litter because fuel bulk density is lower and combustion is, therefore, more efficient. No measurements were made for heading fires in the type; if heading fires in 1- or 2-year-old roughs are contemplated, the same emission factor of 25 should be used. Emissions from the residual combustion stage are considered negligible for heading fires in young roughs.

Heading fires in older roughs would evolve appreciable emissions during residual combustion in the litter layer; a much higher emission factor for this stage of combustion (EF_R) of 125 pounds of particulate matter per ton of palmetto-gallberry fuel consumed is suggested for use. The emission rate (ER_{A+R}) for the convective-lift fire phase of older rough heading fires is:

$$ER_{A+R} = ER_A + ER_R$$

RATE OF SPREAD

Rate of fire spread in palmetto-gallberry fuel was estimated from measures of fuel and fire behavior in this fuel type. Hough and Albini (1976) describe the measurement and analytical procedures used to derive the rate-of-spread equations. If windspeed at midflame height and fine fuel moisture (table VI-F-3, page 107) are known, fire spread rate can be read directly from table VI-F-11, page 115. For backing fires, assume the windspeed is zero.

Figure 17. — Emissions from the residual combustion phase in backing fires, and in heading fires with rough less than 2 years old, are negligible for the palmetto-gallberry fuel type.

The proper value to be used for midflame windspeed in table VI-F-11 (page 115) can be estimated by using values taken from a 20-foot, open-tower installation at the nearest fire-danger station and dividing that value by 4. If desired, the rate of spread can be converted to miles per hour:

$$\text{mph} = \frac{\text{feet per minute}}{88}$$

PINE LOGGING DEBRIS FUEL TYPE

DESCRIPTION

This fuel type is made up of tree parts left on an area following logging, plus a very disturbed natural understory fuel. The debris consists mostly of the upper portion of the central bole, tree branches, and needles. Other residue could include unmerchantable "whip" trees and hardwoods.

Logging debris can be burned in one of two ways. The debris can be piled to permit consumption of all small and much of the larger residue elements (branches and tops exceeding 1 inch in diameter), or it can be left scattered where the individual trees were felled to be consumed by a broadcast burn of the area. The latter type burn usually consumes only residue less than 1 inch in diameter.

We have insufficient data to account for differences in emissions from piled debris because piling methods and pile conditions can vary widely. Therefore, this Guidebook will *not* have a section for piled debris. Further research in this fuel type is in progress. The Guidebook does, however, give a procedure for predicting particulate matter emission rate and heat yield from the burning of broadcast debris. This procedure is based upon very scant observations and little experimental evidence.

FUEL LOADING

Residue weight may be estimated by several methods. The traditional procedure is to gather all material from many small sample plots, separate by size class, dry, and express weight on a unit area

Figure 18. — Unpiled pine logging debris fuel type.

basis. More recent estimating procedures are the line intercept method (Van Wagner 1968) and the planar intercept method (Brown 1971). These methods are useful where the slash from several species of trees is present. The techniques do not require the collection of material, but considerable field time and effort are still needed.

A quicker and more economical method is to relate the quantity of crown residue left on the ground to average diameter at breast height (d.b.h.), basal area, and volume in the stand that was cut. Two studies have been completed on amount of dry residue left on the forest floor following standard logging of two major southern species. One involves loblolly pine residue (Taras and Clark 1974) and the other slash pine residue (data on file at the Southern Forest Fire Laboratory).

Logging debris that has been left undisturbed and is scattered over the entire logged area is generally burned with some form of heading fire. Such fires consume only fuel less than 1 inch in diameter. Table VI-F-12 (page 116) depicts the amount of residue, in tons per cord cut (logged), that would generally be consumed when broadcast burning a logged area. Note that the average d.b.h. of the logged stand has some effect on the amount of residue that will be left on the ground. If d.b.h. of the stand averaged 8 inches and the species was loblolly, for every cord of timber cut there is 0.15 ton of available residue on the ground. If average stand d.b.h. was 11 inches, there is 0.12 ton of available residue per cord. Total residue on an area is the product of tons of residue per cord cut (from table VI-F-12, page 116) and total cords cut on the area. By dividing this answer by the number of acres in the logged area, the residue weight is expressed in tons per acre.

SPECIAL RULE OF THUMB

Debris that has been left broadcast over a logged area is usually burned in one of two ways. It may be head fired from its upwind side toward the downwind side, which is usually backfired in advance. Primary fuel consumption is from the movement of the heading fire, and length of the active burning front for computing heat release rate (HRR) is easily ascertained.

Ring firing may be used instead. This technique usually begins with the firing of the downwind side of the area, followed by the firing of the two flanks simultaneously. Finally, the upwind side is fired to totally encircle the area with fire. Fire movement is toward the center of the area.

Determining the length of active fire for a ring-fired area poses problems. When there is wind movement, the heading portion of the fire is obviously active. But so are the flanks, and as the fire progresses all sides are shrinking in length. For purposes of this Guidebook, the movement of the backing fire will be ignored, even though this side of the fire is obviously contributing some heat and particulate matter to the reaction. Where ring firing is used and there is no wind, all fired sides probably move toward the center at an equal rate.

A rule of thumb has been developed for estimating a length-of-fired line value for computing HRR in Chapter VI. The procedure was developed in an attempt to make an allowance for the fire activity on the burning flanks. To complete the procedure, a scale map of the area to be burned is needed. On the map, draw a line perpendicular to the expected or planned wind direction along the upwind edge of the area to the extremities (fig. 19, line a to b). Draw a second line (c to d) along the downwind edge of the area and connect these two lines with diagonals from the extremities of each. Where the diagonals intersect, label the point (x). Length of fired line for computation of HRR is the sum of scaled lines a to x and b to x. This is the entry needed for Chapter VI.

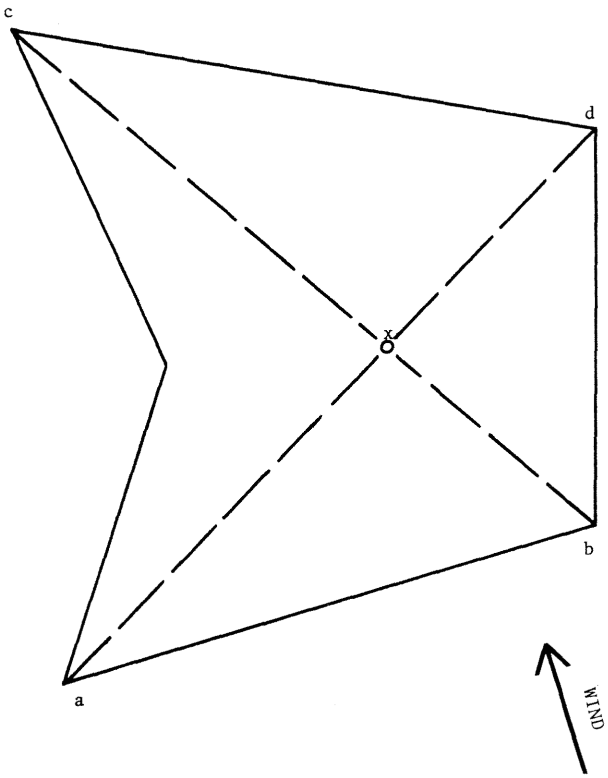

Figure 19. — Procedure for determining length of fired line for heat release rate (HRR) calculations for ring fires in the logging debris fuel type.

EMISSION FACTOR

Emissions from fires moving through unpiled logging debris occur in two phases—the convective-lift phase and the no-convective-lift phase. Emissions during the convective-lift phase are from both the advancing-front combustion stage and the residual combustion stage behind the advancing front.

Six to 18 months usually elapse between logging and burning. During this time much of the accumulated litter breaks down, leaving primarily the logged litter layer of residue over the soil. Upon firing, 75 percent ($y_A = 0.75$) of the available fuel is estimated to be consumed in the advancing-front combustion stage, leaving only 25 percent ($y_R = 0.25$) to be consumed during the residual combustion stage. These proportions are based on data taken from sample areas of debris burned in the southern Piedmont of Georgia near Macon.

Determination of representative emission factors for this fuel type must be partially subjective due to the limited data currently available. Results from the limited fuel beds burned in the laboratory indicate emission factors much below values expected, compared with values for the seemingly similar pine needle litter and palmetto-gallberry fuel types. The difference between expected results and laboratory results can be explained only by hypotheses that: (1) aerial distribution of pine logging debris may result in flame interactions that reduce particulate matter emissions, and (2) laboratory fuel beds used may not have been representative of area-wide fuel arrangements found in actual field situations for pine logging debris.

Laboratory-derived particulate matter EF values of 5 and 75 pounds per ton of fuel for pine logging debris in the advancing-front and residual combustion stages, respectively, must be regarded as tentative until further laboratory and field work is completed. We are suggesting, therefore, that 35 and 180 pounds per ton of fuel be used for the advancing-front and residual combustion stages, respectively. These more conservative EF values for unpiled pine logging debris are drawn from comparisons with other fuel types, but allow for possible interactions indicated by limited laboratory work to date. Use of these values will minimize the risk of unwanted environmental consequences until research is completed.

When computing the emission rate to be used for the convective-lift fire phase for heading (or ring) fires (ER_{A+R}) in this fuel type, the simultaneous activity of both stages of combustion are accountable. The equation is as follows:

$$ER_{A+R} = ER_A + ER_R$$

RATE OF SPREAD

Observations of fire spread rate in this fuel type are limited. Until better data are available, the rate-of-spread curves in NFDRS Model C (Deeming and others 1972) fuel, with modifications (table VI-F-13, page 117), should be used.

The only input variables needed to read rate of spread from table VI-F-13 (page 117) are fine fuel moisture (from table VI-F-3, page 107) and midflame windspeed. The midflame windspeed should be obtained by taking the value at the nearest fire-danger rating station having an anemometer mounted on a 20-foot tower and dividing that value by 2. A factor of 2 is used rather than 4 because of the effect of removing the overstory. If desired, rate of spread can be converted to miles per hour:

$$\text{mph} = \frac{\text{feet per minute}}{88}$$

CONCLUSIONS

Although many voids in knowledge exist, we have presented useful new information on rates of spread and available fuel. These data have been badly needed in the fuel types covered.

In general, practices and fuel conditions that minimize particulate matter production from the burning of forest fuel are:

1. Favoring backing fires where possible
2. Cutting to low stumps and felling dead snags
3. Burning when fuel moisture is low
4. Minimizing amount of logging debris through utilization to small top diameters
5. Burning scattered logging debris rather than piled debris.

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CHAPTER V

SMOKE TRANSPORT AND DISPERSION

by

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The purposes of this Chapter are:

To outline phenomena affecting transport and dispersion of smoke

To introduce concepts of air pollution climatology important to scheduling burning operations when the probability of good smoke transport and dispersion is greatest

To explain the bases we used to select and adapt mathematical models for predicting concentrations of smoke from forestry burning.

The models described were adapted only for common forestry burning situations in the South, but with further adaptation they can be applied elsewhere.

PHENOMENA AFFECTING SMOKE TRANSPORT AND DISPERSION

It has been difficult to achieve a proper balance between too much and too little information for the wide spectrum of readers expected to use this Guidebook. For those who desire more background on basic weather variables, we suggest a text like *Fire Weather* (Schroeder and Buck 1970).

ATMOSPHERIC STABILITY

The definition of atmospheric stability as it affects smoke dispersion is the degree to which the atmosphere resists turbulence and vertical motion. In this discussion it is convenient to consider portions of air as parcels. Parcels of air do not have strict boundaries (as if encased in a wrapper); they tend to mix and take on the characteristics of their surrounding environment.

Consider a parcel of air heated to a certain temperature at the Earth's surface. The more unstable the atmosphere, the more readily the less dense, heated air parcel will rise by convection. Similarly, a more dense, cooled parcel of air will descend more rapidly under unstable conditions. When a parcel of air is heated by a forest fire and carries smoke with it, the rate and height of its ascent are essential to our calculations of subsequent dispersion.

Atmospheric stability is more properly defined by air temperature changes with height over a specific location. The adiabatic lapse rate, a temperature decrease of 1° C per 100 meters (5.5° F per 1,000 feet), defines a neutral atmosphere and is the basic reference for other stability classifications. The atmosphere is unstable if its lapse rate is greater than neutral, and stable if less. Neutral conditions can usually be found below cloud bases during cloudy and windy conditions. An unstable atmosphere usually occurs in early afternoon on clear days with light winds. Stable conditions usually occur at night when the air is clear and the winds are light.

TEMPERATURE INVERSIONS

An inversion layer is a special case of the temperature-height relationship just discussed. Temperature in this layer increases instead of decreases with height. When our previously considered heated parcel of air encounters an inversion layer it soon stops rising. Because it cools quickly as it rises, the parcel reaches the same temperature as the very stable surrounding air. An inversion can thus be thought of as a *lid* on a smoke column.

Forestry smoke managers should be careful to avoid low and intermediate level inversions in order to keep from having such a lid imposed upon the smoke from their burns. If the inversion layer

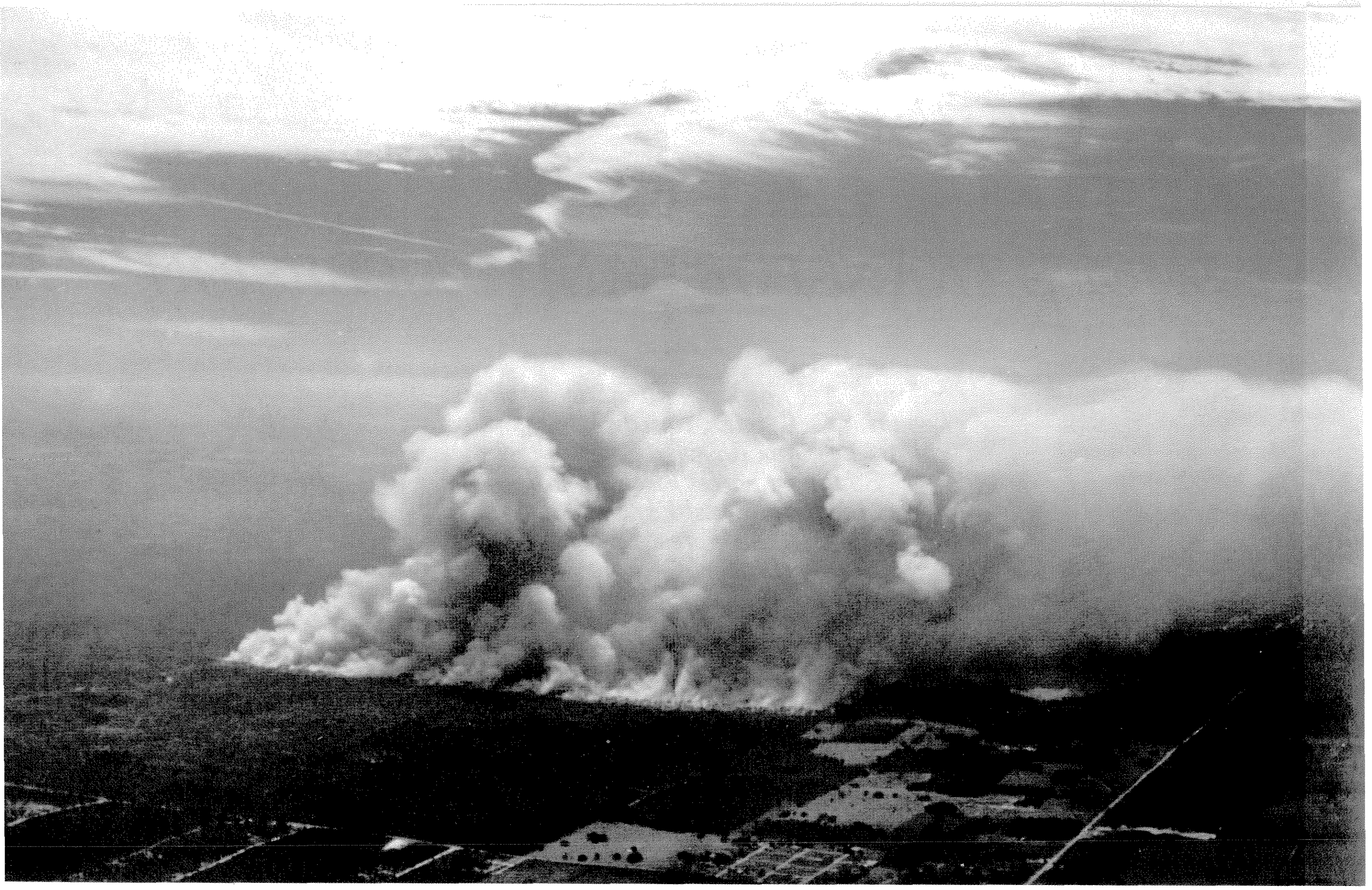

Figure 20. — Major factors affecting smoke transport and dispersion include vertical plume rise, horizontal movement on an azimuth determined by the transport wind direction, and dispersion by physical forces such as atmospheric mixing.

is very weak (i.e., not very thick in the vertical dimension and temperature increase with height is not great), the heated air from a fire can sometimes penetrate this layer. When it does, the smoke then has a better chance for dispersion, but there is often a surprising change in fire behavior. Smoke from the no-convective-lift fire phase will not penetrate the inversion lid. It is, therefore, best to avoid prescribed burning when low inversion layers affecting the fire are predicted.

MIXING HEIGHT

The temperature inversion is one kind of lid that traps smoke beneath it. Stable layers of less than inversion intensity are another form of lid. These lids determine mixing height. Mixing height is the atmospheric limit above which vigorous vertical mixing does not take place. It is a height at which airmass stability is sufficient in strength and depth to inhibit further upward transport of smoke.

Mixing height represents the top of the atmospheric volume available for dispersion. High mixing heights imply that large volumes of air are available for smoke dispersion. Thus, with higher mixing heights, smoke concentrations will be less—especially at long distances from the fire. Mixing heights of less than 500 meters are often associated with air pollution episodes.

TRANSPORT WINDSPEED

You have probably seen smoke columns that go up to one of the lids just described and then just smear out in all directions. This occurs when there is little or no transport wind. The smoke column that bends or shears is encountering wind as it rises.

Windspeeds usually increase with height, except where funneling takes place near the ground (as through a mountain saddle or opening in the forest). Transport windspeed is the arithmetic average of all windspeeds within the mixing layer, including surface windspeed. Smoke concentrations usually decrease as transport windspeeds increase. Transport windspeeds of less than 4 meters per second are indicators of stagnant conditions which often result in air pollution episodes.

TRANSPORT WIND DIRECTION

Wind direction usually veers (changes to the right) with height. Veering with height is important in determining where the smoke will go. The

change in wind direction with height is due to friction that causes ground-level winds to be deflected to the left in the Northern Hemisphere. As the height above the Earth increases, there is a decrease in friction. The rougher the surface, the greater the change. Veering with height over even-aged pine stands on relatively level terrain is between 15 and 20 degrees in the first kilometer (3,281 feet) of height. Over markedly uneven-aged pine stands in rough terrain, it is as much as 40 to 45 degrees. Changes in wind direction with height tend to be more pronounced at night than during the day because vertical motion is usually diminished at night.

LOCAL-SCALE SYSTEMS

Local-scale (sometimes called small-scale) systems are associated with fixed geographic features and do not travel from one location to another like high- and low-pressure systems. They often develop, persist, and dissipate in one small locale. Land and sea breezes are examples of this phenomenon. These breezes change stability, windspeed, and wind direction.

Along coastlines on clear, summer days when early morning winds are light, onshore winds frequently develop by midafternoon—penetrating inland. This sea breeze effect is due to land surfaces being warmer than the sea surface. Similar circulations, much weaker and less widespread, often occur along margins of lesser water bodies, and even open fields, that differ significantly in temperature from adjoining land surfaces.

Mountain-valley or slope-valley wind is another example of a local weather phenomenon that can affect smoke transport and dispersion. On clear nights, high slopes cool by radiation; the air adjacent to them becomes colder and denser, and drains into the valley. The reverse of this drainage flow may occur during the day.

These local-scale systems are important because they directly affect the dispersion of smoke by causing abrupt changes in local atmospheric stability and can influence the direction in which smoke will be transported. They are somewhat predictable—often site dependent.

OBTAINING CURRENT AND FORECAST WEATHER FOR APPLICATION

Limits on values for the phenomena covered in the preceding section need to be specified in a fire prescription, then checked against current and forecast weather for a specific locale, and for specific times.

National Weather Service Forecast Offices can supply the following information in spot forecasts:

Mixing height (also referred to as height of the mixing layer)

Surface windspeed (in the open at a height of 10 meters)

Transport windspeed

Transport wind direction.

Both transport windspeeds and mixing heights are reported in metric units. The probable transport wind velocity (direction and speed) is usually the vector-sum of reported or forecast winds through the mixing height.

As of this writing, stability expressed in the Pasquill (1975) stability classes used in Chapter VI is not available through the National Weather Service. These values may eventually be provided, but until they are the smoke manager must predict the class from reported *cloud cover* and *cloud height* plus angle of the sun. A predicting method is provided in Table 11.

POLLUTION CLIMATOLOGY

Forestry smoke managers responsible for a large number of planned burns are urged in Chapter VI to develop schedules based upon the total number of days with good probability of satisfactory smoke transport and dispersion, as well as other burn objectives. To do this requires an understanding of the climatology of pollution and a knowledge of available sources of appropriate climatologies. This leads us to consider again the phenomena affecting transport and dispersion discussed earlier.

Climate, the synthesis of these conditions over a long time, should be used in formulating long-range prescribed burning plans. Climatic conditions to be considered in prescription burning plans include stagnation, mixing, windspeed, and wind direction frequencies.

To avoid high concentrations of smoke in sensitive areas, burning often has to be done when the

Table 11. — Stability estimating method[1]

Surface windspeed (mph)	DAY									NIGHT	
	Clear or 50% or less cloud cover w/ low & mid clouds; or any high clouds			More than 50% low and mid clouds			More than 50% low clouds			50% or more cloud cover w/low and mid clouds or high overcast	Clear or less than 50% cloud cover w/ low and middle clouds
	6-foot vertical standard shadow length (in feet)										
	Less than 3.5	3.5 to 8.5	Greater than 8.5	Less than 3.5	3.5 to 8.5	Greater than 8.5	Less than 3.5	3.5 to 8.5	Greater than 8.5		
Less than 4	A[3]	A-B	B	A-B	B	D	B	D	D	DO NOT BURN[2]	DO NOT BURN[2]
4 - 7	A-B	B	C	B	C	D	C	D	D	E	F
8 - 10	B	B-C	C	B-C	C	D	C	D	D	D	E
11 - 14	C	C-D	D	C-D	D	D	D	D	D	D	D
More than 14	C	D	D	D	D	D	D	D	D	D	D

1/ After Pasquill (1975), with insolation estimates incorporating shadow length or cloud cover after Lavdas (1976).
2/ Burns will be delayed in Decision-Logic Stage No. 1, Chapter VI.
3/ Shaded areas indicate categories for which typical cases are not presented in Chapter VI.

How to use table:

1. Locate main column head for day or night. Night applies from 1 hour before sunset to 1 hour after sunrise.
2. Locate subcolumn head for cloud cover.
3. If for day situation, locate sub-subcolumn head for 6-foot vertical standard shadow length.
4. Locate row for surface windspeed.
5. In row and under column, read stability class category.

Example: Day with more than 50 percent low and mid clouds and shadow length less than 3.5 feet with windspeed 8 to 10 mph. Read stability category B-C.

wind is blowing in a particular direction. Forestry smoke managers can determine the probability that the wind will be blowing in the proper direction on a given day from summaries of prevailing seasonal wind directions.

Needed climatological information may be found in the literature cited in this section. The Climatic Atlas of the United States (available from the National Climatic Center, Federal Building, Asheville, North Carolina 28801) is another comprehensive source. This publication gives monthly and seasonal averages and totals for most of the phenomena affecting transport and dispersion. Airport summaries of windspeed and direction frequencies are available from the National Climatic Center as well.

Two primary factors that inhibit atmospheric dispersion are light winds and stable atmospheres. When these persist, stagnation occurs. High-pressure systems, or anticyclones, exhibit both of these characteristics. Korshover (1971) used 35 years of upper air observations to determine the relative occurrence of stagnant anticyclones. He found that stagnant conditions in the Southeast occur most frequently during late summer and fall. The maximum number of stagnant episodes lasting 4 days or more occurred in north Georgia and in western North and South Carolina.

Stagnant anticyclones are not the only systems that result in poor dispersion conditions. Dilution capacity of the atmosphere may be poor during other meteorological patterns, such as when inversions persist. Hosler (1961) reported the frequency of low-level (less than 500 feet) inversions over the Continental United States during a 2-year period. His findings agree well with Korshover's (1971)—inversions causing poor dispersion patterns in the Southeastern United States occur most frequently in the fall, but may occur in any season.

Holzworth (1972), in his analysis of 5 years of National Weather Service data, presented mixing heights, windspeeds, and the resulting potential for urban air pollution throughout the contiguous United States. His generalizations may be applied to rural atmospheres.

MATHEMATICAL MODELS

Different assumptions about governing processes and behavior have resulted in many different models for calculating dispersion. Some are different merely because of their intended application. Additional work will undoubtedly yield yet a wider variety from which to choose. In the discussions that follow, we will address the criteria we used for selecting a dispersion model—as well as the related approaches used in the decision logic in Chapter VI. We will also cover modifications imposed upon selected approaches, but will leave full development and defense of previously published equations to cited sources.

Three general criteria were applied in selecting and adapting the model:

1. Predictions close to the burn are the most critical, and the model must accurately reflect source and atmospheric variables.

2. The model must be widely accepted by scientists in regulatory agencies.

3. The model must permit either computer or desk-top calculations.

In order to provide a practical predictive method for smoke concentrations at downwind locations, it has been necessary to assign fixed values for some factors. In Chapter IV two separate fire phases are described: the *convective-lift* and the *no-convective-lift fire phases.* While smoke entrainment will gradually increase then decline in the convective-lift phase, use of a steady state is believed to be realistic in order to make calculations manageable. In the no-convective-lift phase, emissions will gradually decline; but again, using a steady-state condition is necessary if anything but extremely complex equations calling for automatic data processing are to be applied. Similar steady-state compromises are applied in the final transport and dispersion model to be introduced in this section for use in Chapter VI. In addition to these practical considerations, current knowledge does not justify more sensitive, time-dependent adjustments at this time.

PLUME RISE

The height that the center of the smoke plume attains is called plume rise. During the convective-lift phase of combustion, heat released by the fire causes convective lift of emissions from the fire in a definite column. As this heat diminishes, the plume loses its columnar shape to a point where lift of emissions is mostly a result of vertical atmospheric mixing alone. Thus, while atmospheric stability is an important variable at all times, heat release rate, explained in Chapter IV, will be employed only for the convective-lift phase. Winds impinging upon the column during the convective-lift phase tend to bend or shear it, restricting the total possible plume rise. Plume rise, therefore, is a function of heat release rate, atmospheric stability, and transport windspeed. Inversions will also limit plume rise and are accounted for by stability. Mixing height becomes important after the initial convective lift, and is incorporated in the final dispersion model.

In discussions with Dr. Gary A. Briggs of the NOAA Oak Ridge Laboratory, we elected to adapt the plume rise relations he developed for stack emissions handled as point sources. Briggs' (1969, 1971, 1972) plume rise relationships fit satisfactorily for prescribed fires when his term Q_H is expressed as the total rate of heat release from the entire length of fired line, as determined by relationships explained in Chapter IV. Relationships were examined for stability classes A through F (Pasquill 1975). Equations (1) through (4) are used in calculating ultimate plume height, in which:

H = height (in meters)

Q_H = total heat release (in calories per second)

u = transport windspeed (in meters per second).

For stability classes A through D, and Q_H less than 1.40×10^6 cal/sec:

$$H = 0.0101\, Q_H^{\,3/4}\, u^{-1} \qquad (1)$$

For stability classes A through D, and Q_H greater than 1.40×10^6 cal/sec:

$$H = 0.0847\, Q_H^{\,3/5}\, u^{-1} \qquad (2)$$

For stability class E and all values of Q_H (temperature increase with height of 1°C per 100 m assumed):

$$H = 0.917\, Q_H^{\,1/3}\, u^{-1/3} \qquad (3)$$

For stability class F and all values of Q_H (temperature increase with height of 2.5°C per 100m assumed):

$$H = 0.761\, Q_H^{\,1/3}\, u^{-1/3} \qquad (4)$$

Equations (1) through (4) are used to calculate plume rise while the smoke rises for some distance as it travels downwind. Often ultimate height is not reached for several kilometers downwind. This distance is not affected by transport windspeed. Briggs' (1969) ultimate height for a 1 megacalorie per second source is attained about 480 meters (0.3 mile) downwind. From Briggs' work, downwind distances to ultimate heights for sources releasing heat at different rates under stability classes A through D compare as follows:

Heat release (Megacal/sec)	**Approximate downwind distances to ultimate heights (Miles)**
1	0.3
10	0.8
100	2.0

It can be shown that at one-third the downwind distance to ultimate height, one-half the ultimate height is consistently attained. For example, a 10 megacalorie per second fire with an ultimate plume rise limited to 250 meters will have attained a height of 125 meters at 0.27 mile downwind (i.e., 1/3 x 0.8 mile).

When Briggs' (1969) equation (4.30) is applied, most southern prescribed fires are shown to be unable to penetrate a modest inversion of 1° C at 100-meter elevations or higher.

Now we have a means to express the total height of the plume. That portion of the smoke observed to remain unentrained and traveling along the ground still remains to be accounted for. This phenomenon is experienced even during the hottest portion of the convective-lift phase in southern prescribed fires. Additional research is needed, but observations of the phenomenon on three experimental fires were used to arrive at a ratio of 60-rise to 40-no-rise for the amount left unentrained. This ratio was borne only by observations on a fourth experimental fire.

The 60:40 ratio has thus been suggested for a limited number of both heading and backing fires. When heat release (HR, the heat released per unit of fired-line length, rather than the total heat release rate (HRR), or Q_H) is increased, the ratio can logically be expected to increase toward 100:0, provided stability and transport windspeed remain unchanged. For example, a campfire can be seen to lift all emissions by convection so long as its heat causes a *draw* from all portions of the fire. But the same fire, while still maintaining a convection column, will in time cease to draw smoke from its outer portions. Smoke from these portions will then tend to drift free from convective lift. This is essentially what takes place in most southern prescribed fires covered in the logic of Chapter VI. It seems likely additional research will lead to adjustments in the 60:40 ratio.

In working with plume rise under unstable atmospheric conditions, the effect of vertical wind eddies that temporarily bring high smoke concentrations aloft closer to the ground have been evaluated. The largest vertical eddies occur when instability is greatest. Eddy sizes decrease as conditions become more nearly stable, and the plume rise fluctuations become less significant. These conditions have been found to be important to dispersion calculations for emissions from cool sources like elevated smoke stacks, but they have not been observed in our experimental fires in the Southeast.

To summarize, two expressions have been introduced. These are the factor H for ultimate plume height, and the coefficient 0.6 for the amount of smoke entrained in the convection column of the convective-lift fire phase. Both will be noted as adaptations in the dispersion model to be discussed in following subsections.

SELECTION OF A DISPERSION MODEL

Forest managers have been exposed to the "tank concept" and to applications of a "box model" of dispersion. These names are sometimes incorrectly described as interchangeable. Before selecting any more complex model, it was thus necessary to assess possible adaptations of these two relatively simple approaches.

The "tank concept" is a convenient way of thinking about a certain atmosphere's ability to "absorb" a specified level of air pollutants. The atmosphere, of whatever dimension, is thought of as a container with imaginary "walls" (such as mountains, but sometimes only arbitrary or political boundaries) and a "lid" (such as imposed by an inversion or by the mixing height). It is assumed that smoke is distributed evenly, and that emissions can be accommodated until smoke concentrations reach an accepted maximum for the "tank" as a whole. Unfortunately for a management use of this concept, however convenient it may be in gaining an initial grasp of air pollution problems, the real world of smoke transport and dispersion does not operate nearly so simply! Within the "tank," emissions from each source flow along an axis determined by the transport wind direction. Initial horizontal and vertical diffusion (dispersion) is defined by physical laws that do not result in uniform distributions of pollutant concentrations, even when the "tank" has real walls such as a valley or mountain canyon. The result is that along the path of the plume initial smoke concentrations will be greater than in the "tank" as a whole (a very undemocratic consequence for individuals along the plume's path if they are depending upon administrators of the "tank" to assure them their equal share of pure air).

The term "box model" differs from the "tank concept" in that dispersion takes place along an axis determined by transport wind direction. Distribution, however, is considered to be uniform. This model has gained acceptance through application to dispersion problems in the Willamette Valley of Oregon (Reiquam 1970). A derivation labeled the "smoke-volume model" has been suggested by Williams (1974) for application to prescribed fires. This variant differs from the box model in that the plume is restricted by formulas based upon measured heights and widths of experimental fires. The principal advantage of uniform distribution models is the ease with which calculations for different downwind distances can be accomplished. A potential for solution of long-range transport problems has been identified (Pasquill 1972). The chief disadvantage, however, is that because plume rise is not accounted for, the predicted ground-level concentrations due to a uniform vertical distribution are not valid for locations within the first 100 kilometers (62 miles) of sources.

Wide acceptance has been gained for application of the Gaussian distribution to dispersion modeling. A statistical tool, the Gaussian distribution permits a general description of smoke plume dispersion over time. There have been numerous independent validations in both laboratory and field experiments (Hay and Pasquill 1957; Cramer, Record, and Vaughan 1958; and Barad and Haugen 1959). A workbook, published by the U.S. Environmental Protection Agency (Turner 1970), enjoys widespread application by scientists working on dispersion. This approach employs Gaussian distribution, as well as a synthesis of the work of other accepted authorities. Methods of the Turner Workbook (1970) have thus been selected for use in this Guidebook.

ADAPTATION OF THE TURNER WORKBOOK METHODS TO A MODEL FOR MANAGING SMOKE FROM PRESCRIBED FIRE IN THE SOUTH

Our initial adaptation of the Turner Workbook is straightforward, with Equation (5) being the model used. Combinations of terms and derivations are after Turner (1970), except as adaptations are explained in the list of variables and coefficients (table 12).

$$\chi = \frac{q}{\sqrt{2\pi}\, u\sigma_z} \left\{ 1.6 \sum_{N=1}^{N=3} \exp\left[-0.5\left(\frac{H}{\sigma_z}\right)^2\right] + 1.2 \exp\left[-0.5\left(\frac{H}{\sigma_z}\right)^2\right] + 1.2 \sum_{N=1}^{N=3} \left(\exp\left[-0.5\left(\frac{H - 2NM}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{H + 2NM}{\sigma_z}\right)^2\right]\right)\right\} \int_{-L/2\sigma_y}^{L/2\sigma_y} \frac{1}{\sqrt{2\pi}} \exp\left[-0.5\,(y/\sigma_y)^2\right] d(y/\sigma_y) \qquad (5)$$

Table 12.—Variables and adaptive coefficients used in Equation (5). Other coefficients are from Turner (1970).

Variable or coefficient	Definition and discussion	Units
χ	Centerline, ground-level concentration	micrograms/meter^3
H	Plume rise, adapted from Briggs (1969, 1971, 1972) and as recommended by Turner (see Plume Rise discussion)	meters
L	Length of fired-line adaptation	meters
M	Mixing height, the height in the atmosphere to which turbulent mixing occurs	meters
N	Reflection numbers (as smoke bounces off the ground or stable layers) after Bierly and Hewson (1962)	nondimensional
q	Emission rate per unit length of fired-line adaptation (equivalent to ER)	micrograms/meter-second
u	Transport windspeed	meters/second
y	Variable crosswind distance from mid-point of fireline to the limits $\pm$ L/2σ_y	meters
σ_y	Horizontal standard deviation of plume concentration distribution	meters
σ_z	Vertical standard deviation of plume concentration distribution	meters
1.2 and 1.6	Adapted coefficients resulting from combination of terms with the 0.6 coefficient for the 60-percent entrained and 40-percent unentrained smoke covered under Plume Rise.	nondimensional

Besides being a complex series of terms, Equation (5) calls for certain inputs which are difficult to derive. Some simplifications can be achieved by solving for the relative concentration, $\frac{\chi u}{q}$ on the left-hand side. Transport windspeed, u, and mixing height, M, are readily obtainable for field application, but the remaining three variables on the right—horizontal and vertical standard deviation of plume concentration distribution, σ_y and σ_z, and plume rise, H, all call for more than the equation itself.

This need for further adaptation brought us to three alternatives:

1. Using a computer program to generate a series of graphs or look-up tables

2. Offering a computer program in a form that could be accessed by users

3. Providing a combination of look-up tables and typical cases with predicted concentrations that could be adjusted to actual cases.

The first of these alternatives resulted in such an unwieldy set of tables, graphs, instructions, and intermediate calculations that it was discarded. Alternative No. 2 is in progress at this writing. Recognizing the value of close exposure to the actual procedures, and recognizing as well that some users would not have immediate access to automatic data processing, we have pursued alternative No. 3 in this Guidebook.

PLOTTING RESULTS OF CALCULATIONS

When ground-level dispersion patterns calculated with a modified Gaussian distribution model are plotted to scale, they will typically show curves like those of figure 21.

Because of possible deviations of the actual wind direction from the forecast, and the need to avoid underestimating smoke impact at designated targets, the Gaussian model is not used in unmodified form for predicting downwind smoke

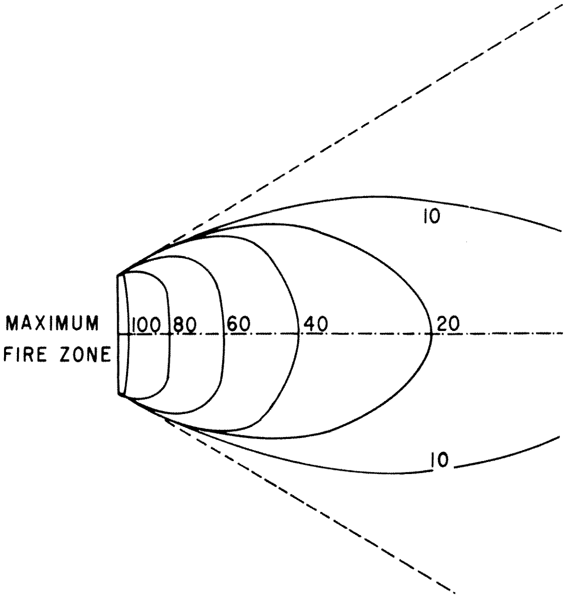

Figure 21. — Ground-level dispersion patterns from a modified Gaussian distribution model. Concentrations are shown on a hypothetical scale of 100 for ease of visualizing changes.

concentrations. Rather, a system that extends the centerline concentrations 30° to either side of the expected downwind direction is used. A possible promise of partially reducing this admittedly conservative allowance, as well as others, lies in automatic data processing for predicting trajectories and concentrations on the day of burning. This promise lies in an ability to work with more massive data from localized weather forecasts which are adjusted over time as the smoke plume travels downwind. While the technology is available now, a conservative procedure must be suggested for use until adaptive work in progress can be completed.

The presently suggested procedure calls for plotting the crosswind length of the line to be fired and plotting a downwind trajectory from the center point of that line. From the ends of the line, downwind trajectories are plotted as dashed lines for a distance of twice the crosswind length of the fired line. From these end trajectories, lines of the limits of possible smoke impact are drawn at 30° outward angles. The trapezoid-like figure that results depicts the area of probable smoke impact.

Concentrations in the impact area are determined by striking arcs through the centerline trajectory at specified distances. At distances less than twice the crosswind line length, two arcs should be struck using the line end points as centers. The two end point arcs are then connected by a straight line passing through the trajectory centerline. Beyond two fired-line lengths downwind, this procedure may be satisfactorily approximated by simply drawing a single arc between the smoke impact limits with the middle of the crosswind line as the center for the arc. The resulting plot, like the one shown in figure 22, differs from figure 21 by intention. This difference allows for a plot of predicted maximum concentrations by zones that extend through the centerline to either edge of the trajectory, thereby avoiding underestimates of concentration due to transient or unexpected wind or centerline shifts.

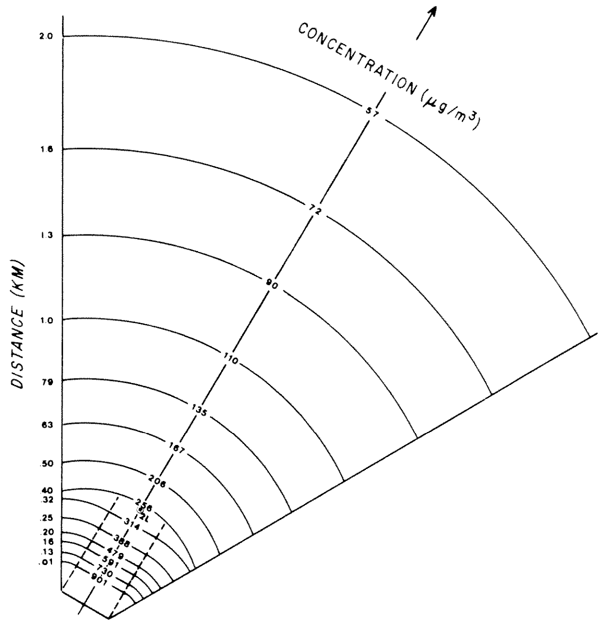

Figure 22. — Plot of predicted centerline concentrations like those to be employed in Chapter VI. The "2L" point indicates twice the fired-line length.

When completed, these plots are used to obtain a total predicted concentration at any potential downwind target by adding the concentration within the zone defined by an arc to the "background" pollutant concentration at the potential target. This permits rapid comparison of total predicted concentrations with acceptable concentrations for all potential targets.

A rule of thumb (Noll and others 1968) can be employed to estimate "background" pollutant concentrations when these have not been quantified by other means. The rule is limited to relative humidities of 70 percent or less and to particulate matter 0.3 micron in diameter and larger. To use the rule, 730 micrograms per cubic meter per mile are divided by the visibility in miles. For example, if the visibility is 5 miles, the "background" pollutant concentration is estimated to be:

$$\frac{730\,\mu g/m^3/mi}{5\,mi} = 146\,\mu g/m^3$$

LONG-RANGE TRANSPORT

Transport of emissions beyond the 100 km (62 miles) limit of the model employed becomes a new predictive problem. Because this problem is almost in a province of regional smoke management, we have made no attempt to provide any adaptation from among the best of several models under study at this time. We have, however, recognized the importance of the normally stable trend toward evening. At the same time, we have attempted to provide a margin of safety to help assure the manager that smoke from a single burn will not contribute to problems beyond 100 km. To do this, we devised a procedure called *Long-Range Transport Margin* which is incorporated in Chapter VI.

BASIS FOR LONG-RANGE TRANSPORT MARGIN

For fires in fuel types known to be relatively heavy emitters, when the convective-lift fire phase will extend beyond 3 hours before sunset, users will find themselves referred to figure VI-M-1 in Chapter VI. To use figure VI-M-1, a graphic intersection of the fire emission rate (ER) and transport windspeed is located. If the intersection is either to the left of, or upon, the sloping internal line

$$\frac{qL}{u} = 7.5 \times 10^8 \text{ micrograms/m}^2\text{-sec,} \qquad (6)$$

the burn may be considered *safe*. If the intersection is to the right of the line, the fire prescription should be modified.

The principal consideration underlying this procedure is to avoid carrying concentrations of particulate matter in excess of 150 micrograms per cubic meter beyond 100 km when stable conditions can be expected.

The following assumptions have been made in constructing figure VI-M-1:

1. D stability
2. No plume rise (because at 100 or more km a plume is well mixed within the mixing layer)
3. Point source (source configuration is of no consequence at 100 km)
4. Relative concentration, $\frac{\chi u}{qL}$, at 100 km is 2×10^{-7} meter^{-2}, which is consistent with 150 micrograms/m^3; variables are the same as previously listed.

LIMITATIONS OF THE MATHEMATICAL MODEL

Of the essential model, Turner (1970) points out that it "... may provide *best estimates* but not infallible predictions." We offer the adapted model in this same frame of reference. In addition to other limitations mentioned in preceding discussions, it is particularly important to note that as the smoke disperses with time, stability and other weather variables will change. The present model does not account for these changes. We have, however, covered one procedure adapted from the model to provide a margin of safety for long-range transport. This procedure is made part of those in Chapter VI to partially compensate for changes in stability. Finally, the user of the procedures in Chapter VI must recognize limitations in the accuracy of weather forecasts. In making these *best estimates* the user is allowing for upward and downward mixing within a zone of concentration. As a consequence, not all potential targets will be receptors at any given instant. He is portraying the potential concentration at each target.

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CHAPTER VI

HOW TO MANAGE SMOKE

by

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This Chapter is written to help manage smoke from forestry prescription burning once the decision to burn has been made. No attempt is made here to evaluate alternatives to burning. Sometimes, the logic steps may lead to a suggestion that the decisionmaker take a new look at other possible treatments. We will first discuss the concepts of smoke management planning and then present a decision-logic procedure. Part 3 of this Chapter contains tables needed to follow some of the more complex logic.

PART 1. PLANNING FOR SMOKE MANAGEMENT

A written burning plan should be prepared in advance for each area to be burned. It should contain a scheduling system and prescription elements that aim at both accomplishment of objectives and avoidance of unwanted air quality effects. We suggest that, as used, the worksheets presented in Part 2 of this Chapter be attached to file copies of completed plans.

SCHEDULING

The number of days during a season with conditions fitting both resource management objectives and air quality objectives is limited. As a consequence, it is likely that the number of large burns will increase on the few days when both sets of constraints are met. Smoke from several forestry sources could tax the smoke-absorbing capacity of target-area atmospheres on these days. A need for systematic and careful scheduling of burns is called for.

A scheduling system that minimizes the effects on air quality should include the following elements:

An analysis of the number of days each year when weather is likely to meet both management objectives *and* air quality objectives

The numbers, sizes, and locations of desired burns listed by priority and difficulty of burn—along with likely-best smoke plume trajectories

A method of allocating available days to desired burns

A procedure for selecting alternate burn tracts when unfavorable weather conditions prevent following the schedule

An inventory of expected *background* particulate matter concentrations in areas likely to be downwind from prescribed burning operations.

PLANNING CHECKLIST

1. Follow a formally prepared plan.
2. Be sure all legal requirements are met.
3. Provide in advance for burning permit, receipt of weather forecasts, and prior measurement of variables like total litter layer moisture content.
4. When windrowing and piling debris, provide for best drying and avoid mixing with dirt.
5. Follow a decision logic to determine the kind of day on which you should be able to burn with good smoke management.

6. Use localized weather information, asking for spot fire-weather forecasts and updates.

7. Burn when wind will not carry smoke into sensitive areas (targets).

8. Seek unstable weather conditions, but not extremes.

9. Avoid days with low morning transport windspeed (less than 4 mph).

10. Avoid days with low morning mixing heights (less than 500 meters).

11. Seek dry fuel conditions, but not extremes.

12. Seek low relative humidity, but not extremes.

13. Be cautious of nighttime burning (if permitted).

14. Be especially cautious when burning a large area or a heavy loading of fuel.

15. Use firing technique that produces the least emissions.

16. Be prepared to mop up stumps and snags, especially if large and decaying.

17. Make last-minute check on weather conditions.

18. Remember that fires have to be controlled, and timber should not be excessively scorched; as dispersal conditions improve, fire intensity increases.

19. Be alert for a change in weather conditions.

PRESCRIPTION ELEMENTS

Combinations of the following fire prescription elements are necessary to plan for maintenance of air quality. Some variables that are foreign to foresters will be needed for smoke management. In the list of elements which follows, numbers in parentheses refer to the decision-logic stages where each is used:

Fuel type (No. 1 and No. 2)
Age of rough (No. 1 and No. 2)
Total litter layer moisture content (No. 2)
Fine fuel moisture (No. 2)
Firing pattern (No. 2)
Length of fired line (No. 1 through No. 3)
Relative humidity (No. 2)
Air temperature (No. 2)
Stability (No. 1 and No. 3)
Mixing height (No. 1)
Surface windspeed and direction (No. 1 and No. 2)
Transport windspeed and direction (No. 1, No.3, and No. 5).

PART 2. DECISION LOGIC

INTENDED USE AND LIMITATIONS

You are now well aware of the large amount of information that must be integrated to determine if fire prescriptions will meet air quality objectives. To accomplish this task, we have developed a decision-logic system for applying the best knowledge available. The system applies the mathematical models and concepts discussed in Chapters IV and V. The criteria for the system are discussed in Chapter III under A VOLUNTARY DECISION PROCEDURE PROPOSED FOR FORESTRY SMOKE MANAGEMENT, starting on page 26.

The system calls for the user to specify his own fire prescription elements and to adopt acceptable levels of total suspended particulate matter (TSP) for target areas downwind. While designed for advance planning, the system should also be used on the day of burning with actual and forecast values substituted for prescribed values.

Our intent is to provide the easiest possible procedure to *AVOID OVERLOADING NATURAL CLEARANCE MECHANISMS.* A model is a representation of beliefs about a natural system, not necessarily what actually takes place. For manageability, models used for dispersion calculations and for heat release rate (HRR) and emission rate (ER) calculations are dependent only upon values expected as averages for *steady-state* conditions during two discreet fire phases. We have chosen this course rather than attempt to impose more realistic, but exceedingly complex, equations—allowing for changes in state during the life of the burn. For these reasons, the logic system's predictions may be incorrect at times even though the system applies the best available technology.

OVERVIEW

The system is divided into six stages to keep the user oriented as he progresses. It is designed for desk-top calculations. As presented here, system responses to variability have been compressed to facilitate use. For example, in one instance, many separate operations and at least 32 tables are represented by only a few typical cases.

Stage No. 1 is for relatively simple screening of prescriptions. From it the user can decide to burn, not to burn, or to proceed with more detailed analyses in subsequent Stages. We expect that this first Stage will cover many prescription burns. Stages No. 2 through No. 5 apply to more complex situations where decisions are not immediately obvious. Stage No. 6 introduces automatic data processing options. 5/

Stage No. 2 is the logic for determining fuel and fire characteristics so that emission rate and heat release rate can be calculated. Stage No. 3 provides for determining a margin of safety for concentrations carried long distances. In Stage No. 4, the user matches his prescription variables to typical burning cases. Provision is made to correct for differences between presented and typical cases. Then, downwind concentrations of total suspended particulate matter can be calculated. In Stage No. 5, comparisons are made between predicted and user-specified total suspended particulate matter concentrations at targets. Decisions to be reached at this point are: to follow the burn prescription, to revise the prescription further, to find an alternative to burning, or to proceed with an analysis that requires automatic data processing.

5/ Programs will be provided in the Forestry Smoke Management Sourcebook.

We recognize that small landowners will find Stages No. 2 through No. 5 especially bothersome without technical staff or assistance. An adaptation of Stage No. 1 has been published for their use in uncomplicated situations (Tangren 1976).

In more complex situations, there are no easy ways to determine smoke dispersion without automatic data processing.

For those who do not have access to a computer, the desk-top decision-logic procedure will seem tedious. We believe it is the only way, however, to assure proper analyses, and we advocate its initial use even for those who have access to automatic data processing.

USE OF WORKSHEETS

Each Stage of the logic is presented in worksheet format. It is suggested that you make copies of these worksheets (yellow pages). Save one set of copies for future use as an original, then use extra copies as working papers to include with each burn plan and prescription.

DECISION-LOGIC STAGE #1: INITIAL SCREENING

To use this decision logic you should have already prepared a written prescription, and you should be familiar with applicable air quality rules, regulations, and standards. If there are no obvious situations that preclude burning, you are ready to proceed.

This Stage will help you decide if your prescription calls for a burn that is:

possible without modification
possible with modification
not possible.

We believe most prescribed fires will fall into the first two categories.

Steps 1.2 and 1.3 contain questions to be answered YES or NO. If all applicable questions are answered YES, the burning prescription can be followed without modification. Burning is still possible if all NO answers can be changed to YES by modifying the fire prescription; for example, by calling for another time to burn when mixing heights are more favorable, or when the transport wind direction will not carry smoke into target areas. If you answer NO and cannot modify the prescription to be able to answer YES, you should not burn unless you favorably complete a more detailed analysis in Stages #2 through #5.

1.1 PREPARATION

1.1a Wind Direction and Targets:

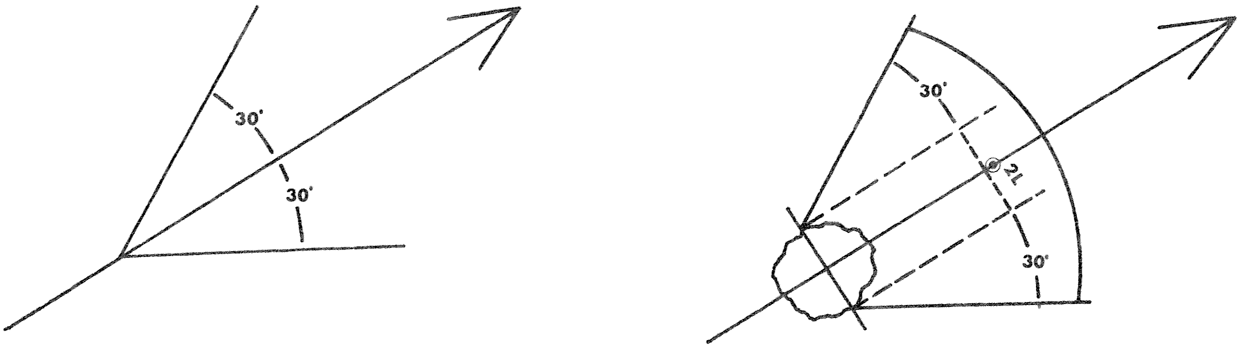
(1) Obtain map(s) covering improvements detail for 60 miles downwind from burn. Obtain azimuths of paths from burn prescription for both the convective-lift (CL) and the no-convective-lift (NCL) fire phases. Locate burn on map and, using protractor and straight edge, draw lines representing centerline of paths of smoke plume. Use two different colors to plot the two phases. Then check here and proceed.

______

Prescription specifics:

Convective-lift phase transport wind azimuth ________°
No-convective-lift phase transport wind azimuth ________°
(NCL is omitted for backing fires)

(2) Now you must allow for the width of the fire and shifts of the smoke plume centerline. Plot as in figure A if the fire is represented by a small dot. If it is larger, plot as in figure B.



Within the plotted areas, look for any improvements or other potential target (e.g.: town, Air Quality Maintenance Area, highway, village, hospital, factory, residence, airfield, etc.) that you consider critical from an air quality standpoint. Then check here and proceed.

_____

(3) If in rare cases no potential targets are found, this logic need not be applied, and you may burn without further use of the procedure. If any targets are identified, you should continue with the procedure. Attach your map(s) to this Worksheet and check *one* of the following:

Target(s) identified, logic will be applied (go on to Step 1.b)_____
No target(s) identified, logic need not be applied further (Stop)_____

1.1b Fuel Type:

(1) At this time, research is not sufficiently complete to cover other than the following fuel types. If your fuel type is other than the ones listed, you must decide if one of these is reasonably comparable to proceed through the rest of the logic *using this type*, or you must plan your prescription without aid of the logic system.

Palmetto-gallberry_____
Grass with pine overstory_____
Pine needle litter_____
Light brush_____
Unpiled pine logging debris_____

(2) Check the appropriate fuel type above if yours matches, or if you select a type as nearly comparable as you can.

(3) If you selected a comparable type, circle the checkmark.

(4) If you checked none of the types listed, you may wish to use this Stage #1 Worksheet, but do so with special caution and *do not attempt to use Stages #2 through #6*.

(5) Now check one of the following:

Type matches or comparable type selected, and logic will be applied _____
Type does not match, and comparable type not selected
but Stage #1 will be applied_____
and Stage #1 will not be applied_____

1.2 CRITICAL TRAJECTORIES

If a NO answer is given to any of the following questions, it is most desirable to prescribe a new *transport wind direction* to avoid target areas in question. *Be sure to also rework Step 1.1a to reflect the new prescribed azimuths.*

If you cannot prescribe a new wind direction you should proceed immediately with Stages #2 through #5, but be prepared to encounter downwind concentrations that may not be acceptable.

1.2a Sulfur Dioxide Interactions:

Does your trajectory avoid the chance that critical sources of atmospheric emissions containing SO_2 will merge with the emissions from your burn.[1]

YES _____
NO _____

1.2b Unacceptable Background Level:

Are all identified target areas likely to be free from other known air pollution problems at the time of burn? (Allow for other forestry burning.)

YES _____
NO _____

1.2c Is the area within 3/4 mile of your burn free of targets?

YES _____
NO _____

1.3 MINIMIZING RISK

You should always determine if you can readily change your prescription to obtain a YES answer whenever you have checked NO in this set of questions.

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[1]Sulfur dioxide, SO_2, is believed by many authorities to become a more likely health hazard in the presence of particulate matter from any source. If local guidance on critical sources is not available to you, a good rule is to avoid all sources.

1.3a Is your fuel type other than logging debris?

YES ______[2]
NO ______

1.3b For all other fuel types if your rough is older than 2 years, is a backing fire prescribed and is total fuel loading less than 10 tons per acre?[3]

YES ______[2]
NO ______

1.3c Will the burn be conducted when background visibility is likely to be at least 5 miles at all points within the first 60 miles along the plotted trajectory? (Step 1.1a)

YES ______
NO ______

1.3d Are all other known or expected sources of emissions (including other prescribed burns) displaced to the side of your plotted trajectory (Step 1.1a) by a distance of at least one-half their downwind distance and are any targets in overlapping area farther than 2 km (1.2 miles)?

YES ______
NO ______

1.3e Does your prescription call for the forecast mixing height to be 500 meters or more?

YES ______
NO ______

1.3f Is the prescribed transport windspeed 4 or more meters per second?

YES ______
NO ______

1.3g If your plan calls for a night burn, have you prescribed a surface windspeed greater than 4 mph and a backing fire?

YES ______
NO ______
NOT APPLICABLE ______

---

[2] Go directly to Stage #2 since prescription cannot be changed.

[3] This question reflects the application of current best available technology in limiting total suspended particulate matter (TSP) regardless of chemical nature.

1.3h If a burning permit is locally required, do your prescription elements match *permit* requirements and does your plan call for obtaining the required permit?

YES _____
NO _____[4]
NOT APPLICABLE _____

NOTE: You now have a set of answers to help you screen your prescription. If you have completed the preparatory Steps in Steps 1.1 and have now answered YES to all questions asked in Steps 1.2 and 1.3, you do not need to go on to Stages #2 through #5. Instead, it is likely your prescription will provide for good smoke management and you are ready to burn. If you have answered NO and cannot revise your prescription, you should not burn until you have favorably completed Stages #2 through #5.[5]

---

[4]Do not proceed to Stage #2 if permit is required and NO has been answered.

[5] CAUTION: Stages #2 through #6 are likely to yield DO NOT BURN decision advice if you are using any of the following:

Less than 500 meters mixing height
Less than 4 mph surface windspeed
Less than 4 meters per second transport windspeed
Background visibility on trajectory less than 5 miles.

SPECIAL INTRODUCTION TO STAGES #2 THROUGH #5

If an automatic data processing procedure for smoke management decisions is available to you, you should skip immediately to Stage #6.

The following interrelated parameters are needed to predict total downwind concentrations that will be used for comparisons with acceptable concentrations. The variables used to derive them are provided.

Parameter	Variables
Total litter layer moisture content	Previous litter layer moisture content, age of rough, yesterday's duration of precipitation (see Chapter IV).
Fuel loading	Fuel type, age of rough, stand basal area, understory height (palmetto only), average d.b.h. (logging residue only), cords cut (logging residue only).
Available fuel	Fuel type, fuel loading, total litter layer moisture content.
Emission factor	Fuel type, combustion stage, age of rough, burning method.
Fire phase	Heat release rate.
Combustion stage	Fire behavior.
Fine fuel moisture	Temperature, relative humidity, sky condition (grass only).
Stand characteristics	Preburn inventory or preharvest inventory.
Rate of spread	Fine fuel moisture, windspeed at midflame height, fuel type.
Length of fired line	Prescription, plot geometry (for ring fires only).
Heat release rate	Available fuel, rate of spread, length of fired line.
Particulate matter emission rate	Available fuel, rate of spread, emission factor.
Mixing height	Observed and forecast weather.
Transport windspeed and direction	Observed and forecast weather.
Stability class	If not forecast by the National Weather Service: solar angle (shadow length), cloud cover and height, 10-meter windspeed (see Chapter V).
Target-area *background* concentrations	Effects of other emissions sources.

This decision logic does not apply to slopes greater than 20 percent.

Two sets of reference figures and tables will be used in working through the logic stages. The first set (tables VI-F-1 through VI-F-13) is related to fuels and fire behavior and is printed on pink paper. The second set (tables VI-M-1 through VI-M-6 and figure VI-M-1) is related to meteorology and is printed on blue paper. Many calculations are represented by these figures and tables. Derivations are explained in Guidebook Chapters IV and V.

In preparing to use the Stages, it is important to recognize two constraints in the system presented:

1. For each fuel type, an average emission factor (EF) has been derived for the most likely fuel conditions. We know that moisture and other variables will affect the EF, but believe the current state of knowledge does not warrant further refinement in calculations at this time.

2. The strategy here is to limit concentrations of total suspended particulate matter (TSP). Future control strategies may include control of specific components of smoke.

DECISION-LOGIC STAGE #2: RATE DETERMINATIONS

You have been directed here from Stage #1 because one of your responses indicated a degree of risk calling for more complex analyses, and/or you were unable to modify your fire prescription.

From the list of parameters in the Special Introduction preceding this Stage, you will have noted a number of new prescription elements. Your prescription will require more detail, and we suggest you prepare the prescription as you work through this and subsequent Stages--adding new variables as needed.

CAUTION: Do not proceed unless your prescription calls for a relative humidity of less than 71 percent during the convective-lift and no-convective-lift phases. (Predictions above this humidity are not to be used and the logic does not apply.)

A. DETERMINATION OF STAGE #2 WORKSHEET SET TO BE USED:

The fuel type you selected in Step 1.1b was (check one, then proceed to next step on indicated Worksheet Set):

Palmetto-gallberry _____	Go directly to Worksheet Set 2B
Grass with pine overstory _____	Go directly to Worksheet Set 2C
Pine needle litter or light brush _____	Go directly to Worksheet Set 2D
Unpiled pine logging debris _____	Go directly to Worksheet Set 2E.

DECISION-LOGIC STAGE #2 APPLIED TO PALMETTO-GALLBERRY FUEL TYPE
You Have Been Directed Here From Worksheet Set 2A

2B.1 FUELS

2B.1a Make the following entries from your inventory of the burn area:

(1) Stand basal area is _____ sq ft/acre
(2) Age of rough is _____ yr
(3) Predominant overstory timber species is (check one):
Slash pine _____
Loblolly pine _____
(4) Average height of understory component is _____ ft

2B.1b With entries (1), (2), and (3) from above, use table VI-F-5 if the predominant species is slash pine, or use table VI-F-6 if the predominant species is loblolly pine, to determine the total litter weight, entering the value here:

_____ ton/acre

2B.1c With entries (2) and (4) from above, use table VI-F-9 to determine the understory vegetative dry weight, entering the value here:

_____ ton/acre

2B.2 TOTAL LITTER LAYER MOISTURE CONTENT

2B.2a Prescribe a maximum total litter layer moisture content (TLLMC). (Review Southern Forestry Smoke Management Guidebook Chapter IV for procedure and requirements.) The TLLMC will be:

_____ %

2B.2b Assure that the burning plan provides for observing and recording actual TLLMC. Then return here, check, and proceed to next step.

_____

2B.3 TOTAL AVAILABLE FUEL

2B.3a With the total litter weight you determined in Step 2B.1b, the understory vegetative dry weight you determined in Step 2B.1c, and the prescribed maximum TLLMC you entered in Step 2B.2a, use table VI-F-10 to determine the estimated total available fuel (litter and vegetation), entering the value here:

_____ ton/acre

2B.4 PINE NEEDLE MOISTURE CONTENT AND BURNING METHOD

2B.4a Make the following entries from your written prescription for subsequent use:

Maximum relative humidity _____%
Minimum windspeed (20-foot tower) _____mph
Burning method (check one):
Heading fire _____
Backing fire _____

2B.4b With the relative humidity entry from above, use table VI-F-3 to determine the pine needle litter moisture content, entering the value here: _____ %

2B.5 WIND EFFECT

2B.5a If you have prescribed a heading fire, divide windspeed you entered in Step 2B.4a by 4 to arrive at an estimated midflame windspeed, entering the value here; if you have prescribed a backing fire, enter a zero here: _____ mph

2B.6 RATE OF SPREAD

2B.6a With the pine needle litter moisture you determined in Step 2B.4b and the windspeed you determined in Step 2B.5a (the windspeed used here for a backing fire is always _0_), use table VI-F-11 to determine rate of spread, entering the value here:

_____ ft/min

2B.7 COMBUSTION STAGES

2B.7a Because a sizable fraction of the fuels, when heading fired, will remain to be consumed in the residual combustion stage after the advancing-front combustion stage passes, an adjustment is needed to proportion the amount of fuel available to each stage. A suggested advancing front:residual ratio of fuel consumed is 50:50. When backing fires are employed, almost all of the fuel is consumed during the advancing-front combustion stage, and a ratio of 1:0 is appropriate. Now select the values you judge most appropriate and enter here:

(1) Decimal fraction of fuel consumed in advancing-front stage (y_A) _____
(2) Decimal fraction of fuel consumed in residual stage (y_R); ($1.00 - y_A$) _____

2B.8 EMISSION FACTORS

2B.8a The suggested TSP emission factors (EF) for the palmetto-gallberry type are:

Age of rough and burning method	Emission factors (lbs/ton)	
	Advancing-front stage EF_A	Residual stage EF_R
≤2 years backing or heading and >2 years backing	25	None
>2 years heading	25	125

Now, opposite your age of rough and burning method, either circle the EF value(s) to be used or enter new values if better data are available to you.

2B.9 EMISSION RATES

2B.9a Perform the indicated multiplications by entering the values from the steps shown in the following equations.

(1) Calculate ER_A, the total suspended particulate matter (TSP) emission rate, for the advancing front combustion stage:

ER_A = 570 x ______ (Available fuel from Step 2B.3a) x ______ (Rate of spread from Step 2B.6a)

x ______ (Consumption adjustment (y_A) from Step 2B.7(1)) x ______ (EF_A from Step 2B.8a)

ER_A = ______ micrograms TSP/meter-second (μg TSP/m-sec)

(2) If your prescription is for a backing fire in any age rough, or for a heading fire in rough 2 years old or less, skip directly to Step 2B.9b.

If your prescription is for a heading fire in rough more than 2 years old, calculate ER_R, the TSP emission rate for the residual combustion stage:

ER_R = 570 x ________________ x ________________
(Available fuel from Step 2B.3a) (Rate of spread from Step 2B.6a)

x ________________ x ________________
(Consumption adjustment (y_R) from Step 2B.7a(2)) (EF_R from Step 2B.8a)

ER_R = __________ µg TSP/m-sec

(3) Now calculate ER_{A+R}, the TSP emission rate for the convective-lift phase of heading fires in rough older than 2 years:

ER_{A+R} = ____________ + ____________
(ER_A from Step 2B.9a(1)) (ER_R from Step 2B.9a(2))

ER_{A+R} = __________ µg TSP/m-sec

2B.9b If you were told to skip to this Step from Step 2B.9a(2), enter the value of ER_A, from Step 2B.9a(1) in the blank below for ER_{CL}, and NONE in ER_{NCL} below, then skip directly to Step 2B.10.

If you calculated ER_{A+R} in Step 2B.9a(3), enter the value for ER_{A+R} in the blank below for ER_{CL}, then enter the value for ER_R from Step 2B.9a(2) in the blank below for ER_{NCL}.

ER_{CL} = __________ µg TSP/m-sec

ER_{NCL} = __________ µg TSP/m-sec

2B.10 HEAT RELEASE RATE

2B.10a Make the following entry from your written prescription:

Length of fired line _____ft

2B.10b Using the length of fired line from the Step immediately above and the same weight of available fuel and rate-of-spread values just used in Step 2B.9a, calculate the heat release rate (HRR) for the convective-lift phase of your fire. Heat release has negligible effect for the no-convective-lift phase.

HRR_{CL} = 0.0012 x ________________ x ________________
(Available fuel from Step 2B.3a) (Rate of spread from Step 2B.6a)

x ________________ x ________________
(Consumption adjustment (y_A) from Step 2B.7a(1)) (Length of fired line Step 2B.10a)

HRR_{CL} = __________ megacal/sec

NOW SKIP DIRECTLY TO STAGE #3

DECISION-LOGIC STAGE #2 APPLIED TO GRASS WITH PINE OVERSTORY FUEL TYPE

You Have Been Directed Here From Worksheet 2A

2C.1 FUELS

2C.1a Make the following entries from your inventory of the burn area for subsequent use:

(1) Age of rough _____ yr
(2) Stand basal area _____ sq ft/acre
(3) Predominant overstory (check one):

Slash pine _____
Loblolly pine _____

2C.1b With entry (1) from above, use table VI-F-1 to determine the total available grass weight, entering the value here:

_____ ton/acre

2C.1c With entries (1), (2), and (3) from above, use table VI-F-5 if the predominant overstory is slash pine, or table VI-F-6 if the predominant overstory is loblolly pine, to determine the total needle litter weight, entering the value here:

_____ ton/acre

2C.1d Compare the entry you made for the grass weight in Step 2C.1b with the entry you made for the needle litter weight in Step 2C.1c. Is the grass component greater?

Yes _____ then proceed to Step 2C.2
No _____ then skip directly to Worksheet 2D and reclassify fuel type as pine needle litter, the more applicable fuel type.

2C.2 WINDSPEED AND RELATED PRESCRIPTION ELEMENTS

2C.2a Make the following entries from your written prescription for subsequent use:

Expected cloud cover (check one): Sunny _____
Cloudy _____
Minimum windspeed (20-foot tower) _____ mph
Temperature _____ °
Maximum relative humidity _____ %
Burning method (check one): Heading fire _____
Backing fire _____

2C.2b If your prescription calls for a backing fire, skip directly to Step 2C.3.

If your prescription calls for a heading fire, divide windspeed you entered above by 4 to arrive at an estimated midflame windspeed, entering the value here:

_____ mph

2C.3 RATE OF SPREAD

2C.3a Use the appropriate prescription entries in Step 2C.2a with table VI-F-2 to determine fine fuel moisture for dead grass, entering the tabular value here:

_____ %

2C.3b If you completed Step 2C.2b, use the midflame windspeed, or for backing fires use a zero windspeed, along with this fine fuel moisture to determine the rate of fire spread for grass from table VI-F-4, entering the tabular value here:

_____ ft/min

2C.4 TOTAL LITTER LAYER MOISTURE CONTENT

2C.4a Prescribe a maximum total litter layer moisture content (TLLMC) (review Southern Forestry Smoke Management Guidebook Chapter IV for procedure and requirements). The maximum TLLMC will be:

_____ %

2C.4b Assure that the burn plan provides for observing and recording actual TLLMC. Then return here, check, and proceed to next step:

_____

2C.5 AVAILABLE LITTER FUEL

2C.5a With the total litter weight (needle fuel) you determined in Step 2C.1c and the prescribed TLLMC you entered in Step 2C.4a, use table VI-F-7 to determine the available fuel in pine needle and associated vegetative litter other than grass, entering this value here:

_____ ton/acre

2C.6 COMBINED TOTAL AVAILABLE FUEL

2C.6a Add the total available grass weight from Step 2C.1b to the available litter fuel from Step 2C.5a, entering the total here:

_____ ton/acre

2C.7 EMISSION FACTORS AND RATES FOR GRASS

2C.7a An emission factor (EF) of 15 pounds per ton of fuel consumed is suggested for grass fuels from experiments to date. Using this or other information available to you, select an EF appropriate to your prescribed burn, entering the value here:

EF = _____ lb/ton of fuel

2C.7b Using the determined values from the Steps shown in the following equation, calculate an emission rate (ER) by performing the indicated multiplications:

ER_A = 570 x ____________ (Combined total available fuel from Step 2C.6a) x ____________ (Rate of spread from Step 2C.3b)

x ____________ (EF from Step 2C.7a)

ER_A = _____ μg TSP/m-sec

2C.7c Since there is no appreciable residual combustion stage (and thus no no-convective-lift fire phase) for this fuel type with all burning methods, the advancing-front emission rate (ER_A) is equivalent to the convective-lift (CL) fire phase. For this reason, enter the ER_A value you determined in Step 2C.7b in the blank below:

ER_{CL} = _____ μg TSP/m-sec

2C.8 HEAT RELEASE RATE

2C.8a From your written prescription, enter here the length of fired line:

_____ ft

2C.8b Calculate the heat release rate (HRR) for your fire by entering the determined values from the Steps shown in the following equation and performing the indicated multiplications:

HRR_{CL} = 0.0012 x ______________ x ______________
(Combined total available fuel from Step 2C.6a) (Rate of spread from Step 2C.3b)

x ______________
(Length of fired line from Step 2C.8a)

HRR_{CL} = _____ megacal/sec

DECISION-LOGIC STAGE #2 APPLIED TO PINE NEEDLE LITTER AND/OR LIGHT BRUSH
You Have Been Directed Here From Worksheet Set 2A, or by fuel type reclassification from Worksheet Set 2C

2D.1 FUELS

2D.1a (1) If you have been directed here from Worksheet Set 2A, skip directly to Step 2D.1b.

(2) If you have been directed here from Worksheet Set 2C, bring forward your entries from that Worksheet as follows:

Total available grass weight ________________ ton/acre
(from Step 2C.1b)

Pine needle total litter weight ________________ ton/acre
(from Step 2C.1c)

(3) Now skip directly to Step 2D.2.

2D.1b Make the following entries from your inventory of the burn area for subsequent use:

(1) Stand basal area is _____ sq ft/acre
(2) Age of rough is _____ yr
(3) Predominant overstory is (check one): Slash pine _____
Loblolly pine _____

2D.1c With the entries (1), (2), and (3) from above, use table VI-F-5 if the predominant species is slash pine, or use table VI-F-6 if the predominant species is loblolly pine, to determine the total litter weight, entering the value here:

_____ ton/acre

2D.2 TOTAL LITTER LAYER MOISTURE CONTENT

2D.2a Prescribe a maximum total litter layer moisture content (TLLMC) (review Southern Forestry Smoke Management Guidebook Chapter IV for procedure and requirements). The TLLMC will be:

_____ %

2D.2b Assure that the burn plan provides for observing and recording actual TLLMC. Then return here, check, and proceed to next step:

_____

2D.2c You will now use either the pine needle total litter weight from Step 2D.1a(2), if you completed this Step, or use the total litter weight from Step 2D.1c, if you completed this Step. With the value for total litter weight and the prescribed maximum TLLMC you entered in Step 2D.2a, use table VI-F-7 to determine the available litter fuel, entering the value here:

_____ ton/acre

2D.3 RATE OF SPREAD

2D.3a Make the following entries from your written prescription:

Relative humidity _____ %
Windspeed (20-foot tower) _____ mph
Burning method (check one): Heading fire _____
Backing fire _____

2D.3b With the relative humidity entry from above, use table VI-F-3 to determine the pine needle litter moisture content, entering the value here:

_____ %

2D.3c If you have a prescribed heading fire, divide windspeed you entered in Step 2D.3a by 4 to arrive at an estimated midflame windspeed, entering the value here; or if you have prescribed a backing fire, enter a zero:

_____ mph

2D.3d With the pine needle litter moisture content you determined in Step 2D.3b and the windspeed you determined in Step 2D.3c (the windspeed used here for a backing fire is always 0), use table VI-F-8 to determine rate of spread, entering the value here:

_____ ft/min

2D.4 COMBUSTION STAGES

2D.4a Because a sizable fraction of the fuels, when heading fired, will remain to be consumed in the residual combustion stage after the advancing-front combustion stage passes, an adjustment is needed to proportion the amount of fuel available to each stage. Limited laboratory data suggest the advancing-front:residual ratio of fuel consumed is 50:50. When backing fires are employed, almost all of the fuel is consumed during the advancing-front combustion stage and a ratio of 1:0 is appropriate. Now, select the values you judge most appropriate and enter here:

(1) Decimal fraction of fuel consumed in advancing-front stage (y_A): _____

(2) Decimal fraction of fuel consumed in residual stage (y_R) ($1.00 - Y_A$): _____

2D.5 EMISSION FACTORS

2D.5a The suggested total suspended particulate matter (TSP) emission factors (EF) for the pine needle/light brush fuel type are:

Age of rough and burning method	Emission factors (lbs/ton) Advancing-front stage EF_A	Residual stage EF_R
≤2 years backing or heading and >2 years backing	50	None
>2 years heading	50	180

2D.6 EMISSION RATES

2D.6a If you completed Step 2D.1a, add the total available grass weight in Step 2D.1a(2) to the available litter fuel you determined in Step 2D.2c, entering the sum in the blank space below.

If you completed Step 2D.1b, enter only the available litter fuel you determined in Step 2D.2c in the blank space below.

Total fuel available: _____ ton/acre

2D.6b Perform the indicated multiplications by entering the values from the Steps shown in the following equations.

(1) Calculate ER_A, the total suspended particulate matter (TSP) emission rate (ER) for the advancing-front combustion stage:

ER_A = 570 x ____________ (Total fuel available from Step 2D.6a) x ____________ (Rate of spread from Step 2D.3d)

x ____________ (Consumption adjustment (y_A) from Step 2D.4a(1)) x ____________ (EF_A from Step 2D.5a)

ER_A = _____ μg TSP/m-sec

(2) If your prescription is for a backing fire in any age rough, or for a heading fire in rough 2 years old or less, skip directly to Step 2D.6c.

If your prescription is for a heading fire in rough more than 2 years old, calculate ER_R, the TSP emission rate (ER) for the residual combustion stage:

ER_R = 570 x ______ (Total fuel available from Step 2D.6a) x ______ (Rate of spread from Step 2D.3d)

x ______ (Consumption adjustment (y_R) from Step 2D.4a(2)) x ______ (EF_R from Step 2D.5a)

ER_R = _____ μg TSP/m-sec.

(3) Now, calculate ER_{A+R}, the TSP emission rate (ER) for the convective-lift phase of heading fires in rough older than 2 years:

ER_{A+R} = ______ (ER_A from Step 2D.6b(1)) + ______ (ER_R from Step 2D.6b(2))

ER_{A+R} = _____ μg TSP/m-sec.

2D.6c If you were told to skip to this Step from Step 2D.6b(2), enter the value of ER_A from Step 2D.6b(1) in the blank below for ER_{CL}, and NONE in ER_{NCL}, below, then skip directly to Step 2D.7.

If you calculated ER_{A+R} in Step 2D.6b(3), enter the value for ER_{A+R} in the blank below for ER_{CL}, then enter the value for ER_R from Step 2D.6b(2) in the blank below for ER_{NCL}:

ER_{CL} = _____ μg TSP/m-sec

ER_{NCL} = _____ μg TSP/m-sec.

2D.7 HEAT RELEASE RATE

2D.7a Make the following entry from your written prescription:

Length of fired line _____ ft

2D.7b Using the length of fired line from the Step immediately above and the same weight of available fuel and rate-of-spread values just used in Step 2D.6b, calculate the heat release rate (HRR) for the convective-lift phase of your fire. (Heat release has negligible effect for the no-convective-lift phase.)

HRR_{CL} = 0.0012 x ______________ x ______________

(Available fuel from Step 2D.6a) (Rate of spread from Step 2D.3d)

x ______________ x ______________

(Consumption adjustment (y_A) from Step 2D.4a(1)) (Length of fired line from Step 2D.7a)

HRR_{CL} = _____ megacal/sec

NOW SKIP DIRECTLY TO STAGE #3

DECISION-LOGIC STAGE #2 APPLIED TO UNPILED LOGGING DEBRIS
You Have Been Directed Here From Worksheet Set 2A

2E.1 FUELS

2E.1a Enter here for subsequent use the following information from your inventory of the burn area:

(1) Average d.b.h. in cut timber stand _____ inches
(2) Species of timber cut (check one): Loblolly pine _____
Slash pine _____
(3) Total number cords removed from area _____
(4) Total acres in burn _____

2E.1b Using the diameter and species entries you made in Step 2E.1a (1) and (2), turn to table VI-F-12 to obtain the tons of logging residue fuel 1 inch in diameter and less per cord for your burn area, entering here:

_____ ton/cord cut

2E.1c Now, using entries you made in Step 2E.1a (3) and (4), divide the total number of cords removed entry by the total acres entry, then enter the result here:

_____ cord cut/acre

2E.1d Now, multiply the ton/cord cut entry you determined in Step 2E.1b by the number of cord cut/acre you determined in Step 2E.1c to calculate the available fuel per acre, entering the product here:

_____ ton/acre

2E.2 FUEL CONSUMPTION

2E.2a Lacking a more precise means to directly express a rate of fuel consumption for this fuel type, rate of fire spread for the fine fuels that dominate its initial spread will be used as a yardstick, and then adjusted. For this purpose, enter here the following elements affecting spread in fine fuels from your written prescription:

(1) Maximum relative humidity _____ %
(2) Surface windspeed (20-foot tower) _____ mph

2E.2b Using the relative humidity entry from Step 2E.2a (1), turn to table VI-F-3 to determine the pine needle moisture content, entering this value here:

Pine needle moisture content _____ %

2E.2c Convert your surface windspeed entered in Step 2E.2a (2) to midflame windspeed by dividing by 2.[5] Then turn to table VI-F-13 and use this converted windspeed value with the pine needle litter moisture value you determined in Step 2E.2b to determine rate of spread, entering the value here:

_____ ft/min

2E.3 COMBUSTION STAGES

2E.3a Because fire spread in fine fuels is only a yardstick by which to gauge emissions and heat yield, and because a sizable amount of the fuels will remain to smolder during the residual combustion stage, an adjustment is needed to proportion the amount of fuel available to each stage. Limited data suggest an advancing-front: residual ratio of 75:25 for fuel consumed. With this and other data available to you, select the values you judge most appropriate and enter here:

(1) Decimal fraction of fuel consumed in advancing-front stage (y_A) _____

(2) Decimal fraction of fuel consumed in residual stage (y_R); (1.00 - advancing-front stage) _____

2E.4 EMISSION FACTORS

2E.4a A total suspended particulate matter (TSP) emission factor (EF_A) of 35 pounds per ton of fuel consumed is suggested for the advancing-front stage. The suggested EF_R for the residual stage is 180 pounds TSP per ton of fuel consumed. As covered in Chapter IV, these values are appreciably higher than laboratory-determined values, but are suggested at this time as a conservative representation of the best overall information available.

From this information, select emission factors (EF) for your prescribed burn and enter here:

(1) EF_A = _____ lb TSP/ton

(2) EF_R = _____ lb TSP/ton

---

[5]A factor of 2 is used rather than 4, as in understory burns, because harvesting has removed sheltering trees.

2E.5 EMISSION RATES

2E.5a Using the determined values from the Steps shown in the equations that follow, calculate emission rates (ER) by performing the indicated multiplications:

(1) For the advancing-front stage:

ER_A = 570 x ______ (Available fuel from Step 2E.1d) x ______ (Rate of spread from Step 2E.2c)

x ______ (Consumption adjustment (y_A) from Step 2E.3(1)) x ______ (EF_A from Step 2E.4a(1))

ER_A = _____ µg TSP/m-sec

(2) For the residual stage:

ER_R = 570 x ______ (Available fuel from Step 2E.1d) x ______ (Rate of spread from Step 2E.2c)

x ______ (Consumption adjustment (y_R) from Step 2E.3a(2)) x ______ (EF_R from Step 2E.4a(2))

ER_R = _____ µg TSP/m-sec

(3) Now, calculate ER_{A+R}, the TSP emission rate for the convective-lift phase of your fire:

ER_{A+R} = ______ (ER_A from Step 2E.5a(1)) + ______ (ER_R from Step 2E.5a(2))

ER_{A+R} = _____ µg TSP/m-sec

2E.5b Enter again in the ER_{CL} blank below the value of ER_{A+R} you just calculated in Step 2E.5a(3). Then enter in the ER_{NCL} blank the value of ER_R you calculated in Step 2E.5a(2).

ER_{CL} = _____ µg TSP/m-sec

ER_{NCL} = _____ µg TSP/m-sec.

2E.6 FIRING PATTERN AND FIRED-LINE LENGTH

2E.6a From your written prescription, enter here your prescribed primary firing pattern (check one, then go to indicated Steps):

Ring firing _____ (if checked, skip to Step 2E.6c)
Heading fire _____ (if checked, proceed to Step 2E.6b)

2E.6b Use planned length of fired line without further adjustment, entering length from your written prescription here:

_____ ft

Now skip directly to Step 2E.7.

2E.6c Determine an equivalent to fired line length by following the rule-of-thumb procedure outlined in the Southern Forestry Smoke Management Guidebook Chapter IV. Enter the equivalent determined here:

_____ ft

2E.7 HEAT RELEASE RATE

2E.7a Using the determined values from the Steps shown in the equation that follows, calculate the convective-lift phase heat release rate (HRR_{CL}) by performing the indicated multiplications. (Heat release is of negligible effect for the no-convective-lift phase.)

HRR_{CL} = 0.0012 x _____ (Available fuel from Step 2E.1d) x _____ (Rate of spread from Step 2E.2c)

x _____ (Consumption adjustment (y_A) from Step 2E.3a(1)) x _____ (Length of fired line from Step 2E.6b or or 2E.6c)

HRR_{CL} = _____ megacal/sec

NOW GO DIRECTLY TO STAGE #3

DECISION-LOGIC STAGE #3: LONG-RANGE MARGIN
You Have Been Directed Here from Stage #2

3.1 FUEL TYPE

3.1a Is the fuel type selected to describe your planned burn unpiled pine logging debris or palmetto-gallberry over 2 years old, or for other fuel types will your convective-lift fire phase last to a time 3 hours before sunset?

NO _____ (skip directly to Stage #4)
YES _____ (proceed to Step 3.2a)

3.2 DETERMINATION OF TOTAL EMISSION RATE, qL

3.2a Enter here again the length of fired line (or its equivalent if determined in Step 2E.6c):

L = _____ ft

Now convert this length in feet to length in meters (multiply feet by 0.3048), entering the converted length here:

L = _____ meters

3.2b Refer back to your Worksheet Set 2B or 2E for the value of ER_{NCL} (which equals q), entering this value again here (if ER_{NCL} not calculated, substitute ER_{CL}):
$q = ER_{NCL} =$ ______ μg TSP/m-sec

3.2c Multiply the entry for L *in meters* (not feet) from Step 3.2a times ER_{NCL} in Step 3.2b for a value of qL, entering the result here:

qL = _____ μg TSP/sec

3.3 SAFETY MARGIN

3.3a From your written prescription, enter here the transport windspeed:

_____ m/sec

3.3b (1) Using the metric value qL you entered in Step 3.2c and the transport windspeed you entered in 3.3a, refer to figure VI-M-1 to determine if the intersection of these two values is in the *safe* or *unsafe* portion of the graph.

If *safe*, it is likely your fire will not result in a long-range (>100 km or 62 miles) concentration greater than 150 $\mu g/m^3$. Which did you determine?

Safe _____ (skip directly to Stage #4)
Unsafe _____ (proceed to Step 3.3b(2))

3.3b (2) Because your long-range transport calculation indicates a risk that the concentration will exceed 150 $\mu g/m^3$ at or beyond 100 km (62 miles), you are redirected to Stage #1 to rewrite the prescription. *NOTE:* If possible, change time of burn for fuel types other than palmetto-gallberry or unpiled pine logging debris, or it may be desirable to modify the prescribed length of fired line or equivalent as a quick way of reducing the qL value, but bear in mind that this will also reduce the HRR_{CL} value with an effect on plume rise, considered later.

DECISION-LOGIC STAGE #4: MATCHING PRESCRIPTIONS TO TYPICAL CASES
You Have Been Directed Here from Stage #3

4.1 SELECTION OF TYPICAL CASE

4.1a To arrive at a set of easily used typical cases rather than an extremely large number of complex tables and computations, it has been necessary to fix certain variables. To use the procedure, you must now either conform your written prescriptions to at least equal those variables that are fixed or you must make a series of adjustments to the typical-case concentrations in order to match your burn situation. All adjustments and all prescribed elements that are more favorable to dispersion than typical will result in overestimates of tabular concentrations (i.e., the estimates are conservative).

NOTE: In this and all succeeding steps, complete no-convective-lift phase only for those burning situations for which you calculated an ER_{NCL} in Stage #2.

Turn now to table VI-M-1 to find the typical case (by fuel type) most closely matching yours, entering the case number here:

Convective-lift phase ________________
(Typical case no.)

No-convective-lift phase ________________
(Typical case no.)

4.2 MATCHING FIXED PRESCRIPTION ELEMENTS

4.2a In this Step, you will have a match to start with, will modify your prescription to match fixed variables, or will indicate a match cannot be made. For each of the following, enter your prescribed value:

Convective-lift phase[6]: Stability class _____
Mixing height _____m

No-convective-lift phase: Stability class _____
Mixing height _____m

4.2b For each of the following, indicate which answer applies.

(1) Column 2: Stability class must be at least as good as shown in table VI-M-I.[7] Indicate how your prescription matches (check one in each phase):

---

[6]For actual day of burn, if National Weather Service is not furnishing stability class, see Southern Forestry Smoke Management Guidebook Chapter V for a method of determining stability class in the field.

[7]Note stability classes decrease in ability to help smoke dispersion as these scale from A to D (i.e., A is better than B, etc.). Classes shown as typical are more likely to be encountered.

	Convective-lift phase	No-convective-lift phase
Matched or is better	_____	_____
Made to match	_____	_____
Is not as good as and cannot be made to match	_____	_____

(2) Column 3: Mixing height must be higher than or at least within 300 meters of the value shown as typical in table VI-M-1. Indicate how your prescription matches (check one in each phase):

	Convective-lift phase	No-convective-lift phase
Matched or is better	_____	_____
Made to match	_____	_____
Is not as good as and cannot be made to match	_____	_____

4.2c In both (1) and (2) of Step 4.2b, did you check that a match could be made? (check only one):

YES (both matched or made to match) _____

Skip to Step 4.3a

NO (one or both variables cannot be made to match) _____

If a match cannot be made, we recommend that you arrange for a computer-assisted analysis for determining the best combination of prescription elements. Is this possible?

YES _____ (If this is possible, proceed directly to Stage #6)

NO _____ (If not possible, you will run a risk of causing or contributing to a pollution episode under your present prescription. An alternative to burning is recommended.)

4.3 OTHER VARIABLES AND CORRECTION FACTORS

4.3a Each of the following variables can be made to match the typical case by correction factors. First enter here for subsequent use the values shown in your written prescription for transport windspeed:

Convective-lift phase _____m/sec No-convective-lift phase _____m/sec

4.3b Now enter the crosswind length of fired line from your prescription. (*NOTE*: Do not use the fired-line equivalent for logging debris from Step 2E.6c here. For this calculation, the crosswind width of the fired area is needed in order to arrive at plume width.)

(1) _____ ft

And then convert this value to meters by multiplying feet by 0.3048, entering the conversion here:

(2) _____ m

4.3c Enter here values from that portion of Stage #2 you completed:

(1) Convective-lift phase heat release rate
HRR_{CL} _____ megacal/sec

(2) Emission rates (ER)
ER_{CL} _____ μg/m-sec

ER_{NCL} _____ μg/m-sec

4.3d In this Step, you will derive individual correction factors for each of the above variables by comparing your entries with typical values in table VI-M-1. (These will be used to the nearest 1/10th in Step 4.4a to develop a single correction factor.)

(1) TRANSPORT WINDSPEED. Calculate a correction factor for transport windspeed by dividing the table VI-M-1 typical-case value by the value you entered in Step 4.3a, entering the result here (if values are equal, enter 1.0):

Convective-lift phase _____ No-convective-lift phase _____

(2) HEAT RELEASE RATE. Is the heat release rate (HRR_{CL}) you entered in Step 4.3c equal to or greater than the table VI-M-1 column #4 typical case? (check one):

If YES, ≥ _____, enter 1.0 below

If NO, < _____, enter a worst-case correction factor of 1.4 below

Correction factor _____

(3) CONVECTIVE-LIFT PHASE EMISSION RATE. Calculate a correction factor for convective-lift phase emission rate (ER_{CL}) by dividing your ER_{CL} from Stage #2 by the table VI-M-1 typical case ER_{CL}, entering the result here (if your ER_{CL} is the same as the typical case ER_{CL}, enter 1.0):

Correction factor = _____ (Stage #2 ER_{CL}) ÷ _____ (Typical ER_{CL}) = _____

(4) NO-CONVECTIVE-LIFT PHASE EMISSION RATE. Calculate a correction factor for the no-convective-lift phase emission rate (ER_{NCL}) by dividing your ER_{NCL} from Stage #2 by the table VI-M-1 typical case ER_{NCL}, entering the result here (if your ER_{NCL} is the same as the typical case ER_{NCL}, enter 1.0):

Correction factor = ________ (Stage #2 ER_{NCL}) ÷ ________ (Typical ER_{NCL}) = ______

(5) FIRED-LINE LENGTH. Is the crosswind length of fired line in Step 4.3b(2) less than or equal to the table VI-M-1 column #5 typical-case length?

If YES, check here then enter 1.0 for a correction factor for all distances in the spaces below

______

If NO, check here then turn to table VI-M-6 and list in the spaces below the given correction factors for each distance

______

Downwind Distances (km)	(miles)	: Crosswind fired-line length correction factors (nearest 1/10th)
0.10	.06	______
.13	.08	______
.16	.10	______
.20	.12	______
.25	.16	______
.32	.20	______
.40	.25	______
.50	.31	______
.63	.39	______
.79	.49	______
1.00	.62	______
1.30	.81	______
1.60	.99	______
2.00	1.24	______
2.50	1.55	______
3.20	2.00	______
4.00	2.50	______
5.00	3.11	______
6.30	3.92	______
7.90	4.91	______
10.00	6.21	______
13.00	8.08	______
16.00	9.94	______
20.00	12.43	______
25.00	15.53	______
32.00	19.88	______
40.00	24.86	______
50.00	31.07	______
63.00	39.15	______
79.00	49.09	______
100.00	62.14	______

4.4 COMBINING CORRECTION FACTORS AND MAKING CORRECTIONS

4.4a Now calculate combined correction factors (nearest 1/10th) to be used at each distance for each fire phase as follows:

(1) Enter here and multiply the following convective-lift phase factors:

______ x ______ x ______ = ______

(Transport windspeed factor from Step 4.3d(1)) x (HRR_{CL} factor from Step 4.3d(2)) x (ER_{CL} factor from Step 4.3d(3)) = (Result, CL phase)

Then use the convective-lift phase multiplication result immediately above to multiply *each* line-length correction factor listed in Step 4.3d(5), entering the final multiplication result in column (B) of the blank table that follows Step 4.4b.

(2) If you are carrying forward a no-convective-lift phase, enter here and multiply the following no-convective-lift factors:

____________	x	____________	=	____________
(Transport windspeed factor from Step 4.3d(1))		(ER_{NCL} factor from Step 4.3d(4))		(Result, NCL phase)

Then use the no-convective-lift phase multiplication result immediately above to again multiply *each* line-length correction factor listed in Step 4.3d(5), entering the final multiplication result in column (D) of the blank table which follows Step 4.4b.

4.4b Use the same typical-case numbers you entered in Step 4.1a to again refer to table VI-M-1, column 8, for the appropriate concentration tables to use next. Enter here the tables to be used.

Convective-lift-phase concentration table VI-M-____

No-convective-lift phase concentration table VI-M-____

Next use the concentration tables you just selected as follows for the worktable immediately below:

(1) Opposite each distance, and in the column that fits your burning situation, read the typical-case concentration, entering it in column (C) for convective-lift phase, or in column (E) for no-convective-lift phase of the worktable which follows.

(2) Now multiply each typical-case concentration entry in the following worktable by its correction factor, and enter the result in the corrected concentration columns, (C') (E'), for convective-lift and no-convective-lift phases, respectively, in the worktable.

Downwind distances (A) (km)	(miles)	Convective-lift phase: (B) Correction factor	(C) Typical-case concentration	(C') Corrected concentration	No-convective-lift phase[1]: (D) Correction factor	(E) Typical-case concentration	(E') Corrected concentration
0.10	.06						
.13	.08						
.16	.10						
.20	.12						
.25	.16						
.32	.20						
.40	.25						
.50	.31						
.63	.39						
.79	.49						
1.00	.62						
1.30	.81						
1.60	.99						
2.00	1.24						
2.50	1.55						
3.20	2.00						
4.00	2.50						
5.00	3.11						
6.30	3.92						
7.90	4.91						
10.00	6.21						
13.00	8.08						
16.00	9.94						
20.00	12.43						
25.00	15.53						
32.00	19.88						
40.00	24.86						
50.00	31.07						
63.00	39.15						
79.00	49.09						
100.00	62.14						

[1]Complete only for those burning situations where you calculated an ER_{NCL} for the no-convective-lift phase in Section 2.

NOW PROCEED TO STAGE #5.

DECISION-LOGIC STAGE #5: PLOTS OF CONCENTRATION, COMPARISONS, MODIFICATIONS, AND MULTIPLE-SOURCE ANALYSIS

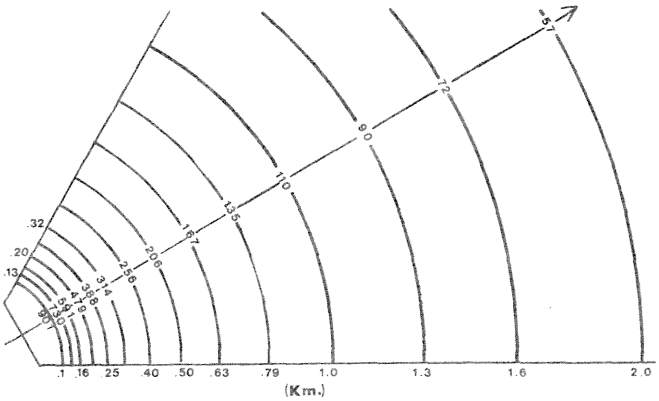
5.1 PLOTTING ZONES OF CONCENTRATION

5.1a Using a drawing compass, set it to scale for each distance in Column (A) of the Worktable you just completed in Step 4.4b, and strike distance arcs on the trajectory plots you made on the map in Steps 1.1(1) and (2) as follows:

Until the distance from the fire is twice the length of the fired line, strike two arcs--one centered at each end of the fired line--then connect them by a straight line parallel to the fired line. After the distance from the fire is twice the fired-line length, strike only one arc centered at the intersection of the fired line with the plume centerline.

NOTE: If target backgrounds are low and multiple fires are not expected, you need to plot arcs only to the distances where your corrected concentrations (Step 4.4b, Columns (C') and (E')) will be of importance. If important distances are within 2 kilometers, a plot on a separate, large-scale map will be desirable.

5.1b Now use the same two colors for the combustion stages that you used in Step 1.1a to write the corrected concentrations from the Worktable in Step 4.4b on your map at each corresponding distance arc. A completed trajectory plot with zones on concentration will look like this:



5.2 COMPARING CRITICAL TARGET ACCEPTABLE CONCENTRATIONS WITH PREDICTED TOTAL CONCENTRATIONS

5.2a Starting in the map area with the highest zone of concentration and working toward zones of lower concentrations, select the most critical targets expected to experience the concentrations plotted. List these selected targets one at a time in Column (A) of the Worktable immediately below, entering the corresponding values the table calls for at the time you list each target. The following instructions apply to determining values for entries called for by the Worktable.

Column (B) - Applicable Smoke Concentration Zone Value.--For targets directly on an arc, use the concentration zone value shown with the arc. For targets falling between two arcs, always use the higher of the two concentrations unless you interpolate logarithmically.

Column (C) - Expected Background Concentration at Target.--Entries in this column must be for the time of year for which a planned burn prescription is being applied to this logic procedure or must be actual These can be obtained, in some cases, from air quality personnel; or lacking this help, a rule of thumb will give you an expected particulate matter concentration based upon the expected visibility (which can be drawn from experience, airport climatological records, or local residents). It is based upon the relationship:

730 μg-miles/m^3 $\div$ miles of visibility = TSP concentration in μg/m^3.

Some typical values are:

25-mile visibility = 29 μg/m^3; 20-mile visibility = 36 μg/m^3;
15-mile visibility = 49 μg/m^3; 10-mile visibility = 73 μg/m^3;
5-mile visibility =146 μg/m^3; 2-mile visibility =365 μg/m^3.

Column (D) - Predicted Total Concentration.--The entry for this column is simply the sum of the value entered in Column (B) and the value entered in Column (C).

Column (E) - Maximum Acceptable Concentration.--This entry is best obtained from local air quality personnel. Lacking this help, it is suggested you use a visibility criterion and the same rule of thumb as was suggested in the Column (C) instructions above. In this case, you set the minimum visibility you believe will be acceptable (*CAUTION*: This is reportedly rarely less than 5 miles), then enter the corresponding concentration. EXAMPLE: 10-mile visibility is believed to be the minimum below which public complaints will be raised; then the corresponding maximum acceptable concentration entry is 73 μg/m^3, (730 $\div$ 10).

WORKTABLE

(A) Target name or other identifier	(B) Applicable smoke concentration zone value: CL phase	(B) Applicable smoke concentration zone value: NCL phase	(C) Expected background concentration at target	(D) Predicted total concentration Col. (B) + Col. (C): CL phase	(D) Predicted total concentration Col. (B) + Col. (C): NCL phase	(E) Maximum acceptable concentration

5.2b Now compare the Column (E) entries with both the convective-lift and no-convective-lift phase entries in Column (D).

Is the predicted total concentration less than the maximum acceptable concentration for all entries? (check for each phase)

Convective-lift phase	No-convective-lift phase
Yes ______	Yes ______
No ______	No ______
	Not applicable ______

5.2c (1) If you checked YES for applicable phases above and do not anticipate that other burns may contribute to concentrations in target areas, check here and STOP using logic at this point. PROCEED WITH YOUR BURN.

______

(2) If you checked YES for applicable phases above but anticipate other prescribed burns may contribute to concentrations in target areas and want to run a further analysis, check here and skip to Step 5.4.

______

OR, if you do not want to skip to Step 5.4 check here and STOP using logic.

______

PROCEED WITH YOUR BURN ONLY IF YOU WANT TO RISK POSSIBLE TARGET-AREA CONCENTRATIONS IN EXCESS OF DESIRED NET.

(3) If you checked NO in either phase, proceed to Step 5.3.

5.3 DETERMINING WHICH PRESCRIPTION VARIABLES TO MODIFY

5.3a Look back to the Worktable you completed in Step 5.2a for the worst case (i.e.: greatest amount Column (D) exceeds Column (E)).

Now divide the Column (D) entry by the Column (E) entry, entering the result of division here:

______

(1) If the result of division is less than 2, your chance of making a desk-top revision of your prescription for an acceptable concentration is good. Check here and skip directly to Step 5.3b.

______

(2) If the result of division is less than 5, there is a chance of making an acceptable revision of your prescription--but repeated trials are likely to be needed, and a Stage #6 analysis will be most desirable.

If you can arrange for assistance with a Stage #6 automatic data processing analysis, check here and STOP further work on Phase #5.

______

If you cannot arrange for assistance, you may elect to try a desk-top revision and should skip directly to Step 5.3b after checking here.

______

If you cannot arrange for assistance and do not elect to try a desk-top revision, skip directly to Step 5.3g after checking here.

______

(3) If the result of division is greater than 5, skip directly to Step 5.3g after checking here.

______

5.3b If your prescription calls for a heading fire, first consider revising the prescription to call for a backing fire. Check here, then proceed to Step 5.3c BEFORE modifying your prescription.

______

5.3c Examine the correction factors you calculated in Stage #4, entering a check here for each that is greater than 1.0.

Variable	Calculated in Step	Convective-lift phase factor (√)	No-convective-lift phase factor (√)
Transport windspeed	4.3d(1)		
Length of fired line	4.3d(2)		
HRR_{CL}	4.3d(3)		Not applicable
ER_{CL}	4.3d(4)		Not applicable
ER_{NCL}	4.3d(5)		

5.3d If any of the above checked factors include transport windspeed and/or fired-line length factors, you will next want to modify your prescription to lower these. The fired-line length correction factor is lowered by shortening the prescribed fired-line length. The transport windspeed correction factor is lowered by increasing the prescribed speed. NOTE: For this analysis, it will not benefit your calculations to reduce the fired-line length below that used in the typical case (see table VI-M-1). Check here, then proceed to Step 5.3e BEFORE modifying your prescription.

______

5.3e If your exceeded allowable concentration is only in the convective-lift phase and your heat release rate correction factor is checked in Step 5.3c, this is the next prescription item to consider modifying. Before deciding to do so, make sure the emission rate correction factor IS NOT also checked. HRR_{CL} is best increased, resulting in a lower correction factor, by increasing rate of spread (which is a function of lower fine fuel moisture and higher surface windspeed). These, however, will all increase emission rate, which can offset your gains. Check here and then proceed to Step 5.3f BEFORE modifying your prescription.

5.3f Now, having considered the instructions in Steps 5.3b through 5.3e, list here any variables you intend to modify in your prescription. Then use a colored pencil to enter new values in the prescription and in the preceding Stages #2 through #5, Steps 5.1 and 5.2, reworking all dependent calculations and comparisons until you have again arrived at Step 5.3. If there are no variables that can be modified, enter NONE, then proceed to Step 5.3g.

Variables to be modified

____

____

____

____

CAUTION: Do not simply modify the prescription and then use new correction factors in Stage #4. Many of the variables are interdependent, resulting in offsetting changes. Hopefully, after reworking Stages #2 through #4 and Steps 5.1 and 5.2, you will be able to skip to Step 5.3 on the next pass through!

5.3g You have arrived at this Step either because of too great a difference between predicted total concentration and maximum acceptable concentration, or because of computational difficulties that cannot be remedied.

If this is the case, you may wish to consider exploring exceeded maximum acceptable concentrations at some targets for a very short time period. By limiting the dimension of the burn area which is on the same azimuth as the transport wind direction, the duration is limited. For example: Wind at right angle to road. A 200-foot-wide burned area will at least provide a good fuel break. If instead of burning the entire tract you burn to a 200-foot limit, the time of high smoke concentration will be shortened and you may be able to work with local authorities to provide traffic control for safety on the road for the short period this size burn would take to burn out. Other than this, you may need to select a treatment alternative other than fire.

Enter your decision here and STOP using the logic procedure:

____

____

____

5.4 RUDIMENTARY MULTIPLE-SOURCE ANALYSIS

5.4a This Step is for conducting a rudimentary multiple-source analysis if there is a likelihood that more than your prescribed burn will contribute to target concentrations.

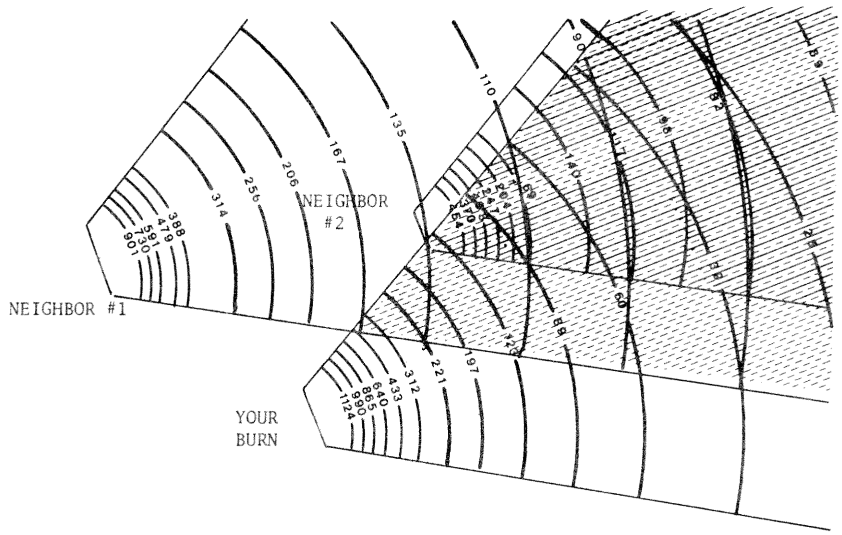
For all such suspect simultaneous sources, follow this procedure:

(1) For each, plot the trajectory and 30° deviations as you did in Steps 1.1a (1) and (2).

(2) For all those where the 30° deviations overlap with those from this burn, it will be most desirable to have available completed, separate analyses such as this. If not available, use either the final trajectory plots from Step 5.1b of this burn again, or simply use the unadjusted values from a typical case (see table VI-M-1 and corresponding tables), whichever comes closest.

(3) With the new burn trajectory(s) plotted to show arcs as zones of concentration, as you did for this burn, you can now sum the zones in all overlapping areas to prepare a mutual targets worktable in the same format as you did in Step 5.2a for this burn alone.

EXAMPLE:



In this example, the applicable concentration zone values, relating two neighbors' burns to your burn, become:

Your burn alone	Your burn and neighbor #1	All three burns
1,124		
990		
865		
640		
433	433 + 167	
312	312 + 167	
221	221 + 167	
221	221 + 135	
197	197 + 167	
197	197 + 135	
123	123 + 135	123 + 135 + 454
123	123 + 135	123 + 135 + 370
123	123 + 135	123 + 135 + 303
123	123 + 135	123 + 135 + 247
123	123 + 135	123 + 135 + 204
88	88 + 135	88 + 135 + 204
88	88 + 135	88 + 135 + 169
88	88 + 110	88 + 110 + 169
88	88 + 110	88 + 110 + 140
60	60 + 110	60 + 110 + 169
60	60 + 110	60 + 110 + 140
60	60 + 110	60 + 110 + 117
60	60 + 90	60 + 90 + 117
60	60 + 90	60 + 90 + 98
39	39 + 90	39 + 90 + 117
39	39 + 90	39 + 90 + 98
39	39 + 82	39 + 82 + 82
25	25 + 82	25 + 82 + 90
25	25 + 82	25 + 82 + 82
25	25 + 82	25 + 82 + 69

DECISION-LOGIC STAGE #6: AUTOMATIC DATA PROCESSING ASSISTED ANALYSIS

This Stage is under development at this time and will be issued later. The following is a brief outline of what is planned:

1. *A program in FORTRAN for use on any compatible computer.*--This program will be printed as a "separate" that can be inserted into copies of the Sourcebook. With the program, rapid reiterations of combinations of variables now made by hand in Stages #2 through #5 will be possible. Hence, the user will be able to quickly select the best of his prescription options. Instructions for use will also be printed as a "separate" that can be inserted into copies of the Guidebook.

2. *An adaptation of the above program for use in a central computer.*--Data from spot weather forecasts would be entered, along with user inputs to determine likely downwind concentrations.

3. *A refined system for analyzing the effects of multiple forestry emissions sources on air quality.*

PART 3. TABLES

The tables that follow are for use with the Steps in the preceding instructions. Sources of these tables are discussed in preceding chapters—fuel and fire behavior tables (VI-F-1 through VI-F-13, printed on pink paper) in Chapter IV and meteorology tables and figure (tables VI-M-1 through VI-M-6 and fig. VI-M-1 printed on blue paper) in Chapter V. For the convenience of users and to permit periodic updating, each table is presented on a separate page.

Table VI-F-1. — Effect of age of rough on total available grass accumulations under pine overstories

Age of rough (years)	Total available grass accumulation
	Tons per acre
1	1.86
2	1.00
3	.71
4	.57
5	.48
10	.31
15	.26
20	.23
25	.21

Table VI-F-2. — Fine fuel moisture content of dead grass (1-hour timelag)

Cloud cover and dry bulb temperature 1/ (°F)	Relative humidity									
	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74
	Percent									
Sunny:										
10-29	5	5	6	7	8	8	8	9	9	10
30-49	5	5	6	7	7	7	8	9	9	10
50-69	5	5	6	6	7	7	8	8	9	9
70-89	4	5	5	6	7	7	8	8	8	9
Cloudy:										
10-29	6	7	8	9	10	11	12	12	14	15
30-49	6	7	8	9	9	11	11	12	13	14
50-69	6	6	8	8	9	10	11	11	12	14
70-89	5	6	7	8	9	10	10	11	12	13

1/Adapted from Deeming and others (1972).

Purpose. — To compute the fine fuel moisture content of dead grass 0.25 inch and less in diameter.

Procedure. — Use "cloudy" if there is 60 to 90 percent cloud cover; an overcast covering more than 90 percent of the sky; fog, showers, or thunderstorms in the vicinity; or if the observation is being taken before 10:00 a.m. or after 3:00 p.m. local standard time. "Sunny" covers all other conditions.

Table VI-F-3.— Moisture content of pine needle litter [1/]

Relative humidity (percent)	Moisture content
	Percent
25 to 29	8
30 to 34	8
35 to 39	9
40 to 44	9
45 to 49	10
50 to 54	11
55 to 59	12
60 to 64	13
65 to 69	15
70 to 74	17

1/ Based on Blackmarr (1971).

Table VI-F-4. — Expected rate of fire spread in grass fuels 1/ 2/ as a function of midflame windspeed and fine fuel moisture content where land slopes do not exceed 20 percent

Midflame windspeed 3/ (miles per hour)	Rate of spread					
	Fine fuel moisture (percent)					
	4	6	8	12	16	20
	Feet per minute					
0	5	4	4	3	3	2
1	11	9	8	6	6	5
2	25	21	18	14	13	11
3	45	37	32	26	23	19
4	71	59	50	41	36	30
5	101	84	72	59	51	43
6	137	114	98	79	69	58

1/ Adapted from Rothermel (1972).

2/ Factors used in Rothermel's (1972) equation:

$W_o = 0.088$ lb/ft^2 MCE = 30

d = 1.0 WS = 0, 1, 2, 3, 4, 5, 6

s/v = 2,500 MC = 4, 6, 8, 12, 16, 20

mc = 0.0555 HV = 8,000

sc = 0.01 DEN = 32

3/ Under a tree canopy, midflame windspeed can be estimated by using windspeed values from the nearest 20-foot, open-tower installation and dividing that value by 4.

Table VI-F-5. — Total litter weight under slash pine stands as affected by stand basal area and age of rough 1/

Stand basal area (square feet per acre)	Age of rough (years)								
	1	2	3	4	5	7	10	15	20
	Tons per acre								
30	1.5	2.5	3.4	4.2	4.8	5.9	7.0	8.1	8.4
50	1.6	2.8	3.8	4.7	5.4	6.6	7.9	9.0	9.4
70	1.8	3.2	4.3	5.2	6.1	7.4	8.8	10.1	10.5
90	2.1	3.5	4.8	5.9	6.8	8.3	9.9	11.3	11.7
110	2.3	4.0	5.4	6.6	7.6	9.3	11.1	12.7	13.2
130	2.6	4.4	6.0	7.3	8.5	10.4	12.4	14.2	14.7
150	2.9	5.0	6.7	8.2	9.5	11.6	13.9	15.9	16.5
175	3.3	5.7	7.7	9.5	11.0	13.4	16.0	18.3	19.0
200	3.8	6.6	8.9	10.9	12.6	15.4	18.4	21.1	21.9

1/ Applies to stands with or without understory vegetation (McNab and Edwards 1976).

Table VI-F-6. — Total litter weight under loblolly pine stands as affected by stand basal area and age of rough

Stand basal area (square feet per acre)	Age of rough (years)							
	1	2	3	4	5	7	10	15
	Tons per acre							
30	1.4	2.2	2.9	3.4	3.8	4.5	4.7	4.7
50	1.5	2.4	3.2	3.9	4.3	5.0	5.3	5.3
70	1.6	2.8	3.7	4.3	4.8	5.6	5.9	5.9
90	1.9	3.0	4.1	4.8	5.4	6.3	6.6	6.6
110	2.1	3.5	4.6	5.4	6.0	7.1	7.4	7.4
130	2.4	3.8	5.1	6.0	6.7	7.9	8.3	8.3
150	2.7	4.3	5.7	6.7	7.5	8.8	9.3	9.3
175	3.0	5.0	6.6	7.8	8.7	10.2	10.7	10.7
200	3.5	5.8	7.6	8.9	10.0	11.7	12.3	12.3

Table VI-F-7. — Estimated available litter fuel weights for different total litter weights and moisture contents1/

Total litter weight (tons per acre)	Total litter layer moisture content (percent)										
	10	20	40	60	80	100	120	140	160	180	200
	Tons per acre										
2	1.2	1.0	0.5	—	—	—	—	—	—	—	—
4	3.4	3.1	2.7	2.2	1.7	1.2	0.8	0.3	—	—	—
6	4.6	4.4	3.9	3.4	3.0	2.5	2.0	1.5	1.1	0.6	0.1
8	5.6	5.4	4.9	4.4	4.0	3.5	3.0	2.5	2.1	1.6	1.1
10	6.5	6.3	5.8	5.3	4.9	4.4	3.9	3.4	3.0	2.5	2.0
12	7.4	7.1	6.7	6.2	5.7	5.2	4.8	4.3	3.8	3.3	2.8
14	8.2	8.0	7.5	7.0	6.6	6.1	5.6	5.1	4.7	4.2	3.7
16	9.0	8.8	8.3	7.8	7.4	6.9	6.4	5.9	5.5	5.0	4.5

1/ Based on unpublished data on file at the Southern Forest Fire Laboratory, Southeastern Forest Experiment Station, USDA Forest Service, Macon, Ga.

Table VI-F-8. — **Expected rate of fire spread in pine needle and low brush fuels 1/ 2/ as a function of midflame windspeed and pine needle litter moisture content where land slopes do not exceed 20 percent**

Midflame windspeed 3/ (miles per hour)	Rate of spread — Pine needle litter moisture content (percent)				
	6	8	12	16	20
	Feet per minute				
0	1	1	1	1	1
1	2	2	2	1	1
2	5	4	3	3	2
3	7	6	5	4	4
4	10	9	7	6	5
5	13	11	9	8	7
6	16	14	11	10	8

1/ Adapted from Rothermel (1972).

2/ Factors used in Rothermel's (1972) equation:

W_0 = 1.25 ton/acre = 0.057 lb/ft^2	MCE = 0.40
d = 0.25 (3 inches)	WS = 0, 1, 2, 3, 4, 5, 6
s/v = 1,500	MC = 6, 8, 12, 16, 20
mc = 0.04 (min. content)	HV = 8,000
sc = 0.01	DEN = 26

3/ Under a tree canopy, midflame windspeed can be estimated by using windspeed values from the nearest 20-foot, open-tower installation and dividing that value by 4.

Table VI-F-9. — Understory vegetative dry weight in the palmetto-gallberry type as related to age of rough and understory height

Understory height (feet)	Age of rough (years)							
	1	2	3	5	7	10	15	20
	Tons per acre							
1	0.4	0.4	0.5	0.6	0.9	1.4	2.6 1/	4.2 1/
2	1.2	1.3	1.3	1.5	1.7	2.2	3.4 1/	5.1 1/
3	2.6	2.6	2.7	2.8	3.1	3.5	4.7	6.4
4	4.5 1/	4.5	4.6	4.7	5.0	5.5	6.6	8.3
5	7.0 1/	7.0 1/	7.0	7.2	7.4	7.9	9.1	10.8
6	10.0 1/	10.0 1/	10.0 1/	10.2	10.4	10.9	12.1	13.8

1/ Represents a situation not likely to be found in nature.

Table VI-F-10. — Estimated total available fuel (litter + vegetation) as a function of total litter layer moisture content, total litter weight, and understory vegetative dry weight

Understory vegetative dry weight (tons per acre)	Total available fuel (litter + vegetation) — Total litter weight in tons per acre: 1	2	3	4	5	6	8	10	12	14	16
	Tons per acre										
10 PERCENT TOTAL LITTER LAYER MOISTURE CONTENT											
1	0.0	2.0	3.2	4.1	4.8	5.4	6.5	7.5	8.4	9.3	10.2
3	.4	3.3	4.6	5.5	6.1	6.7	7.8	8.8	9.8	10.7	11.6
5	1.7	4.7	5.9	6.8	7.5	8.1	9.2	10.2	11.1	12.0	12.9
7	3.1	6.0	7.3	8.2	8.8	9.4	10.5	11.5	12.5	13.4	14.3
9	4.4	7.4	8.7	9.5	10.2	10.8	11.9	12.9	13.8	14.7	15.6
11	5.8	8.7	10.0	10.9	11.5	12.2	13.2	14.2	15.2	16.1	17.0
20 PERCENT TOTAL LITTER LAYER MOISTURE CONTENT											
1	0.0	1.7	3.0	3.8	4.5	5.1	6.2	7.2	8.1	9.1	10.0
3	.1	3.0	4.3	5.2	5.9	6.5	7.5	8.5	9.5	10.4	11.3
5	1.4	4.4	5.7	6.5	7.2	7.8	8.9	9.9	10.8	11.8	12.7
7	2.8	5.7	7.0	7.9	8.6	9.2	10.2	11.2	12.2	13.1	14.0
9	4.1	7.1	8.4	9.2	9.9	10.5	11.6	12.6	13.5	14.5	15.4
11	5.5	8.5	9.7	10.6	11.3	11.9	13.0	13.9	14.9	15.8	16.7
40 PERCENT TOTAL LITTER LAYER MOISTURE CONTENT											
1	0.0	1.1	2.4	3.3	4.0	4.6	5.6	6.6	7.6	8.5	9.4
3	.0	2.5	3.8	4.6	5.3	5.9	7.0	8.0	8.9	9.9	10.8
5	.9	3.8	5.1	6.0	6.7	7.3	8.3	9.3	10.3	11.2	12.1
7	2.2	5.2	6.5	7.3	8.0	8.6	9.7	10.7	11.6	12.6	13.5
9	3.6	6.5	7.8	8.7	9.4	10.0	11.0	12.0	13.0	13.9	14.8
11	4.9	7.9	9.2	10.0	10.7	11.3	12.4	13.4	14.3	15.3	16.2
80 PERCENT TOTAL LITTER LAYER MOISTURE CONTENT											
1	0.0	0.0	1.3	2.2	2.9	3.5	4.5	5.5	6.5	7.4	8.3
3	.0	1.4	2.7	3.5	4.2	4.8	5.9	6.9	7.8	8.8	9.7
5	.0	2.7	4.0	4.9	5.6	6.2	7.2	8.2	9.2	10.1	11.0
7	1.1	4.1	5.4	6.2	6.9	7.5	8.6	9.6	10.5	11.5	12.4
9	2.5	5.4	6.7	7.6	8.3	8.9	9.9	10.9	11.9	12.8	13.7
11	3.8	6.8	8.1	8.9	9.6	10.2	11.3	12.3	13.2	14.2	15.1
120 PERCENT TOTAL LITTER LAYER MOISTURE CONTENT											
1	0.0	0.0	0.2	1.1	1.8	2.4	3.4	4.4	5.4	6.3	7.2
3	.0	.3	1.6	2.4	3.1	3.7	4.8	5.8	6.7	7.6	8.6
5	.0	1.6	2.9	3.8	4.5	5.1	6.1	7.1	8.1	9.0	9.9
7	.0	3.0	4.3	5.1	5.8	6.4	7.5	8.5	9.4	10.4	11.3
9	1.4	4.3	5.6	6.5	7.2	7.8	8.8	9.8	10.8	11.7	12.6
11	2.7	5.7	7.0	7.8	8.5	9.1	10.2	11.2	12.1	13.1	14.0
160 PERCENT TOTAL LITTER LAYER MOISTURE CONTENT											
1	0.0	0.0	0.0	0.0	0.6	1.3	2.3	3.3	4.3	5.2	6.1
3	.0	.0	.5	1.3	2.0	2.6	3.7	4.7	5.6	6.5	7.5
5	.0	.5	1.8	2.7	3.4	4.0	5.0	6.0	7.0	7.9	8.8
7	.0	1.9	3.2	4.0	4.7	5.3	6.4	7.4	8.3	9.3	10.2
9	.3	3.2	4.5	5.4	6.1	6.7	7.7	8.7	9.7	10.6	11.5
11	1.6	4.6	5.9	6.7	7.4	8.0	9.1	10.1	11.0	12.0	12.9

Table VI-F-11. — **Expected rate of fire spread 1/ in palmetto-gallberry fuels as a function of midflame windspeed and pine needle litter moisture content where land slopes do not exceed 20 percent**

Midflame windspeed 2/ (miles per hour)	Rate of spread				
	Pine needle litter moisture content (percent)				
	6	8	12	16	20
			Feet per minute		
0	3	2	2	2	2
1	6	5	5	4	4
2	12	11	10	9	8
3	20	19	17	15	13
4	30	28	25	22	20
5	42	38	33	31	27
6	54	49	44	39	35
7	67	61	54	49	44

1/ Adapted from Hough and Albini (1976).

2/ Under a tree canopy, midflame windspeed can be estimated by using windspeed values from the nearest 20-foot, open-tower installation and dividing that value by 4.

Table VI-F-12. — Available fuel 1 inch in diameter and less in the unpiled pine logging debris type

Average d.b.h. in cut stand (inches)	Undisturbed logging residue	
	Loblolly	Slash
	---- Tons per cord cut ----	
5	—	0.47
6	0.20	.30
7	.17	.24
8	.15	.21
9	.13	.21
10	.11	.23
11	.12	.28
12	.13	—
14	.11	—
16	.10	—

Table VI-F-13. — Expected rate of fire spread in broadcast southern pine logging debris (Fuel Model C) 1/ as a function of midflame windspeed and pine needle litter moisture content where land slopes do not exceed 20 percent

Midflame windspeed 2/ (miles per hour)	Rate of spread — Pine needle litter moisture content (percent)				
	6	8	12	16	20
	Feet per minute				
0	3	2	2	1	1
1	4	4	4	3	3
2	10	8	7	6	4
3	16	15	12	10	7
4	30	24	18	15	12
5	36	30	24	21	18
6	48	42	36	30	24
7	66	60	48	42	30
8	78	72	60	48	36
9	102	90	72	60	42
10	120	102	90	72	54

1/ National Fire-Danger Rating System classification adapted.
2/ Since this fuel type is not under a tree canopy, midflame windspeed can be estimated by using windspeed values from the nearest 20-foot, open-tower installation and dividing that value by 2.

Table VI-M-1. — Summary of variables used in compiling typical case examples in tables VI-M-2 through VI-M-5

Typical case no.	1 Typical for	2 Pasquill stability class	3 Mixing height	4 Heat release rate (HRR)	5 Length of fired line or equiv.	6 Transport windspeed	7 Emission rate (ER)	8 See concentration in table
			Meters	Megacal/sec	Meters	M/sec	μg/M-sec	
1	Grass:							
	Backing fire	C	1,500	14.112	800	8	37,800	VI-M-2
2	Grass:							
	Heading fire	C	1,500	75.624	400	8	403,200	VI-M-2
3	Pine needle litter:							
	Backing fire	C	1,500	4.704	400	8	84,000	VI-M-3
4	Pine needle litter:							
	Heading fire							
	CL phase	C	1,500	11.76	400	8	966,000	VI-M-3
	NCL phase	C	1,500	0	400	8	756,000	VI-M-3
5	Palmetto-gallberry:							
	Backing fire	C	1,500	37.632	800	8	168,000	VI-M-4
6	Palmetto-gallberry:							
	Heading fire in							
	2-year-old rough	C	1,500	137.984	800	8	616,000	VI-M-4
7	Pine logging debris:							
	In winter							
	CL phase	C	1,500	211.68	500 (eq.)	8	5,745,600	VI-M-5
	NCL phase	C	1,500	0	500 (eq.)	8	3,628,800	VI-M-5
8	Pine logging debris:							
	In summer							
	CL phase	B	2,000	70.56	500 (eq.)	5	1,915,200	VI-M-5
	NCL phase	B	2,000	0	500 (eq.)	5	1,209,600	VI-M-5

Table VI-M-2. — Particulate matter concentrations at various distances downwind for typical cases No. 1 and No. 2

Distance downwind X(km)	Concentration (X)	
	Backing fire	Heading fire
	$\mu g/m^3$	$\mu g/m^3$
0.10	203	2,161
.13	164	1,751
.16	133	1,481
.20	108	1,149
.25	87	931
.32	71	754
.40	58	611
.50	47	495
.63	39	400
.79	31	319
1.00	26	249
1.30	21	188
1.60	18	138
2.00	17	98
2.50	15	68
3.20	12	47
4.00	10	33
5.00	8	24
6.30	5	19
7.90	4	15
10.00	3	11
13.00	2	8
16.00	2	6
20.00	1	4
25.00	1	3
32.00	0	2
40.00	0	2
50.00	0	2
63.00	0	1
79.00	0	1
100.00	0	1

Table VI-M-3.— Particulate matter concentrations at various distances downwind for typical cases No. 3 and No. 4

Distance downwind X(km)	Concentration (X)		
	Backing fire	Heading fire	
		CL phase	NCL phase
	μg/m3	μg/m3	μg/m3
0.10	454	5,179	10,132
.13	370	4,196	8,208
.16	303	3,401	6,649
.20	247	2,757	5,386
.25	204	2,237	4,363
.32	169	1,818	3,535
.40	140	1,480	2,864
.50	117	1,208	2,319
.63	98	987	1,873
.79	82	801	1,497
1.00	69	638	1,169
1.30	61	495	883
1.60	51	397	646
2.00	40	329	459
2.50	30	266	319
3.20	22	206	218
4.00	15	153	147
5.00	10	109	98
6.30	7	76	66
7.90	5	52	44
10.00	3	35	29
13.00	2	24	19
16.00	2	16	13
20.00	1	11	8
25.00	1	7	6
32.00	0	6	4
40.00	0	5	4
50.00	0	4	3
63.00	0	3	2
79.00	0	3	2
100.00	0	2	2

Table VI-M-4. — Particulate matter concentrations at various distances downwind for typical cases No. 5 and No. 6

Distance downwind X (km)	Concentration (X)	
	Backing fire	Heading fire in 2-year-old roughs
	$\mu g/m^3$	$\mu g/m^3$
0.10	901	3,302
.13	730	2,675
.16	591	2,167
.20	479	1,756
.25	388	1,422
.32	314	1,152
.40	256	933
.50	206	756
.63	167	612
.79	135	496
1.00	110	402
1.30	90	325
1.60	72	261
2.00	57	206
2.50	45	157
3.20	37	116
4.00	31	83
5.00	25	59
6.30	19	43
7.90	14	32
10.00	10	25
13.00	7	20
16.00	5	15
20.00	3	10
25.00	2	8
32.00	2	7
40.00	1	6
50.00	1	5
63.00	1	4
79.00	1	3
100.00	1	3

Table VI-M-5. — Particulate matter *concentrations* at various distances downwind for typical cases No. 7 and No. 8

Distance downwind X(km)	Concentration (χ)			
	In winter		In summer	
	CL phase	NCL phase	CL phase	NCL phase
	μg/m3	μg/m3	μg/m3	μg/m3
0.10	30,801	48,633	11,527	18,201
.13	24,952	39,397	9,301	14,687
.16	20,213	31,915	7,505	11,850
.20	16,375	25,855	6,056	9,561
.25	13,265	20,944	4,829	7,625
.32	10,746	16,967	3,851	6,080
.40	8,705	13,745	3,070	4,847
.50	7,052	11,135	2,380	3,758
.63	5,712	9,018	1,827	2,885
.79	4,615	7,287	1,373	2,169
1.00	3,692	5,827	1,002	1,581
1.30	2,887	4,559	708	1,115
1.60	2,188	3,455	487	765
2.00	1,604	2,532	334	512
2.50	1,142	1,803	222	338
3.20	794	1,254	155	220
4.00	543	858	119	142
5.00	367	580	92	91
6.30	248	389	69	58
7.90	173	259	49	38
10.00	127	173	34	24
13.00	98	115	24	17
16.00	76	76	21	14
20.00	57	50	18	11
25.00	42	33	15	9
32.00	36	27	12	8
40.00	32	22	10	6
50.00	28	18	8	5
63.00	23	15	7	4
79.00	19	12	6	4
100.00	16	10	5	3

Table VI-M-6. — Fired-line length correction factors

For typical cases with fired-line length of 400 m when Stability Class C and your fired-line length (meters) is:			
Distance downwind X (km)	800	1600	3200
0.10	1.0	1.0	1.0
.13	1.0	1.0	1.0
.16	1.0	1.0	1.0
.20	1.0	1.0	1.0
.25	1.0	1.0	1.0
.32	1.0	1.0	1.0
.40	1.0	1.0	1.0
.50	1.0	1.0	1.0
.63	1.0	1.0	1.0
.79	1.0	1.0	1.0
1.0	1.1	1.1	1.1
1.3	1.1	1.1	1.1
1.6	1.2	1.3	1.3
2.0	1.4	1.4	1.4
2.5	1.5	1.7	1.7
3.2	1.6	2.0	2.0
4.0	1.7	2.3	2.4
5.0	1.8	2.7	2.9
6.3	1.9	3.0	3.5
7.9	1.9	3.3	4.2
10.0	1.9	3.5	4.9
13.0	2.0	3.6	5.6
16.0	2.0	3.8	6.3
20.0	2.0	3.8	6.7
25.0	2.0	3.9	7.1
32.0	2.0	3.9	7.4
40.0	2.0	3.9	7.6
50.0	2.0	4.0	7.7
63.0	2.0	4.0	7.8
79.0	2.0	4.0	7.9
100.0	2.0	4.0	7.9

For typical cases with fired-line length of 500 m when Stability Class C and your fired-line length (meters) is:			
Distance downwind X(km)	800	1600	3200
0.10	1.0	1.0	1.0
.13	1.0	1.0	1.0
.16	1.0	1.0	1.0
.20	1.0	1.0	1.0
.25	1.0	1.0	1.0
.32	1.0	1.0	1.0
.40	1.0	1.0	1.0
.50	1.0	1.0	1.0
.63	1.0	1.0	1.0
.79	1.0	1.0	1.0
1.0	1.0	1.0	1.0
1.3	1.1	1.1	1.1
1.6	1.1	1.1	1.1
2.0	1.2	1.2	1.2
2.5	1.3	1.4	1.4
3.2	1.4	1.6	1.6
4.0	1.4	1.9	2.0
5.0	1.5	2.2	2.3
6.3	1.5	2.4	2.8
7.9	1.5	2.6	3.4
10.0	1.6	2.8	4.0
13.0	1.6	2.9	4.5
16.0	1.6	3.0	5.0
20.0	1.6	3.1	5.4
25.0	1.6	3.1	5.7
32.0	1.6	3.1	5.9
40.0	1.6	3.2	6.1
50.0	1.6	3.2	6.2
63.0	1.6	3.2	6.2
79.0	1.6	3.2	6.3
100.0	1.6	3.2	6.3

continued

Table VI-M-6. — Fired-line length correction factors (Continued)

For typical cases with fired-line length of 800 m when Stability Class C and your fired-line length (meters) is:		
Distance downwind X(km)	1600	3200
0.10	1.0	1.0
.13	1.0	1.0
.16	1.0	1.0
.20	1.0	1.0
.25	1.0	1.0
.32	1.0	1.0
.40	1.0	1.0
.50	1.0	1.0
.63	1.0	1.0
.79	1.0	1.0
1.0	1.0	1.0
1.3	1.0	1.0
1.6	1.0	1.0
2.0	1.0	1.0
2.5	1.1	1.1
3.2	1.2	1.2
4.0	1.3	1.4
5.0	1.5	1.6
6.3	1.6	1.9
7.9	1.7	2.2
10.0	1.8	2.5
13.0	1.9	2.9
16.0	1.9	3.2
20.0	1.9	3.4
25.0	2.0	3.6
32.0	2.0	3.7
40.0	2.0	3.8
50.0	2.0	3.9
63.0	2.0	3.9
79.0	2.0	3.9
100.0	2.0	4.0

For typical cases with fired-line length of 500 m when Stability Class B and your fired-line length (meters) is:			
Distance downwind X(km)	800	1600	3200
0.10	1.0	1.0	1.0
.13	1.0	1.0	1.0
.16	1.0	1.0	1.0
.20	1.0	1.0	1.0
.25	1.0	1.0	1.0
.32	1.0	1.0	1.0
.40	1.0	1.0	1.0
.50	1.0	1.0	1.0
.63	1.0	1.0	1.0
.79	1.0	1.0	1.0
1.0	1.1	1.1	1.1
1.3	1.2	1.2	1.2
1.6	1.3	1.4	1.4
2.0	1.4	1.6	1.6
2.5	1.4	1.9	1.9
3.2	1.5	2.1	2.2
4.0	1.5	2.4	2.7
5.0	1.5	2.6	3.3
6.3	1.6	2.8	3.8
7.9	1.6	2.9	4.4
10.0	1.6	3.0	4.9
13.0	1.6	3.1	5.3
16.0	1.6	3.1	5.6
20.0	1.6	3.1	5.9
25.0	1.6	3.2	6.0
32.0	1.6	3.2	6.1
40.0	1.6	3.2	6.2
50.0	1.6	3.2	6.3
63.0	1.6	3.2	6.3
79.0	1.6	3.2	6.3
100.0	1.6	3.2	6.4

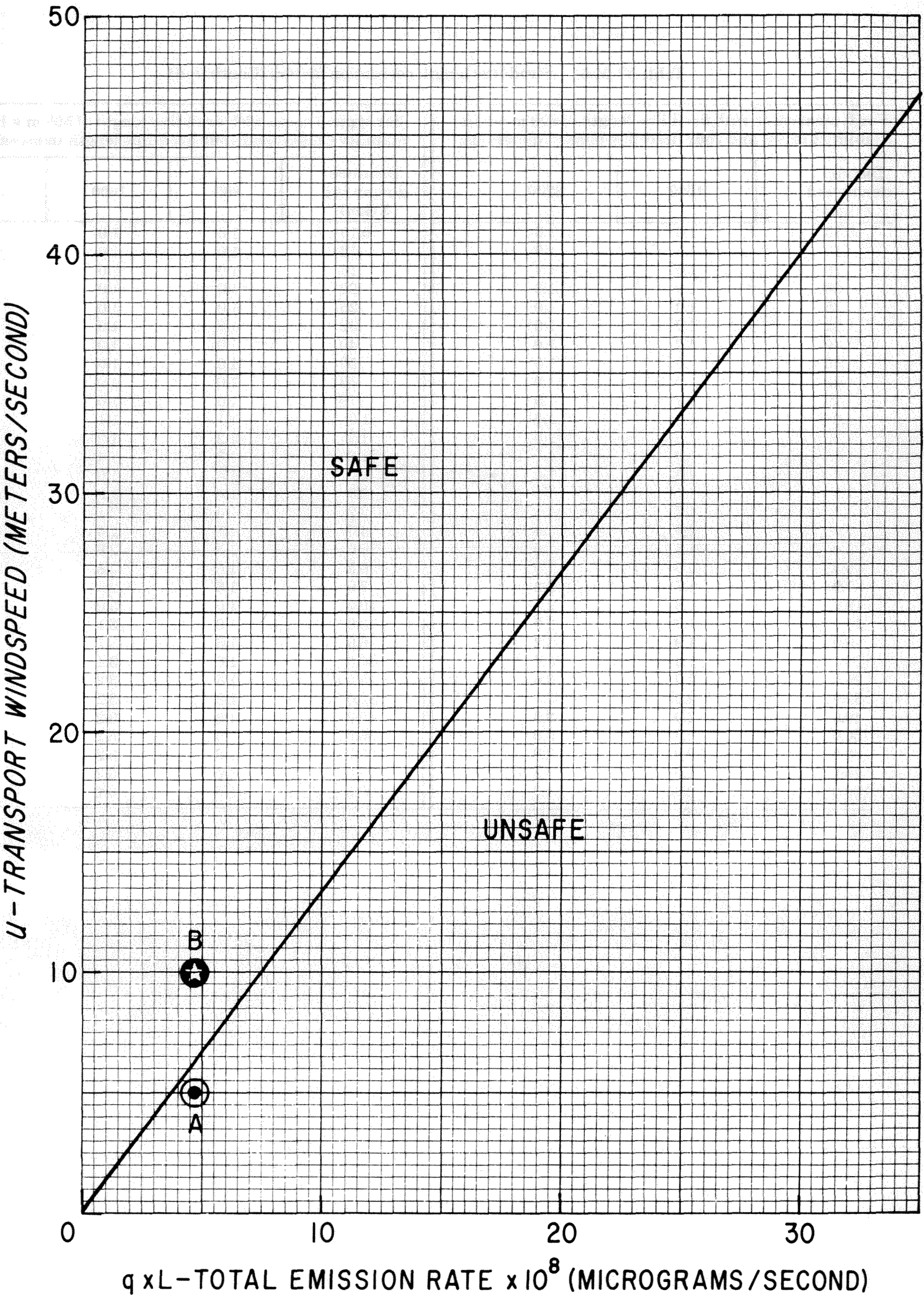


Figure VI-M-1. — Plot of total emission rate (qL) versus transport windspeed (u); ($\frac{qL}{u}$ = 7.5 x 10^8 μg/m^2-sec). To help determine if a fire might deliver 150 micrograms of particulate matter per cubic meter of air to a location 60 or more miles downwind, locate the intersection of your total emission rate (emission rate (ER) x fired-line length (L) with your transport windspeed. For example, a fire with an ER of 1,200,000 μg/m-sec and a 400 m line has a total ER of 480,000,000 μg/sec (i.e., 4.8 x 10^8 μg/sec). Such a fire is unsafe if the transport windspeed is 5 m/sec, but safe if it is 10 m/sec. (See example plotted as A and B, respectively.)

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GLOSSARY

Advancing-front combustion stage. — The period of combustion when a fire is spreading, usually accompanied by flaming combustion that releases heat that sustains the convection column.

Aerosol. — See **Particulate matter.**

Age of rough. — Time in years since the forest fuel was last reduced.

Ambient air. — Literally, the air moving around us; the air of the surrounding environment.

Available fuel. — The portion of the total combustible woody material that fire will consume under given conditions.

Backing fire. — A fire spreading against the wind. Flames tilt away from direction of spread.

Basal area. — The area of the cross section of a tree stem near its base, generally at breast height and inclusive of bark.

Bound water. — Bound moisture. Moisture that is intimately associated with the finer wood elements of the cell wall by molecular sorption.

Breast height. — On standing trees, a standard height (4-1/2 feet) from ground level for recording diameter, girth, or basal area.

Broadcast burn. — The burning of forest residue scattered over an area.

Char. — Charcoal. The residue from the destructive distillation of wood or animal matter with exclusion of air; contains carbon and inorganic matter.

Clearcutting. — Strictly, the *removal* of the entire standing crop.

Climax. — The culminating stage in plant succession for a given environment, the vegetation being conceived or having reached a highly stable condition.

Coagulation. — A separation or precipitation from a dispersed state of suspended particles resulting from their growth.

Combustion. — The burning or rapid oxidation of the pyrolysate vapors escaping from the surface of the fuel.

Condensation. — (1) The linking together of two or more molecules, resulting in the formation of long-chain compounds. (2) The process of forming a liquid from its vapor.

Convection column. — That portion of a smoke plume sharply defined by the buoyant forces of heated air and effluents.

Convective-lift fire phase. — The phase of a fire when most of the emissions are entrained into a definite convection column.

Cord. — A unit of gross volume measurement for stacked round or cleft wood; i.e., based on external dimensions. A standard cord contains 128 stacked cubic feet and generally implies a stack of 4 x 4 feet vertical cross section x 8 feet long, with a small percent extra in height to allow for settlement.

Crop tree. — Any tree forming, or selected to form, a component of the final crop.

Decomposition. — The more or less permanent breaking down of a molecule into simpler molecules or atoms.

Denitrification. — Reducing nitrates to nitrites, nitrous oxide, or nitrogen under anaerobic conditions.

d.b.h. — Diameter at breast height (4-1/2 feet above ground level).

Diffusion. — In meteorology, the exchange of fluid parcels (and hence the transport of conservative properties) between regions in space, in the apparently random motions of a scale too small to be treated by the equations of motion.

Dispersion. — In air pollution terminology, loosely applied to the removal (by whatever means) of pollutants from the atmosphere over a given area; or the distribution of a given quantity of pollutant throughout an increasing volume of atmosphere.

Eddy. — Any circulation drawing its energy from a flow of much larger scale, and brought about by pressure irregularities as in the lee of a solid obstacle.

Effluent. — The mixture of substances, gases and liquids, and suspended matter, discharged into the atmosphere (or ground, river, ocean) as the result of a given process.

Emission. — Pollutants released to the atmosphere from any combustion process. Sometimes used synonymously with effluent, but it is more applicable to atmospheric discharges.

Emission factor. — The quantity of pollutant released to the atmosphere per unit weight of dry fuel consumed during combustion (pounds per ton).

Emission rate. — The quantity of pollutant released to the atmosphere per unit of time per unit length of fire front.

Fermentation layer. — The layer consisting of partly decomposed organic matter. The structure of the plant debris is generally well enough preserved to permit identification of its source.

Fine fuel. — Flash fuels. Fuels; e.g., grass, ferns, leaves, draped (i.e., intercepted when falling) needles, tree moss, and some kinds of light slash, that ignite readily and are consumed rapidly by fire when dry.

Fire behavior. — The manner in which fuel ignites, flame develops, and fire spreads and exhibits other phenomena.

Firing technique. — A method of igniting a wild land area to consume the fuel in a prescribed pattern; e.g., heading or backing fire, spot fire, strip-head fire, and ring fire.

Flaming combustion. — Luminous oxidation of the gases evolved from the decomposition of the fuel.

Flaming phase. — That phase of a fire where the fuel is ignited and consumed by flaming combustion.

Fossil fuels. — Coal, oil, and natural gas; so called because they are the remains of ancient plant and animal life.

Free water. — Free moisture. In wood, moisture contained in the cell cavities and intercellular spaces and held by capillary forces only.

Fuel loading. — The amount of fuel present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel or total fuel and is usually dry weight.

Fuel type. — An identifiable association of fuel elements of distinctive species, form, size, arrangement, or other characteristics, that will cause a predictable rate of fire spread or difficulty of control, under specified weather conditions.

Glowing phase. — That phase of a fire where the char left from the flaming phase is consumed by solid oxidation.

Heading fire. — A fire spreading with the wind. Flames tilt in the direction of spread.

Heat release rate to the atmosphere. — The amount of heat released to the atmosphere from the advancing-front combustion stage of a fire per unit of time.

Heat yield. — To a very close approximation, the quantity of heat per pound of fuel burned that passes through a cross section of the convection column above a fire that is burning in a neutrally stable atmosphere.

Herbaceous. — Soft and green, containing little woody tissue.

Hydrocarbons. — A general term for organic compounds that contain only carbon and hydrogen in the molecule. They are divided into saturated and unsaturated hydrocarbons, aliphatic (paraffin or fatty), and aromatic (benzene) hydrocarbons.

Humus. — (1) A general term for the more or less decomposed (plant and animal) residues in the soil; litter, therefore, being excluded. (2) More specifically, the more or less stable fraction from the decomposed soil organic material, generally amorphous, colloidal, and dark colored.

Inversion. — Temperature inversion. A layer in which temperature increases with altitude.

Litter. — The uppermost layer, the L-layer, or organic debris on a forest floor; i.e., essentially the freshly fallen or only slightly decomposed vegetable material—mainly foliate (leaf litter)—but also bark fragments, twigs, flowers, fruits, etc.

Micron. — One millionth of a meter, a micrometer.

Mixing. — A random exchange of fluid parcels on any scale from the molecular to the largest eddy.

Mixing height. — The height to which relatively vigorous mixing occurs (meters).

Model. — A mathematical or physical system, obeying certain specified conditions, whose behavior is used to understand a physical, biological, or social system to which it is analogous in some way.

Moisture content. — The amount of water present in a material; e.g., wood or soil, generally expressed as a percent of the material's ovendry weight.

National Fire-Danger Rating System. — The method currently used by the USDA Forest Service and other Federal, State, and county agencies to uniformly describe the cumulative effects of weather on wildfire behavior.

Naval stores. — A term of historical pedigree, still applied to the products of the United States resin industry, nowadays particularly to turpentine and resin, but also to pine tars and pitch.

No-convective-lift fire phase. — The phase of a fire when most emissions are not entrained into a definite convective column.

Nucleate. — To form into or around a nucleus, as in the formation of particulate matter.

Organic soil. — Any soil or soil horizon consisting chiefly of, or containing at least 30 percent of organic matter; examples are peat soil and muck soil.

Ovendry. — Of wood dried to constant weight in a ventilated oven at a temperature above the boiling point of water, generally 103 ± °C.

Overstory. — That portion of the trees, in a forest of more than one story, forming the upper or uppermost canopy layer; e.g., frequent emergents in multi-storied tropical forests or, in a two-storied forest, seed bearers over regeneration and standards over coppice.

Particulate matter. — Any liquid or solid particles suspended in or falling through the atmosphere.

Total suspended particulate matter (TSP) is that portion of the total particulate matter that, because of its size (below 5 to 10 microns in diameter), is transported long distances in the atmosphere and has the greatest potential for environmental impact. Respirable suspended particulate matter (RSP) is that portion of the total particulate matter that, because of its size (below 2 to 3 microns in diameter), has an especially long residence time in the atmosphere and penetrates deeply into the lungs. Aerosol is used interchangeably for the smaller airborne particulate matter by many authorities. However, aerosols are more precisely defined as particles in a gaseous medium.

Particulate mass concentration. — The amount of particulate matter per unit volume of air ($\mu g/m^3$).

Perturbation. — Any departure introduced into an assumed steady state of a system.

Photochemical process. — The chemical changes brought about by the radiant energy of the sun acting upon various polluting substances. The products are known as photochemical smog.

Photosynthesis. — The building up of organic compounds, particularly carbohydrates, in green cells, from CO_2 in the presence of H_2O and light, the energy of the latter being transformed by chlorophyll and enzymes.

Physiological. — Relating to the functions of plant or animal as a living organism.

Plume. — The segment of the atmosphere occupied by any of the emissions from a single source. A convection column, if one exists, forms a specific part of the plume.

Point source. — See **Source.**

Pollutant. — With respect to the atmosphere, any substance within it that is foreign to the *natural* atmosphere or that exceeds its *natural* concentrations in the atmosphere. The universal connotation is that a pollutant is potentially deleterious.

Polymer. — A complex molecule formed from the combination of several molecules and having the same empirical formula as the simple ones.

Pre-ignition phase. — That phase of a fire when the fuel is heated to ignition temperature.

Prescribed burning. — Controlled application of fire to wild land fuels in either their natural or modified state, under such conditions of weather, fuel moisture, soil moisture, etc., as allows the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to further certain planned objectives of silviculture, wildlife habitat management, grazing, fire hazard reduction, etc.

Pyrolysis. — The thermal or chemical decomposition of fuel at an elevated temperature.

Rate of spread. — The amount that a fire extends its horizontal dimensions within a unit of time. This can be expressed as forward rate of spread of the advancing fire front, area rate of spread, or perimeter rate of spread.

Residual combustion stage. — The smoldering zone behind the zone of an advancing fire front.

Respirable suspended particulate matter (RSP). — See Particulate matter.

Rough. — An accumulation of living or dead material that is susceptible to burning.

Smoke management. — Conducting a prescribed fire under fuel moisture and meteorological conditions, and with firing techniques that keep the smoke's impact on the environment within acceptable limits.

Smoldering phase. — The combined processes of dehydration, pyrolysis, solid oxidation, and scattered flaming often occurring after the flaming phase of a fire. Often characterized by emissions of large amounts of smoke.

Soluble. — That can be dissolved; capable of passing into solution, as sugar is soluble in water.

Sorption. — The uptake and retention of one substance (the sorbate) at the surface (adsorption) or in the interior (absorption) of another (the sorbent).

Source. — A point, line, area, or volume at which mass or energy is added to a system, either instantaneously or continuously. Conversely, at a *sink,* mass or energy is removed. Examples of sources in the context of air pollution are as follows: a smoke stack is a *point source;* a freeway or aircraft trajectory is a *line source.*

Surface fuel. — The loose surface litter on the forest floor, normally consisting of fallen leaves or needles, twigs, bark, cones, and small branches that have not yet decayed sufficiently to lose their identity. Also grasses, shrubs less than 4 feet in height, heavier branchwood, down logs, stumps, seedlings, and forbs interspersed with or partially replacing the litter.

Synergism. — The cooperative action of separate substances which, together, have greater total effect than the sum of their individual effects.

Target. — Any place at which adverse effects of smoke concentrations may be experienced.

Temperate zone. — Either of two zones of the Earth between the Tropics and the Polar circles.

Thermal energy. — Heat energy.

Total fuel. — The total combustible woody material.

Total suspended particulate matter (TSP). — See **Particulate matter.**

Toxic. — Relating to a harmful effect by a poisonous substance on the human body by physical contact, ingestion, or inhalation.

Transport windspeed. — A measure of the average rate of the horizontal transport of air within the mixing layer (meters per second).

Turbulence. — A complex spectrum of fluctuating, disordered motion superimposed on the mean flow of a liquid or gas.

Understory. — Any plants growing under the canopy formed by others—more particularly—herbaceous and shrub vegetation under a brushwood or tree canopy.

METRIC CONVERSION AND PREFIX TABLE

Metric Conversion

From	Symbol	To	Symbol	Multiply by
		Length		
Inches	in	Centimeters	cm	2.54
Centimeters	cm	Inches	in	0.3937
Feet	ft	Meters	m	0.3048
Meters	m	Feet	ft	3.281
Miles	mile	Kilometers	km	1.609
Kilometers	km	Miles	mile	0.6214
		Area		
Acres	acre	Square meters	m^2	4047
Square meters	m^2	Acres	acre	0.00025
Acres	acre	Hectares	ha	0.4047
Hectares	ha	Acres	acre	2.471
		Volume		
Cubic inches	in^3	Cubic centimeters	cm^3	16.39
Cubic centimeters	cm^3	Cubic inches	in^3	0.061
Cubic feet	ft^3	Cubic meters	m^3	0.0283
Cubic meters	m^3	Cubic feet	ft^3	35.31
		Mass		
Pounds	lbs	Grams	g	453.6
Grams	g	Pounds	lbs	0.0022
Pounds	lbs	Kilograms	kg	0.4536
Kilograms	kg	Pounds	lbs	2.205
Short tons	sh. ton	Metric tons	m. ton	0.9072
Metric tons	m. ton	Short tons	sh. ton	1.102
		Speed		
Feet/minute	ft/min	Meters/minute	m/min	0.3048
Meters/minute	m/min	Feet/minute	ft/min	3.281
Miles/hour	mph	Kilometers/hour	km/hr	1.609
Kilometers/hour	km/hr	Miles/hour	mph	0.6214
		Temperature		
Fahrenheit	°F	Celsius	°C	5/9 after subtracting 32
Celsius	°C	Fahrenheit	°F	9/5 then add 32
		Energy		
British thermal units	Btu	Calories	cal	252.0
Calories	cal	British thermal units	Btu	0.004

Multiple	Prefix Prefix	Symbol
$1{,}000{,}000{,}000 = 10^9$	giga	G
$1{,}000{,}000 = 10^6$	mega	M
$1{,}000 = 10^3$	kilo	k
$100 = 10^2$	hecto	h
$10 = 10^1$	deka	da
$1 = 10^0$		
$0.1 = 10^{-1}$	deci	d
$0.01 = 10^{-2}$	centi	c
$0.001 = 10^{-3}$	milli	m
$0.000\ 001 = 10^{-6}$	micro	μ
$0.000\ 000\ 001 = 10^{-9}$	nano	n

SPECIAL ACKNOWLEDGMENTS

While the authors accept full responsibility for their final products, we all gratefully acknowledge the contributions of the following individuals in reviewing portions of this Guidebook.

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In addition to the above named reviewers, the authors wish to thank all other members of the staff at the Southern Forest Fire Laboratory for their helpful advice and other assistance while the Guidebook has been in progress.

ERRATA SHEET

SOUTHERN FORESTRY SMOKE MANAGEMENT GUIDEBOOK

To save space and avoid duplication, tables necessary for making predictions are printed only on the colored sheets. The descriptions (on white sheets) of the use of these tables contain page references that are incorrect. The correct paging for work tables is:

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VI-M-4	126
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VI-M-6	128

Southern Forest Fire Laboratory Staff

1976. Southern forestry smoke management guidebook. USDA For. Serv. Gen. Tech. Rep. SE-10, 140 p. Southeast. For. Exp. Stn., Asheville, N.C.

A system for predicting and modifying smoke concentrations from prescription fires is introduced. While limited to particulate matter and the more typical southern fuels, the system is for both simple and complex applications. Forestry smoke constituents, variables affecting smoke production and dispersion, and new methods for estimating available fuel are presented.

Keywords: Air quality, pollution, prescribed burning, smoke management, particulate matter, smoke concentrations, emission factors, components of forestry smoke, fuel loading.

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