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AIR QUALITY AND SMOKE FROM URBAN AND FOREST FIRES

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Colorado State University

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Conducted by

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Smoke. Smoke is unquestionably a nuisance. Smoke from industry may be destructive and toxic. Smoke from any source can be considered a pollutant that impinges on the quality of the air we breathe. Yet, man uses smoke for his convenience or pleasure. Smoke is a necessary by-product of man's use of fire to maintain society and civilization.

Smoke has many beneficial uses. Curing meat and fish, flavoring food, coagulating sap, stupifying bees, repelling insects, checking radiational cooling, and signaling are examples. Obscuration by smoke has been used in science and war. Smoke has cultural and ritualistic delights when it emanates from a campfire, cottage hearth, autumn leaves or an incense pot. Smoking is a gratifying indulgence to its habitues and a notorious political trapping. The toxicity of smoke is ignored when smoke is exploited by the individual; when smoke is defined a pollutant by society, toxic limits are chosen that challenge feasibility in the real world of economics or conservation.

The participants of this Symposium address themselves to smoke from urban and forest fires. Obviously smoke from accidental fires defies control except by early extinguishment or confinement. The crucial problem is the control of smoke from fires used by man for the management of the forest, the suppression of insects and disease in agriculture or the disposal of slash in the forest and trash on the farm.

In outdoor fires obscuration is the chief hazard from smoke remote from the fire scene. Meteorologic circumstances have produced scattered episodes of toxic hazards to populations. Despite the debate on air quality, the fact remains that the highest concentrations of smoke in vital organs result from the purposeful burning of two and one-half billion pounds of agricultural trash harvested from the nation's tobacco farms. Judging from the haze in the auditorium where the Symposium was held, air quality in confined spaces is considered to be of minor import to health. In that context the papers merit exploration as heroic attempts to control smoke as a pollutant of the atmosphere.

The goal of the initial Symposium was to establish a perspective on the role of smoke in the welfare of man, despite the obscuration caused by smoke from the debate on prohibition. This Symposium served as an amalgamating force for a diverse group of specialists who exchanged views from many disciplines.

INTRODUCTION

OUR PROFESSIONAL RESPONSIBILITIES IN FOREST FIRE MANAGEMENT

Theodore A. Schlapfer
U.S. Forest Service

As we look at forest fuels and their relationship to air quality, there is one basic premise that we have to accept. As long as energy is stored in wood, and as long as there are people and lightning storms, there will be smoke in the air on a recurring basis. Another obvious truism is that wood will continue to be used as a source of shelter for man. I do not see this country ever reaching the point where orderly harvest of natural resources is not practiced. This would be as unlikely as a meatless society in the United States where animals, fish, and poultry were not used for domestic consumption. People need shelter, and this must come from only a few basic resources. To build homes we can use either wood fiber, or we can use soils, clay, sand, gravel, concrete, steel, or aluminum, but these alternatives to wood all come from the earth. To drastically reduce the amount of wood fiber harvested now, we would be trading commercial forests for giant holes in the ground. Trees can be regrown in a relatively short time span, from 100 to 150 years, but there is no way to regrow the rocks, soils, or minerals taken from the earth.

Energy consumption to produce building materials must also be considered. Lumber can be sawn into wood for about 430 kilowatt hours per ton. On the other hand, it takes seven times that amount to make steel, about 2,700 kilowatt hours, and 40 times as much to make aluminum, about 17,000 kilowatt hours. In terms of insulating homes from heat and cold, one inch of wood is four times as efficient as cinder block, six times as efficient as brick, 400 times more efficient than steel, and 1,770 times as efficient as aluminum. With our national energy crisis, the role of wood is becoming increasingly important as a building material because it is renewable, and because it is efficiently converted from raw material into finished product.

In order to maintain a high quality forest resource, fuel reduction is a necessary part of the job. Slash burning has been practiced in the Northwest since the early 1900's. The Oregon legislature passed laws in 1911 requiring logging slash abatement, and Washington did so in 1917. Slash smoke has been coming under increasing criticism in recent years as a source of air pollution. Much of the impetus for this was caused not by forest burning, but by field burning of grass stubble by farmers in the Willamette Valley. In the fall of 1968, fire control agencies worked with a citizens' committee on air pollution set up by the chairman of the Oregon State Sanitary Authority. Their mission was to prepare legislation to control smoke from agricultural and forestry burning, to keep from further aggravating an already bad situation.

A fire action council made up of fire control administrators from the Oregon Forestry Department, Oregon Forest Protective Association, Bureau of Land Management, Bureau of Indian Affairs, and the Forest Service agreed to look into the possibility of a smoke management system. The effort culminated on September 9, 1969, with the signing of a memorandum of agreement by state, federal, and private fire control agencies, and with the Department of Environmental Quality. The State Forester serves as coordinator, and the Department of Environmental Quality reviews daily burning plans as they relate to overall air quality considerations.

Basically the system operates by fire-weather forecasts. Burning and smoke dispersal conditions are determined from the weather forecast. The amount of slash that may be burned without violating air quality standards is computed. Quotas are set or adjusted from the day's burn. Under the terms of the agreement, all slash burning is conducted in a way to produce minimum visible smoke. Although the system works well, it will not completely satisfy everyone. Some people do not want *any* smoke in the air.

It is my contention that we will have smoke from forest lands one way or the other. It will either be a result of planned burning when weather conditions will allow minimum pollution, or it will come from wildfires burning through the enormous amounts of fuel that will inevitably build up if we do not burn forest debris currently.

When a person hikes through a virgin forest, he delights at the beauty of the environment and clarity of the streams and the air. Most likely he does not think of the wildfires which periodically burned through, removing brush and smaller trees, filling the air with smoke and the streams with debris. In nature, these periodic cataclysms are very much a part of the natural scheme of things.

In the early days of this country when these fires burned through hills and valleys, the dense smoke did not get the attention that it does now because the population was so sparse. But as people migrated to the United States and began moving west, these effects became a matter of public record. The "dark days," when daylight was partially or almost completely obliterated by smoke have been recorded in this country since the very early 1700's. It is hard to imagine this, but the great Idaho fires of 1910 were reported to have created darkened skies from Canada to Wyoming, and as far east as New York State, requiring artificial light during the daytime. The British ship *Dunfermline* reported the smoke during the same period 500 miles west of San Francisco, making it impossible to take navigational observations for ten days. In 1845, smoke from the Nestucca fire in Oregon was so bad that ships remained at the mouth of the Columbia River rather than risk passage down the Oregon coast.

Some excerpts from the Portland *Oregonian* in 1902 give an idea as to the severity of the smoke that summer:

"It was as dark as night between Goble and Scappoose along the lower Columbia River so that the train was lighted at 2:00 PM."

"People were badly scared today by an extraordinary phenomenon. The smoke backed up from the coast in a solid bank and the setting sun turned the sky a yellow-green. All lights were turned on at 3:00 PM. The captain of the *Bailey Gatzert* was compelled to use his searchlight at 11:00 AM, and all the way down the river." (News item from Astoria.)

"By 11 o'clock the day was as dark as the average night at midnight. The schools were dismissed and work on the capitol buildings and all outside labor were abandoned." (News item from Olympia.)

Periodic large fires are not limited to days gone by. To mention a few more recent ones, there were the Saddle Mountain and Sleeping Child fires of 1960 and 1961, the Sundance and Trapper Peak fires of 1967, the Wenatchee area and Southern California fires of 1970, and severe fires throughout the west in 1973.

We will continue to have forest fires for the foreseeable future, and we need forests for their many resources, including timber for consumptive use; therefore, we must do the best job of forest fuels management possible with the least disruptive effect on our environment. Prescribed burning is a way to do this. It is done to reduce forest fuels, to improve regeneration in some forest types, to recycle certain nutrients, to control endemic and epidemic diseases and for improvement of browse and forage species and wilderness management. If we do not fully integrate fire management into land use planning, and go ahead with well planned and executed prescribed burning, we will continue to build residues up to the point that major wildfires will become increasingly common. What we must do is recognize the need for burning and the adverse effects of smoke on air quality.

Logging wastes have typically been burned in the spring or fall to reduce the fire hazard and prepare the seed bed for the next crop of timber. The most commonly used burning technique on clearcut areas in the Northwest is to broadcast burn. Moisture conditions must be rather narrowly defined to allow flashy fuels to spread the fire properly, but there must also be enough moisture in the live timber stands around the edges to prevent fire from spreading into green timber.

From the standpoint of air pollution, broadcast burns create a large volume of visible smoke. Noxious chemicals, the chief contributors to air pollution problems, are very low in wood smoke. The most objectionable characteristic of slash burning smoke seems to be impairment of visibility caused by the particulate matter.

Before further air quality limitations are made on forest slash burning and other prescribed burning, we must examine our frame of reference. Industrial and domestic air pollutants are located at low elevations, are often dangerous, are more or less continuous, and are usually in small and only slightly buoyant plumes. These plumes are not too obvious when mixed among the large buildings and the inherent noise and confusion of a city.

On the other hand, forest smoke usually comes from high elevation lands that are more remote and less populated. The smoke column is large and reaches high into the sky. Unfortunately, smoke from one source looks a lot like smoke from another. Rather than indict smoke from prescribed fire as air pollution in the generic sense, I think it is imperative that whatever decisions are made must be based on fact supported by good, solid research.

We need to know more about the effects of wood smoke as a contributor to air pollution in populated areas. Although slash burning smoke usually is carried high enough to be dispersed above low-elevation metropolitan areas, it still contributes to the atmosphere's load of particulate. It also obstructs visibility and contains some hydrocarbons and particulate matter that reduces air quality. The important point is not the emission, but the concentration and duration of exposure where people are.

One thing that must be recognized is that decisions in the working world are made in the social-political-economic arena. Some people want social change, for example, a cleaning up of airsheds. Others whose livelihood comes from a pollutant source are willing to tolerate much more in terms of air pollution. The politics of the situation must weigh the advantages and disadvantages to the public and attempt to come up with an equitable solution. Where we as professional resource managers get involved is in providing the most accurate, up-to-date facts possible, so that these decisions can be made with better information.

Considerable effort has been put into research in the whole field of fuels management in the United States, but more is necessary. I hope that the research work that is forthcoming earns its rightful position in the land management marketplace. We have to learn, interpret, and accomplish a program of fuels management that will minimize adverse effects on the environment and on the people who live in it.

Of major importance is the cooperative relations between agencies, universities, and all those involved with environmental management. A lot more can be accomplished when all parties work with each other to contribute towards a common goal. With these thoughts, I want to wish you all a very successful smoke management symposium. With the talent assembled here, I know some really good results will be forthcoming.

SESSION I

NATURE OF COMBUSTION PRODUCTS FROM FIRES

Moderator:

William J. Christian
Underwriters' Laboratories, Inc.

SMOKE PRODUCTION OF PARTICULATE MATTER FROM AMERICAN CITIES

Michael H. Jones
U.S. Environmental Protection Agency

Introduction

The purpose of this paper is to discuss the major sources of particulate emissions in urban areas. We will consider not only that component of particulate emissions normally associated with a smoke plume but also those more discrete emissions not manifesting themselves as conspicuous stack emissions. Several aspects of particulate production will be addressed: (1) location and contribution of various particulate sources, (2) fine particulate sources, (3) ambient particulate concentrations in urban and rural areas, and (4) particulate production from selected American cities. In an attempt to evaluate the magnitude of urban emissions with respect to emissions from forest fires, some data will be presented on particulate emissions from prescribed burning in several western states.

Sources and Distribution of Particulate Emissions (1)

In 1970 industrial and nonindustrial sources were responsible for some 25.5 million tons of particulate emissions. The distribution of these emissions by major source category is illustrated in Figure 1. Industrial processes accounted for more than half (53%) of the total emissions nationwide; the quantity of these emissions is estimated at 13.6 million tons. In this source category are the primary and secondary metals industries, the mineral products industry, the chemical industry, and miscellaneous processes such as cotton ginning and manufacture of fertilizers. Major sources of particulate emissions other than industrial processes include fuel combustion (6.7 million tons), agricultural and forestry burning (3.2 million tons), solid waste disposal (1.1 million tons), and transportation (.9 million tons). Table 1 is another distribution of particulate sources, in this case based on major fine particulate sources. The fine particulate emissions are important because they are persistent in the atmosphere and play a key role in restricting visibility. (Secondarily formed particulates are also important in limiting visibility but are not included in the scope of this paper.) As illustrated in Table 1, the major source of fine particulates is combustion both stationary and mobile sources. Other important sources include crushed stone operations, the iron and steel industry, and kraft pulp mills.

Table 1. Selected Major Fine Particulate Sources - 1968 Production Data*

	Fine Particulate Emissions Thousand tons/yr
Stationary and Mobile Combustion	2501.6
Crushed Stone Industry	868.0
Iron and Steel Mills	302.4
Kraft Pulp Mills	319.0
Cement Plants, Rotary Kilns	177.0
Hot-Mix Asphalt Plants	170.5
Ferroalloys Industry	153.1
Lime Plants	113.0
Secondary Nonferrous Metals Industry	127.0
Carbon Black Production	93.0

*Technical and Economic Feasibility of Emission Standards Based on Particle Size, Midwest Research Institute, Kansas City, Missouri, EPA Contract Number 68-01-0428, 15 July 1973 Draft. (Reference 3)

Table 2. Emissions and General Location of Selected Sources of Particulates

	Emissions* (Thousand tons/year)
Predominately Urban Locations	
• Combustion Coal - Industrial	1800
• Secondary Metals	344
• Iron and Steel	1940
• Ferroalloys	52
• Municipal Incinerators	137
• Iron Foundry	233
• Asphalt Roofing	15
Predominately Urban/Rural Locations	
• Combustion, Coal-Electric Utility	3610
• Kraft Pulp Mills	550
• Asphalt Batching	525
• Lime Plants	1060
• Combustion, Natural Gas	203
• Combustion, Coal-Commercial & Residential	113
• Combustion, Fuel Oil	231
• Primary Aluminum, Zinc and Lead	2106
• Structural Clay	137
Predominately Rural	
• Crushed Stone	4190
• Cement	1120
• Primary Copper Smelters	280
• Forest Fire and Prescribed Burning	2680

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*OAQPS Data File of Nationwide Emissions 1970 (Revised) Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. (Reference 1)

This discussion has provided a review of the major sources of particulates nationwide; the following section will address the location of sources and the impact of particulate emissions in urban and rural areas.

Location of Emitters and Urban/Rural Ambient Concentrations

I would like now to provide a general appreciation of how particulate emitters are distributed in urban and rural areas and some indication of the ambient particulate concentrations in these respective locations.

In order to provide some idea of the distribution of sources, Table 2 lists selected sources and emissions by rural, urban, and urban/rural designations. These designations were developed in the Midwest Research Institute study previously referenced. As expected, a significant number of sources fall into the category of being both rural and urban. The largest offenders in this dual category are coal-burning electric utilities, primary aluminum, zinc and lead processes, and lime plants. The primary urban emitters are industrial coal combustion sources and iron and steel processes. Rural locations have several significant sources, including crushed stone operations, forest fires and agricultural burning, and cement plants. The impact of these and other sources in terms of ambient concentrations of particulate matter is considered next.

Figure 2 shows the cumulative distribution of National Air Surveillance Network (NASN) urban and nonurban sites for particulate concentrations measured by the annual arithmetic mean in micrograms per cubic meter ($\mu g/m^3$). Data for this evaluation is for the year 1971 and was published by EPA in November 1972 (2). Urban sites are identified as those located somewhere within a city or town or its suburban environs, while nonurban sites are those located in rural or remote areas. A total of 247 urban and 23 nonurban sites comprise the sample. The distributions in Figure 2 show that urban concentrations of particulates are significantly higher than in rural areas. For example, fifty percent of the urban sites had annual mean concentrations of 88 $\mu g/m^3$ or more, while none of the rural sites measured had annual mean concentrations higher than 82 $\mu g/m^3$. Ninety percent of the nonurban sites had annual mean concentrations less than 44 $\mu g/m^3$ while ninety percent of the urban sites recorded concentrations less than 140 $\mu g/m^3$. Let us take a closer look at the urban areas by considering the nature of emissions from several selected cities.

Particulate Emission in Selected Metropolitan Areas

In order to assess the nature and distribution of particulate emissions from major urban locations, 10 metropolitan Air Quality Control Regions (AQCR) were selected for evaluation. Emission data are from the Environmental Protection Agency's National Emissions Data System (NEDS) and are for the following AQCR's:

> Metropolitan Los Angeles, Metropolitan Chicago, Metropolitan Philadelphia, Metropolitan Detroit, San Francisco Bay Area, National Capital Area, Metropolitan Boston, Metropolitan St. Louis, Metropolitan Baltimore, and Metropolitan Cleveland.

The distribution is as shown in Figure 3.

Of special interest in reviewing the distribution of sources from these cities is the wide variation in the origin of particulates from city to city. Although variations occur in all source categories (fuel combustion and industrial process, solid waste disposal, and transportation), fuel combustion and industrial process are responsible for the major differences.

Fuel combustion was the greatest source of particulate production in five cities and industrial processes the principal source in the remaining five cities. The contribution of fuel combustion sources varied from a high of 81% in metropolitan Philadelphia to a low of 2% in the Los Angeles area. The low figure for Los Angeles can probably be attributed to the extensive use of clean fuels in that area, particularly natural gas. On the other hand, the high concentration of particulate emissions from fuel combustion in Philadelphia is due primarily to the use of bituminous coal by point and area industrial sources. The five cities with major sources of particulates from fuel combustion are listed in Table 3 with the type of combustion and its contribution to total particulates from combustion sources:

Table 3
Cities with Major Sources of Particulates from Fuel Combustion

City	Type Fuel Combustion	Contribution to Total Particulates in Fuel Combustion Category (in percent)
Philadelphia	Electrical generation--bituminous coal	52
Detroit	Industrial fuel process gas	37
Cleveland	Electrical generation--bituminous coal	54
Boston	Residential oil	32
Washington	Electrical generation--bituminous coal	63

In the other major source category, industrial process, the primary metals and mineral products industries were the major contributors in the cities listed in Table 4.

Table 4
Cities with Major Source of Particulates from Industrial Process

City	Type Industrial Process	Contribution to Total Particulates Industrial Process Category (in percent)
Los Angeles	Mineral products	99
Chicago	Mineral products plus primary metal	90
San Francisco	Mineral products	87
St. Louis	Primary metal	78
Baltimore	Mineral products	96

Transportation, as a contributing particulate source category, ranged from a low of 1.5% in Baltimore to 16% in Boston. In all cases, gasoline-powered vehicles are the major offender in the transportation source category.

The final major source category of particulates is from solid waste disposal. Cities displayed no consistent patterns as to the specific type of disposal being a major problem. Municipal, residential, and commercial-institutional and industrial incineration comprised the various subcategories for solid waste disposal.

A final observation with respect to particulate loading from major metropolitan areas concerns the identification of sources as point or area. Table 5 shows the percent contribution of emissions from point and area sources for the cities considered. Only Boston, Philadelphia, and Cleveland show a significant contribution of particulate emissions from area sources; in the other seven cities particulate emissions are primarily from point sources. The composite figures for all ten cities is 86% of particulate emissions from point sources and 14% from area sources.

Some Estimates of Particulate Emissions from Prescribed Burning

Before concluding this review of particulate emissions from urban areas, it seems appropriate to put in context these emissions and those from forest fires. Table 6 provides emission estimates for several western states commonly using prescribed burning. When the contribution of particulates from this source is computed for that period when burning is under way, it can be seen that prescribed burning can be a very significant source of particulate loading.

Table 5. Percent of Total Emissions from Area and Point Particulate Sources for Selected Cities

Cities with Predominantly "Area" Sources	Cities with Predominantly "Point" Sources
Metropolitan Boston - 75%	Metropolitan Baltimore - 94%
Metropolitan Philadelphia - 55%	Metropolitan St. Louis - 89%
Metropolitan Cleveland - 51%	Metropolitan Los Angeles - 88%
	Metropolitan Detroit - 85%
	Metropolitan Chicago - 82%
	National Capitol Area - 63%
	San Francisco Bay Area - 58%

Composite - 86% Point, 14% Area

Table 6. Particulate Emissions for Selected Western States Due to Prescribed Burning*

State	Emissions Tons/yr	Emissions during Burning Season Tons/day	Percent Total Emissions during Burn Season
California	27,200	906	40
Idaho	31,535	1051	93
Montana	47,600	1586	72
Oregon	41,650	1338	76
Washington	47,600	1586	78

*Unpublished report, Open Burning of Agricultural and Forestry Debris, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. (Reference 5)

Summary

Nationwide particulate emissions total 25.5 million tons per year, and are emitted from five major source categories: industrial process (13.6 tons), fuel combustion in stationary sources (6.7 tons), agricultural and forestry burning (3.2 tons), solid waste disposal (1.1 tons) and transportation (.9 tons). Iron/steel mills and combustion of coal by industrial facilities are major particulate sources located primarily in urban areas. Predominately rural sources include crushed stone operations and forestry burning. Annual mean ambient particulate concentrations are considerably higher in urban areas than nonurban; fifty percent of nonurban sites have annual mean values of approximately 32 $\mu g/m^3$ while the comparable figure for urban sites is 88 $\mu g/m^3$. Major emissions in metropolitan areas are from either industrial process sources or fuel combustion; this distribution is probably a function of the types of fuel used for electric power generators in the area. Particulate emissions from prescribed burning can be significant in certain western states, accounting for 40-90% of total emissions during the burn season.

References

(1) U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, N.C. 27711. *OAQPS Data File of Nationwide Emissions 1970* (revised).

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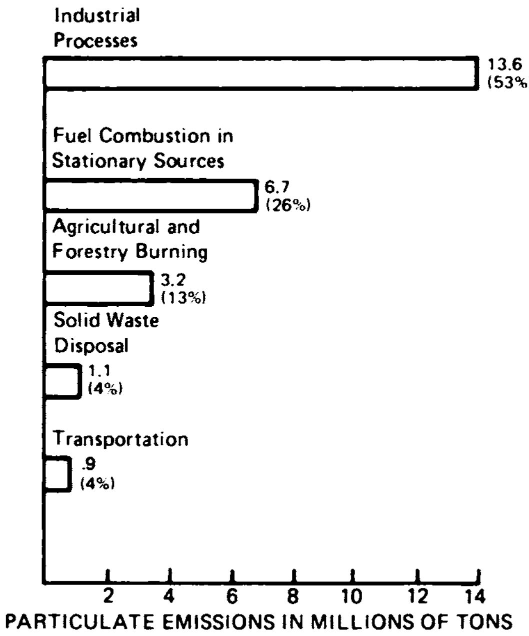


FIGURE 1. Major industrial and non-industrial sources of particulate emissions - nationwide data for 1970. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, N.C. 27711. OAQPS Data File of Nationwide Emissions 1970 (Revised).

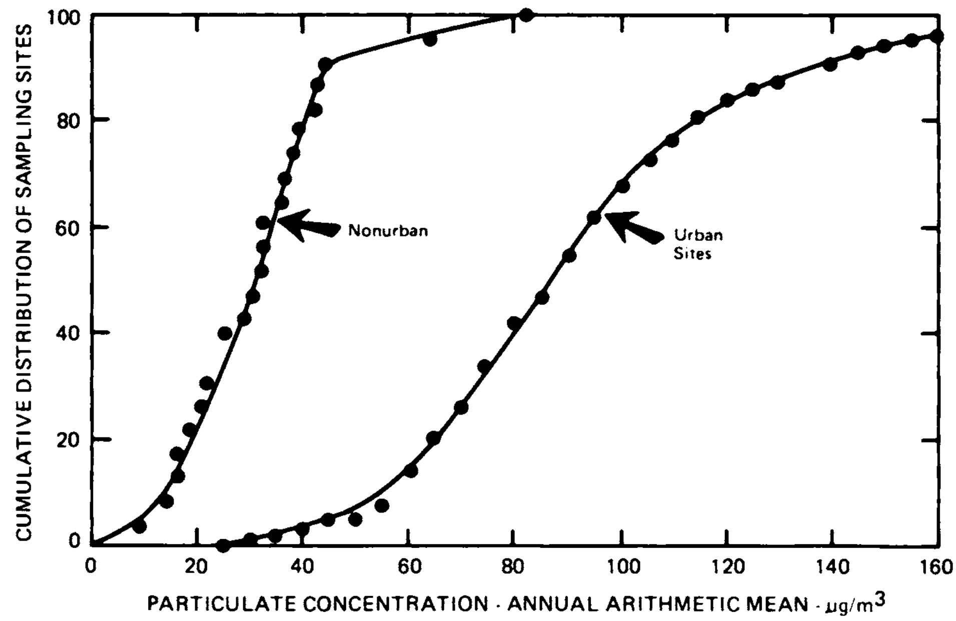
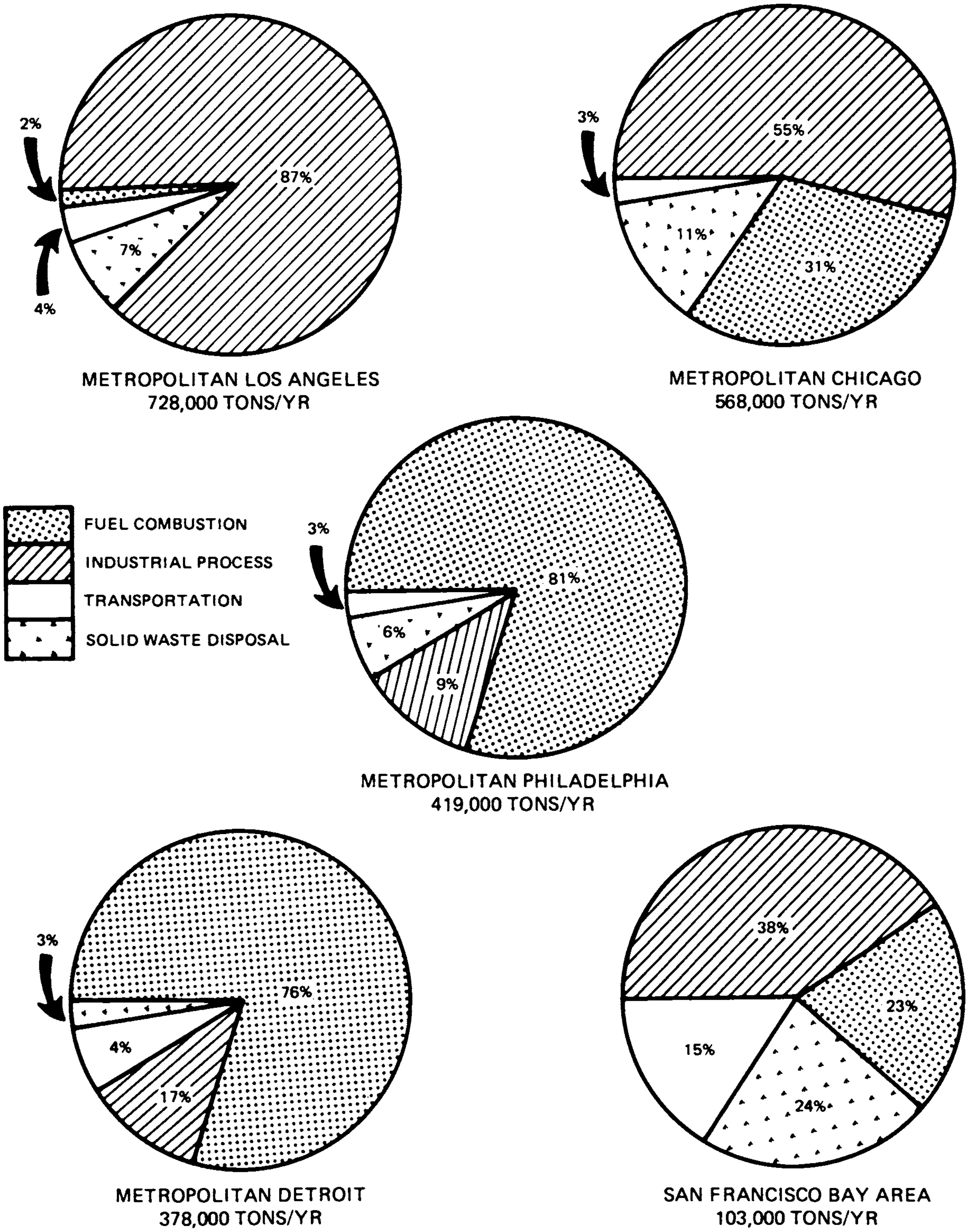


FIGURE 2. Cumulative distribution of particulate concentrations (annual arithmetic mean) at urban and rural sites - 1971 data from National Air Surveillance Network.



METROPOLITAN LOS ANGELES
728,000 TONS/YR

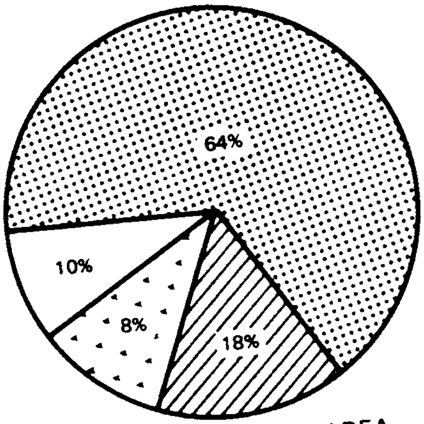
METROPOLITAN CHICAGO
568,000 TONS/YR

METROPOLITAN PHILADELPHIA
419,000 TONS/YR

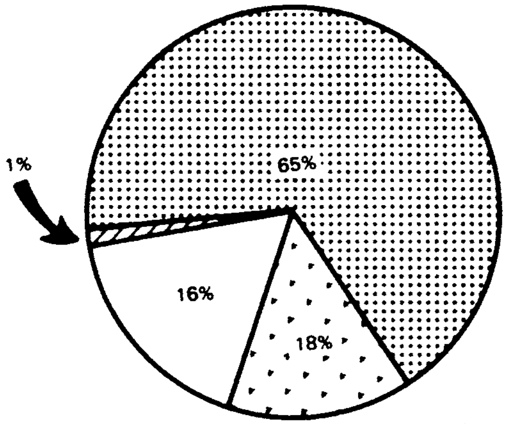
METROPOLITAN DETROIT
378,000 TONS/YR

SAN FRANCISCO BAY AREA
103,000 TONS/YR

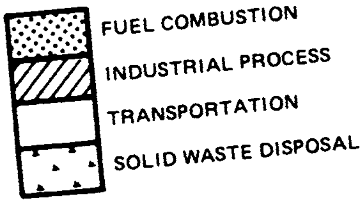
FIGURE 3. Particulate production in selected cities (National Emissions Data System, Environmental Protection Agency, Research Triangle Park, N.C. 27711).

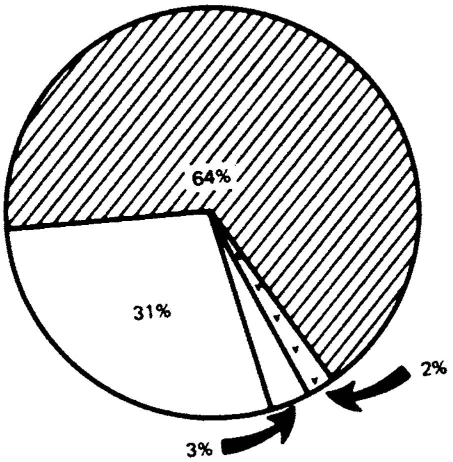


NATIONAL CAPITAL AREA
96,000 TONS/YR

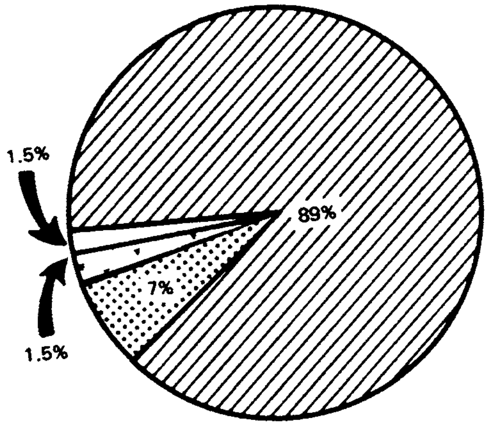


METROPOLITAN BOSTON
37,000 TONS/YR

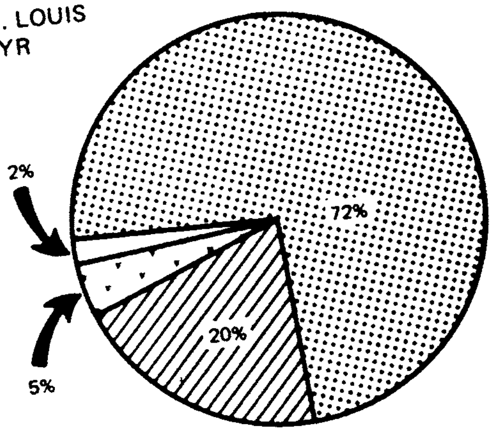




METROPOLITAN ST. LOUIS
283,000 TONS/YR



METROPOLITAN BALTIMORE
423,000 TONS/YR



METROPOLITAN CLEVELAND
344,000 TONS/YR

THE TRADE-OFFS BETWEEN SMOKE FROM WILD AND PRESCRIBED FOREST FIRES

Robert W. Cooper
U.S. Forest Service

It is really quite simple, this trade-off business. Prescribed fires enhance and protect the environment; wildfires, for the most part, degrade it. To be sure, all forest fires put out smoke. Yet all smokes are not the same. In combustion room experiments at the Southern Forest Fire Laboratory in Macon, Georgia, evidence indicates that the emissions from simulated wildfires differ considerably from those produced by simulated prescribed fires. The biggest difference is in the amount of smoke produced--often ten times greater in wildfire situations. Also, because of the high intensities encountered in wildfires, certain products of combustion are present that are not detected in prescription burning. Nitrogen oxide is probably the best example.

Some years ago we conducted a study in the piney woods of the Deep South to evaluate the effectiveness of prescribed fires in reducing the number, size, and intensity of wildfires. Data were collected from 380 wildfires on nearly a million acres for a four-year period, a span that included two bad and two relatively easy fire years. Although a higher wildfire occurrence rate was indicated for roughs three years and older, the differences between young and old roughs were not very great. On the other hand, the differences in burned acreage and intensities were extreme (Figs. 1 and 2). Annual wildfire burn percents ranged from 0.03% in the 0-year-old roughs to 0.14% in the five-year-old roughs to more than 7.0% in roughs older than five years. In roughs less than three years of age, height of bark char, an indication of fire intensity, averaged less than five feet; in roughs five years and older, it averaged about 20 feet. In addition, 12 project-size wildfires (300 acres or larger) occurred in the study area during the four-year-period and all of them originated and burned primarily in the five-year-plus roughs.

What has all this got to do with the trade-offs between smoke from wild and prescribed forest fires? A great deal! Because the per acre fuel consumption by wildfires is considerably more than from prescribed fires--about three to one--and because the particulate count per ton of fuel consumed is also about three times greater, the per acre particulate production (smoke) from wildfires is many times what it is from prescription burning. In many instances, it can amount to about ten times as much. Coupled with the anticipated increase in wildfire activity and associated burned acreage if prescribed use of fire were to be severely

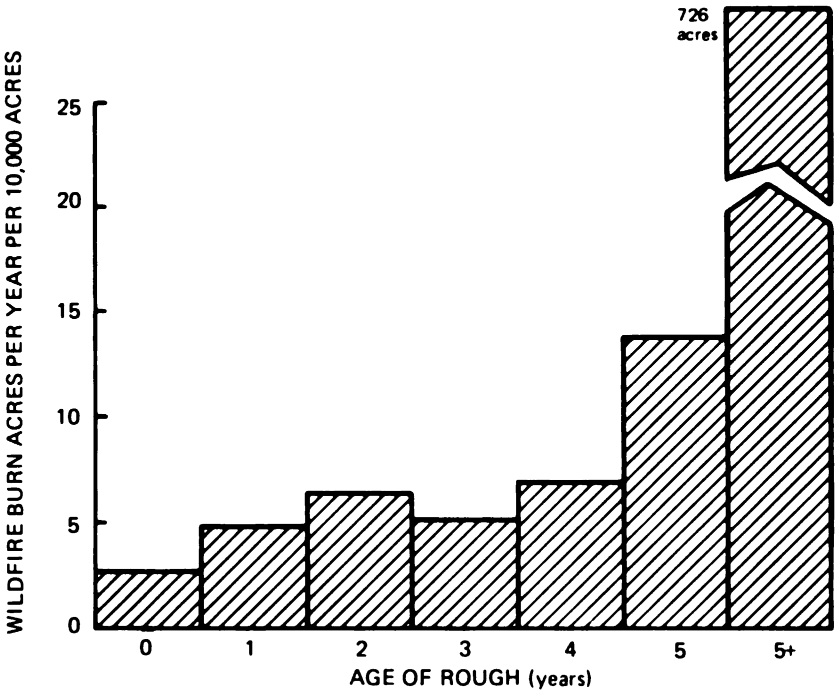


FIGURE 1. Annual wildfire burn acreage.

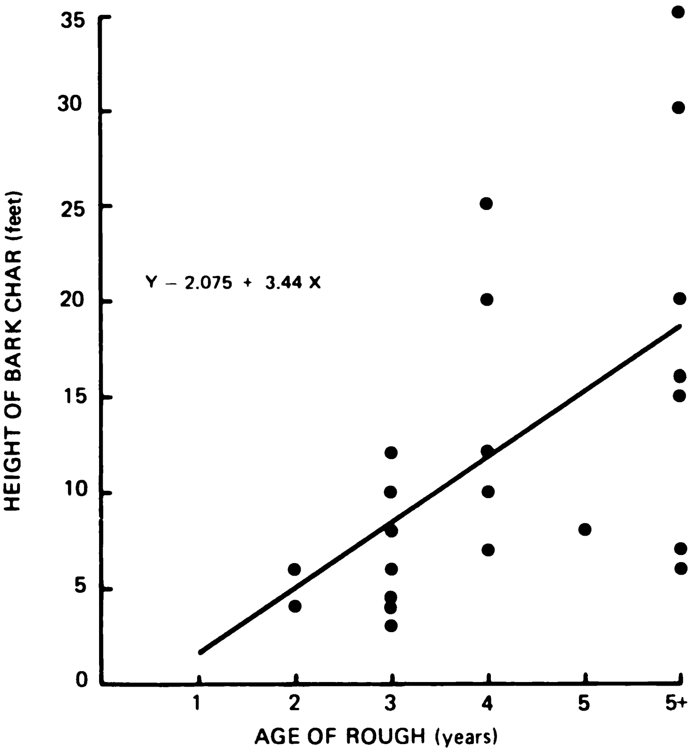


FIGURE 2. Relationship between fire intensity (height of bark char) and age of rough.

curtailed, we suspect that total particulate production might be five to ten times greater without prescribed burning than with it (Table 1).

What this really boils down to is that a little smoke in the right place at the right time may be the best answer to the problem and consequences of wildfires and their big smokes. It may very well be necessary to endure certain annoyances in order to prevent greater evils. Such may be the case with prescribed burning; trading off large quantities of objectionable smoke for small quantities of less offensive smoke is just good business!

If we are going to look at the trade-offs in smoke in greater detail, then we are going to have to examine fuel properties, weather conditions, and the manner in which fires burn and behave. For the most part, these factors account for differences in the quantity and quality of emission products from burning forest fuels--as well as the manner in which they are dispersed.

Fuels

Those fuel properties that have an influence on combustion and smoke production include (1) loading, (2) chemistry (dead or alive), (3) moisture content, (4) size, and (5) arrangement and composition. In most instances, fuel conditions encountered in a wildfire situation are considerably different from those in a prescribed fire.

On an average, prescribed fires in the South consume about three tons of fuel per acre, with a range of perhaps 1 to 10 tons. About nine tons of fuel per acre are consumed by the typical wildfire, with a range of perhaps 1 to 50 tons. If everything else were equal, which of course it is not, wildfires should put about three times as much material into the atmosphere as a result of the heavier loadings.

Dead fuels (litter, slash, and similar dead parts of the forest floor) generally burn more efficiently than living fuels (shrubs, herbs, grasses, and trees). Prescribed fires burn in, and consume, mostly dead and live fuels. Although there are still some unexplained discrepancies in our data, wildfires--per pound of fuel burned--apparently put more emissions into the atmosphere partly because of the chemical and physiological makeup of the fuel consumed.

Combustion efficiency increases as fuel moisture decreases. Prescribed fires are planned and executed when moisture contents are relatively low--for example, when fine fuel moistures are less than 20%. Although wildfires also require low fuel moisture contents if they are to develop high intensities and grow in size, they often burn through low-lying areas or crown out through tree crowns. Fuel moisture levels are high in both instances, and combustion efficiency suffers.

The intensities of prescribed fires are generally such that they consume mostly what we call fine fuels. Fine fuels include grass, ferns, leaves, needles, tree moss, and some light slash that ignite readily and

Table 1.--Annual Particulate Production from Forest Fires in the South

	At Present Level	Without Prescription Burning	With Increased Prescription Burning
Prescribed Fires			
Acres burned (millions)	2.25	0	5.0
Fuel consumed (tons/acre)	3.0	0	3.0
Measured particulate produced (pounds/ton of fuel)	17.0	0	17.0
Total, million tons	0.057	0	0.128
Wildfires			
Acres burned (millions)	2.37	14.50[1]	1.0[2]
Fuel consumed (tons/acre)	7.5	9.0	6.0
Measured particulate produced (pounds/ton of fuel)	58.0	58.0	58.0
Total, million tons	0.515	3.790	0.174
Total particulate production, millions tons (prescribed fires & wildfires)	0.572	3.790	0.302

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[1] Predicted wildfire loss, study reported in J. For. 61(12), December 1963.

[2] Probable minimum level to which wildfires can be reduced.

are consumed rapidly by fire when dry. They have a high surface area-to-volume ratio that permits more complete combustion. Wildfire intensities are almost always greater than those generated by prescribed fires and as such are capable of activating combustion in fuels with lower surface area-to-volume ratios. Combustion efficiency in these larger fuels, however, is very poor and the net result is more smoke.

The arrangement of forest fuels does not differ drastically between a prescribed fire and a wildfire situation, although there are subtle differences that may influence the products of combustion. For example, under certain instances it may be advisable to modify fuel accumulations with chemicals or mechanical treatments before installing a prescription burn. It is not possible to do much to modify fuels in the path of a wildfire. Because wildfires are more intense with higher flame heights, there are more opportunities for vertical development where fuel arrangements encourage it. The associated erratic combustion and behavior means more smoke.

Weather

When we plan for a fire prescription, we designate the specific weather elements necessary to achieve fire intensities and behavior capable of accomplishing the objectives of the burn. Then we wait until they occur before carrying out the prescription. Wildfires, on the other hand, select their own weather regime--that which prevails during the burning period. Under blowup situations, wildfires often create their own weather.

Optimum prescribed burning weather calls for steady, persistent winds, relatively dry air (relative humidity 20 to 40 percent), and an atmosphere that is neither completely stable nor unstable. These conditions are conducive to efficient combustion and lend themselves to rapid and desirable smoke dispersion. In addition, it is possible to select winds that blow smoke away from smoke-sensitive areas rather than toward them.

Because we do not have much control over the time and manner in which wildfires burn, the prevailing weather conditions are often not the best--either for complete combustion or for the effective dispersion of smoke. When winds are gusty and shift direction rapidly and sporadically, fires are most erratic. Intensities build up and subside; rate and direction of spread change constantly; control becomes difficult.

For the most part, wildfires and prescribed fires alike burn under similar conditions of relative humidity. When wildfires are not controlled promptly, however, they may burn over an extended period of time and be subjected to relative humidities that are not conducive to efficient combustion. They may also be exposed to strong wind conditions (either ambient or self-generated) that favor conflagrations. Prescribed fires are normally limited to a relatively narrow time span.

An extremely unstable atmosphere is conducive to blowup fire activity--rapid spread, convective activity, long-distance spotting--

all of which contribute to erratic combustion and a most difficult control situation. A completely stable atmosphere, although not generally fostering difficult-to-control fires, lends itself to incomplete combustion and poor smoke transport and dispersion. Wildfires are possible under either of these extremes. Prescribed fires are designed for the in-between situations where a degree of instability exists to promote more complete combustion and smoke dispersion.

Behavior

Fire behavior has a direct relation to the quantity and quality of smoke produced and how it is dispersed. Wildfires generally burn with the wind, at least wherever possible. They spread rapidly, exhibit sporadic behavior, are usually difficult to control, elicit poor fuel consumption, and produce high flame heights and heavy smokes. Wildfires behave according to the environment in which they burn. Prescribed fires behave as man forces them to within the controls of a selected environment. This is what makes a wildfire wild and uncontrolled and a prescribed fire a true prescription. A prescribed fire spreads and behaves in a manner that conforms with our desires because we utilize fire breaks and firing patterns to manage the fire, and we take advantage of selected weather situations to produce desired behavior. A wildfire spreads and behaves erratically--in a manner that conforms with its individual appetite--influenced only by prevailing fuel, weather, and topography.

Backfires spread slowly (about 1/2 to 2 chains per hour), burn deep into litter layers with good fuel consumption, develop low flame heights, and produce light smoke. They are the most common type of prescription burning and undoubtedly the most efficient. Flank fires and head fires are used as prescriptions in some instances; their smoke characteristics resemble those of many wildfires under the same fuel and weather conditions. The big difference, of course, is that we can exercise complete control over the period of smoke production when we use prescribed fires.

The Western Picture

Up to this point, my discussion has concerned itself with the tradeoffs between smoke from wild and prescribed forest fires from the southern viewpoint. I have done this because I am more familiar with the South--with its wildfire problem and the many reasons for using prescribed fire as a management tool. Many of the comparisons made are applicable to any part of the country; a few may not be. Perhaps a brief review of the western situation is in order.

Slash disposal continues to be the principal objective of prescription burning in the West--about 80% of all burns are prescribed for this reason. Type conversion, range and game habitat improvement, and general silvicultural objectives comprise the remaining justification for the use of prescribed fire in the West. These figures support the hypothesis in favor of trading smoke and damage from wildfires for smoke and benefits from prescribed fire.

In the West forest fuels are heavier, build up larger tonnages per acre, and are generally not as well distributed as those in the East and South. Latest figures indicate that less than one million acres of forest and range land are burned by prescription annually in the West, as compared with at least two million acres in the East and South. Because of the differences in the nature of the fuel and its distribution, burning in the West is considerably more difficult--particularly from the standpoint of smoke and its effect on air quality and activities of people in the region.

Heavy fuels do not lend themselves to as efficient a combustion process as do light, fine fuels. As a result, they produce more smoke. In addition, they generally require longer periods of conditioning and more precise weather parameters to accomplish the objectives prescribed.

The question of distribution is still a matter of conjecture. When logging debris is piled, a common practice in the West, studies show that combustion is more complete and flame temperatures considerably higher than if the debris had been broadcast over the area. If the piled fuel has not been conditioned properly, however, or if it is not arranged to permit adequate flow of oxygen, the reverse is often true. The ideal situation is one where the fires are of short duration and consume the smaller fuels. When the heavy fuels dry out and become a major part of the combustible material, the burning period is extended, glowing combustion increases, and smoke output may be multiplied several times.

Because of the greater per acre fuel weights, burns in the West are usually restricted to smaller individual areas on any given day. Within these restraints, the general principle remains: "The more intense the fire, the higher the smoke plume and the better the chances of prompt, efficient dispersal by strong winds in the upper atmosphere." In the South, where most of our burns are made under a stand of crop trees, high-intensity fires of this nature cannot be tolerated.

The cost of wildfire suppression in the West in 1972 exceeded 100 million dollars. An estimate of the damages is also in the neighborhood of 100 million dollars. These are staggering figures. Yet, when forest managers were asked about the trade-offs between smokes from wild and prescribed fires and the consequences of a curtailment in the use of prescription burning, their response was unanimous:

1. The adverse effects would be severe,

2. The fuel accumulation problem would become worse,

3. Incendiary fires would increase,

4. More large wildfires,

5. Increased logging costs,

6. Reduced timber cut,
7. Unbearable management costs,
8. Environmental deterioration.

East is East, and West is West--but there is countrywide agreement on the paramount issues. The smokes from prescribed fires can be managed and controlled; they represent the price we must pay for a healthy environment, as well as a bountiful resource.

Discussion and Summary

Prescribed fires and wildfires, alike, emit small quantities of carbon monoxide, hydrocarbons, and particulates into the atmosphere. Although there is no evidence to indicate that these products of combustion have a lasting effect on air quality, they result in some temporary impairment to the atmosphere--as well as being an annoyance in smoke-sensitive areas.

Prescribed burning is a scientific prescription designed to cure ailments of the forest. It is a preferred treatment because of its low cost and compatibility with other land-use objectives; it is capable of accomplishing more than one objective at one time, is less destructive to the site than other remedies, and produces a minimum of undesirable side effects. For example, a single fire can reduce hazardous fuel accumulations, control undesirable understory species, enhance the wildlife habitat, and produce a favorable seedbed all at one time. No other treatment can come close to these accomplishments either from the standpoint of efficiency, cost, or safety.

As long as we have forests, we will have forest fuels. If we do not control the buildup of these fuels one way or the other, we will eventually have forest fires and many of them will cause excessive damage. Is it not logical to reason that we are better off living with some innocuous smokes and the many benefits achieved by prescribed fires in contrast to the obnoxious smokes and damages associated with wildfires? The trade-off between the smokes from these divergent fires is a good one. Can we afford other means of fuel manipulation; can we develop less expensive or more efficient alternatives; can we develop new products and markets, and utilize the forest material we are now burning; can we tolerate wildland fires; or can we build up our control forces to the extent that we never allow a fire to get big? The answer is no to all of these questions, at least not in the immediate future. If these assumptions are sound, then perhaps it is best that we face up to the situation. Prescribed burning is an essential tool of forest management; carried out properly, its benefits far exceed any adverse side effects, including smoke contamination.

THE PRODUCTION OF OPTIMUM PARTICLE SMOKES IN FOREST FIRES

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State University of New York at Albany

Whenever fire consumes inflammable material such as cellulose, lignin, pitch, sap and other materials in a forest, brush or grass conflagration, a complex mixture of gases as well as invisible and visible particles, both liquid and solid, rise into the air from the combustion process (1).

The visible smoke consists of particles produced by the condensation of gaseous vapors as well as inorganic residues. The invisible smoke consists of similar materials that have not grown large enough to become visible along with the gases and their molecular reaction products.

The smokes from such fires, depending on the size, intensity and nature, can be classified in the following four categories.

1. Invisible Smoke Plume Fires

This type of fire is uncommon except in localized areas of a big fire or other special conditions. It must be a very hot fire which forms in very dry grass, brush or timber under windy conditions, with air of low relative humidity. Such a fire receives an adequate supply of oxygen to achieve complete combustion, while the vapors rising in the fire plume are quenched so rapidly that the condensation particles do not grow large enough to become visible. Depsite the absence of visible smoke, such a fire will produce very high concentrations of gases and condensation nuclei.

2. Blue Smoke Plume Fires

The fire which produces a blue smoke is only slightly different from that having an invisible plume. It may be a larger fire with a higher concentration of condensible vapors, or for some other reason its particles have sufficient time to grow large enough to scatter light at the blue end of the visible spectrum. The particles from such a fire range in size from the submicroscopic to those having a maximum diameter of 0.3 microns. If viewed in a small chamber with good illumination and low power magnification, such visible smoke particles exhibit a large amount of Brownian motion and are strongly polarized (so much so that when viewed with a polarizing analyzer at right angles to the illuminating beam, the smoke becomes virtually invisible).

3. The White Smoke Plume Fire

A fire which produces a white plume of smoke is the type most commonly observed. Such a fire is rarely driven by a strong wind but burns actively due to a rich source of fuel. Particle sizes in the plume range from the submicroscopic to a few microns in diameter. It is this type of smoke which is most effective in reducing visibility since the median size is at about 0.6 microns (2). This is the most effective size for producing light scattering in the visible spectrum. Such particles are likely to remain airborne until removed by some natural scavenging process. Large fires producing such particles may have plumes extending from hundreds to thousands of miles if convected into the upper part of the troposphere. When they produce dense clouds of smoke, the sun may be viewed easily with the unprotected eyes, and its disc is likely to show colors ranging from red to pink to orange to blue, depending on the dominant average size of particles.

4. The Yellow-Grey-Black Plume Fire

The final category of mass fire that produces specific types of particles is characterized by a running wild fire that consumes everything in its path. Because of its nature, such a fire from time to time causes the ignition of a mass of material of such large dimension that insufficent air is entrained even when the wind is blowing 30 to 50 miles an hour (15-25 meters per second). Under such conditions dense plumes of black smoke may rise from time to time to mingle with the yellow and grey smoke billowing from the fire zone. This black smoke often consists of fragments of charred or only partially burned leaves, needles, twigs or other combustible materials that did not receive enough oxygen to be efficiently burned. As a result, some of the residues are quite large and soon fall back to the earth. The particle size from such fires ranges from the submicroscopic to partially burned debris up to several centimeters or more in cross-section--a spread in size of more than a millionfold.

The Opportunity of Controlling Particle Size

With the increase in favor of controlled fire in forestry practice, which if intelligently and skillfully used can have environmentally favorable results, it is important that the use of fire be handled in the best manner possible. An attempt should be made to develop fires that either produce particles so small as to be invisible (less than 0.1 microns), or of the blue smoke category (0.15-0.3 microns diameters), and thus of little consequence in causing esthetic insult, or so large that most of the particles fall back to the earth within a relatively short distance. This would avoid the type of smokes that have long residence times in the atmosphere, such as the types described in Categories 3 and 4.

The wild fire and others difficult to control that cause economic and esthetic disasters might be greatly reduced in occurrence with the wise use of intentional (prescribed) fire. When this is done, however, every effort should be expended to induce a fire which either produces invisible or only slightly visible particles, or such large ones that they have short residence times in the atmosphere.

Considerable field experimentation will be required to develop an expertise that achieves these results. Successful smoke particle control will mark an important advance in fire practice.

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THE NATURE AND CONCENTRATION OF COMBUSTION PRODUCTS FROM URBAN FIRES

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INTRODUCTION

General Background

Normally one expects that flame contact is the major cause of injury and death during fires. Perhaps the first event focusing attention to the hazards of fire from plastic materials was that of the Cleveland Clinic fire in 1929, in which x-ray films, composed of highly combustible nitrocellulose, caught fire and brought death to 125 persons. Analysis of the death pattern revealed that most of the deaths were not due to flame contact but were a consequence of the production of carbon monoxide and nitrogen oxides. Since then numerous other fires in this country and abroad (Table 1) have also led to deaths, not only due to the actual flames, but to the gaseous products evolved from synthetic materials. Not too surprising, however, is the fact that research on the toxicological aspects of pyrolysis and combustion during fire exposure has lagged so far behind other aspects pertaining to the flammability characteristics of materials, that even a fair assessment of the toxic hazards cannot be adequately described at this time except in great generalities. The time has passed for the toxic consequences during combustion to be ignored or minimized.

The major emphasis within the scope of this paper will relate to the physiological and toxicological aspects of smoke produced during the combustion of materials. Since few definitive studies have been reported in the open literature pertaining to smoke and its effect on humans during and after fire exposure, the author will supplement this report with appropriate references as well as the results of recent studies carried out in the Flammability Research Center of The University of Utah.

Definition of Smoke

A dictionary definition of smoke (1) is "the volatilized products of the combustion of an organic compound, as coal, wood, etc., charged with fine particles of carbon or soot; less properly, fumes, steam, etc."

Gaskill (2) defined smoke as "the airborne products evolved when a material is decomposed by heat or burning (oxidation)." He further stated that "smoke may contain gases, liquid, or solid particles, or any combination of these."

Hilado (3) defined smoke as "the gaseous products of burning organic materials in which small solid and liquid particles are also dispersed; smoke can also be defined as solid particles, such as carbon and ash, suspended in air." Hilado further stated "that the broader definition is the more appropriate because the nongaseous portion of smoke from some materials contains significant amounts of tarry or liquid droplets." Thus, little difference is noted in the three definitions of smoke described previously.

FACTORS AFFECTING LIFE SUPPORT IN FIRES

The major factors affecting life support in confined space fires are listed in Table 2 in the order of greatest danger to human survival. From a toxicological point of view, factors 1, 3, and 5 become important considerations since factors 2 and 4 will cause immediate death, while factor 6 may or may not lead to death, depending upon whether a panic-strickened person makes a rash decision such as jumping out of a building rather than waiting for rescue.

Exposure of humans to the various combustible gases normally encountered in fires as well as to the particulate matter in smoke may bring about acute episodes of toxicity, ranging from minor irritant effects to death.

A series of disasters in recent years has focused considerable attention on the growing list of problems connected with the burning of polymeric materials, such as fibers, coatings, elastomers, foams, and reinforced plastics. The crash of the United Airlines Boeing 727 jetliner at the Salt Lake City Airport in November 1965 was one of the most dramatic incidents illustrating the dangers arising from intense heat, toxic fumes, and dense smoke. This tragedy, which took the lives of 43 persons out of the 91 aboard, was one of the rare instances of what the Civil Aeronautics Board termed "survivable crash with no fatalities on impact." Yet the big question remained: *What was the contribution of the plastic materials inside the plane to the development of fumes and smoke?* Previous attempts by industry to fire-retard plastics produced improved resistance to flame contact; however, hazards due to smoke generation were, in general, not fully understood and recognized. Disasters of the Salt Lake City type clearly spell out the need for the use of plastic materials that exhibit both adequate flame resistance, as well as low-smoke generation. The necessity exists, therefore, for the development of synthetic materials with these properties and the more accurate evaluation of such materials to allow prediction of their behavior in emergency situations.

A critical analysis of the hazards of life support in fires involving plastics has been carried out by the author and his research group. The burning process takes place in several steps:

1. A destructive distillation of the plastic takes place, producing gases whose nature depends on the composition of the materials, temperature, and the rate of heating.

2. Oxygen unites with free carbon to form carbon monoxide. At this time dense smoke is usually formed, presenting additional hazards.

3. When sufficient oxygen is present, it combines with the flammable gases produced in the first step, as well as with carbon monoxide. If sufficient excess oxygen is available to combine with all the combustible materials, the carbon monoxide burns to form the relatively harmless carbon dioxide. Ordinarily, the products of complete combustion are less harmful than those of incomplete combustion.

The author, in his role as Deputy Fire Marshal for the State of Utah and Special Consultant to the Salt Lake City Fire Department, has served as an investigator in a number of fires in which severe injury or loss of life was attributed to smoke as well as toxic gases resulting from the combustion of materials commonly encountered during such conflagrations. The fire in the Lil-Haven Nursing Home (September 15, 1971) in Salt Lake City, Utah, serves as an excellent example to illustrate conditions encountered in many confined space fires. Six patients died in this fire that lasted approximately ten minutes. The first fire equipment arrived on the scene less than one minute after the rate-of-rise detector signaled the alarm to the central fire station. It is interesting to note that none of the six patients who died showed any evidence of body burns. Figure 1 shows the exterior front view of the Lil-Haven Nursing Home. It should be noted that with the exception of a slight trace of smoke damage in the eaves just under the roof, there was no outward evidence of a fire having taken place. Figure 2, a side view of the Lil-Haven Nursing Home, shows slight evidence of fire in the second story section of the building. Figure 3 shows the burned exterior of the hollow-core wood panel door, typical of those found in the second-floor hallway of the nursing home. It should be noted that while the door was severely damaged, it did provide a suitable fire barrier, as exhibited by the interior of this door shown in Figure 4. Firefighters found all of the doors leading to the hallway in rooms located on the second floor open at the time of the fire. Figures 5 and 6 show the typical smoke and soot patterns, indicative of a fast-spreading fire, on the interior of two of the rooms in which four of the victims died. The smoke patterns serve to corroborate the view that had these doors been shut, sufficient protection would have been provided until this fire was brought under control so as to preclude the loss of life.

The propensity of certain materials to ignite and burn with a rapid propagation rate has encouraged the industry producing these materials, as well as government agencies, to find ways of preventing or diminishing the ignition and flame-spread characteristics of these materials. Generally, polymeric materials contain chemical agents, called fire retardants, to reduce the original flammability characteristics of the material. The use of fire retardants is increasing at a prodigious rate each year. Unfortunately, as may happen on occasion, the treatment may bring about another hazard equal to the problem which originally required the treatment. In this case, the flame retardants do improve the flammability characteristics of the materials, but by so doing, they increase the concentration and types of pyrolysis products which may be liberated during fire exposure. These products may have biological implications not previously appreciated.

PHYSIOLOGICAL FACTORS AFFECTING SURVIVAL DURING FIRE EXPOSURE

The factors that critically limit survival response during fire exposure must be defined. In actual fire exposure it is difficult, if not impossible, to separate the physiological parameters from the toxicological parameters. Within the scope of this paper, the author has made this separation in order to elucidate that which is presently understood about the response of humans in fires and to indicate those areas where further study is required.

In many respects, it is more important to determine the limits for survival than the mechanism of death from exposure to noxious gases or hypoxia. Additional studies are required to determine the long-range effects of acute exposure to carbon monoxide, temperature, and a variety of interacting noxious and toxic by-products of combustion.

Visual Parameters Affecting Survival

Considerable attention has been directed to the measurement by optical techniques of the quantity of smoke produced during the combustion process. It should be noted that while many chemical and physical factors can affect the quantity of smoke produced, the size, and concentrations of particulates in the smoke, and the chemical composition of the smoke, *the optical techniques commonly used can measure only the light-obscuring potential of smoke and cannot measure the physiological factors relating to human survival during fire.*

The particulates contained in smoke can and do affect the vision of firefighters using gas masks and sustained breathing equipment. The results obtained using the Rohm and Haas XP-2 chamber or the National Bureau of Standards Smoke Chamber can relate directly to the ability of firefighters to see under fire conditions. On the other hand, persons encountering smoke in a fire may not be able to see due to such factors as lacrimation caused by components in the smoke. Einhorn, *et al.*, (4), reported that fluorocarbons exposed to pyrolysis or combustion caused severe opacification of the cornea in test animals exposed to their degradation products. The hydrogen fluoride, fluorine gas, and carbonyldifluoride, identified in the smoke produced was in sufficient concentration to etch glass coverslips placed in the test chamber. Thus, even though relatively low smoke was generated during the pyrolysis or combustion process, humans exposed in a similar environment may well have had their sight hampered to an extent that they would not have been able to escape a fire area in time to prevent exposure to lethal concentrations of toxic fumes or temperatures sufficient to cause death.

The Escape Response

Little reliable data is available concerning the escape response of humans during fire exposure. The influence of hypoxia alone and in combination with carbon monoxide and noxious gases must be determined both at ambient temperatures and at rates of temperature increase that are encountered in "typical" fires. Numerous investigators have reported cases where a victim has died during a fire with no visible barrier observed to easy escape. Victims of fires, such as those caused by cigarette ignition of mattresses or furniture, where long periods of smoldering have preceded actual ignition are often found away from the ignition source. Figure 7a shows an example of a woman found near a doorway after causing a fire on a mattress by smoking in bed. It should be noted that chemical analysis of the blood showed a 0.265 blood alcohol level accompanied by 33% carboxyhemoglobin saturation. Figure 7b shows the body outline on the floor which clearly indicated that death occurred prior to the onset of flaming combustion. This analysis confirms that the combination of alcohol and blood carboxyhemoglobin, as well as increased temperature, may have been the cause of death. But questions must be asked as to the possible loss of sight, prior to death, the possible effect on nerve impulse velocity reduction, the effects on muscle activation and contraction and other effects similar to these which may have prevented escape from a hazardous area even though the victim realized that he must egress the fire area in order to survive.

Noxious gases which find their way into the circulation, either because they are odorless or are in low concentrations, may act in still unknown ways in producing neuromuscular dysfunction. The peculiar affinity of carbon monoxide for hemoglobin and cyanide radicals for cytochrome oxidase are two well-known examples of this phenomena. Other degradation products may also affect oxidative metabolism at various levels either by influencing oxygen transport or intermediary metabolism. The enzyme systems concerned directly with muscle activation and contraction may also be affected.

Studies comparing responses to hypoxia of various types of CO interaction have disclosed significant differences. Since arterial $P(O_2)$ may be normal despite a reduced oxygen-carrying capacity, reflexes which normally increase respiratory rate and tissue blood flow are not activated (5,6). Recovery from hypoxia associated with CO intoxication is greatly prolonged in comparision to recovery from hypoxia alone (7,8).

A reduced partial pressure of oxygen is found in the poorly-ventilated environment in which combustion occurs. Combined with the pressure of carbon monoxide and other gases impairing oxidative metabolism, very little reduction in ambient oxygen may be lethal. From observations of subjects at high altitude, lassitude and lack of motivation progressing to somnolence are primary behavioral responses during hypoxia (9). These effects threaten survival both at altitude and during accidental fire. The ability to continue automatic motor activities, such as running, depends both upon the central nervous control of this activity and the neuromuscular system. The ability of these systems to continue normal function during fire exposure must be determined. It should be possible to assess the relative importance of central nervous and peripheral neuromuscular systems as responsible for loss of motor control. As yet unknown mechanisms dependent upon particular combinations of noxious gases may be operating which can significantly impair peripheral motor mechanisms. Noxious gases may exert specific effects upon activation and/or contraction properties of skeletal muscles. Failure to respond appropriately under the stressful circumstances of a fire may depend upon loss of these peripheral motor mechanisms.

TOXICOLOGICAL ASPECTS OF COMBUSTION

General Background

The most controversial and most complicated aspect of fire research is that phase of study directed toward an understanding of the toxicological properties of materials during fire exposure. Hundreds of articles have appeared in the literature reporting the nature and quantitative analysis of pyrolytic decomposition products. Bulletin 53 (10) published by Underwriters' Laboratories cites 297 references dealing with toxicity studies using animals which were exposed to a wide range of environments under many experimental conditions. In the summary of this report it was stated that considerable variance was observed in the experimental results and that little correlation was obtained by different investigators.

If laboratory animals are subjected directly to the pyrolytic decomposition products at temperatures normally encountered in real fires, they perish from the effects of heat before being overcome by the decomposition products.

In recent investigations, Einhorn, *et al.* (11) studied the effect of temperature on lethality (LD 100) of laboratory rats of varying body weights. A preliminary heat transfer mechanism was postulated. Although an induction period was observed due to the insulating characteristics of the animal's fur, the relatively large surface-to-volume ratio resulted in their inability to survive extensive thermal shock to the degree that humans can. Present research studies are being carried out under the National Science Foundation-RANN grant. The gross physiological effects of smoke are being studied as part of this program. A series of experiments have been designed to determine the physiological effects of smoke developed during the pyrolysis and combustion of polymeric materials on laboratory animals. Initial experiments were designed to determine the maximum levels for temperature exposure before introducing permanent changes in vital functions. The equipment used in this research is shown in Figure 8. A maximum body temperature of 42°C for extremely brief durations has been established as a ceiling for Sprague-Dawley rats. Exposures at this level will produce major dysfunction in the central nervous system, the respiratory system, and possibly, other systems.

Previous studies utilizing animals have suffered from several defects in design. First, the number of animals was small. Second, there was often a lack of control. Third, there were few standardized pre- and post-exposure tests of the animals' responses. Fourth, routine necropsy examinations of all major organs were not the rule.

A further weakness in many investigations pertaining to toxicological aspects of combustion is the failure to simulate conditions of common prototype fires such as aviation fires, home fires, automobile and boat fires, etc. For example, the likely time of exposure and the likely conditions of exposure such as temperature and varying oxygen concentrations have not been key factors in this experimentation. Analysis of decomposition products resulting from pyrolysis or combustion has indicated major changes in the nature of the products due to condensation, recombination, or cross-reactions where the temperatures of combustion are modified. Experimental design considerations must also be given to changes in the degradation of a single material as compared to the degradation of the same material in the presence of one or more materials of different chemical composition.

Respiratory Burns

In 1962, Phillips and Cope (12) labeled respiratory tract damage as "a principal killer" in burn victims. In 1967, Stone and Martin (13) reported respiratory involvement in 15% of 197 burn patients studied. Zikria (14) analyzed the causes of death among fire fatalities which had occurred in New York City during the years 1966 and 1967. Table 3 summarizes the results of this study. A study of the information presented in Table 3 shows that 311 of 534 fire victims were autopsied, 60% of whom died at the site of the fire or on the way to the hospital. Seventy percent of these early fatalities had respiratory involvements.

One hundred and five of the fire fatalities had less than 40% body surface burns; 77% of these victims could have been expected to survive, if statistical predictions were based solely on the extent of body surface burns (15).* Respiratory involvement was found as a

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*Medically the "rules of nine" (15), are used to express the extent of a burn. One arm is 9%, a leg is 9%, front and back 9%, etc. The percent of the body involved is important for both treatment and plotting survival figures. If a 3rd degree burn involves 50% of the body surfaces, the mortality rate is about 50%. If a 3rd degree burn involves 70% or more of the body surfaces, survival is nil. A healthy adult may survive a 10-15% 3rd degree burn without too much difficulty; a healthy child may survive a 5-10% 3rd degree burn without too much difficulty.

primary diagnosis among the majority of these fatalities. Specifically, 43% had smoke poisoning and/or asphyxiation; 50% had carbon monoxide poisoning; and 27% had pathologically evident damage to the tracheobronchial tree and lungs. These figures clearly indicate the magnitude and seriousness of the problem of inhalation injuries in fire victims.

It is generally accepted that the tracheobronchial tree and pulmonary tissues can sustain heat damage, chemical damage, anoxic damage, or any combination of these injuries during fire exposure. Pressure damage may also occur when the fire is accompanied by an explosion.

Until the late 1960's many investigators doubted that caloric inhalation damage could occur in the tracheobronchial tree because of the low specific heat of gases. Moritz (16) conducted experiments on dogs using high-temperature torches as the source of combustion. This study seemed to indicate the physical impossibility of caloric damage. In 1968 Zikria, *et al.* (17) and Stone (18) demonstrated heat fixation of the tracheal mucosa in fire victims as well as the presence of varying degrees of injury to the tracheobronchial tree. All the victims who had severe tracheobronchial damage were dead at the scene of the fire or soon after.

Smoke Poisoning

Zikria (14) indicated that smoke poisoning was a primary diagnosis in 119 victims of the 185 early burn fatalities studied (Table 4).

Lethal levels of carbon monoxide poisoning were discovered in 45 of the 185 early deaths studied by Zikria (17)(Table 5).

In real fire exposure it becomes nearly impossible to ascertain which one or two agents (excluding absence of oxygen, presence of carbon monoxide, and perhaps direct evidence of large quantities of particulate matter in the upper respiratory tract) caused death. It becomes even more difficult to ascertain the toxic potential of a specific material when it burns or is heated. Presently, the simplest approach is to have some knowledge of what gases are formed and to seek toxic information on the individual compounds if such knowledge is available. From this point on, the problem of identifying the role of a single product on life support becomes greatly magnified since the combination of products being inhaled may not, and generally does not, produce the same biological response as when only one of the compounds is inhaled.

When man is placed in contact with a chemical agent, it can produce an acute toxic effect in a number of ways, the most important of which are listed below:

1. The compound may act as a primary irritant upon the skin and/or mucous membranes.

2. The compound may be absorbed into the blood stream, leading to definite toxic symptoms and signs, and which may result in death on continued exposure.

3. The compound may act as a sensitizing agent, producing antibodies to the antigen. A repeated exposure to the same, or nearly similar compound, may produce allergic manifestations ranging from mild to very serious.

4. The compound may be absorbed in very low concentrations, producing no definite signs and symptoms of toxicity, but may affect mental functions.

The first two can lead to rapid death during fire exposure, or if not death, may result in sufficient damage to cause hospitalization. The third (sensitizing agent) consequence has not received much attention in regard to fires but it should not be overlooked, at least in those cases where death does not occur or even in those instances in which no apparent harm is noted. An allergic response may, however, develop at another date but may have been initiated due to the fire or the pyrolysis of a polymeric material. Such injury is often reported where approximately 10 per cent of those individuals exposed to carbon monoxide seemingly recover and some months after the actual exposure, develop major dysfunction which may lead to death. Finally, low levels of a compound may be sufficient to alter mental functions which, in turn, lead to serious accidents or consequences for the person as well as for a large number of individuals.

The Fire Gas Research Report (19) evaluated the effect of oxygen concentration as it pertains to human response during fires. Table 6 summarizes the signs and symptoms of toxicity caused by reduced levels of oxygen due to fire conditions.

Shorter, *et al.* (20) reported that temperatures in excess of 300°F (149°C) were capable of causing loss of consciousness or death within several minutes. The temperatures recorded in several controlled experimental fires in buildings exceeded the maximum survivable levels within 5-10 minutes. This period of time is expected to be greatly reduced, for instance in aircraft fires, due to the large concentrations of available fuel, and thus egress from the cockpit area must be carried out within approximately 90 seconds if survival of the passengers is to be realized.

Smoke development measurements have been made by a number of experimental techniques. Dense smoke discharged into the atmosphere by burning wood, cotton, paper, or plastics contains toxic products of thermal decomposition including carbon monoxide, hydrogen cyanide, hydrogen halides, a number of organic irritants, such as acetic acid, formic acid, formaldehyde, furfural, etc. During the early stages of a fire, the smoke may contain so little carbon monoxide that the major injuries resulting from smoke inhalation may be caused by the irritants. These attack the mucous membranes of the respiratory tract and create conditions favoring the onset of pneumonia. In cases of actual exposure, the physiological effects of inhaling smoke depend upon its physical state. When the smoke is very hot, it will destroy the tissues by burning, regardless of its chemical compositions; when cooled, the smoke may be non-irritating because the irritants have been removed by condensation and settling. Consideration must also be given to the size of the particulates entrapped in the smoke. If these materials are large, they may be easily removed by ciliary action within the body. If, however, they are small, the removal process may become more difficult. Numerous chemical components, usually aromatic in nature, tend to condense on the exterior of the smoke particulates. These compounds may actually cause serious biological consequences. Recent studies have shown that another factor may play an important role in human response to smoke. Samples of particulates screened from smoke generated during pyrolysis or combustion of polymeric materials have been examined using the techniques of electron spin resonance. All the evidence indicates that many of the free radicals, normally having extremely short half lives, may be entrapped in the smoke particles and strong signals are obtained for periods as long as 5 or 6 weeks. Preliminary tissue culture experiments have shown the development of abnormal nuclei when subjected to particulates having entrapped free radicals. It should be pointed out that this work is in its very early stages and considerable additional studies must be carried out before any definite conclusions can be drawn.

In addition to causing injury or death by the methods previously described, dense smoke may prevent exit from the area in which the fire is located by obscuring vision. This same obscuration effect may prevent location of the source of the fire and thus hinder fire control.

Many investigators have conducted studies on single materials under controlled laboratory pyrolysis or combustion conditions. In actual fires, combustion of single materials is seldom encountered, and there is ample evidence to show that the sum of the toxicity potential of two or more gases or vapors may synergistically affect life (21). When encountered in a fire, the toxicity of such mixtures may be further increased by low oxygen concentrations and accompanying high temperatures. Carbon dioxide, for example, causes stimulation of the respiratory center of the brain; and if breathed in excess during a fire, it causes an abnormally high intake of other gases causing toxic or lethal concentrations which might have been avoided if carbon dioxide had been absent.

Although the lungs and associated structures are principal sites of action for irritant fire gases, corrosive vapors such as acids and acetaldehyde will also affect the unprotected skin and the cornea of the eye. Whatever the tissue exposed, the effect will cause inflammation. If the concentration of irritant gas or vapor is high or the exposure prolonged, fluid accumulates in the respiratory organs, being drawn from the blood and tissues. This condition is called tracheal, bronchial, or pulmonary edema, according to the level in the respiratory tract which is affected.

To date, the major concern of those engaged in the development of fire-retardant materials has been the reduction of the ignition tendency and flame propagation. Thus, it has been possible to meet the code and regulatory requirements regarding flame spread, but in the opinion of the author, the total hazard resulting from incomplete combustion has been increased. A study of several recent fires has indicated that smoke development and the production of copious amounts of toxic decomposition products have resulted in the loss of life or bodily injury long before the spread of flame has reached those individuals trapped in the conflagration.

In addition to an increase in hazards caused by improper methods of fire-retardation of plastics, recent studies conducted by the author have shown that the flammability characteristics measured by small-scale testing procedures, with slow heating rates, do not correspond with the performance of the same materials in actual large-scale fire exposures. The incorporation of a fire retardant into a polymeric composition will lower the thermal degradation temperature of the polymer (22). If the material is exposed to a flame in an environment of rapidly diminishing oxygen content, the fire-retardant material may burn more readily than the non-fire-retardant composition. Further studies using sensitive thermal analytical procedures have shown that incorporation of nonreactive low molecular weight retardants may lead to sublimation of the retardant prior to actual flame contact resulting in a material which also will burn more readily than the non-retarded material.

TOXIC EFFECTS FROM GASES AND THERMAL DEGRADATION PRODUCTS

Oxygen

In this case the important factor is the absence of oxygen rather than the release of oxygen due to fire or pyrolysis of polymeric materials. Complete lack of oxygen will lead to death within a few minutes and lesser concentrations of oxygen in the air than normally available will produce a number of signs and symptoms of hypoxia in persons exposed to that environment. Even if death does not occur due to the lower levels of oxygen in the immediate atmosphere, denial of sufficient oxygen to brain tissues for short periods of time will produce irreparable brain damage. Higher concentrations of oxygen, but still below that considered normal, will affect the brain cells in a reversible manner, but during this period the person will have behavioral changes which may produce faulty judgment leading to serious accidents and possible death and grave injuries to himself as well as to others. Table 6, shown earlier, presents estimates of the signs and symptoms due to oxygen deficiency.

Carbon Monoxide

Of all of the gases generated from the burning of a material (both natural and synthetic), the gas which produces the most deaths in real fire situations is carbon monoxide. The air we breathe has levels of carbon monoxide in parts per million; animals and man apparently can tolerate concentrations up to 100 ppm for short periods of time (up to eight hours) without undue harm. Fire conditions, however, can release large concentrations of CO in air and these levels can lead to death in very short periods of time. The main action of carbon monoxide after it is inhaled is to combine reversibly with hemoglobin (Hb) to form carboxyhemoglobin (CO-Hb). This reaction displaces oxygen in the blood and leads to apoxia and death if the reaction is not reversed. Carbon monoxide also interferes with oxygen release in the tissues but this appears to be of secondary importance as compared to combining with hemoglobin. Both animal and human studies have demonstrated that correlations can be made between signs and symptoms of toxicity and the per cent CO-Hb formed. Table 7 (23) summarizes this information and shows that concentrations below 10% produce no signs or symptoms. Most medical personnel and toxicologists agree that, in general, most persons will not show toxic symptoms below a level of 20% carboxyhemoglobin. From this level on, however, extremely toxic manifestations will occur and death will be imminent in concentrations of 60% or more. Henderson, *et al.* (24) reported on the physiological response to various concentrations of carbon monoxide. (See Table 8.)

In order to determine the relationship between the concentration of carbon monoxide in the air and the CO-Hb content, several investigators have exposed laboratory animals at various concentrations of carbon monoxide and measured the time required to reach a given blood level. Table 9 summarizes the work of Hofmann and Oettel (25) pertaining to the blood CO-Hb levels between rat and man.

It should be recongized (as illustrated in Table 9) that saturation curves for humans are not directly applicable to rats, because these animals inhale a larger volume of air per unit time in relation to their body weight and their blood can thus be more rapidly saturated with carbon monoxide.

Considerable differences in the reported lethal concentrations of carbon monoxide are found in the literature. This may be due in part to the animals used, the conditions of exposure, or the methods used to monitor the environment. For example, Kishitani (26) reported the lethal concentration of CO-Hb in mice to be approximately 40%. This is considerably lower than previous references mentioned in this paper.

Kishitani exposed mice, in groups of three, to concentrations of carbon monoxide ranging from 0.1 to 1.8% by volume of air. Exposure time was set at 15 minutes in order to correlate with safe evacuation times predicted for individuals trapped in real fire exposures. Electrocardiograms of the mice were recorded during the tests in order to determine the effect of carbon monoxide on the heart. Table 10 presents the relationship between CO-Hb concentration and the time of animal death at constant concentration. Table 11 presents similar information at rising concentrations of carbon monoxide. Autopsy observations showed the blood vessels colored a bright scarlet color typical of carbon monoxide poisoning. Delicate changes were noted in the electrocardiogram with the rise in carbon monoxide concentration. At high carbon monoxide concentrations, myocardial anoxia was recognized. Figure 9 presents the electrocardiograms taken of mice exposed at varying carbon monoxide concentrations.

In recent years, attention has been given to possible toxic effects of carbon monoxide at levels where signs and symptoms of toxicity are not noted, as for example, below 10% CO-Hb. Schulte (23) has explored this problem and has found that concentrations as low as 5% CO-Hb can affect certain psychomotor abilities. For example, in experiments with humans he noted that both the rate of errors and the time needed to complete an arithmetical chore would increase. He also employed other tests in his human experiments and came to the conclusion that low levels of carbon monoxide could have, and most likely do have, an effect upon judgment and situational decisions and responses. Some investigators have reported that certain cigarette smokers may at times show up to 10% carboxyhemoglobin in their blood, depending upon the number of cigarettes smoked and the manner in which they are smoked. Other figures, however, generally show a level of less than 5%.

If low concentrations of carbon monoxide can indeed affect decision making and other psychomotor responses this may provide a possible answer for the inability of victims to escape an area wherein they have been exposed to high concentrations of carbon monoxide.

Carbon monoxide has 300 times the affinity for hemoglobin than does oxygen. When carbon monoxide is included in inhaled air, the following reaction occurs in the lung cells:

$$O_2 \cdot Hb + CO \rightleftarrows CO \cdot Hb + O_2 \qquad (1)$$

Although this is a reversible reaction, as the affinity for carbon monoxide is stronger than for oxygen, oxygen hemoglobin ($O_2 \cdot Hb$) no longer can be formed. As the carboxyhemoglobin is formed, the hemoglobin loses its capacity to transport oxygen resulting in an oxygen shortage in tissues and organs. It should also be pointed out that there is strong belief by our medical personnel that a similar relationship exists between carbon monoxide and myoglobin (a molecule one quarter of the hemoglobin molecule) and thus, additional physiological effects may take place with regard to muscle activation and contraction, again limiting the ability of the victim to egress the fire area.

Consideration must also be given to methods which favor the rapid reversal of the concentration of carboxyhemoglobin in the blood. Einhorn, *et al.* (4), exposed laboratory animals exhibiting convulsions during the agonal episode, which is consistent with a cerebral hypoxia due to carbon monoxide poisoning, to pure oxygen. The convulsions ceased with a minute and the animals were grooming themselves within thirty minutes. Kishitani (26) exposed mice to fresh air after carbon monoxide exposure and observed a rapid return to normal carboxyhemoglobin levels (see Figure 10).

Further studies are necessary to determine if this reversal of carboxyhemoglobin content will persist when animals are exposed to a variety of toxic gases under temperature conditions approaching those experienced in actual fires. Present research carried out within the Flammability Research Center of The University of Utah also includes the study of several corticosteroids which may have the potentiality for enhancing the reversal of the carboxyhemoglobin to the desired oxyhemoglobin as well as possibly promoting anaerobic metabolism thus inhibiting long-term undesirable effects. The action of drugs is complicated by the fact that not only may tissue response be altered, but the rate of equilibrium of CO hemoglobin may be affected as well; for example, a sedative drug may depress respiratory rate so that the rate of increase of CO-Hb may be slow in comparision to the normal state. This could mean an increased survival time provided tissue response to a given CO-Hb level is unaltered. It should be pointed out that considerable additional work is required prior to commencement of human studies.

In studies of the influence of ambient carbon monoxide upon neuropsychological function in animals, it is customary to describe toxicity with respect to a specific behavioral measure. Alteration in function is then related to ambient carbon monoxide concentration or carboxyhemoglobin levels. Traditionally, studies have been directed at determining lethal levels of toxicity. Results were expressed as the time to death at a given carbon monoxide concentration. It is important to recognize that toxicity progresses in distinguishable steps. Also the rate of development of toxicity seems to be dependent upon many factors only one of which is ambient carbon monoxide. Thus, the time to development of a given level of toxicity is highly variable.

In present studies the level of toxicity is described in terms important to survival of the animal, e.g., its ability to escape from a noxious environment. It is the object of this study to describe the physiological status of the animal at selected stages of toxicity.

Definition of Levels of Toxicity

For the purpose of the present experiments, five levels of toxicity have been defined by members of The University of Utah's Flammability Research Center as follows:

Level 1 - Ataxia: Animal movements are unsteady and inaccurate; titubation of the head and trunk occurs. Grooming behavior loses precision of movement.

Level 2 - Loss of Survival Response: Rats conditioned to avoid a shock by bar pressing lose this response. The rat generally leaves the manipulandum and moves aimlessly about the chamber.

Level 3 - Loss of Postural Tonus: There is progressive loss of postural tonus until the rat is flattened out upon the floor of the chamber. When this level of toxicity is reached, electric shock will produce local limb withdrawal, but no movement to a different area of the chamber nor elevation of the body from the floor.

Level 4 - Anoxic Shock: There is no response to electric shock other than local muscle contraction. Respiratory rate drops to approximately half the resting level either consistently or in brief epochs of bradypnea. Cardiac arrhythmia is seen at this stage.

Level 5 - Death.

Experimental Protocol - Carbon Monoxide Studies

Adult male Sprague-Dawley rats were exposed to carbon monoxide in the air, ranging from concentrations as low as 500 parts per million to concentrations in excess of 3200 parts per million, in an especially constructed Plexiglas chamber equipped with shock grid floor and manipulandum for operant conditioning. CO was introduced through a micro-flow meter so that CO levels could be calibrated to various CO and air mixtures. Gas samples were taken from the center of the chamber and analysis was carried out by means of gas chromatography. Carbon monoxide concentrations were selected to allow specific levels of toxicity to develop over approximately one to one and a half hours.

Levels 2, 3, and 4 were investigated. Upon reaching a given level of toxicity, the rat was removed from the chamber and a sample of blood was obtained either by amputation of the tail tip or direct cardiac puncture. Modified procedures were used in the analysis of carboxyhemoglobin so as to permit multiple determinations.

Investigation of Level 2

The rats were conditioned daily in the exposure chamber for an avoidance response (CO was not introduced into the chamber during this conditioning period). Figure 11 illustrates the animal pressing the manipulandum in order to avoid electric shock. Shocks were presented at regular intervals of 10 seconds delivered through the floor grid. If the rat depressed the bar momentarily, the subsequent shock was not delivered until 20 seconds later. If the bar was maintained for a longer time in the depressed position, no shock was delivered until 20 seconds after the bar was returned to the normal position.

Using this conditioning schedule, it has been possible to train most rats in less than 20 minutes. It should be pointed out that all rats used in this study were males in order to avoid hormonal changes which in previous work has been shown to affect the animals' response to noxious gases. The rats were conditioned on five consecutive days before being tested for the survival response. After five sessions all rats were able to press the bar within one minute after entering the chamber.

The Survival Response Test Protocol

The rat was placed in the chamber and the CO was immediately turned on. During the first five minutes of exposure the animal received no shock. From t (time) = 5 minutes to t = 7 minutes the animal was subjected to a shock every ten seconds if not on the bar. If the bar was depressed, then no shock was delivered. From t = 7 to t = 10 minutes no shock was delivered. Then from t = 10 until t = 12 minutes the animal was again subjected to a shock every 10 seconds if not on the bar. The same alteration of 2-minute shocking periods and 3-minute free periods was continued throughout the experiment. As soon as the 2-minute shocking period elapsed during which the bar was not depressed at least once, the test was immediately terminated and the total elapsed time from the beginning of the experiment was termed "the time to loss of the survival response."

Using the above protocol, a group of eight rats was tested. During this test period the animals were exposed to concentrations of CO of 500 ± 50 ppm. At the altitude of the Flammability Research Center this concentration represents a partial pressure of carbon monoxide of 0.302 mm of mercury, mercury being Hg. For this pilot group of animals, the mean time from the beginning of the exposure until the loss of survival response was 32 minutes with a standard deviation of 10 minutes. After the pilot study was completed a few minor modifications were made to the chamber which slightly altered the rate of flow of gases through the chamber. A second group of eight rats was tested for the loss of survival response. As soon as the animal lost the survival response he was immediately removed from the chamber and two separate 20 microliter samples of blood were withdrawn from the tail for analysis. For this group of animals the mean time for loss of survival response was 47 minutes with a standard deviation of 20 minutes. This difference in time until loss of survival response implied that the altered rate of flow through the chamber had a great effect on the survival response. This could have resulted from an actual difference of velocity of air movement in the chamber; however, it is more likely that the concentration of CO in the chamber was a function of the velocity of air movement.

The survival response test as initially utilized had several important limitations. In every test conducted, the animal eventually left the bar and completely lost the conditioned response of depressing the bar, during one entire shock interval. But during many of the experiments, the rat would appear to be collapsed on the bar for a long period of time. In such a case it was impossible to determine whether the animal was on the bar in order to escape the shock or whether he was collapsed and was completely ignorant of an imminent shock. To correct the deficiencies of the initial chamber, several design features of the initial prototype exposure chamber were subsequently modified to permit a greater degree of sophistication in monitoring behavioral and physiological events during carbon monoxide exposure experiments. The modified chamber, with the animal positioned in a canvas sling, is illustrated in Figure 12. The animal is actually located within an inner chamber.

A second chamber was constructed around the first, which permitted the elimination of undesirable electrical interference during the telemetering of vital function response. This outer chamber also serves to isolate the subject from sources of extraneous noise.

An animal conditioning chamber was also designed and constructed, which permits a greater degree of sophistication than was possible previously. This conditioning chamber utilizes a strobe-light warning of impending electrical stimulus. The test subjects have been trained in avoidance response utilizing a hind-leg flexion response mechanism. Figure 13 illustrates the operational experimental set-up now in use. This avoidance response will be used to monitor the loss of survival responses during exposure studies.

The use of the sling restraining device, in the conditioning and exposure studies maintains the subject in a convenient position for determination of respiratory rate, EEG, EKG, peripheral nerve conduction velocity, reflex response latency, carboxyhemoglobin, body temperature and operant behavior. The animal exposure chamber was appropriately modified to contain the sling and necessary connecting ports for physiological monitoring. The new system provides an animal model for investigation of the effects of a variety of noxious gases and a number of factors affecting animal response, such as age, drug action, altered body temperature and repeated exposures.

It was necessary to develop analytical procedures for determining carboxyhemoglobin in small volumes of rat blood as well as to develop a method which permits withdrawal of blood aliquots during actual exposure.

A system has been developed for the removal of small quantities of arterial blood (400-600 microliters) for toxicological study. A polyethylene #10 tube is placed in the femoral artery and threaded to the level of the abdominal aorta. A 3-way stopcock, illustrated in Figure 14, attached to the other end is mounted on the cranium. Electrodes for recording EEG, EKG, etc., are also attached to this pedestal. The heparinized cannula runs from the pedestal on the cranium subcutaneously to the femoral artery. It is now possible to withdraw blood samples, illustrated in Figure 15, during chamber experiments, for a variety of determinations including carboxyhemoglobin, oxyhemoglobin, electrolytes, serum enzymes, and various intoxicants.

A description of the studies completed and in progress follows.

Cerebral Level Response

The conditioned avoidance response has been modified so that it can be determined with the animal in the sling. The rat's rear leg is affixed to a lever which stabilizes and controls the direction of leg flexion and to which a weight can be added to compel the rat to exert force when withdrawing the leg. A metal plate that activates a relay lies beneath the foot, which when touched delivers a shock to the rat's leg by means of a fine needle electrode inserted just beneath the skin of the leg. A strobe light provides a warning signal, which is followed in five seconds by a shock. The warning signal and shock are delivered every ten seconds for a period of one minute, with a one-minute rest period in between. Rats can be conditioned to avoid the shock in response to the warning light, that is receiving only one reminder shock, in two sessions of one hour each. The conditioning chamber, previously described, has been built for training rats, and the necessary response counters are in operation. This response is now defined as the "survival response," the loss of which defines Level 2. Modification of this response can include changing of the warning stimulus mode (sound, touch, etc.), and the amount of work required to accomplish the flexion response.

Six rats have been conditioned to avoid the shock with the new paradigm. These rats will be instrumented for determination of carboxyhemoglobin and physiological status as described below. The following experiments are being carried out on the conditioned animals:

1. Determination of carboxyhemoglobin and vital functions when the survival response is lost.

2. Determination of influence of having experienced a given level of intoxication upon the acquisistion rate of the survival response.

3. Determination of the loss of the learned survival response as a consequence of having experienced a given level of intoxication.

4. Determination of the alteration of nervous system function, such as peripheral nerve conduction velocity, spinal reflex activity and cortical activity which accompany loss of the operant response.

In summary, the above experiments examine conditions responsible for the acute loss of the survival response, as well as its loss or impaired acquisition as a late sequela of carbon monoxide exposure.

In previous experiments on eight rats, the loss of the survival response, measured as a failure to depress a bar to avoid a shock, occurred after 47 ± 20 minutes during exposure to 500 ppm carbon monoxide, which produced an approximate level of 50% carboxyhemoglobin. These data will undoubtedly require revision when the experiments applying the new model are complete, for the following reasons:

1. Exposure to carbon monoxide was probably not uniform between animals, because of varying flow rates of air in the chamber and differing carbon monoxide concentrations at various points in the chamber.

2. The technique for determination of carboxyhemoglobin was not adjusted to account for differences between rat and human hemoglobin. All of these problems have been solved by modification of the chamber, measurement of air flow in the chamber, use of the sling, and application of reliable technique for determination of rat carboxyhemoglobin in small volumes of blood.

Neuromuscular Level Response

Sensory and motor nerve conduction in the ventral caudal nerve has been determined *in vivo* in rats reaching Levels 3 and 4. Fine 26-gauge needle monopolar electrodes are used for stimulating and recording the evoked muscle or nerve action potential. Initial experiments determined the change in conduction velocities following exposure to Level 3. At Level 3, carboxyhemoglobin ranged from 60% to 80%. Control conduction velocity was 26-28 meters/second. Animals exposed to Level 3 have a greater than 20% decrease in conduction velocity within the first hour after exposure. In 50% of the animals, the nerve became unresponsive after the first hour. Conduction remained significantly decreased for 24-48 hours then tended toward normal, but remained erratic over the next four weeks. Sensory nerve conduction was most affected. An important observation of these experiments was the continued decrease in conduction following removal from the chamber. This effect is compatible with the observation that carbon monoxide migrates into muscles and other tissues from blood during hypovolemic shock (27). Animals exposed to Level 4 developed neuropathy similar to that seen at Level 3, but an additional effect is seen as well. Following the recovery period neuropathy may develop again as a late sequela.

Using the animal model, conduction velocity can be determined during the course of exposure to carbon monoxide. In a second series of experiments, conduction velocity is being followed through all levels to Level 4. The continued decrease in velocity following exposure to room air is again being seen. Follow-up studies are being done every week in conjunction with detailed pathological studies of the nerves and other tissues.

The essential observation of this experiment is that attainment of Level 4 is essential for the development of latent pathology. At this level conditions prevail which allow the "penetration" of carbon monoxide into tissues. Apparently metabolism is affected in such a manner that processes essential to cell function are impaired. The effect may involve cell nutrition, in which case action is primarily upon the blood vessels, or may involve nerve cell metabolism directly.

Pathologic Changes in Rats Exposed to Carbon Monoxide

Pathological Studies

Electron microscopy of the peripheral nerves have shown striking changes due to the effects of CO on rats. At Level 2 where the animal appears to lose his survival response, gross and light microscopic pathological studies of brain, spinal cord, peripheral nerves and internal organs of animals sacrificed immediately after removal from the chamber have shown no differences from control animals.

Level 3 is the level of motor collapse or loss of postural tonus. Ten of the rats at this level were studied grossly and by light microscopy 30 days after exposure. Brain, spinal cord, organs and peripheral nerves showed no differences from control animals. However, with the electron microscope, slight changes were seen in peripheral nerves. Some myelinated fibers had increased neurofilaments and some myelin degeneration, but most were normal. Moderate numbers of unmyelinated fibers showed loss of microtubules and clumping of neurofilaments. There did not appear to be any marked loss of nerve fibers or increase in collagen, though fibroblasts appeared activated when compared with control nerves. The anterior horn cells of the spinal cord showed no axonal chromatolysis or increased satellitosis.

In Level 4, the level of anoxic shock, all animals lost their ventral caudal nerve conduction. If the animals survived, ventral caudal nerve conduction returned completely, and then after several days disappeared again. These findings suggested a delayed peripheral neuropathy such as has been reported in man. Since the delayed central nervous system lesions are demyelinative in character, it might have been expected that the peripheral nerve changes would be primarily demyelinative. However, this has not been borne out by our electron microscopic studies. Seven animals were studied 30 days after exposure. The brain and other organs showed no differences from control animals grossly or with light microscopy, except for evidence of a possible period of congestive heart failure. Hemosiderin-laden macrophages were present in lungs and spleen. Some animals showed axonal chromatolysis of some small anterior horn cells but no increased satellitosis. The only lesions seen in peripheral nerves with light microscopy were an increase in mast cells and some areas of vacuolated myelin. No decrease in axons or myelin sheaths was evident.

With the electron microscope the damage to the peripheral nerve was seen primarily in the axon and Schwann cell with apparent secondary changes in the myelin. There was no evidence of typical Wallerian degeneration or segmental demyelination. The lesions seemed closest to those described in the dying-back neuropathies, where changes take place in longest axons first, and the process beings distally. In our animals, some myelinated and some unmyelinated axons remained normal. There was no apparent decrease in myelinated or unmyelinated axonal numbers or increase in collagen, although fibroblasts appeared activated. Many myelinated axons showed a marked increase in neurofilaments with a relative decrease in microtubules and the appearance of double-membraned structures, which appeared to arise from the Schwann cells as shown in Figure 16. Some myelinated sheaths appeared hypertrophied and rolled in, a stage that appeared to precede degeneration of myelin with uncovering of the axon as noted in Figure 17.

Unmyelinated fibers developed irregular shapes and showed increased microtubules and neurofilaments (Figure 18) or, more rarely, loss of microtubules and clumping of neurofilaments as seen in Figure 19. Schwann cells showed dilated endoplasmic reticulum in their cytoplasm often whether the axon and myelin were normal or not as observed in Figure 20.

The dying-back neuropathy is usually thought to be due to injury to the axon's cell body, causing a decrease in production of metabolites necessary for axonal action. They may also be due to a decrease in axonal flow or some primary injury to the axon, causing decreased catabolism of waste products and abnormalities of axonal function. However, Schwann cells appeared to be affected by CO, as evidenced by their dilated endoplasmic reticulum. Although they are sometimes thought to be active only in the production of myelin, they may also play a role in nourishing the axon. In electron micrographs of longitudinal sections of axons, changes were seen at the nodes of Ranvier. These changes increased in animals at Level 3 to Level 4 and consisted of constriction and outpouching axoplasm at the node of Ranvier, narrowing of the nodes of Ranvier, and an increase of neurofilaments in axons beyond the node of Ranvier, as seen in Figure 21. Some defect in Schwann cell nutrition of the axon may account for the changes seen in the ultrastructure of the nerve and its function.

These pathologic studies of rats exposed primarily to the anoxic shock level of CO will be continued and extended. Animals exposed to this level will be studied approximately one, two, three, and over four weeks after exposure. Light microscopy of all organs, the brain and peripheral nerves will be done. Electron microscopic studies of peripheral nerves will be continued. Muscle, anterior horn cells, dorsal root ganglia and heart muscle will also be studied by electron microscopy. When possible we will study the cytochrome oxidase, succinic dehydrogenase, lactic acid dehydrogenase and NADH levels of muscle, anterior horn cells, and dorsal root ganglia in exposed animals immediately sacrificed versus control animals. Methods used will be semi-quantitative.

Carbon Dioxide

All fires will produce some levels of carbon dioxide which, in turn, may be inhaled by those in the vicinity of a fire. Since O_2 is an important constituent of the body process, CO_2 is not considered as a toxic agent at normal concentration. Inhalation of carbon dioxide will, however, stimulate respiration which, in turn, will increase inhalation of possible toxic components from the combustion and noncombustion gases present from the fire. It is not correct to assume, however, that toxic signs and symptoms will not occur in man. For example, inhaling of CO_2 in concentrations of 10 per cent have caused in segments of test groups headaches and dizziness, as well as other symptoms. Higher concentrations (above 20 per cent) can lead to narcosis in animals and in most people.

Sulfur Dioxide (28)

Certain natural materials, as well as man-made materials such as natural and synthetic rubbers, may have sufficient sulfur content to generate sulfur dioxide directly or indirectly when the materials are exposed to heat and fire. This gas (SO_2) is a pungent, heavy gas and is extremely toxic to animals and humans. The threshold limit value (TLV) is given as 5 ppm.* Sulfur dioxide, in contact with water (moisture), will form sulfuric acid which, in turn, produces the extremely irritant response when the gas has contact with skin. Mucous membranes, in particular in the respiratory tract and in the eye, are highly susceptible to the irritant effects. Exposure to high concentrations of the gas lead to death most likely because of asphyxiation (blockage of air transport in the upper respiratory tract). Chronic exposure to sulfure dioxide appears to have greater toxic effects upon those having cardiorespiratory diseases than those not suffering with these ailments. Epidemiologic studies have also led to suggestions that a cause-effect relationship may exist for the high incidence of death during episodes of smog.

Hydrogen Cyanide

Hydrogen cyanide is produced in varying concentrations from many nitrogen-containing organic compounds during pyrolysis or combustion. Since hydrogen cyanide is a highly endothermic compound, its concentration will increase as the temperature of combustion rises.

Cyanide reacts with Fe^{III} of the cytochrome oxidase in the body, thus preventing the utilization of oxygen by the tissue (blocking of intracellular oxygen transport).

Concentrations above 20 ppm in the air are considered as dangerous to health. Initial inhalation of the vapors of HCN will cause a reflex stimulation of breathing which in turn will lead to greater concentrations of the gas entering the body. The cause of death is paralysis of the respiratory center of the brain. Table 12 (29) presents a summary of symptoms in humans in relation to the HCN concentrations in the air.

Hydrogen Chloride

Degradation of polyvinyl chloride produces as one of its major degradation products hydrogen chloride. On combining with water, hydrogen chloride forms hydrochloric acid. This compound will cause destructive damage to mucous membranes. If inhaled, the upper respiratory

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*Threshold Limit Value (TLV) - concentration of a compound in the air which if exceeded may cause toxic signs and symptoms. The concentration is a weighted average over an eight-hour period of exposure.

tract will be severely damaged and this may lead to asphyxiation and death. Tables 13 and 14 (29) present a summary of the toxicological effects of HCl to humans and animals.

Aliphatic Hydrocarbon (28)

Thermodegradation of all organic polymers will produce a variety of aliphatic compounds having a range of molecular weights. The lower molecular weight compounds will produce narcosis in animals and man but as the series is ascended, the biological activity will decrease. With certain polymers there may be present unsaturated hydrocarbons when the polymer is degraded and these compounds will generally have a greater toxic effect than the saturated compound. In these mixtures there may also be present acids, alcohols, and aldehydes, each contributing a toxic property. Table 15 presents a summary of the maximum allowable concentrations of common aliphatic hydrocarbons.

Aromatic Hydrocarbons (28)

These compounds, starting with benzene and leading to other aromatic structures, will have both irritating properties, as well as systemic toxicity. As the structure of the aromatic molecule is altered, the toxicity may be increased or decreased. Several of these aromatic compounds, such as benzene, will be absorbed not only by inhalation, but by absorption through the skin. Levels of 100 ppm and above are considered dangerous to health. Styrene is a degradation product of polystyrene and is considered as safe in concentrations below 100 ppm. Levels above 100 ppm can produce irritation to mucous membranes, symptoms of toxicity and impairment of neurological functions.

Acrolein, Formaldehyde, Acetaldehyde, Butyraldehyde

Acrolein, formaldehyde, acetaldehyde, and butyraldehyde are examples of low-molecular-weight compounds which are commonly found in the smoke from pyrolysis or combustion of plastic materials. Acrolein is a three-carbon compound possessing the chemical formula CH_2CHCHO. This compound, due to its extreme lachrymatory effect, serves as its own warning agent. It affects particularly the membranes of the eyes and respiratory tract. The maximum allowable concentration is 0.1 ppm. Table 16 (17) presents the concentration of acrolein and other toxic aldehydes found in the smoke released during the combustion of several common materials.

Zikria (17), in a recent paper, pointed out that carbon monoxide alone cannot account for the pulmonary edema, tracheobronchial and pulmonary parenchymal damage resulting from smoke poisoning. He exposed dogs to standardized smokes of wood and kerosene, without heat, in a smoke chamber. The animals exposed to kerosene smoke did not have any pulmonary edema, tracheobronchial or parenchymal damage, and all survived. On the other hand, the animals exposed to wood smoke did develop pulmonary edema and tracheobronchial and parenchymal damage, causing 50% of the test animals to die within 1-3 days after exposure.

Deichmann and Gerarde (30) reported that acrolein in a concentration of 5.5 ppm has been shown to cause irritation of the upper respiratory tract; at higher concentrations, pulmonary edema occurs; and at concentrations of 10 ppm, death occurs within a few minutes. Sim and Pattle (31) subjected human volunteers to acrolein. They reported that inhalation of acrolein causes lacrimation and irritation of all exposed mucous membranes at concentrations of as little as 0.805 ppm.

Synergistic Effects During Fire Exposure

Recent investigations by personnel of the Applied Physics Laboratory, Johns Hopkins University and the Flammability Research Center of The University of Utah, have determined that a strong synergistic effect may occur as the result of inhalation of the products of combustion of natural and synthetic materials by an individual under the influence of alcohol. Approximately 85% of those fire deaths involving cigarettes and mattresses or upholstered furniture have been traced to individuals who fell asleep while smoking and under the influence of alcohol. Laboratory analysis of the blood of these victims indicates that the carbon monoxide saturation is typically below 40% when the individual has a blood alcohol level of 0.15% or greater. Several cases have been studied where blood alcohol levels exceeding 0.4 volume percent were measured. In all of these cases the carboxyhemoglobin saturation was less than 25%. Reconstruction of the fire scene as well as information gathered during test burns of selected mattresses and upholstered furniture in room and corridor tests have indicated that a period of 3 to 5 hours is required before the onset of flaming ignition. However, inasmuch as the victim falls asleep and the ignition source, the cigarette, is permitted to come in contact with the surface on which the individual is sleeping, the victim is then subjected to a highly localized concentration of carbon monoxide and other toxic or noxious gases during the smoldering period before the onset of flaming combustion.

SUMMARY AND CONCLUSIONS

A critical analysis of the effects of smoke on the survival response during fires involving natural and synthetic materials has been carried out by personnel of the Flammability Research Center of The University of Utah. Smoke may, in several ways, directly affect the survival response. If smoke is hot, it may interact with the mucosa and cause rapid death. If smoke resulting from pyrolysis, oxidative degradation, or flaming combustion of natural and synthetic materials is permitted to cool, the results of particulates, particulate size, the nature of the particulates or aerosols and gases found in smoke may lead to periods of acute toxicity resulting in death. Severe injury may result from moderate exposure to the products of combustion found in smoke. To date, the major emphasis by researchers in the field of fire retardation has been directed toward the development of systems which have a greater tendency to resist ignition and flame propagation. Incorporation of halogen, phosphorus, boron, antimony and other elemental constituents into these natural and synthetic materials may greatly enhance the flammability characteristics mentioned above. Little consideration has been given to date to possible adverse effects which may result from the incorporation of chemical fire retardants with regard to the increase in noxious and toxic products of degradation accompanied by an exponential increase in smoke.

Virtually all of the test procedures which have been promulgated during the past decade to evaluate the smoking tendency of materials do not provide a measure of how much material is needed to produce a given quantity of smoke under specified conditions within a given period of time. Recent developments carried out at the Flammability Research Center of The University of Utah have provided for the incorporation of a transducerized weighing device which permits simultaneous monitoring of weight loss and measurement of specific optical density. The information gained through the use of this equipment is being utilized in the development of a hazard index for rating smoke. This index considers specific optical density divided by weight loss over a period of time. Using this technique, it should be possible to obtain an accurate rating of the obscurating effect of smoke produced during pyrolysis, oxidative degradation and flaming combustion. The present studies utilize a radiant heat source capable of providing 1.5 to 15 watts per square centimeter. This is sufficient to reproduce the temperatures encountered during stoichiometric burning in air of virtually all materials commonly used in confined spaces such as buildings, transportation vehicles, mobile homes, etc. A second index is being developed which will monitor the lacrimation effect caused by such degradation products as acrolein and other short-chain aldehydes or several of the acids commonly found as degradation products of natural and synthetic materials. When these two indices are further developed, it should be possible to promulgate a standard which, using this information, will rate not only the obscurating effects of smoke, but also the physiological and toxicological effects of smoke produced during fire exposure.

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TABLE 1

SUMMARY OF MAJOR FIRES IN WHICH SMOKE AND TOXIC GASES WERE ATTRIBUTED TO BE A PREDOMINANT FACTOR CAUSING LOSS OF LIFE

Year	Place	Deaths
1929	Cleveland Clinic	125
1942	Cocoanut Grove Night Club (Boston, Mass.)	492
1963	Nursing Home (Fitchville, Ohio)	63
1965	727 Aircraft Crash (Salt Lake City, Utah)	43
1970	Harmar House Nursing Home (Marietta, Ohio)	22
1972	Sunshine Mine Disaster	92
1973	Isle of Mann Resort	50

TABLE 2

FACTORS AFFECTING LIFE SUPPORT IN FIRES

1. Reduction of oxygen concentration accompanied by increase in the concentration of carbon monoxide.
2. Development of extremely high temperatures.
3. Presence of smoke.
4. Direct consumption by the fire.
5. The presence of noxious or toxic gases.
6. The development of fear.

TABLE 3

BURN MORTALITY - NEW YORK CITY 1966 AND 1967

	Total Cases (Survival Time)		Autopsied Cases (311)	
Post-Burn Survival Time	Cases	%	Cases	%
<12 hours	283	53	185	60
>12 hours	158	30	72	23
Not known	93	17	54	17
Total	534	100	311	100

TABLE 4

RESPIRATORY TRACT COMPLICATIONS IN 257 AUTOPSIED CASES

	Post-Burn Survival Time (<12 Hours)		Post-Burn Survival Time (>12 Hours)	
	Cases	%	Cases	%
Smoke Poisoning and/or Asphyxia only	99	53.5	4	5.6
Respiratory Tract Damage and/or Pulmonary Damage only	11	5.9	28	38.9
Both	20	10.8	1	1.4
Neither	55	29.9	39	54.1
Total	185	100.0	72	100.0

TABLE 5

CARBON MONOXIDE POISONING IN 185 AUTOPSIED CASES, WITH DEATH OCCURRING UNDER 12 HOURS

	Carboxyhemoglobin Saturation	Cases	%
Laboratory Determination		(130)	(70.3)
Usually lethal	>50%	45	24.3
Significant	11% - 49%	64	34.6
No contribution	7% - 10%	21	11.4
Clinical Diagnosis only		14	7.6
No indication		41	22.1
Total		185	100.0

TABLE 6

SIGNS AND SYMPTOMS OF TOXICITY OF REDUCED LEVELS OF OXYGEN DUE TO FIRE CONDITIONS

% of Oxygen in Air	Signs and Symptoms
20% (or above)	Normal
12% to 15%	Muscular coordination for skilled movements lost
10% to 14%	Consciousness continues but judgment is faulty and muscular effort leads to rapid fatigue
6% to 8%	Collapse occurs quickly but rapid treatment would prevent fatal outcome
6% (or below)	Death occurs in 6 to 8 minutes

TABLE 7

SIGNS AND SYMPTOMS AT VARIOUS CONCENTRATIONS OF CARBOXYHEMOGLOBIN

% CO-Hb	Signs and Symptoms
0% to 10%	No signs or symptoms
10% to 20%	Tightness across forehead, possible slight headache, dilation of the cutaneous blood vessels
20% to 30%	Headache and throbbing in the temples
30% to 40%	Severe headache, weakness, dizziness, dimness of vision, nausea, vomiting, and collapse
40% to 50%	Same as above, greater possibility of collapse; syncope and increased pulse and respiratory rates
50% to 60%	Syncope, increased respiratory and pulse rates, coma, intermittent convulsions, and Cheyne-Stokes respiration
60% to 70%	Coma, intermittent convulsions, depressed heart action and respiratory rate, and possible death
70% to 80%	Death in less than an hour
90% +	Death within a few minutes

TABLE 8

PHYSIOLOGICAL RESPONSE TO VARIOUS CONCENTRATIONS OF CARBON MONOXIDE

Response	CO in Air	
	PPM by Vol.	Vol. %
Concentration allowable for an exposure of several hours	100	0.01
Concentration inhaled for 1 hour without appreciable effect	400 - 500	0.04 - 0.05
Concentration causing just appreciable effects after 1 hour of exposure	600 - 700	0.06 - 0.07
Concentration causing unpleasant but not dangerous symptoms after 1 hour	1000 - 1200	0.10 - 0.12
Dangerous concentrations for exposure for 1 hour	1500 - 2000	0.15 - 0.2
Concentration fatal in exposures of less than 1 hour	4000 and above	0.4 and above

TABLE 9

SPECIES DIFFERENCES WITH REGARD TO CO-Hb CONCENTRATION IN BLOOD

CO Concentration PPM	Rat		Man	
	20% CO-Hb	50% CO-Hb	20% CO-Hb	50% CO-Hb
10,000	in minutes	in minutes	in minutes	in minutes
5,000	in minutes	in minutes	in minutes	in minutes
2,000	in minutes	15 minutes	20 minutes	60 minutes
1,000	15 minutes	240 minutes	60 minutes	300 minutes
500	30 minutes	-	90 minutes	-
250	90 minutes	-	360 minutes	-

NOTE: Negative sign indicates 50% level not reached. Rats will die at 70% CO-Hb concentration within 30 minutes.

TABLE 10
CARBON MONOXIDE HEMOGLOBIN CONCENTRATION AND TIME OF DEATH (AT CONSTANT CONCENTRATION)

CO Concentration (%)	Mouse	CO-Hb (%)	Time of Death* (min.sec.)
0.1	A	5.0	L
	B	0.0	L
	C	6.5	L
0.2	A	18.0	L
	B	23.5	L
	C	--	L
0.3	A	30.0	L
	B	25.0	L
	C	27.0	L
0.4	A	35.0	L
	B	29.5	L
	C	32.0	L
0.5	A	29.5	L
	B	31.5	L
	C	31.0	L
0.6	A	42.0	5'00"
	B	40.5	L
	C	43.5	9'00"
0.7	A	45.5	L
	B	46.0	12'00"
	C	36.0	L
0.8	A	24.0	4'30"
	B	50.0	L
	C	35.0	L
0.9	A	43.5	L
	B	52.5	7'00"
	C	44.0	L
1.0	A	48.0	8'30"
	B	48.5	5'30"
	C	--	11'15"
1.1	A	51.5	5'00"
	B	45.5	L
	C	40.0	2'45"
1.2	A	42.0	L
	B	41.0	10'20"
	C	42.5	2'00"
1.3	A	36.0	L
	B	41.5	L
	C	38.0	L
1.4	A	40.0	4'00"
	B	41.0	3'00"
	C	39.0	4'00"
1.6	A	52.5	3'30"
	B	27.0	L
	C	49.5	3'30"
1.8	A	34.0	1'45"
	B	48.5	2'45"
	C	49.0	3'45"

*L: Living after 3 days.

TABLE 11

CARBON MONOXIDE HEMOGLOBIN CONCENTRATION AND TIME OF DEATH (AT RISING CONCENTRATION)

Conditions of Rising Concentration [Value of α at $C=\{1-\exp(-vt/V)\}$]	Mouse	CO-Hb (%)	Time of Death (min.sec.)
0.1	A	10.5	L*
	B	1.0	L
	C	0.0	L
0.2	A	1.0	L
	B	1.0	L
	C	19.0	L
0.3	A	6.0	L
	B	11.5	L
	C	13.5	L
0.4	A	--	L
	B	--	L
	C	--	L
0.5	A	21.0	L
	B	26.0	L
	C	29.0	L
0.6	A	25.5	L
	B	26.5	L
	C	22.0	L
0.8	A	27.5	L
	B	20.0	L
	C	24.0	L
1.2	A	37.0	L
	B	32.5	L
	C	30.0	L
1.4	A	27.5	L
	B	32.5	L
	C	26.5	L
1.6	A	34.5	L
	B	34.0	L
	C	27.5	L
1.8	A	30.0	10'30"
	B	33.0	15'00"
	C	33.5	10'30"
2.0	A	35.0	12'30"
	B	34.5	15'00"
	C	34.5	12'00"
2.2	A	36.5	12'00"
	B	37.0	8'00"
	C	34.0	12'00"

*L: Living after 3 days.

TABLE 12

RELATION OF HYDROGEN CYANIDE CONCENTRATION IN AIR AND SYMPTOMS OF HUMANS

HCN Concentration (ppm)	Symptoms
0.2 - 5.0	Threshold of odor
10	(TLV - MAC)
18 - 36	Slight symptoms (headache) after several hours
45 - 54	Tolerated for 1/2 to 1 hour without difficulty
100	Death - 1 hour
110 - 135	Fatal 1/2 to 1 hour
181	Fatal after 10 minutes
280	Immediately fatal

TABLE 13

INHALATION EFFECTS OF HYDROGEN CHLORIDE ON HUMANS

Hydrogen Chloride Concentration in Air (ppm)	Symptoms
1 - 5	Limit of odor
5 - 10	Mild irritation of mucous membranes
35	Irritation of throat on short exposure
50 - 100	Barely tolerable
1,000	Danger of lung edema after short exposure

TABLE 14
INHALATION TOXICITY OF HYDROGEN CHLORIDE ON ANIMALS

Hydrogen Chloride Concentration in Air (ppm)	Species	Effects
50	Monkeys	Tolerable for 6 hours daily
300	Guinea pigs	Mild corneal damage after 6 hours
3,200	Mice	No mortality after 5 minutes
4,300	Rabbits	Lung edema, death after 30 minutes
13,745	Mice	LD_{50} - 5 minutes
30,000	Rats	No mortality - 5 minutes
41,000	Rats	LD_{50} - 5 minutes

TABLE 15
MAXIMUM ALLOWABLE CONCENTRATIONS OF COMMON ALIPHATIC HYDROCARBONS

Compound	MAC (ppm)
Propane	1,000
Butane	1,000
Hexane	500
Heptane	500
Octane	500
1,3 Butadiene	1,000

TABLE 16
SMOKE ANALYSIS OF SEVERAL COMMON MATERIALS (Concentration ppm Vol./Volume)

Toxic Compound	Wood	Kerosene	Cotton	M.A.C.*
Acrolein	50	< 1	60	0.1
Formaldehyde	80	<10	70	5.0
Acetaldehyde	200	60	120	200
Butyraldehyde	100	< 1	7	Not Tested

*Industrial maximum allowable concentration.

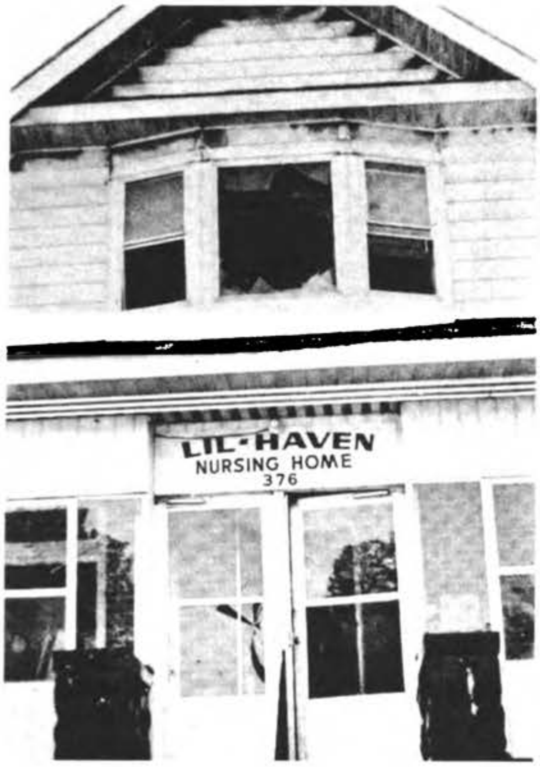

FIGURE 1. Exterior front view of the Lil-Haven Nursing Home after fire.

FIGURE 2. Exterior side view of the Lil-Haven Nursing Home after fire.

FIGURE 3. Burned exterior of hollow-core wood panel door.

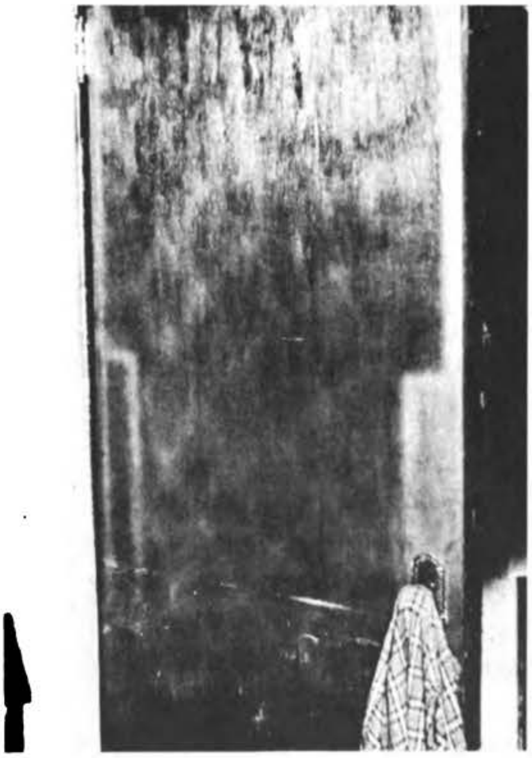

FIGURE 4. Interior view of hollow-core wood panel door.

FIGURE 5. Typical smoke and soot pattern north second story bedroom.

FIGURE 6. Typical smoke and soot pattern south second story bedroom.

FIGURE 7a. Victim on floor near bed.

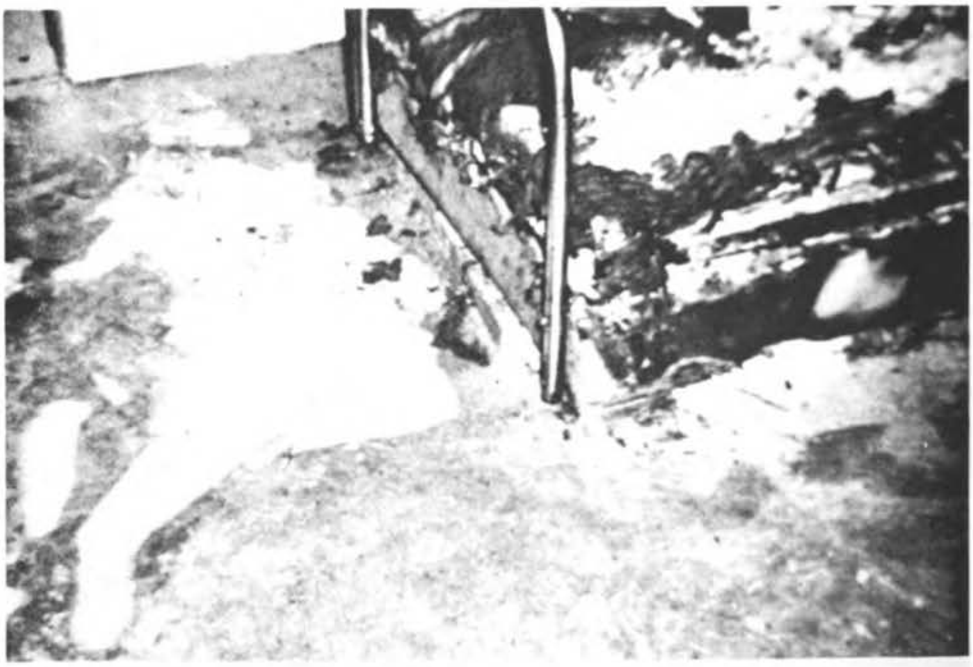

FIGURE 7b. Body pattern on floor indicating death prior to conflagration.

FIGURE 7. Victim of mattress fire.

FIGURE 8. Heat-stress apparatus.

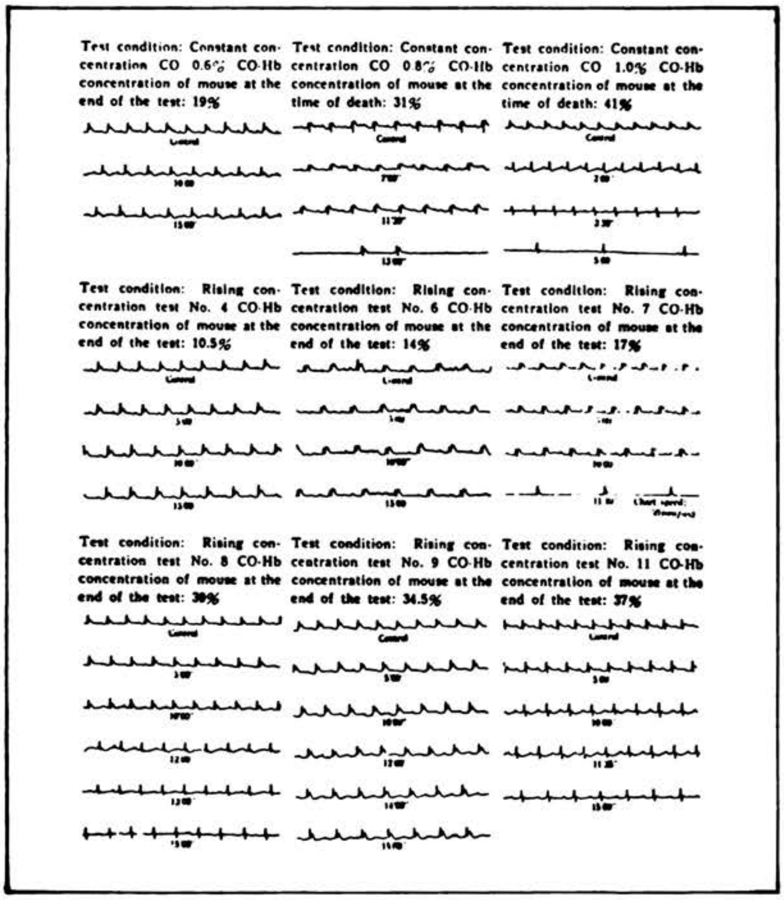

FIGURE 9. Mouse electrocardiograms during CO-exposure studies.

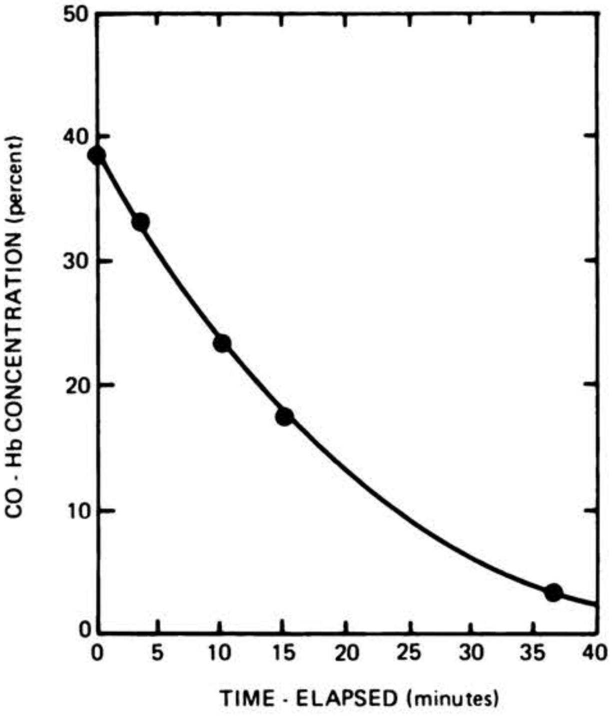

FIGURE 10. Reduction of carboxyhemoglobin during air exposure treatment.

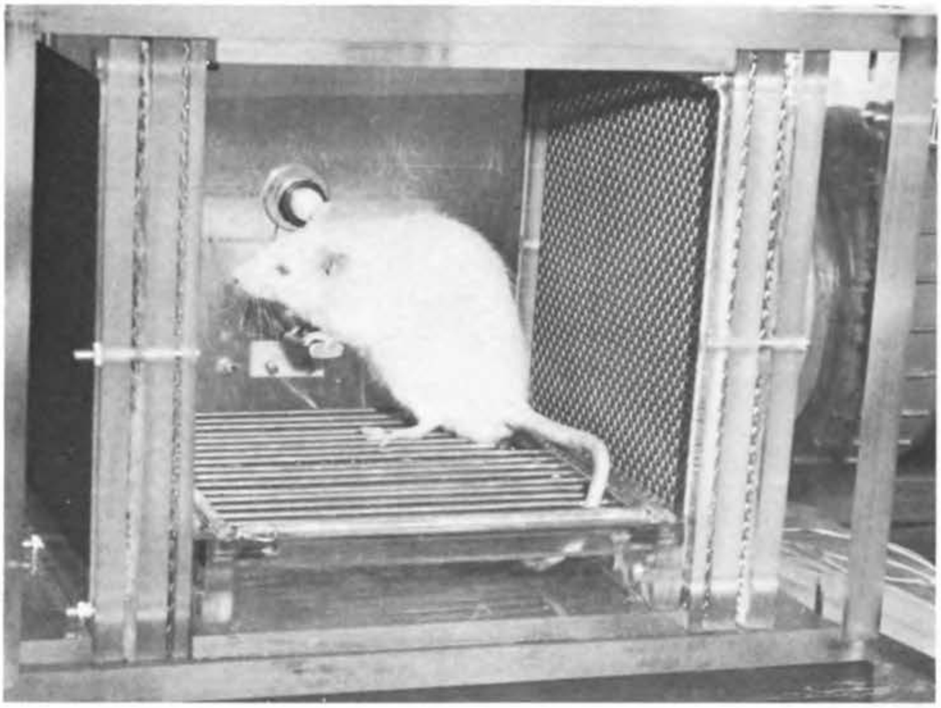

FIGURE 11. Conditioned response during exposure studies.

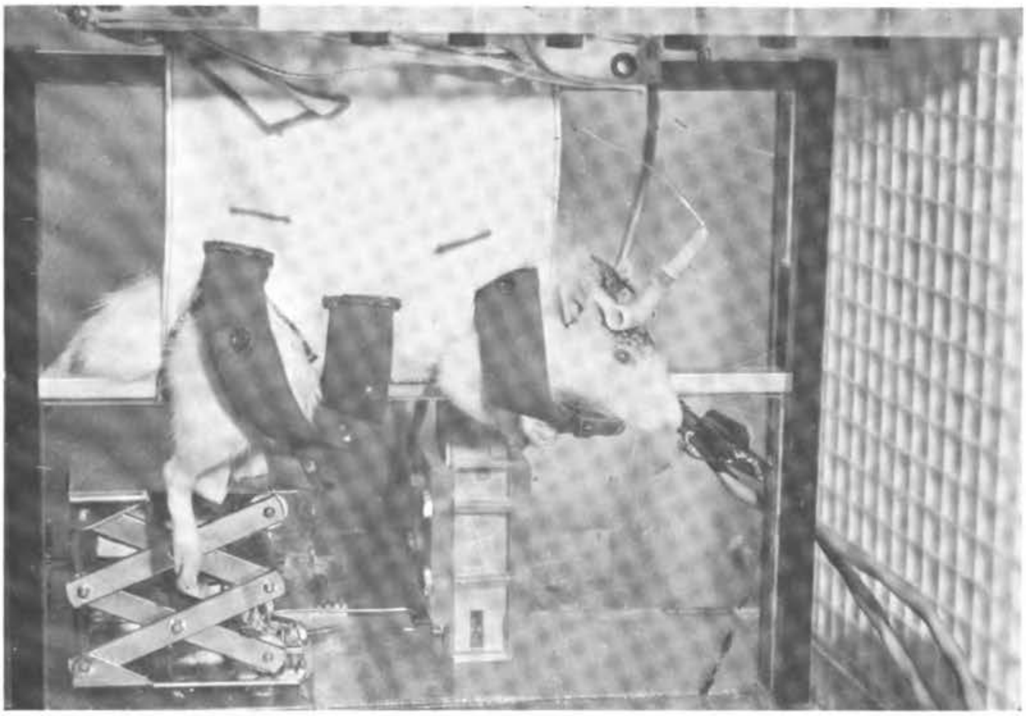

FIGURE 12. Animal sling restrainer.

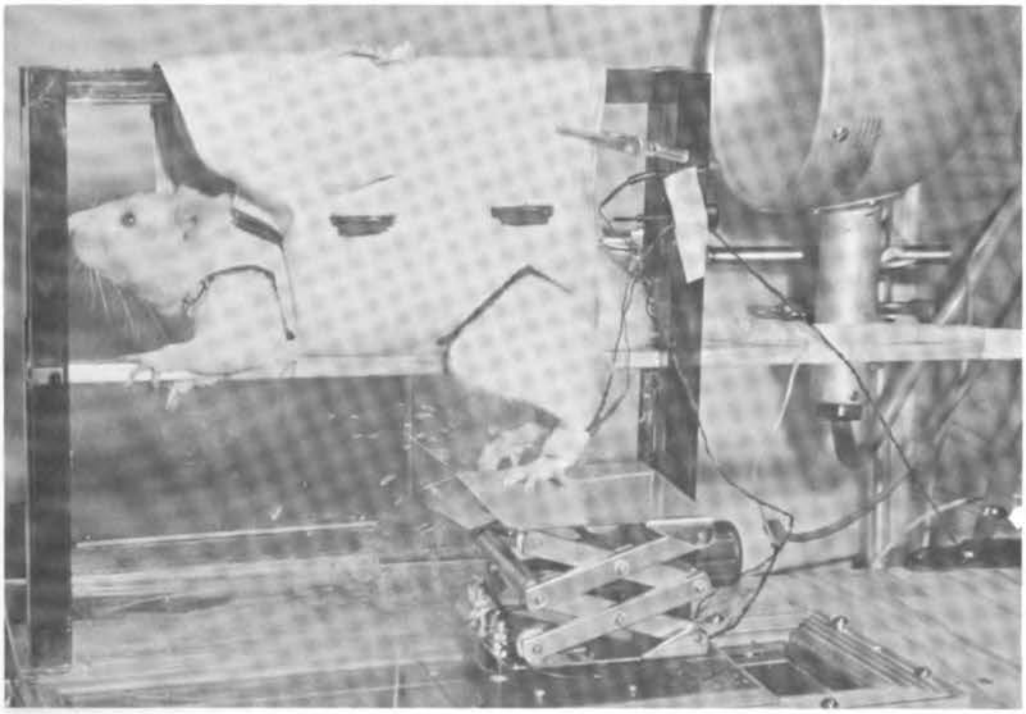

FIGURE 13. Experimental set-up for animal conditioning chamber.

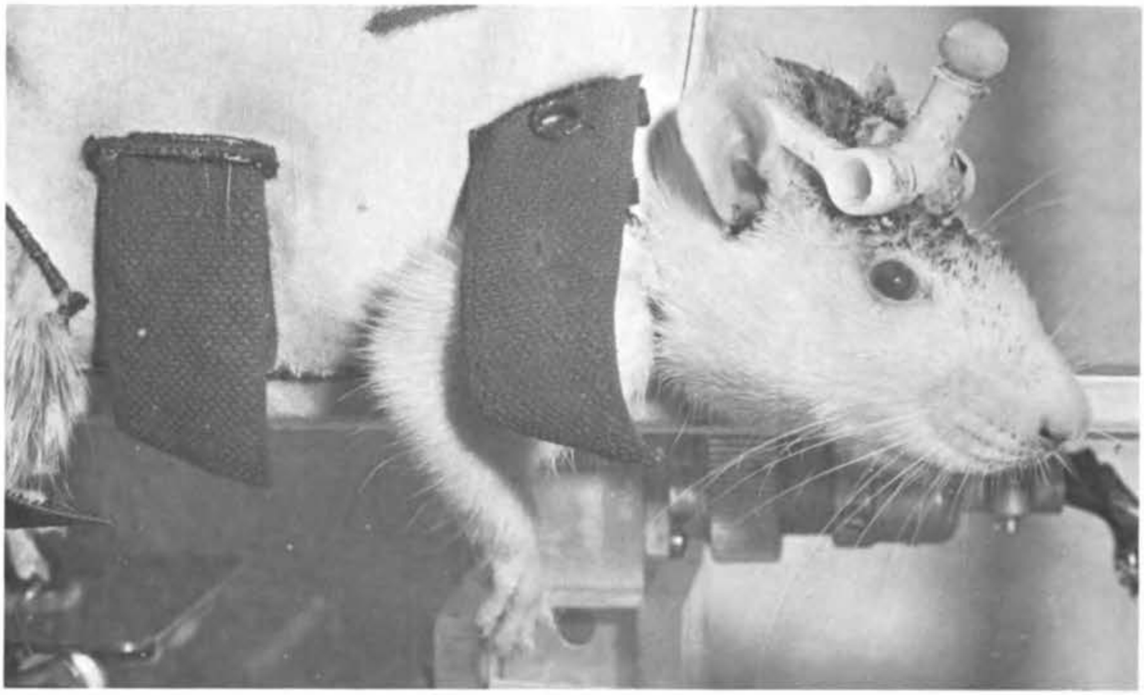

FIGURE 14. Set-up for toxicological studies.

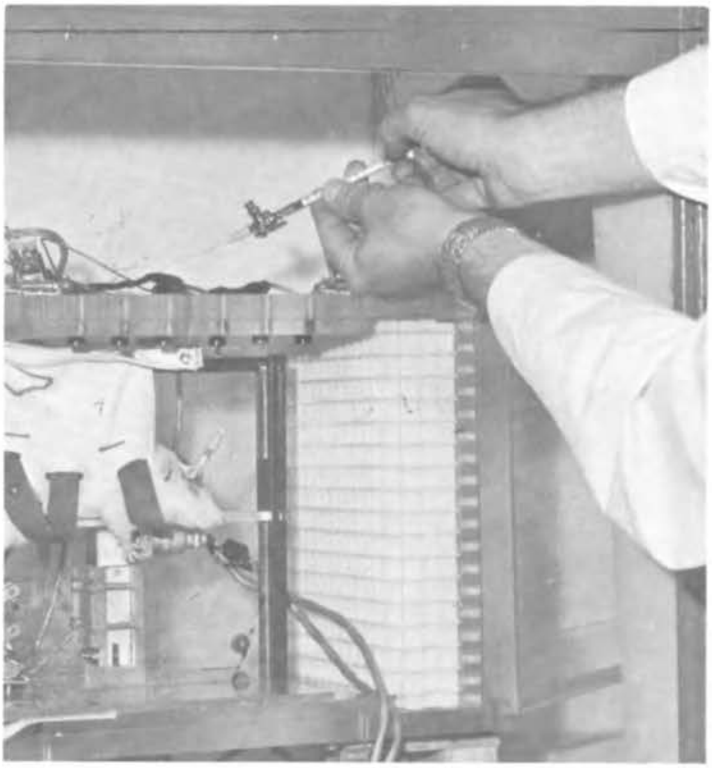

FIGURE 15. Withdrawal of blood samples.

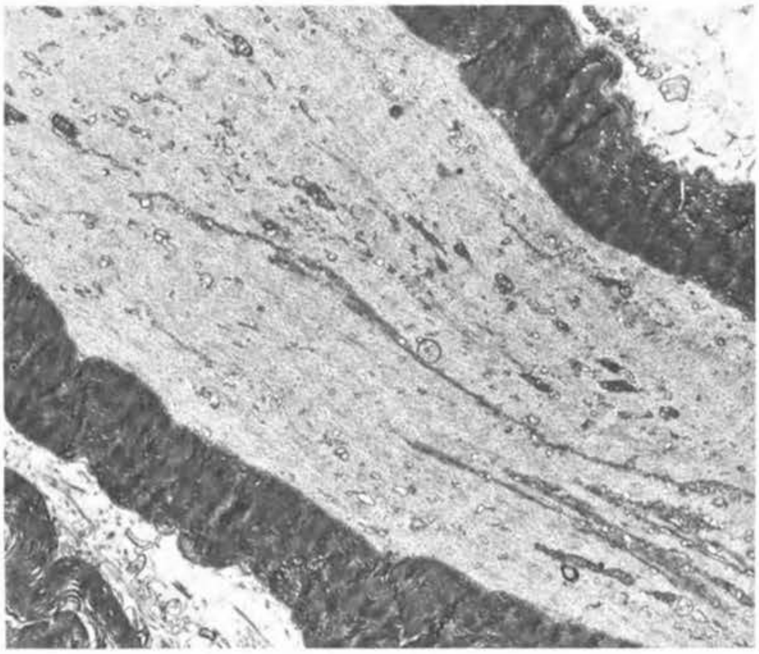

FIGURE 16. A longitudinal section of the peroneal nerve of a rat exposed to the anoxic shock level 30 days prior to sacrifice. (Note the marked increase in neurofilaments and appearance of double membraned cytoplasmic bodies.) X 6000.

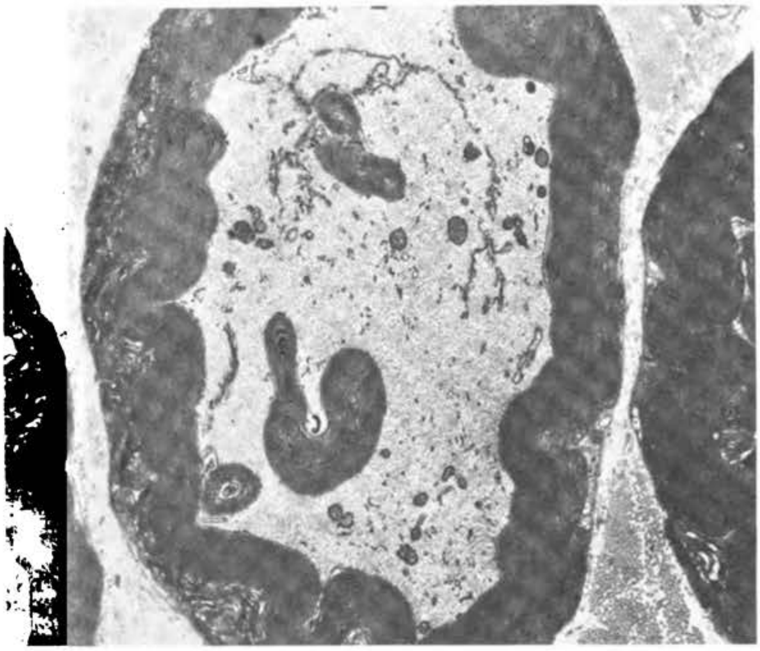

FIGURE 17. A cross section of the peroneal nerve of a rat exposed to anoxic shock level 30 days prior to sacrifice. (Note the thickening and rolling in of the myelin sheath.) X 6000.

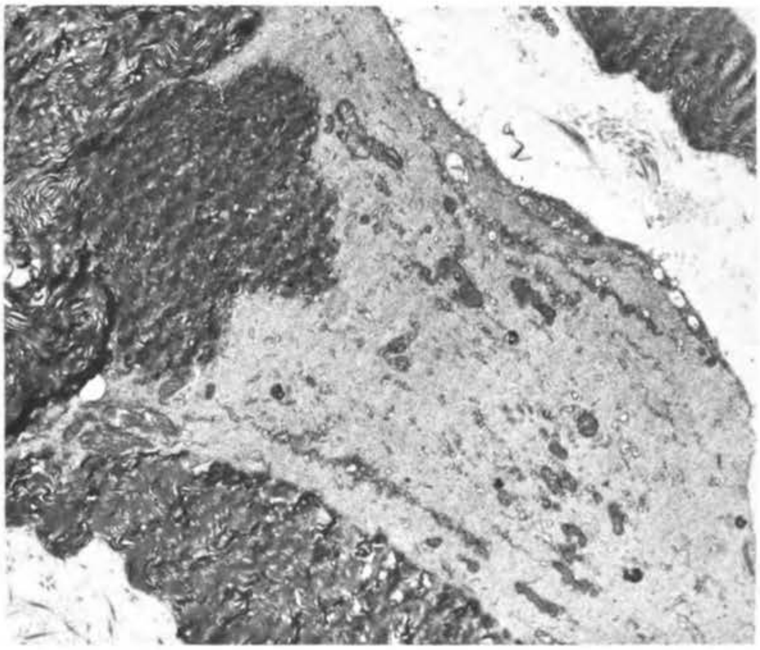

FIGURE 18. A longitudinal section of the peroneal nerve of a rat exposed to the anoxic shock level 30 days prior to sacrifice. (Note the degeneration of myelin and uncovering of the axon.) X 6000.

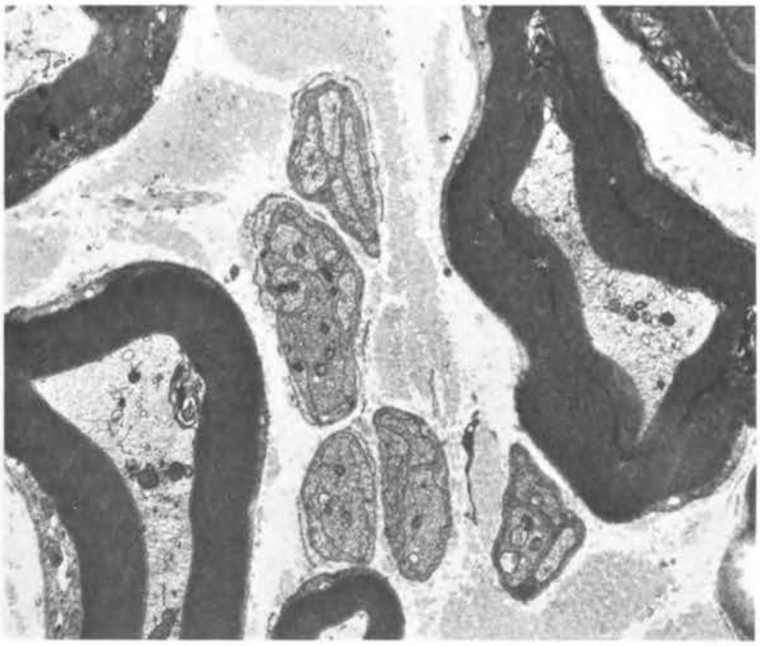

FIGURE 19. A cross section through a group of myelinated and unmyelinated fibers from the ventral caudal nerve of a rat exposed to the anoxic shock level 30 days prior to sacrifice. (Note the abnormalities of shape of unmyelinated fibers and the increased numbers of microtubules in some fibers.) X 6000.

FIGURE 20. A cross section of a peripheral nerve fiber of a rat exposed to the anoxic shock level 30 days prior to sacrifice. (Note the marked dilatation of the endoplasmic reticulum of the Schwann cell and the thickening of the myelin sheath of the nerve fiber.) X 6000.

FIGURE 21. A longitudinal section of a node of Ranvier in the ventral caudal nerve of a rat exposed to the anoxic shock level 30 days prior to sacrifice. (Note the construction of the node and the axoplasm of the node plus the outpouching of axoplasm toward the Schwann cell basement membrane with collection of intracellular vesicles and the increase in neurofilaments past the node.) X 6000.

LABORATORY TESTING FOR GASEOUS AND PARTICULATE POLLUTANTS FROM FOREST AND AGRICULTURAL FUELS

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and

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Introduction

Fire has long been used as the most practical means of ridding various agricultural lands of the unwanted debris of crop production; in many cases it was an important management tool for control of insect pests and plant diseases. More recently, forest managers have used fire increasingly as a management tool for the several purposes of fuel reduction, planting site preparation, and wildlife and watershed management which will be discussed in the several papers in this symposium.

As the result of the expansion of urban communities into rural areas, these fires and the resultant smoke have received great attention from those concerned with the quality of the atmosphere. Thus, to place such burning in proper perspective in relation to other sources, it is necessary to determine the kinds of amounts of gaseous and particulate emissions in terms of the amounts of material burned. One approach is to monitor laboratory-type small-scale fires. The purpose of this report is to describe such a laboratory approach to determine emission factors, how emissions might be minimized by modifying burning practices, and results of preliminary studies on the size and morphology of the particles in smoke.

Facilities

Experimental procedures for burning fuels and sampling emissions are carried out in an out-of-doors burning tower and adjacent instrument building which has been described by Darley, *et al.*(3). Some important modifications have been made as noted below. The facility simulates open burning but channels the combustion products so that representative samples of gas and particles can be taken.

The tower is in the form of an inverted funnel, 16 feet in diameter at the base, decreasing to 28 inches in a length of 20 feet, and topped with a stack 8 feet in length. The tower is erected above a table 8 feet in diameter, which is positioned on a scale with a maximum capacity of 125 pounds. The sample site for gases, particulate, and for recording temperature and airflow is in the stack about two feet from the top. Stack gases for analysis of total hydrocarbon, CO, CO_2, and oxygen are drawn through sample lines into the approriate analyzers in the instrument building to give a continuous millivolt equivalent recording of concentrations. Taps on the gas sampling system lead to bottles which may be used to grab samples at any desired point during a fire. These samples are subsequently analyzed for individual hydrocarbons and oxides of nitrogen. Airflow is monitored with a 4-cup anemometer mounted in the stack. A shaft encoder is positioned on the end of the anemometer shaft, just outside of the stack. The encoder generates a millivolt signal by making and breaking a light beam through an 800-slot disc. One revolution of the shaft creates 800 pulses, and 3000 pulses per second generates the full-scale 50 mv signal. The maximum airflow encountered during the peak of the hottest fires is between 40-45 mv, or approximately 10,000 cubic feet per minute. A transducer was adapted to the actuating mechanism of the scale so that a change in weight generated a millivolt signal; 1 mv is equivalent to 1 pound and full range is 50 mv.

All recording instruments are connected to a data acquisition system, which in turn is connected to the campus computer. The computer polls each recorder every 2.6 seconds and stores the millivolt response of each instrument on tape or discs. A computer program has been written from which the yield of pollutants in pounds per ton of fuel burned can be calculated using the data collected on temperature, gas concentration, and airflow.

Particulates are collected isokinetically on standard Type A glass fiber filters held in either one or two modified HIVOL samplers positioned in series in the sample line and outside of the tower. The purpose of the two filters will be discussed below. The approximately 1-inch diameter particulate sampling orifice in the stack is one of a pair of piezometer rings, the exhaust side of which is connected to the sample line through the filter holders. The sample air flows sequentially into the sampling orifice and through the filter, a pneumatically controlled globe valve, and a constant speed exhaust blower. The exhaust of the second piezometer ring is open to the atmosphere. The static pressure plenum of each ring is connected with appropriate tubing to a pneumatic controller located in the instrument building. The pneumatic controller senses any pressure difference between the piezometer rings resulting from airflow rate differences through the rings, and tries to equalize the pressure (and thus the airflow), by opening the globe valve. In a typical fire, the blower is turned on prior to ignition. Since there is no flow up the stack, and thus no pressure difference between the piezometer rings, the controller is already balanced and the globe valve remains closed. As heat generates an airflow through the stack and the open-ended piezometer ring, a pressure difference develops which immediately causes the controller to open the globe valve until the pressure is equalized. This, of course, is a continuous response and isokinetic sampling is achieved. The sample volume is approximately 0.13% of the total flow through the stack.

Special attention has been given to particulate collection because this is the pollutant that is most obvious to the public and is of the most concern to public officials. The principal use made of the isokinetic collection system has been to determine the total weight of particulate from given fuels to establish emission factors. Until recently, these factors have been based on one filter holder placed in the line about four feet downstream from the sample site. In this arrangement, efficiency of a single filter paper was determined by placing two filters back-to-back and noting that the second filter had no color and that all of the particulate appeared to be held up by the first paper; the second paper was not weighed. It was suggested that the emission factor from this system might be too low because the filter site is at a higher temperature than ambient, and gases have not yet cooled down by the time they reach the filter. Thus some of the condensible materials that might eventually appear as particles, would not yet have condensed; a second filter holder sufficiently downstream to be at ambient temperature would collect these particles.

In response to this suggestion, the filter system has been modified recently without altering the isokinetic aspects. The first filter has been enclosed in a laboratory-type drying oven so that if desired its collection temperature can be maintained approximately equivalent to that of the sample site. With the heat off and the oven door open, the filter functions as in the past. A second filter holder has been installed in series downstream from the first at a distance to assure that its collection temperature is nearly ambient. Considerable evaluation of the two-filter system is required, but results to date indicate that when filter papers are placed in each holder, the second filter collects about 25-30% additional particulate. That these materials passed through the filter paper in the first holder as gases was indicated by again placing two filter papers back-to-back in the first holder and a single paper in the second holder. The second paper of the back-to-back pair was free of any color, although it had a very slight gain in weight. The single paper in the second holder was very dark and its gain in weight was about 25% of the particulate collected on the first paper of the back-to-back set.

Calibration of Airflows

Calibration of the anemometer to give cubic feet per revolution (cfr) was first done with the vertical discharge from a large squirrel cage blower set at table level. A range of airflow rates was achieved by damping the blower intake. This was a so-called cold calibration in that it did not simulate airflow characteristics at the higher temperatures experienced during fires. The method gave erratic responses at very low and very high airflows, but an average was established at 50 cfr. The isokinetic sampler was calculated to give 0.14% of the total flow based on the ratio of the cross-sectional area of the stack to that of the sampling orifice. More recently, a "hot" calibration system has been used employing a four-foot diameter, three-concentric-ring, multi-jet propane burner that rested on the burning table. By varying the propane flow, airflows through the stack could be established at several steady-state levels that covered the range of flows resulting from a fire. Factors which affected the density of the air (temperature, humidity, and pressure) were taken into account in making calculations of air volume. The results of these tests established that the airflow rate was still 50 cfr, but the smoothness of the operation throughout the full range was greatly improved. Furthermore, it was interesting to note that when several agricultural fires were compared with the calibration data, the rates of airflow through the stack at given temperatures were essentially the same. By using a gas meter in the isokinetic line, the calibration was established at 0.13% of the total flow, a slight change from the theoretical value used earlier.

Fuel Arrangement and Burning Techniques

With many agricultural fuels, the wastes generated at the end of each growing season are generally loosely arranged on the ground, either from the harvesting process itself or from subsequent spreading, raking, or piling. It is thus less critical as to how such fuels are collected and arranged on the burning table except to duplicate the range in fuel size and weight per unit area that one finds with a given crop. The same general conditions apply for forest fuels that are cut and piled. Some fuels, however, such as sugar cane, standing asparagus fern, and the forest floor cover, should be placed on the table to duplicate as nearly as possible the arrangement occurring in the field. For the former example, appropriate racks provide for standing the fuel on the table in a reasonable facsimile of field conditions. For the latter example, shallow hardware cloth trays are used into which blocks of undisturbed needles and duff are lifted. The trays are then set into the spot vacated by the fuel and allowed to remain for several months so the blocks of plant material will reknit. The trays are then brought to the tower in an undisturbed condition; fire across the surface consumes fuel components in the same order it would on the forest floor.

Fuel moisture is an important factor governing pollutant emissions. Samples of fuel are taken just before ingition and oven dried to constant weight at 105°C. For fuels that are received green and/or fairly moist, fires are run at appropriate intervals as the fuel dries naturally. Where higher moisture levels are to be studied with fuels that are received dry, calculated amounts of water are sprayed on the fuel contained in a large plastic bag. The bag is sealed and the contents allowed to come to equilibrium.

The simplest fire situation is to place a given weight of fuel (5-50 pounds, depending on bulk density) either in a pile and ignite from the top or along the edge, or to spread it uniformly in a rectangle four by six feet and ignite along one four-foot edge. This is a "batch" type fire as compared to the steady-state fire system noted below. A small propane torch is used for ignition. Prior to ignition filters are placed in the holders and all gas analayzers and other instrumentation are turned on. The analyzers record the background levels and indicate completion of the fire when concentrations again return to background. Weather conditions, ambient temperature, and relative humidity are recorded.

Two principal variations from the above procedures are either to simulate head and back firing by placing a given weight of fuel on an inclined plane, or to establish steady-state burning conditions on a horizontal plane.

For "batch" type head and back firing on a slope, methods suggested by the staff at the U.S. Forest Service Fire Laboratory at Macon, Georgia were used. Fuel is placed in a shallow four by eight-foot hardware cloth tray lined with asbestos sheeting. The tray is set on a rack of the same dimensions which has adjustable legs so that the slope of the fuel bed can be varied from 0 to 50%. The rack sets directly on the table and the scale is adjusted to account for tray and rack tare so that only the initial weight of the fuel and its subsequent rate of weight loss are recorded.

A number of trays similar to those above but measuring four feet square are used for the steady-state fires. An easily dismountable angle iron track of sufficient length to extend about five feet beyond the opposite lower edges of the tower can be set a little above the table. The track is equipped with rollers to facilitate easy movement of the trays. As trays are loaded with a uniform density of fuel, they are placed end-to-end on the track, and adjacent trays are coupled with a metal clip. The fuel is joined so that the flame will move uninterrupted from tray to tray. The leading edge of the train of trays is rolled to an appropriate position under the tower (not necessarily the center) and ignited. The train is then rolled manually at such speed as to keep the flame zone in the area at which ignition took place. Rate of movement per four foot tray is timed to give an estimated rate of weight loss since the table and scale cannot be used in the steady-state procedure. As burned-out trays reach the far side of the tower, the fuel may have stopped smoldering if the rate of flame advance is slow. In such cases, the tray can be removed from the track, the ashes emptied, and the tray taken to the other end of the track and reloaded to keep the continuous bed going. If, on the other hand, the tray is still smoldering, it is set on a platform under the tower and to one side of the table until smoldering ceases so as to assure that all of the effluent is sampled. In order to simulate head and back firing in steady-state fires equipment is presently being developed that will provide winds up to seven miles per hour along the axis of tray movement. Since the fuel bed is moved, the flame zone will be stationary at a given distance from the wind source. Moving the fuel bed into the wind will create a head fire, and moving with the wind will create a back fire.

Pollutant Emissions

A great number of individual "batch" type fires have been conducted using a variety of agricultural fuels and some forest fuels. Over the course of several years, during which modifications in facilities, sampling procedures, and firing techniques have occurred, almost all of the fires have been monitored for hydrocarbon and carbon monoxide (CO) emissions. Many have been run since the isokinetic sampler was installed, and special attention has been given recently to comparing head and back fires at several moisture levels.

The results to date indicate that hydrocarbon yields from fairly dry fuels burned flat may vary from 4 to 18 pounds per ton of fuel burned; the average is about 14 pounds (1,3). Carbon monoxide yields vary from 40 to 140 pounds and average about 92 pounds.

Prior to installing the isokinetic sampler, particulate matter from several grass fires was determined from a small glass fiber filter that is installed as a cleaning device in the gas sample line (1). The yield averaged about 16 pounds per ton of fuel burned. Particulate yields from a variety of relatively dry fuels using only the first filter as described earlier, have varied from 4 to 17 pounds.

Sandberg, *et al.* (6) constructed a series of fires in the tower using ponderosa pine fuel in flat beds to simulate logging slash. Moisture of the various components varied from 3 to 14% on a dry weight basis. Some of the fuel beds were treated with the flame retardant diammonium phosphate. Emission of hydrocarbons, CO, and particulate were 8.4, 146, and 9.1 pounds per ton of fuel, respectively. Yields from treated beds increased to 11.7, 166, and 19.3 pounds respectively, indicating a doubling of the particulate matter.

Air dry loblolly pine needles sent to Riverside from Georgia were burned in the sloping trays to compare head and back firing. Only particulate was monitored during these fires. The yield from head fires varied from 53 to 69 pounds per ton of fuel whereas back fires yielded 15 pounds, confirming field observations that back fires are cleaner than head fires.

Rice straw at varying fuel moistures has recently been burned on the sloping trays to compare head and back firing and some trends are apparent. Back fires produce less particulate than do head fires. Further, whereas particulate yield increased with fuel moisture content in both types of fires, the rate of increase from back fires was not as great as from head fires. Back fire particulate emissions appeared to level off at about 23 pounds per ton above 25% moisture (dry basis), while head fires yielded about 40 pounds at the same moisture and more than 70 pounds at 67% moisture. Below 14% moisture, yields from both types of fires were between 6 and 10 pounds per ton of fuel burned.

At the moisture range of 10 to 43%, hydrocarbon emissions from head and back fires were essentially the same and varied from about 5 pounds per ton at the lowest moisture to between 20 and 30 pounds at the highest moisture. Carbon monoxide varied from 100 to 300 pounds in the same moisture range but the rate of increase appeared to be a little greater from back fires than from head fires; it is not yet known if this is a significant trend. From these results to date, it is apparent that all three pollutant emissions are reduced as the fuel becomes drier, but that the influence of head versus back fires is not as evident with hydrocarbons and CO as it is with particulates.

Particle Size Distribution and Morphology

Investigation of particle size distribution and morphology was begun recently and some preliminary results are of interest. Size distribution was determined with the Brink five-stage cascade impactor and the Weathermeasure cascade impactor.* Morphology was examined with light and scanning electron microscopy.

With cascade impactors, particles are sized by their aerodynamic size rather than their geometric size. The method accounts for the three major aerodynamic factors of size, shape, and mass density. With the Brink, calculation of particle size distributions was based on the generalized calibration curve determined by Ranz and Wong (5). The characteristic diameter for each stage of the impactor was calculated following Brink's calculation (2). For the Weathermeasure, particle cut-off sizes for each stage are determined by calculations based on the theory developed by Marple (4). With this impactor, correction was made for a 50 cfm flow and for both impactors a mass density of 0.9 g/cc was selected as a reasonable approximation.

Because the Brink impactor uses relatively low sample flow rates (3000 ml per minute), it was difficult to obtain adequate samples during the short burning period of "batch" fires. Reliable samples were obtained from nearly steady-state fires by hand-feeding the fuel at a uniform rate over a 20-minute period onto an existing fire. This was done prior to developing the steady-state fuel bed system described earlier.

A specially designed glass cyclone precedes the Brink impactor and a nuclepore membrane filter follows the last stage to provide an additional cut point. The complete apparatus is mounted in a temperature controlled box as described by Brink (2). Rather than use the sample cups as collecting surface, the bottom of the cup of each stage was lined with a pre-weighed aluminum foil disc held in place with a retention ring. This modification reduced the ratio between the weight of the collector and the weight of particles collected and also provided a medium for direct mounting on the specimen holder of the electron microscope. The aluminum foil had been washed previously with $MeCl_2$/acetone, dried in an oven, and held in a dessicator prior to weighing.

In an experiment to determine the particles' size distribution of smoke from a given fuel, and at the same time to determine the nature of

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*Use of brand names does not constitute an endorsement of the product either by the University of California, the U.S. Environmental Protection Agency, or the California Air Resources Board.

the particles that condensed after passing through the first filter holder of the isokinetic particulate sampling system, the sample port of the Brink was placed in the isokinetic line just above the second holder. The temperature of the impactor was held at 90°F, which was ambient at the time. For one test, no filter was placed in the first holder so that all particle sizes at ambient collection temperature were available to the impactor; this was designated as a pre-filter sample. In a second test, a filter was placed in the first holder so that the Brink was sampling particles that had condensed after passing the first filter; this was designated as the post-filter sample and would indicate the nature of the particles collected by the second filter holder. The particle size distribution of smoke collected under these conditions is plotted in Figure 1.

The pre-filter curve indicates that approximately 85% of the particles were less than 1 µm and that about 50% were less than 0.5 µm. The post-filter curve shows that there were no particles above about 0.7 µm and represent materials that condensed after passing through the first filter.

Light microscope photomicrographs of particles collected on the second stage of the Brink in the pre- and post-filter samples of the citrus fires are shown in Figure 3. The large dark clusters of particles in the pre-filter sample probably represent the soot component in the smoke. These clusters appear to be an agglomeration of smaller particles and to have a spongy structure. Most of the single particles are transparent, yellowish brown in color and may be the tar fraction. There are a few greyish angular particles of various sizes which may represent ash. In the post-filter sample, the large clusters are missing, having been removed by the filter in the first holder. Most of the particles are of the transparent, yellowish-brown tar fraction which passed the first filter and condensed as liquid aerosols.

Scanning electron microscope photomicrographs of two collection stages of the pre-filter sample are shown in Figure 4. The same aluminum disc from stage 2 of the impactor as shown in Figure 3 was used in making the upper photograph. The large clusters appear more clearly to consist of a spongy substance unlike the individual rounded and angular small particles. A comparison of the light and SEM micrographs also indicates that there is no significant alteration in the morphology of particles from the vacuum imposed in the SEM column. The lower micrograph in Figure 4 shows particles collected on the nuclepore membrane filter which followed the last stage of the impactor. These are all below 0.4 µm and represent 52 mass % of the particles collected. Many particles are in the 0.1 µm range and appear to agglomerate somewhat.

The Weathermeasure impactor is somewhat easier to use with the tower because the flow rate is high enough to obtain adequate samples in a short time. As was done with the Brink, the normal collection surface (slotted glass fiber filters) in each of the five stages was replaced with slotted aluminum foil of exactly the same dimensions. The foil was washed and dried as noted above. The last stage was followed with a nuclepore membrane filter. A suitable sample probe was attached to the impactor and of such length to assure that collection was made at ambient temperatures. The probe was inserted into the stack at about the same position as the sampling orifice of the isokinetic system. Particle size distribution of smoke from head fires of rice straw and sugar cane leaves at 20% moisture are plotted in Figure 2. More than 90% of the particles from both species were less than 0.5 µm and the slope of the curve of the two is not too different.

Acknowledgments

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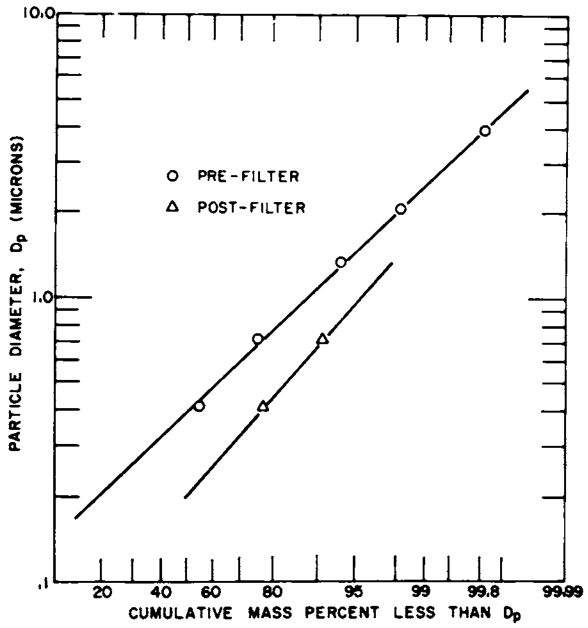

FIGURE 1. Cumulative particle size distribution of smoke from burning citrus prunings. Particles collected with the Brink five-stage cascade impactor with the sample site downstream from the first filter holder in the isokinetic system (see text). Pre-filter--no filter in the holder. Post-filter--filter placed in the holder.

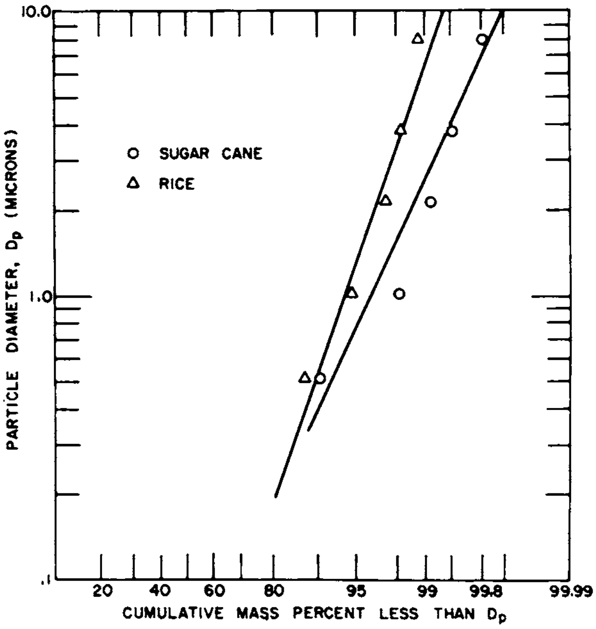

FIGURE 2. Cumulative particle size distribution of smoke from head fires of rice straw and sugar cane leaves at 20% moisture. Particles collected with the Weathermeasure HIVOL cascade impactor.

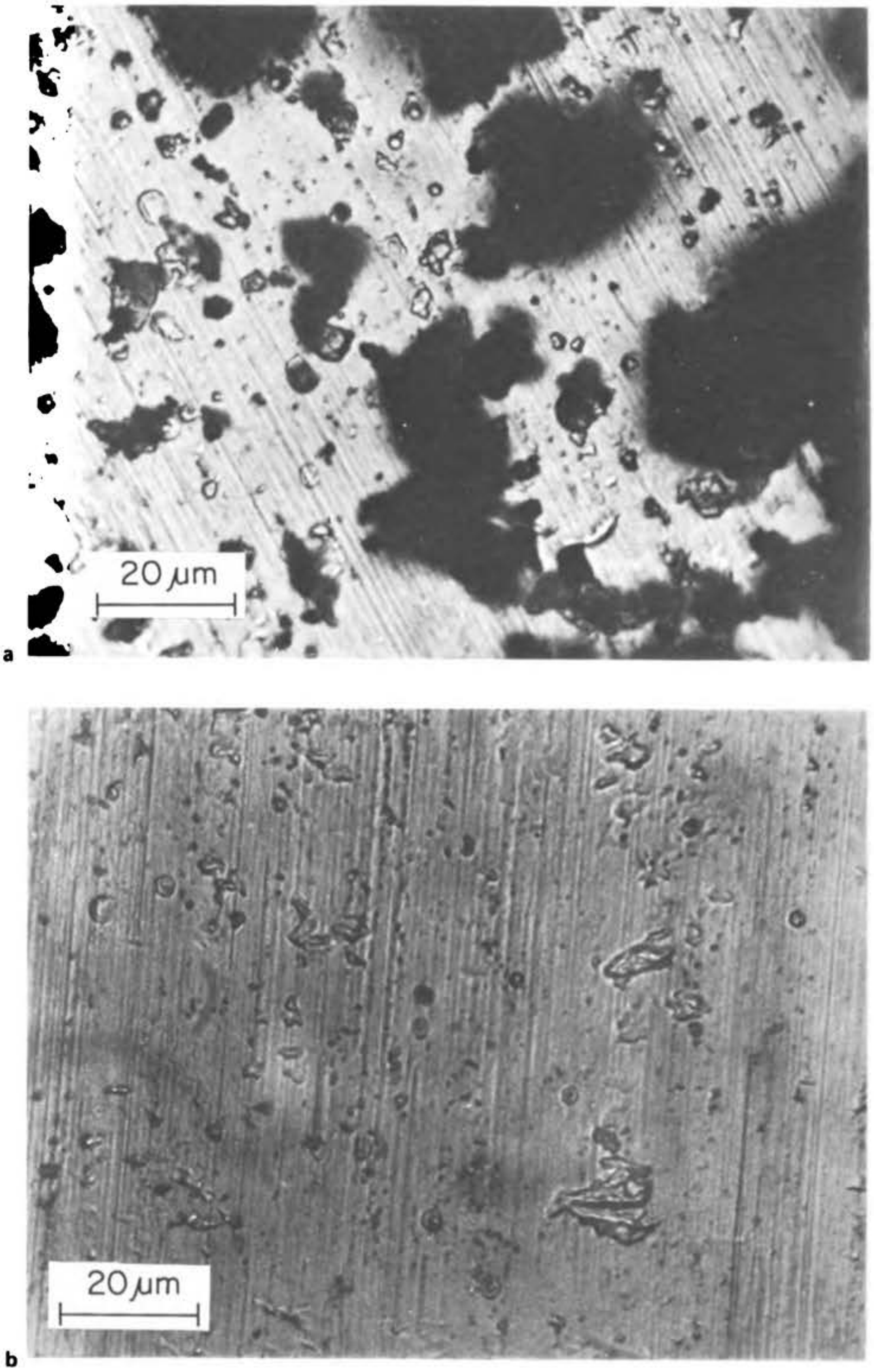

FIGURE 3. Light microscope photomicrographs of particles collected on aluminum foil disc in the second stage of the Brink cascade impactor. 400x. A) The pre-filter sample, and B) The post-filter sample, from burning citrus prunings.

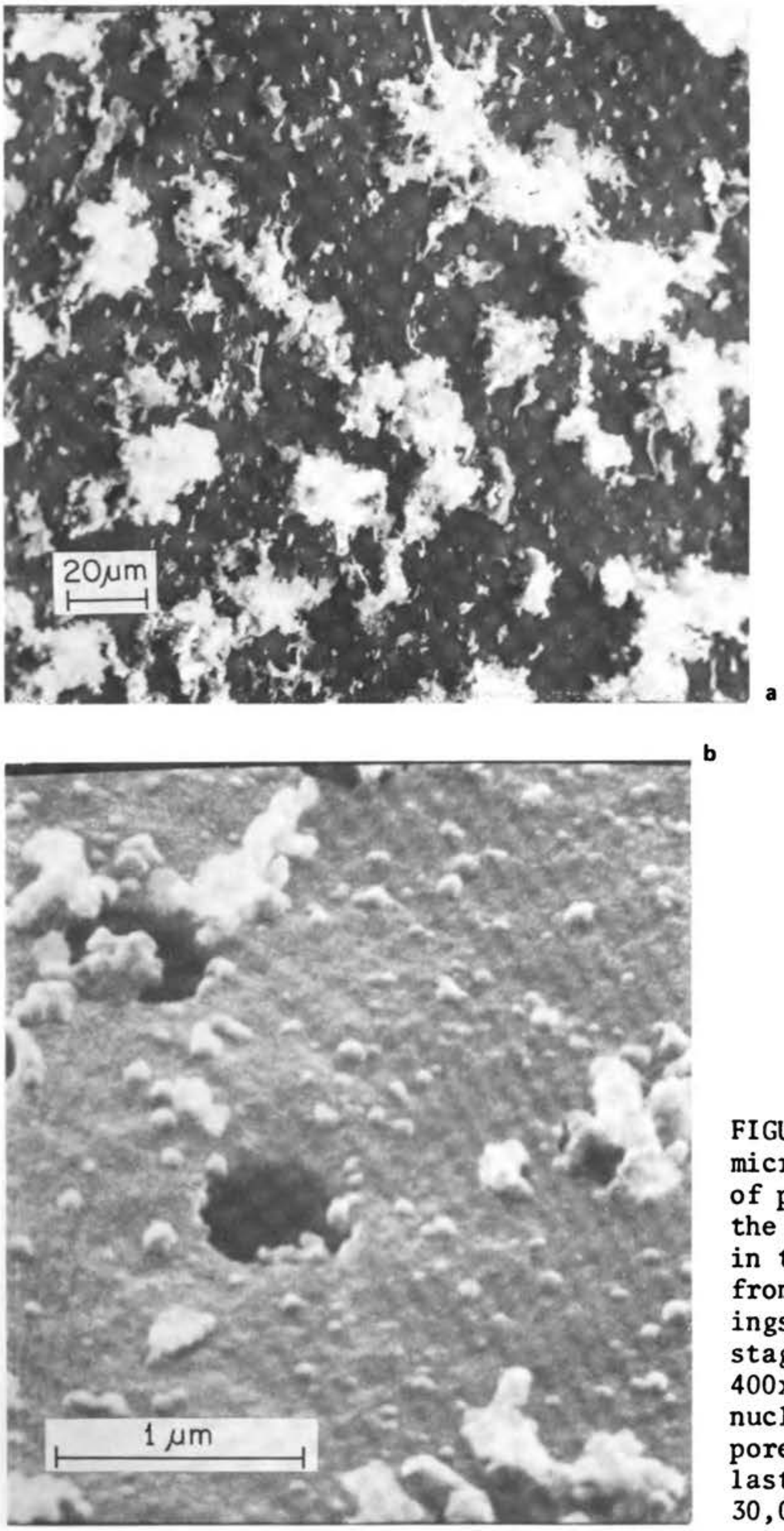

FIGURE 4. Scanning electron microscope photomicrographs of particles collected in the Brink cascade impactor in the pre-filter sample from burning citrus prunings. A) Particles from stage 2 as shown in Fig. 3. 400x. B) Particles on the nuclepore filter (0.4 μm pore size) following the last stage of the impactor. 30,000x.

PHYSICS OF SMOKE FORMATION

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Introduction

It would, indeed, be presumptuous on my part to attempt a full discussion of the topic given above in the space of half an hour. Instead, I will consider some of the physical and chemical processes taking place during the combustion of carbonaceous materials and attempt to relate the nature of these processes to the properties of that complex mixture termed "smoke". Smoke is a mixture of substances in gaseous, liquid and solid states; the particulates in themselves are mixtures whose composition varies not only from particle to particle but also within the particles. The particle size distribution is initially variable with time but may finally achieve a steady state. The impact of smoke upon the environment is a function not only of the mass concentration of its constituents but also of the chemical composition, particle size distribution, distribution of composition, and component interaction.

Those parameters significant in the smoke formation process and which contribute to the nature of the final product may be divided into two sets: (a) the obvious parameters of nature of fuel, flame temperature, oxygen supply, ventilation, etc. and (b) the somewhat more subtle parameters of trace impurity content (and its effect on nucleation), nucleant concentration, surface composition, gas-particle interactions, etc. The two sets are, of course, not independent. Since the term "air quality" appears prominently in the title of this symposium, I will attempt to relate these formation parameters to those properties of the final product, smoke, which are of major concern with respect to human health, the prime component of air quality.

The treatment will be largely qualitative since neither the currently available experimental information or existing theory permit more quantitative interpretation. I will consider (a) the formation and distribution within the smoke of toxic substances, (b) the nucleation process and the mechanisms by which particle composition and particle size distributions are achieved, and (c) the interaction of particulate matter with the gases formed during composition or occurring in the "normal" atmosphere.

The Production of Toxic Substances

The toxic materials in smoke are found in gaseous and condensed phases. The toxic gases include carbon monoxide, aldehydes, nitrogen oxides, peroxides, acids and products specific to the combustion of chlorine or nitrogen containing polymers. The solid and liquid phases may contain carcinogens, irritants, and trace metals. Some toxic materials may be dissolved in liquid droplets, or adsorbed at the solid-gas or liquid-gas interfaces.

Free Radical Reaction: Many of the processes occurring in flames are free radical reactions; i.e., they involve the participation of chemical species, highly unstable in nature, containing one or more unpaired electrons. Free radical reactions are often chain reactions involving (a) an initiation step in which the free radicals are formed, (b) a propagation step or steps in which the free radical reacts to form products and additional free radicals, and (c) a termination step in which the free radicals react to form more stable materials. In flames the initiation step may be an oxidation

$$RH + O_2 \rightarrow R\cdot + HO_2 \qquad (1)$$

in which R represents a hydrocarbon free radical, or a pyrolysis illustrated by

$$C_{12}H_{26} \rightarrow C_{11}H_{23}\cdot + CH_3 \qquad (2)$$

The high molecular weight free radical, $C_{11}H_{23}\cdot$ may react further to produce another methyl radical and a highly reactive olefin

$$C_{11}H_{23}\cdot \rightarrow C_{10}H_{20} + CH_3\cdot \qquad (3)$$

The free radicals thus initiated react with hydrocarbons, oxygen, and unsaturated materials in a complex series of reactions to form adlehydes, ketones, peroxides, polymers, polycyclic organic species, etc. I will make no attempt here to analyze even the simplest of such reaction chains. In general, the rates of these reactions increase exponentially with temperature; the higher the flame temperature the greater the reaction rates. The reaction scheme may be competitive and the reaction products thus highly sensitive to temperature and the nature of the radical initiation step. The greater the oxygen supply the greater the production rate of oxygenated products including carbon dioxide, carbon monoxide, aldehydes, ketones and acids. The reaction rates are highly sensitive to radical concentrations even though these are very small compared to the concentrations of other reaction species; this effect is typical of free radical chain reactions.

Nitric oxide, NO, produced by a high temperature reaction between the nitrogen and oxygen in the air, is a free radical; it contains an unpaired electron. Nitric oxide may act as a chain-breaker and since its production rate is a function of flame temperature, the flame temperature will determine the efficiency of the hydrocarbon chain reaction and the amount of nitrogen incorporated into the product of the combustion process.

Carcinogens: Probably the most toxic materials found in the aerosol portion of the smoke are carcinogens and toxic trace metals. This toxicity refers to long-term exposures; in the shorter term the toxic effects are due primarily to gases such as carbon monoxide, sulfur dioxide, etc., with the aerosols acting primarily as irritants. The carcinogens are substances which produce cancer upon application to the skin or inhalation into the lungs. They may be polycyclic organic material such as benzo (a) pyrene, a condensed five ring system, or finely dispersed fibrous material such as asbestos.

The polycyclic organic compounds are formed in the flame via a free radical mechanism (1). The initiation reaction occurs in the high temperature (500°-800°C) region at the flame front and the propagation steps in the reducing atmosphere at the center of the flame. A large number of compounds may act as carcinogens (2). The extent of carcinogen emission is a complex function of the nature of the combustion process but, in general, the cooler and less efficient the flame, the greater the carcinogen production. This is illustrated by the fact that the carcinogen emission rate from hand-stoked coal burning residential furnaces (an inefficient use of coal) is about three orders of magnitude greater per BTU than that from coal-fired steam power plants. An estimate of the yearly emissions of benzo (a) pyrene in the United States is given in Table 1.

Table 1
Yearly Emissions of Benzo (A) Pyrene in the United States

Source	Emissions (tons per year)
Transportation	45
Heat and Power	475
Refuse Disposal	590
Coke Production	200
Total	1310

Of this total, 140 tons or 11% originate with forest fires or agricultural burning, 420 tons or 32% from coal-fired residential furnaces and 340 tons or 26% from coal refuse fires. The contribution from combustion of natural gas and fuel oil distillate is small.

There is increasing evidence that the emission rate of benzo (a) pyrene from gasoline fueled automobiles increases with increasing aromatic content of the fuel. This fact is significant with respect to the current controversy over the use of leaded fuels; to maintain the necessary antiknock characteristics in the absence of the lead alkyls, aromatics must be added to the gasoline stocks.

Trace Metals: Trace metals and their compounds, such as mercury, lead and cadmium, may be highly toxic in aerosol form. If the proper particle size exists the particles may enter and be retained in the lung alveoli; the adsorption into the blood from the alveoli is a much more efficient process (say on the order of 80%) than adsorption into the blood through the intestinal wall (about 15%). The toxicity is dependent upon the specific nature of the compound; thus methyl mercury is far more toxic than inorganic mercury compounds. With respect to combustion processes, trace metals may be placed into one of two categories: (a) those which volatilize in the flame such as lead, antimony, cadmium, arsenic, chromium and zinc and (b) those which remain in solid or liquid form with very low vapor concentrations such as copper, cobalt, and titanium.

It has been shown by Natusch *et al.* (3) that the concentration of metals in category (a) in the particulate combustion products is inversely proportional to the particle size; no such relation exists for metals in category (b). It has been argued that the volatile metals are deposited on the surface of a refractory material by a condensation process. The number of deposited molecules per particle is proportional to the surface area or r^2, while the concentration is expressed as number per unit volume (proportional to r^3); the concentration is thus related to r^2/r^3 or $1/r$.

It has been demonstrated (4) that the lung retention of aerosols is related to their particle size. Maximum retention occurs in the range 0.4 to 5 microns. The incorporation of trace metal species in particles of respirable size range greatly increases the toxicity of such aerosols. Thus the average concentration of toxic trace metals in aerosols is a misleading parameter with respect to toxicity; it is the concentration of metal in the respiratory range which is significant. One might therefore expect that the greater the flame temperature and the greater the gas phase concentration of trace metals and their compounds, the greater the possibility of incorporation into small particles with accompanying increased toxicity.

Nucleation and Particle Growth

Nucleation: In the combustion process various substances may exist as stable entities in the gas phase; i.e., their pressures are less than the equilibrium pressures over the liquid or solid at flame temperatures. These substances may be new compounds resulting from chemical reactions in the flame or components of the fuel which have evaporated or sublimed at the higher temperature. As these materials move away from the high temperature zone their pressures may become equal to or greater than the corresponding equilibrium pressures over the condensed phases. In the bulk sense the condensed phase then becomes the more stable phase. In the conventional P, T phase diagram the chemical potential of a given species in the various phases is equal along the equilibrium curves. This, however, is true only if the contribution of surface free energy is negligible. When a condensed phase is first formed, for example from the vapor, the new phase exists as very small droplets or solid particles; in this configuration the surface free energy contribution is not negligible and the small droplet or particle is not stable with respect to the vapor along the equilibrium curve in the phase diagram. Thus although the bulk phase is stable at the temperature and pressure in question the first particles of this phase formed are not stable. This leads to the phenomenon of nucleation. I will not attempt a treatment of nucleation in detail but rather attempt to point out the most important features, indicate the nature of the theoretical attack, and point out the significance of nucleation in establishing the properties of the final aerosol phase in smoke.

Types of Nucleation: Homogeneous nucleation occurs during a phase transition in the absence of any foreign material. Heterogeneous nucleation is the process involving interaction with a foreign material. This latter may reduce the energy barrier for the formation of a new phase via an adsorption process or a solubility effect. The energy barrier for heterogeneous nucleation is always less than that for the homogeneous process and thus in a "dirty" nature in which foreign species are always present, homogeneous nucleation does not occur. The basic theory for the homogeneous process, however, is the basis for all nucleation processes and hence will be briefly considered.

Theory of Homogeneous Nucleation: The change in Gibbs free energy for the formation of a small droplet of liquid or radius r from the vapor is given by

$$\Delta G = n_L(\mu_L - \mu_V) + 4\pi r^2 \sigma \qquad (4)$$

in which ΔG is the change in Gibbs free energy, n_L is the number of moles of liquid in the drop, μ_L and μ_V are the chemical potentials in the liquid and vapor phase and σ is the interfacial free energy (surface tension) of the liquid-vapor interface. The Kelvin equation defines the drop radius, r^*, stable at a given value of $\mu_V - \mu_L$ as

$$\mu_V - \mu_L = 2\sigma V_m / r^* \qquad (5)$$

in which V_m is the molar volume of the liquid. Substituting (5) in (4)

$$\Delta G = -(4\pi r^3/3V_m)(2\sigma V_m/r^*) + 4\pi r^2 \sigma$$

$$\Delta G = 4\pi r^2 \sigma\{1-(2r/3r^*)\} \qquad (6)$$

This is a measure of the energy barrier toward condensation. It may be shown that ΔG increases with r until $r = r^*$; spontaneous growth of the drop can, therefore, not occur until $r = r^*$. The maximum value of ΔG at $r = r^*$ is

$$\Delta G^* = 4\pi r^{*2} \sigma/3 \qquad (7)$$

The homogeneous nucleation process is then treated as a problem in fluctuations. The number of critical embryos per unit volume, n_e, is calculated from the Boltzmann expression as

$$n_e = n(1)\exp(-\Delta G^*/kT) \tag{8}$$

The formation of an embryo capable of growth occurs when a gas phase molecule collides with a critical embryo. The nucleation rate, J, in number per cm^3 per second is then a product of the gas-surface collision rate and the number of critical embryos per unit volume. It is convenient in this calculation to define r* in terms of saturation ratio, S by,

$$RT\ln(p/p^o) = RT\ln S = 2V_m\sigma/r^* \tag{9}$$

The nucleation rate, J, is then given by

$$J = \{n(1)B/4\}4\pi r^{*2}n(1)\exp(-4\pi r^{*2}\sigma/3kT) \tag{10}$$

in which B is the mean gas molecule velocity. To explicitly include S, a substitution may be made for r* by equation (9). A characteristic of equation (10) is a very rapid increase in J at a given S. Thus the onset of nucleation is very sharp. Some typical values for the nucleation rate of water at 273°K are shown in Table 2

Table 2.
Nucleation Rates for Liquid Water at 273°K

$S(p/p^o)$	$J(cm^{-3}sec^{-1})$
4.03	$1x10^{-3}$
4.10	$5x10^{-3}$
4.20	$4x10^{-2}$
4.30	$2x10^{-1}$
4.40	16
4.50	100

Most of the observations of nucleation processes in the atmosphere have dealt with the formation of liquid water (condensation nuclei) or the formation of ice (ice nuclei).

Heterogeneous Nucleation: Heterogeneous nucleation may occur with a soluble particle. The chemical potential of the species in the liquid phase is decreased by a solubility effect which may be approximated by

Raoults Law; i.e.,

$$p/p^o = X = n_{H_2O}/(n_{H_2O} + in_N) \tag{11}$$

in which X is the mole fraction of liquid, n is the number of moles of liquid, i is the van't Hoff factor (essentially the number of ions produced per molecule of nucleant) and n_N is the number of moles of nucleant. The energy barrier toward nucleation is thus reduced by a factor equal to $(4\pi r^3/3)RT\ln X$.

Ions may also act as heterogeneous nucleants; this effect was demonstrated in the Wilson cloud chamber. In this case the free energy barrier to condensation takes the form

$$\Delta G = 4\pi r^2\sigma\{1-(2r/3r^*)\} + (Q/2)(\varepsilon-1/\varepsilon)(r_o-r/r_o r) \tag{12}$$

in which Q is the charge on the ion and r_o its radius. Again the barrier (in the exponential term) is decreased and appreciable nucleation occurs at lower saturation ratios.

The action of insoluble and uncharged particles as heterogeneous nucleants occurs through a surface interaction. The details are presently not completely clear but a surface-gas interaction undoubtedly leads to the reduction of the nucleation energy barrier. The surface must possess at least two characteristics: (a) cluster formation must occur with respect to the adsorbed gas molecules which demands a surface containing active adsorption sites on a background of relatively inactive zones and (b) there must be a reasonable match between the structure of the solid and that of the species which it nucleates.

Nucleation in Combustion: The considerations discussed above lead to the following general conclusions with respect to particle formation in combustion and the nature of the particulate material thus produced.

1. Homogeneous nucleation is not significant.

2. Ions are formed in a combustion process as evidenced by the use of flame ionization detectors in gas chromatography. These ions will act as condensation and inverse sublimation nucleants. Ions are not specific in their behavior and no differentiation in composition will occur through their action.

3. The particles formed will generally be heterogeneous in composition. The solid inorganic nucleants will act primarily to nucleate the phase transitions (condensation) of the more similar inorganic gaseous species rather than the dissimilar organic materials. The solid organic species will likewise act to nucleate the condensation of organic species. The

heterogeneity will arise due to adsorption effects (to be discussed later).

4. The more supersaturated vapors (those of the high boiling materials) will nucleate first upon the appropriate foreign nucleant and thus form the core of the solid particulates. Thus the first deposition will be that of the inorganic gaseous species on the inorganic nucleants. The organic gases will probably nucleate upon solid carbonaceous materials in the cooler portion of the flame.

5. The adsorption of organic species will occur on all solid particles while the adsorption of inorganic (polar) material will occur largely on the inorganic solids. Thus a tendency will exist to obtain relatively clean inorganic particles and mixed organic-inorganic particulates.

6. Since in general the density of inorganic substances is greater than that of organic and since the square root of the density is involved in the relation between aerodynamic and geometrical size, the aerodynamic size (which determines entry and retention in the alveoli) will differ for these two classes of particulate matter.

7. Since in general the supply of organic vapor will be greater than that of the inorganic and since the particle growth rate is a function of supersaturation and particle radius, one might expect the geometrical size of the organic material to be greater than that of the inorganic.

It is important to differentiate between nucleation and adsorption. Nucleation results in the formation of a new bulk phase; to attain bulk properties the extent of the phase must be on the order of 10 molecular layers or greater. Adsorption leading to the formation of a film at an interface will produce layers of from less than one to about five in molecular dimensions. The adsorption process occurs with a reduction in free surface energy relating both to the nature of the clean solid surface and the nature of the adsorbed gas. Inorganic materials generally have a high surface free energy and will consequently adsorb both organic and inorganic gases. The surface of organic solids is considerably less active and, in general, they will adsorb organic and not inorganic gases of a polar nature. Thus in (5) above the tendency for mixed growth which will be most significant in the first stages of particle growth with a high surface to volume ratio. The effect will tend to become mixed during the agglomeration process.

Once the primary particles are formed an agglomeration process will take place. The agglomeration rate is a function of particle velocity achieved through a Brownian effect and hence highly dependent upon temperature and a sticking coefficient. The coagulation rate at constant temperature is a function of the square of the particle concentration. Hence the most rapid agglomeration will occur in the region of high particle density which presumably will be close to the flame. The agglomeration will tend to increase the compositional heterogeneity of the aerosol particle.

It is highly unlikely that the basic consideration of the physical and chemical processes occurring in a flame will provide more than clues with respect to the relations between the nature of the flame and the distribution of chemical species as a function of aerosol particle size. Some experimental studies are definitely in order.

Gas-Particle Interactions

This discussion, as differentiated from that above, will deal with the interaction of aerosol particles and gases after the smoke has reached ambient temperatures. It may properly be considered as part of the smoke formation process especially when viewed from the standpoint of air quality. A major gas-particle interaction is adsorption; this may take two forms, (a) physical adsorption in which the interaction energy between the gas and solid surface is that of the van der Waals type; i.e., on the order of energies of condensation and (b) chemisorption in which a high-energy chemical-bond is formed between the adsorbed species and the substrate.

Physical Adsorption: This adsorption is characterized by a relatively low energy and long range force interaction. The potential due to the interaction of many surface atoms or molecules falls off with $1/r^3$ and the adsorption generally proceeds (given a sufficiently high gas phase concentration) to multilayers.

Corrin and Nelson (5) have investigated the adsorption of sulfur dioxide on several solids simulating the chemical nature of atmospheric particulates with gas phase concentrations at the ppm level. The adsorption of sulfur dioxide on a carbon black (Thermax MT) and on a flame silica, Cabosil M5, was physical in nature. The adsorption isotherms were of the Freundlich type in which $\log C^s = a\log P + b$; C^s is the surface concentration in molecules per cm^2 (the monolayer capacity is $5x10^{14}$), P is the equilibrium pressure in microatmospheres, while a and b are curve fitting constants. This type of adsorption is characteristic of an energetically inhomogeneous surface. Table 3 illustrates the adsorption behavior at 273° and 310°K.

This Table illustrates two features characteristic of physical adsorption, (a) the small amount of gas adsorbed at low equilibrium pressures and (b) the decrease in adsorption at constant pressure with an increasing temperature. Consider a situation in which we have a very high particulate concentration of one $milligram/meter^3$ in the ambient temperature region near a flame; let the mean particle size be 0.5 microns, the roughness factor 10 and the true density of the particulate matter 2 g/cm^3.

Table 3
Adsorption of Sulfur Dioxide on Carbon Black and Silica

$P(atm^{-6})$	C^s(molecules/cm^2) Thermax MT	C^s(molecules/cm^2) Cabosil M5
	273°K	
5.0	1.8×10^{12}	0.8×10^{11}
1.0	0.6	0.2
0.5	0.4	0.1
0.1	0.1	0.03
	310°K	
5.0	3.2×10^{11}	1.3×10^{10}
1.0	0.7	0.3
0.5	0.4	0.2
0.1	0.08	0.04

The area for spheres is then $A = 3\times10^5$ cm^2/g. The total surface area per cubic meter of air is then 300 cm^2 and the quantity of sulfur dioxide adsorbed at 5 ppm is 5.4×10^{14} molecules for the carbon black (0.04 statistical monolayers), at 273°K. The number of sulfur dioxide molecules per cubic meter at a concentration of 5 ppm is 10^{20}. The ratio of molecules adsorbed to free molecules in the ambient air is thus 5×10^{-6}. This ratio is still lower for adsorption on the silica. Thus physical adsorption is a negligible sink for ambient gases on particulates. The amount adsorbed would have little effect on the chemical composition of aerosols.

Chemisorption: A chemisorption process by virtue of the high interaction energy between the adsorbed gas and the solid substrate leads to monolayer formation at very low equilibrium pressures. Corrin and Nelson found sulfur dioxide formed monolayers on ferric and aluminum oxides at equilibrium pressures less than one microatmosphere. In terms of the above example this would lead to the adsorption of 2×10^{16} molecules of sulfur dioxide. The fractionation ratio is only 2×10^{-4} at an ambient concentration of 5 ppm; at 0.1 ppm, however, the adsorption remains the same and the fractionation ratio increases to 0.01. The mass of sulfur dioxide per particle is 1.7×10^{-14} grams, the particle weight is 10^{-12} grams and the percent sulfur dioxide is 1.6. For very small particles, say 0.05 microns this percentage increases to 16%. Thus chemisorption does not provide a significant sink for trace gases; the composition of very small particles may, however, be altered by this process. The rate of the chemisorption process also increases with increasing temperature. This process can thus occur in the flame with both smaller particles and higher ambient concentrations.

The adsorption of water vapor (or more strictly sorption in which the process is not limited to the surface) should be negligible for a physical process, significant for very small particles and a major factor for hygroscopic materials at the lower temperatures existing well out of the flame. The extent of pickup would depend on the specific nature of the hygroscopic and soluble material and the vapor pressure-temperature-composition behavior of their aqueous solutions.

Summary

Some of the physical and chemical processes occurring during combustion and the quenching of combustion processes are considered qualitatively in terms of their effects upon the properties of the resulting smoke which are of major significance with respect to air quality. It is concluded that a quantitative treatment must await further experimental observations.

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Characteristics and Behavior of Bushfire Smoke

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Introduction

The results of Australian work on this subject have been reported in two earlier papers (1,2). It appears that bushfire smoke is unlikely to be a health hazard, for even large fires will not give rise to dangerous concentrations of pollutants in the air above them. To this extent, the smoke from bushfires is in no way to be compared with the emission of noxious gases from industrial complexes.

The major problem is, of course, particulate concentrations. Close to a large fire, smoke can be so dense that visibility is reduced to a few hundred meters, and this can be a nuisance both to vehicles on the ground and to aircraft. However, in this connection, there is a real difference between wild-fires and prescribed burns--for with adequate planning, and sensible fire-management, the smoke nuisance from the latter can be minimized.

Preliminary Findings

As a result of Australian experiments, in which a light aircraft was flown through the smoke columns from a series of large prescribed fires in Western Australia, the following statements can be made.

Particle Size: Most smoke particles were less than 1μm in diameter, the majority being about 0.1μm: but there were some very large particles (tarry in nature and obviously agglomerates), which were up to 50μm across.

Particulate Concentrations: In thick smoke, the concentration of smoke particles appeared to be between 10^5 and 10^6 per cm^3.

Smoke Composition: This was variable, but was on average: tar* ∿ 55%, carbon ∿ 25% and ash ∿ 20%.

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*A brief investigation of the carcinogenic properties of this tar was kindly carried out by Professor George Christie in the Pathology Department of the University of Melbourne. Though the results of tests on mice were inconclusive, the tar from the bushfire-smoke collected in the aircraft appeared much less carcinogenic than the coal-tar and benzpyrene used as controls.

Gaseous Combustion Products: In different parts of the smoke column, both close to the fire and down-wind, typical concentrations of the various components were:

CO,	0.5-2 ppm.
CO_2,	about 150 ppm above clean air level.
O_3,	0.02-0.03 ppm (the same as in clean air).*
NO_x,	less than 0.5 ppm.
NH_3,	not detected.
SO_2,	not detected.

Dangerous concentrations of any of these gases in the smoke columns were never recorded. It thus appears that reduced visibility, arising from smoke build-up, is the most undesirable feature of any large fire.**

Smoke Diffusion

For all the fires studied, when winds were between 15 and 30 knots, the smoke spread out in a narrow fan with included angle between 12° and 13°. A photograph of an extended smoke column from a wild-fire in Queensland (observed by a Gemini space-craft) shows exactly the same feature; and this interesting result is probably due to the fact that turbulent transport cross-wind is roughly proportional to wind-speed.*** From the measurements, it is estimated that coefficients of turbulent diffusion cross-wind were of the order of 10^7 $cm^2 sec^{-1}$ in every case.

Smoke Quantities

It is important to know the mass of smoke produced from a given quantity of fuel. In the Western Australian experiments carried out in 1970, estimates were obtained by measuring smoke concentrations over the life-time of each fire and comparing the integrated smoke-flux with the

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*In more recent work in Western Australia, use of an ozone analyser of fast response has shown that the concentration of ozone can, in fact, rise above ambient--depending upon the length of time the smoke is exposed to sunlight. Thus ozone concentrations up to 0.06 ppm were detected in the upper parts of a smoke column well downwind of the fire area. It follows that photochemical-smog reactions may possibly result during the prolonged exposure of smoke to sunlight: and it is proposed to investigate this matter further by making simultaneous measurements of NO_x concentrations, on those occasions when O_3 concentrations are higher than normal.

**In Western Australia, measured "visual ranges" varied from about 200 meters in thick smoke, to 5 miles, or more, in diffuse haze.

***The spread of smoke is obviously important in planning prescribed burning operations and, if accurate meteorological forecasts are available, smoke can clearly be kept away from populated areas.

amount of forest-litter consumed. For each of the typical, large-scale prescribed fires, the total weight of solid particulate matter entering the atmosphere was between 1% and 2% of the mass of fuel burnt.

These estimates, requiring measurement of total smoke-fluxed, were time consuming, and it was hoped that simpler methods of obtaining accurate smoke to fuel ratios could be developed. This has now been done by determining carbon dioxide concentrations in the air above a fire at the same time as smoke is collected (Evans, King, Packham and Stephens, to be published).

The principle is as follows. When fire consumes a 100 g sample of fuel (which is largely composed of cellulosic material), approximately 183 g of CO_2 is obtained. This mass of CO_2, as well as the smoke produced on burning, is diluted by mixing with air: and, if diluted by a volume of x cubic meters, the resulting concentration of CO_2 is (183/x) g/m^3 above normal. Thus, by *accurately* measuring CO_2 concentrations in the air in the vicinity of a fire, it is possible to estimate x--which, by definition is that volume of air containing the combustion products from the fuel sample. But, if at the same time as the CO_2 measurements are made, the smoke concentration, e, is also determined,* then the mass of smoke derived from the fuel is equal to the product of e by x.

Proceeding in this fashion, Evans, King, Packham and Stephens have collected smoke samples in an aircraft, simultaneously measuring CO_2 concentrations in the air with an airborne infra-red gas analyser. During the spring of 1972 when they worked above a further series of prescribed fires in Western Australia, they obtained (over the lifetime of each fire) smoke to fuel ratios of between 1 and 2%: this is essentially the same result as that found during the earlier measurements in the spring of 1970.

The new method has the distinct advantage that it is not necessary to know fuel quantities on the ground, for these are derived from the CO_2 analyses. Further, since measurements are made over a relatively short period, variations in smoke yield can be followed during the progress of a fire.

The technique was used early in 1973 to obtain smoke to fuel ratios during a hot burn in extensively piled windrows.** The large windrow-fuels were dry, and the smoke yield was correspondingly less than in the earlier prescribed fires: over a period of two hours the measured values

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*Smoke concentrations may be determined by optical means: in the Australian work a nephelometer was usually used, as well as direct filtration methods.

**The smoke from this hot windrow-fire had a very different composition from that of the prescribed-burns in Western Australia. The proportion of "tar" was very much reduced, and "ash" was increased.

were 0.21%, 0.26%, 0.34% and 0.43%. It will be noted that the smoke to fuel ratio increased progressively with time.

The method is obviously versatile, and it should be possible to determine the smoke yield of wildfires--or, for that matter, fires occurring in different fuel types, or at different seasons of the year. Indeed, it is hoped that such measurements can be made in the near future.

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AIR AND SURFACE MEASUREMENTS OF CONSTITUENTS OF PRESCRIBED FOREST SLASH SMOKE

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Introduction

Prescribed burning has been considered to be of economic significance in achieving the objectives of perpetuation of the forest for timber production, recreation and wildlife, and protecting the resources from wildfire, insects and disease. A cooperative field study was designed by personnel of the U.S. Forest Service, Northern Forest Fire Laboratory in Missoula, Montana, (NFFL) to evaluate the effectiveness of prescribed burning in the accomplishment of these objectives, as well as to determine the effects of burning on air quality. The burn schedules were selected to represent a range of fuel moistures and air temperatures, some of which were previously considered impractical from the view point of fire control.

This report presents data describing the air quality within 50 km of the Miller Creek experimental block in terms of 24-hour average mass loadings in the atmosphere, some results of the airborne analysis of the combustion products from two typical flights, diffusion analysis of the downwind characteristics of the plot plumes, and determination of the range of mass emission of selected combusion products from known weight of fuel consumed on instrumented laboratory burning tables.

Experimental

The first in a series of field studies of experimental prescribed burns was located in a larch-fir stand in the Miller Creek drainage of the Tally Lake District, Flathead National Forest, approximately 64 km north of Kalispell, Montana, Fig. 1. Fifteen 10-acre clear-cut units on each of four cardinal exposures were developed by Forest Service personnel for prescribed burning over a wide range of fuel moisture and meteorological conditions from May through October of 1967 and 1968. Slopes ranged from 9 to 35%.

The second series of field studies of experimental prescribed burns was located in a larch-fir stand (up to 60%) with lesser amounts of lodge pole pine and other species. This study on Newman Ridge near St. Regis, Montana, on the Lolo National Forest, consisted of 16 units ranging from 19 to 50 acres. Newman Ridge was slightly higher in elevation and the slopes were much steeper, ranging from 44 to 76%.

The fuel was logging slash and laydown resulting from special timber sales and cutting schedules designed to maintain constant, effective curing time. The broadcast logging debris from both areas was burned within one year following clearcutting. The fuel loads averaged 100 tons/acre (1).

A wildfire on Miller Creek in 1967 burned four plots of standing timber and several adjacent plots of slash. This fire of larger proportion produced the most intense emissions observed. Details of the extensive fire spread and intensity instrumentation and fuel measurement techniques used by Forest Service personnel have been reported elsewhere (1).

These sixty-five treatment areas have enabled forest resource managers to evaluate fuel consumption by size class, duff depth reduction, convection column altitude, seed losses, germination rate, root development, seedling survival, length of time the sites remain receptive to seeding and planting, soil moisture before and after burning, soil stability, water repellancy of the soil, effect on wildlife habitat and populations, root kill attributed to effects of the fire, and air quality.

Air quality studies during the 1967 season in which 25 units were burned (10 of which were destroyed by the wildfire) were limited to ground-based measurements at five sampling sites. During the 1968 season an instrumented, twin-engined, light aircraft (Cessna Skymaster 336) was used to follow the dispersion of selected combustion products. Sixteen flights were conducted during the burning of 24 10-acre plots. Toward the end of the 1968 season two plots were burned in sequence per day to complete the field studies by early October.

Ground-Based Measurements

Five ground-based sampling sites were established in August and September 1967 to provide 24-hour average suspended particulate matter data using the standard "hi-vol" sampler. These data were used to relate the natural background loadings in forested and inhabited areas, and possible contribution to this loading from the prescribed slash burns and/or wildfires which occurred through late October 1967 and throughout the summers of 1968-1969 (June - mid-October). The Tally Lake sampling sites are depicted in Fig. 2. Sampling sites were selected to have an open exposure and 117VAC power.

Similarly, five ground sites were selected in the vicinity of Newman Ridge. Here because of the more rugged, less populated terrain it was not possible to locate representative sites having electrical power. Thus it was necessary at three of the sites to install gasoline-powered, 5Kw electric generators. Daily hi-vol samples were obtained throughout the study period. Fresh filters were installed daily within the time period of 1100-1300 hours. The reported mass loading value for each daily sampling period was calculated for the actual duration of the sampling period.

It was arbitrarily decided to change the 24-hour hi-vol filters at noon daily since the study plan called for ignition of the experimental plot prescribed burns during the afternoon or early evening. Thus smoke from these burns, especially from the latter ignitions, would continue to be released after midnight. Had the hi-vol filters been changed on the usual midnight to midnight schedule, the standard hi-vol time span would have complicated subsequent evaluation of these data in terms of the prescribed burn contributions. However, the noon to noon schedule of the daily 24-hour average suspended particulate concentration did complicate evaluation of urban, commercial, and industrial particulate contributions in terms of the weekly work-days versus weekends (Saturday and Sunday). Thus the reported "Friday" values included the midnight to noon portion of Saturday and the "Sunday" values include the midnight to noon Monday contribution. This latter contribution was especially significant at Site #5 (Miller Creek) because of the use schedule of the several wood waste teepee burners in the vicinity.

Measurements from Aircraft

An aircraft was instrumented for the real time analysis and recording of visual range, carbon monoxide, carbon dioxide, temperature, relative humidity, altitude, rate-of-climb, and indicated air speed. All varibles were recorded once each 0.3 seconds--equivalent to once each 12 meters of traverse--on a 7-track, 200 bits per inch, 27-channel, magnetic tape data logging system. The instrumented aircraft and its analysis and data logging system have been previously described in detail (2).

RESULTS

Suspended Particulate

Figures 3 and 4 and Table 1 show the monthly geometric mean average suspended particulate matter for 1967 and 1968 related to the Miller Creek study. It is obvious that site #5, located in the inhabited valley between Columbia Falls and Kalispell, showed the highest suspended particulate levels for seven of the eight months during 1967 and 1968 for which comparable data were obtained.

Figure 5 is an aerial view of the area surrounding Site #5 and is typical of the weekday lower level atmospheric conditions which prevailed in this valley. The visual range in the Kalispell valley improved on weekends because the several "teepee" wood waste burners were not operated on Saturday and Sunday. Visible emissions from the aluminum plant, however, continued at a relatively constant rate throughout the entire year.

These data were analyzed by (a) all days on which prescribed burns were conducted, (Fire Days), (b) all weekdays on which no prescribed fires occurred, (c) all Saturdays, all Sundays, and (d) all days. These distinctions were possible since only one prescribed burn was conducted on a Saturday or Sunday - Saturday, August 31, 1968.

Figures 6 and 7 combine all data obtained during 1967 and 1968 respectively, and display the geometric mean particulate loadings for each of these four conditions. From these data it appears that fire days tended to have somewhat higher suspended particulate than non-fire days and weekends, particularly during 1968.

Figures 8-15 show these same day-type relationships on a monthly basis. The number of each day-type is noted at the end of each bar. Again the prescribed fire days appear to have higher suspended particulates than did the days in the three non-fire categories.

Figure 16 compares the geometric mean and maximum daily concentrations of suspended particulates for the five study sites and for two NAPCA (EPA) hi-vol sites in Montana (3). The Helena site should be compared with study site #5 although it represents an urban site having a larger population and fewer larger point sources. The Glacier Park site is comparable to the study sites #1-4. The two urban sites generally compare within 10%. There is more scatter among the five rural sites with NAPCA's Glacier Park site having a lower mean and a significantly higher maximum day.

Statistical analysis. These data have been evaluated statistically using the "Student's" t test to determine whether these observed differences are statistically significant. Two sets of "Student's" t values have been prepared for each data set evaluated and are shown in the "horizontal" and the "vertical" tables.

Fire days vs. other days. The first data set thus evaluated is for all data for all sites and for each of the fire sites comparing (a) All Plot Fire Days (APFD) vs. All Week Days, (b) APFD vs. Saturday and Sunday and (c) APFD vs. All Days, Table 2.

These tables are interpreted in the following manner:

(Horizontal). Each day-type is identified across the top of Table 2. Each hi-vol site is identified in the left-hand vertical column. To determine whether there is significant difference between the various sites for any specified day-type, find the "t" value on the desired site. The first "t" value column under Fire Days (APFD) relates only experimental plot fire days to the Week Days for the desired site, or all sites. The second "t" value column under Fire Days relates plot fire days to all Saturdays and Sundays and the third "t" value column relates Fire Days to All Days. Similarly, Week Days without plot fires can be compared statistically by all sites, or site to Saturdays and Sundays or to All Days by the "t" values provided in the two columns under Week Days. Finally, all Saturdays and Sundays can be compared statistically to All Days in the final column. Any "t" value greater than approximately 2.10-2.50 (depending upon the sample size) indicates a statistically significant difference in 24-hour average suspended particulate. The 97.5%, 99%, and 99.5% confidence levels have been identified by "*", "**", and "***" respectively, when they occur.

Thus Fire Days at All Sites show highly significant differences from all other day-types. Sites 1 and 2 which were located to the west and north of the Tally Lake experimental block do not show any statistically significant differences by Day-type. This would be expected since the winds were predominately westerly, especially when experimental prescribed burns were conducted. Sites 3 and 4 showed highly significant differences in suspended particulate between Fire Days and all other day-types; whereas no significant differences in suspended particulate were measured between Week Days and Saturdays and Sundays. Site 5 also showed statistically significant differences in suspended particulates between Fire Days and Weekdays. However, highly significant differences were also found between Week Days and Saturdays and Sundays. Saturdays and Sundays were not statistically different from non-fire days at any other site. These differences apparently reflect the influence of weekday commercial and industrial activities upon the suspended particulate levels at Site #5 in the populated area.

(Vertical). A similar approach was used to determine statistically significant differences among the various sampling sites for any given Day-type. In this case the "t" values are read vertically. The top "t" value in any column describes the significance of the difference between All Sites and Site 1. The second "t" value in any column describes the difference between All Sites and Site 2. Comparison between Site 1 and Site 2 is represented by the "t" value opposite the Site 1 line in the table. The highly significant differences in suspended particulate are again noted with "*", "**", and "***".

<u>Fire days + one vs. other days</u>. Similar comparisons were made between Fire Days + 1 and other days (Table 3) to determine whether there might be a carry over effect on suspended particulate. No statistically significant differences were found between Fire Days + 1 and Week Days and All Days. This shows that there was no carry over effect following the day after the prescribed burn which could be ascribed to continued smoldering of the plot fuel.

<u>Seasonal effect on comparison of APFD vs. other days</u>. Review of Fig. 3 and 4 indicate that the monthly average suspended particulate obviously varied from a seasonal low in the spring within the range of 25-50 $\mu g/m^3$ to a maximum range of 80-110 $\mu g/m^3$ in the late summer. To minimize the standard deviation in 24-hour average seasonal suspended particulate related to these obvious climatic variations, all of the available 24-hour suspended particulate data were examined by month. The obvious disadvantage of this treatment is related to the reduction of the monthly Fire Day sample size down to an average N of 1-3. Even with this shortcoming, statistically significant differences in suspended particulate were measured at Site 4 between Fire Days and Week Days at the 97.5% confidence level when the fire days exceeded five days in a month, Tables 4-9. Reference to these Tables indicates that the maximum "t" values are generally associated when comparisons are made between either May or October and June, July, August or September at Site #1-4 inclusive. The "t" values for these same comparisons are somewhat lower at Site #5, but the measured differences in suspended particulate are still statistically significant at the 99% level.

Measurements from the Aircraft

The airborne integrating nephelometer and the infrared carbon dioxide analyzer were used to search out and define the widths of the plumes by detecting the presence of two major combustion products - smoke particles and carbon dioxide. The additional contribution of these materials to the atmosphere from discrete sources was readily detected under all wind conditions because of the background nature of the prevailing influx air. Even under northerly flow when the prescribed burn combustion products drifted south and tended to coexist with the polluted air over the urban area, the burn energy pushed the combustion plume at least a thousand meters above the top of the urban pollution level. This is illustrated by the burn of July 3, 1968, one of the burns reported below.

The generation rate of the burn combustion products was a continuously changing function and therefore the plumes did not behave in the classical mode of steady state, high energy power plant plumes or even in the mode of steady state, short-term releases of fluorescent, smoke or gas tracers.

The rapid rise and fall of the rate of energy release from the burns resulted in a relatively rapid plume development and dissipation in terms of rate of combustion product contribution and the transport altitude. Because of the changing nature of the plume during each burn and the individual nature of each burn, no definite preflight plan was in effect. In addition, many of the burns were ignited just prior to sunset and the plumes did not dissipate until well after dark. Therefore, aircraft sampling was sometimes discontinued before the final stages of some burns when the plumes subsided to near ground level. The energy release during the latter phase of the burns was frequently insufficient to give the necessary plume rise above the rugged, mountainous terrain to permit safe flight clearance of the terrain after dark.

Ideal definitions of the plume width, thickness, concentration, and rate of movement would require a series of traverses normal to the plume at each desired downwind location. In actuality, the aircraft did not always fly normal to the plume axis.

During certain parts of a plume traverse the flight pattern was parallel with the plume when the objective was to trace the plume until it disappeared into the natural variation of the background.

Estimate of Plume Transport Speed -- Flight No. 2. An estimate of the speed of smoke plume spread was obtained by measuring the distance and elapsed time between intercepts No. 2 and 5 (Case No. 1) and later between intercepts No. 7 and 8 (Case No. 2). The flight pattern is shown in Fig. 17 and the plume interceptions are given in Fig. 18. In both cases the plume was traversed on intercepts No. 2 and 7. intermediate downwind traverses were completed at a constant altitude of 3950 meters MSL without intercepting the plume and the plume was then subsequently intercepted again on the third traverses, No. 5 and 8 respectively. Figure 19 shows the measured changes in light scattering coefficient during this flight from the first intercept of the prescribed burn plume at 1948 hours to the penetration of the lower level pollution layer generated in the Flathead Valley 2013-2018 during the descent and landing approach.

Case No. 1- Intercepts No. 2 and 5 -- Since it required 103 seconds to traverse Intercept #2, it is assumed that the leading edge of the plume extended to the south of the traverse. However, no contact was made with the plume on a parallel course 6500 meters SE of intercept No. 2 approximately 240 seconds later. Contact was again made with this plume 600 seconds later and 10,000 meters SE of the approximate position of the leading edge of the plume at 1905. The calculated minimum rate of plume movement was 16.8 m/sec. If the leading edge of the plume was traversed on Intercepts No. 2 and 5, the plume was required to move approximately 14,500 meters in 810 seconds. The maximum rate of plume movement under these conditions would have been 17.9 m/sec.

Case No. 2 - Intercepts No. 7 and 8 -- Following the same logic the minimum plume movement would have been 8000 meters in 540 seconds or 14.8 m/sec. The maximum movement would have been 5000 meters in 240 seconds or 20.9 m/sec.

RAWINSONDE measurements obtained at the nearest Weather Bureau station having this capability (Spokane, Washington, approximately 390 km west of the study area and separated from the study area by the Rocky Mountain range) reported winds aloft at approximately 3950 meters above Spokane to be 320-330° at 5.8-6.1 m/sec. The reported direction at Spokane correlates well with the observed trajectory of the smoke plume in the study area 390 km to the east. However, the measured Spokane wind speed (5.8-6.1 m/sec) at 3950 m was only approximately 35% of that calculated from the observed rate of smoke plume movement from the contolled burn. A better estimate of the average, local winds aloft speed between 2160 and 3950 meters MSL at the study area can be calculated from the time required to fly the final leg of Flight No. 2 (Figure 17) from the north end of Flathead Lake to a point west of Whitefish on the Stillwater River. This flight path was directly upwind and was flown at an indicated air speed of 40 m/sec (90 mph) on a descending course from 3950 to 2160 meters MSL and an air temperature ranging from -2° to +5°C. Under these conditions the calculated true air speed was 49 m/sec (110 mph). Twenty-three minutes was required to traverse 40 km for an average ground speed of 29.0 m/sec (65 mph). The difference between the true air speed and the average ground speed is equal to the average wind component between 3950 and 2160 meters MSL within the study area and was approximately 20 m/sec (44.7 mph). This calculated average wind aloft to the 3950 m level in the range of 20 m/sec is in reasonable agreement with the calculated rate of plume travel at 3950 m (14.8-20.9 m/sec).

Carbon dioxide measurements -- Flight No. 13 -- Following the installation of a stable AC power supply (Leland rotary inverter) in the aircraft on August 30, 1968, a no-drift operation of the non-dispersive infrared carbon dioxide analyzer was achieved. Flight No. 13, Fig. 20, represents the flight pattern in which simultaneous real time meteorological range and carbon dioxide measurements were obtained over the greatest distance from the fire--up to 50 km. Figure 21 shows the plume intercepts on this flight. Figure 22 displays these simultaneous measurements of meteorological range and carbon dioxide for the period 1745-1905 MDT, September 9, 1968.

Although it was impossible to calculate the rate of plume movement because of the flight pattern flown, the data show the relationship between increased light scattering and carbon dioxide in the plume over a distance of 50 km from the source.

Bovee, *et al.*, (5) attempted to measure the carbon dioxide enhancement of the air downwind from the approximately 18.4 acres Pack River prescribed broadcast slash burn in 1968. Using batch sampling techniques they were unable to demonstrate a measurable increase in the background carbon dioxide from the burning of approximately 260 metric tons of wood refuse. A 10 sec grab sample representing a 400 m segment of the plume was obtained while flying through the plume at 40 m/sec. Their failure to demonstrate an increase in carbon dioxide within the plume was undoubtedly related to several factors including (a) the nature of the aircraft sampling (single evacuated bottle opened in the plume), (b) the lack of comparative background concentrations, and (c) the relatively low increase in carbon dioxide in the plume.

Conversely, real time sampling in the plume, illustrated by Flight No. 13, indicated simultaneous increases in carbon dioxide concentration and light scattering coefficients for nearly all plume intercepts up to 43 minutes after fire ignition and at distances up to 25 km from the source, Fig. 22.

Plume Diffusion Studies. The aircraft flight tracks were of three types: (1) circling and penetration of the smoke column rising above the fire, (2) circling outside the column to observe and measure the rate of rise of the column during the early phases of burning, and (3) intercepts of the altitude-stabilized smoke plume as it drifted downwind from the fire area. This analysis is concerned only with data from the downwind intercept phase of the program made more or less at right angles to the axis of the plume and the mean wind. The measurements are considered indicative of the maximum spread of the plume. However, the lack of multiple penetrations at various altitudes prevents the direct estimation of vertical dispersion parameters and the flux of total pollutant mass.

Intercept cases were determined by an examination of the print-out of the in-flight data system compared with the plotted track of the aircraft and the axis of the smoke plume as indicated by upper level winds. In most cases the beginning of the plume intercept could be determined within ± 2 data points or ± 1.6 seconds because typically there was an abrupt change in the integrated scattering between the low background level outside the plume and the much higher scattering levels from the plume itself.

The plume intercept times, air speed, and altitude were used to calculate the length of the intercept. Since the intercept tracks were assumed to be normal to the plume axis, the intercept length was used as the plume width, Y.

In visual plume measurements it is frequently assumed that the edge of the plume is characterized by some concentration relative to the axis of the plume. A value of 10% of the axial concentrations is often used (5). For an edge concentration equal to 10% of the axial value for a Gaussian or normally distributed plume, the standard deviation of the plume in the lateral direction becomes:

$$\sigma_y = Y/4.28$$

where Y is the total plume intercept length.

This relationship has been used to relate the observed plume width as determined by the aircraft intercept data to the standard deviation of a Gaussian plume as a function of distance from the fire. The Gaussian model was used even though it is in apparent contradiction to the observations of our plume conditions. It should be recalled that the Gaussian model is a statistical model extending over a finite period of time while these intercept data are essentially instantaneous slices of the plume. Had it been possible to make repeated measurements of the plume at a given distance it is quite probable that the resultant average plume cross section would have been more nearly Gaussian in shape. Thus the use of the Gaussian model is considered satisfactory.

Table 10 lists the plume dispersion data for each of the available intercepts of the slash fire smoke plumes. The time of the intercept is Mountain Daylight Time, the locally observed time. The times given in the table emphasize a point made previously that much of the test program was done after sunset, during twilight or near dark conditions. The altitude given in column 4 is based on aircraft altimeter data corrected for the approximate elevation of the local test area. The altitude range for both test fire source areas ranged between 4500 and 5500 ft MSL and an average value of 5000 ft was used as an estimate of the height of the source and as a base for expressing the height of the plume intercept above the terrain. The wind data given in column 5 was taken from pibal observations made prior to the start of the fire and applies as closely as possible to the altitude level of the intercept. Columns 6 and 7 give the downwind distance and calculated σ_y data for the individual intercepts.

Figure 23 shows the intercept σ_y values plotted as a function of downwind distance; also shown on Fig. 23 are the relationships of σ_y and X as a function of the Pasquill stability classes widely used in air pollution plume dispersion calculations (6).

Statistical analysis of the data in Table 10 shows a strong correlation of log σ_z and log X of 0.92 and a regression line on a log-log basis of:

$$\log \sigma_z = 1.689 + 0.943 \log X.$$

This regression line is also shown on Fig. 23 where it falls between the D and E stability categories. This indicates a slightly stable dispersion situation.

The data represent dispersion conditions during (a) evening hours, (b) surface wind of less than or equal to 10 mph, (c) neutral lapse rate through the transport layer with probably an underlying shallow radiation inversion. The observational results as shown by Fig. 23 indicate that the lateral dispersion for these plumes approximates a "slightly stable" or Class E stability category of Pasquill(6) over much of the dispersion range. This stability category is in general agreement with much of the meteorological situation. Although according to radiosonde flights made prior to the ignition of the fire these experimental periods were all characterized initially by a deep neutral or adiabatic lapse rate zone, the major diurnal effect seen at plume level would be a gradual decay of eddy turbulence. On this basis it would seem reasonable for the atmospheric turbulence structure to develop a slightly stable status, and thus the results shown in Fig. 23 are logical just on a physical basis.

It should be pointed out that the data in Table 11 and Fig. 23 do not include any points closer than 5 km to the ignition. After study of all the data in this set of observations, the atmospheric-related dispersion effects seemed to become evident at about 5 km. The subjective discarding of the closer traverse data does not materially affect the research results.

The dispersion data from these Montana slash fires have been compared with plume data on Australian brush fire smoke published by Vines, *et al.* (7). The data given by Vines leading to σ_y were calculated by the same methods as used for the Montana data in Table 10. Figure 24 shows the log-log plot of the Australian data and the calculated regression line:

$$\log \sigma_y = 0.122 + 0.669 \log X,$$

where, as before, σ_y is in meters and the downwind distance X is in kilometers. The correlation between σ_y and X for this Australian data is 0.84. The slope, 0.669, is not significantly different from the Montana data or the Pasquill stability class lines on the basis of a "Student's" t test.

As indicated by Fig. 24 the Australian data indicate a more unstable diffusion class than did the Montana data of Fig. 23 approximating a stability class B as compared with E. This observed difference is believed to be due to the fact that the Australian program was conducted in the early summer and the fires were ignited in the late morning hours. Thus the plumes represent dispersion conditions during the middle of the day when unstable mixing would be logical. The Australian data cover a somewhat greater altitude range than do the Montana data, from 2000 to 10,000 ft as shown by Table 11 compared to 1500 to 8200 ft.

Horizontal diffusion parameter data for transport of materials over distances from 10 km to more than 1000 km were summarized by Heffter (8). The longer range data reported by Heffter includes the tropospheric and stratospheric nuclear debris data and was obtained at a wide variety of altitudes. The data from Montana and the Australian data of Vines, *et al.*, are quite consistent with the data presented by Heffter.

To calculate downwind plume dispersion models values of the vertical dispersion, σ_z, are also required, but from the Montana program there are no data that would permit the direct calculation of σ_z values.

A consideration of situations directly applicable to forest smoke conditions can indicate that values of σ_z for these situations during neutral or stable periods should be somewhat less than the values considered applicable to stack plume conditions. This follows from the greater height of the slash fire and brush fire smoke plumes and the fact that vertical turbulence decreases with altitude for these stability categories. For unstable conditions two situations may prevail. If the plume rises above the lower friction or Ekman layer and is transported by gradient-level winds values of σ_z characteristic of neutral or slightly stable conditions would probably be applicable. If the plume does not reach the gradient wind level then it would be strongly affected by convective turbulence and a direct application of Pasquill's categories would be reasonable.

Estimates of Smoke Plume Mass Concentrations and Emissions. Nephelometer scattering data have been used by various investigators as a way of estimating total particle mass in the atmosphere (9). The scheme is an approximation and requires a number of assumptions as to the nature of the aerosol; however, experience has shown that reasonable results can be obtained.

The individual plume transects from the Montana fire data have been evaluated for average b_{scat} values. In general the values were within the range of 0.4/km to about 1.0/km. In Australia, Vines found that airborne brush fire particulate material or "smoke" followed the expression:

$$C = 230\ b_{scat},$$

with reasonable precision. This is certainly well within the range of values determined by Charlson, *i.e.* $C = 300\ b_{scat}$. Using the brush smoke data of Vines, the Montana range of b_{scat} values indicated smoke particulate concentrations to be within the range from about 90 to 230 $\mu g/m^3$. Background values of b_{scat} in the areas unaffected by the Montana fire plumes was about 0.8/km with a range from about 0.05/km to 0.1/km. This translates to an average background concentration of about 18 $\mu g/m^3$ using Vines' expression.

The Montana plume data cannot be used directly to estimate the total mass of smoke produced by the fires because the plume transect data are not detailed enough to calculate smoke flux through a downwind vertical plane. However, fuel weights were estimated in detail by Forest Service personnel for all the test fires and averaged 100 tons/acre before burning and 60% less after burning (1). The loss was made up of CO_2 and other gases as well as water vapor, and smoke. Based on a typical 1968 fire unit area of ten acres the fuel available averaged 1,000 tons per fire of which an average of 600 tons was burned.

Forest Slash Emission Factors Determined from Burning Tables Studies

The burning of agricultural waste in a manner to simulate open burning and yet permit measurement of the combustion products has been accepted as a useful method to provide pollutant emission factors (10). Such emission factors can then be used to estimate the total quantity of various emissions from the disposal of similar material by open or prescribed burning.

Darley designed an instrumented burning tower at the University of California at Riverside (UCR) which has an 8 ft diameter burning table (11). Darley and co-workers have used this facility to describe the range of combustion products from the burning of a variety of agricultural wastes. The fuel charge to this facility averages 25 pounds. Adams and Koppe subsequently designed and built a small, laboratory-sized, instrumented burning table in which 100 gram fuel samples could be burned (12).

The NFFL fuel inventory showed that the major tree species at both Miller Creek and Newman Ridge were larch, Douglas fir and spruce in almost equal quantities and constituting approximately 90% of the fuel (1). Table 12 provides the average species distribution within the two experimental burn areas.

Samples of forest slash and duff fuels were obtained from the Miller Creek and Newman Ridge experimental plots. Seventeen to 56 pound portions of these samples were burned by Darley, *et al.*, in the large UCR facility. Koppe burned 100 gram portions of these and other samples from the Montana plots on the small WSU laboratory table. Both groups determined the particulate, CO and CO_2 emission rates. No spruce samples were burned in the WSU facility and no duff samples were burned at Riverside.

UCR's data on the Montana fuels showed that the particulate emissions from spruce were approximately equal to the average of the particulate emissions from larch and Douglas fir. Therefore, the average of the UCR particulate emission factors for fir and larch was used to represent all three species for estimating the particulate emissions.

The UCR emission factors were obtained from single samples of mixed fuel size classifications ranging from needles through twigs (Table 13). The average particulate emission factor for larch and fir for this broad fuel size class was 3.95 Kg/metric ton. This single factor was applied to the preburn fuel inventory including needles, 0-1 cm, and 1-10 cm sizes (Table 13).

Emission factors were developed at WSU for both fir and larch for several fuel size classifications: duff, needles, 0-1 cm, and 1-2.5 cm. The emission factors for fir and larch for each of these size classes was subsequently applied directly to the corresponding NFFL fuel inventory classes except that the 1-2.5 cm emission factor was applied to the 1-10 cm fuel class.

Since no fire table emission factors were developed by either group for the greater than 10 cm fuel size class, an emission factor of 3 Kg/metric ton was used as a best estimate to calculate the particulate emission for this size category after downward adjustment of the greater than 10 cm fuel inventory by 60% to account for the fuel of this size which was not consumed in the prescribed fires, Table 14.

The duff fraction of the fuel was considered separately from the other fuel classes because the UCR laboratory had not been provided with duff samples. Duff collected for burning on the WSU laboratory table was separated into upper and lower layers and each fraction was burned separately. The average particulate emission from the upper layer of duff from each of the four exposure aspects was 6.2 Kg/metric ton of fuel burned and for the lower layer the emission rate was 8.8 Kg/metric ton of fuel burned. Since it was virtually impossible to estimate the percentage of upper and lower layers of duff burned in each of the field burns, the upper and lower duff emission factors were averaged. This average factor was multiplied by the duff weight loss to estimate the particulate emissions from duff consumed.

Table 15 provides the particulate emission factors as determined in these two experimental burning facilities. Despite the obvious scale-up factor of approximately 125 between the 100 gram and average 25 pound fuel charges used in these two facilities, the correspondence among the factors is good. These forest fuel emission factors for the Montana fuel, as obtained from the UCR and WSU fire table burns, were then used to estimate the particulate emissions from the experimental plot fires. Particulate emissions were calculated for each of the four cardinal exposure aspects for Miller Creek and Newman Ridge study areas.

Three levels of complexity were used in developing these particulate emission estimates. In the first approach, the average of UCR's larch, fir, and spruce emission factors for the single mixed fuel size (comprised of fuels from needles through 2.5 cm diameters) was used. The second particulate emission estimate was made by weighting the fuel inventory with the individual emission factors obtained for (a) needles, (b) 0-1 cm, and (c) 1-2.5 cm fuel. In both of these computations, fuel from the NFFL inventory in the 1-10 cm size class was multiplied by the UCR's "needle-2.5 cm" factor or with WSU's "1-2.5 cm" factor. Finally, a third estimate of particulate emissions from the prescribed burn plots was made utilizing the more detailed WSU fuel size class emission factors plus the duff emission factor.

All three estimates of particulate emissions have been summarized in Table 15. The estimate of particulate emissions using UCR's broad fuel size classification and WSU's three fuel size class factors are remarkably close. However, the comparison further indicates that the duff contributes a significant and variable quantity of particulate to the forest fuel emission estimates. Highly variable quantities of duff were reported in the preburn inventory(1) and quite variable quantities of the duff were burned - Table 14.

Table 16 shows trend toward lower particulate emission factors as the fuel size increases. The lower particulate estimate obtained from UCR's less detailed "needle-2.5 cm" size class is in the anticipated direction because the WSU factors for needles and 0-1 cm fuel are 30-60% greater than the average particulate emission factor for all three fuel size categories.

SUMMARY

Daily 24-hour hi-vol suspended particulate concentrations measured during the 1967-1968 Miller Creek study were significantly higher at the three downwind sampling sites on prescribed fire days as compared with non-fire days. Contributions to the atmospheric burden of suspended particulate related to the week day character of human activity in the vicinity of Kalispell produced air quality that was significantly lower on week days than on Saturday or Sunday.

The two sets of field data, from Montana and from Australia, covered the approximate range from 5 to more than 60 km downwind from the fires. Transects were flown at altitudes between 1500 ft and 10,000 ft above the terrain. The resulting data indicate that long range smoke dispersion from slash or brush fires can probably be estimated to a satisfactory degree of accuracy using techniques developed for calculating point source diffusion and that the stability classification applicable to these types of plumes can be estimated from synoptic surface observations and the technique developed by Turner and commonly used for urban air pollution studies.

The particulate emission factors for forest slash fuel generated on two different sized fire tables ranged from 2.8-11.4, with averages from 3.3 to 6.6 depending upon fuel size class. Considering all of the possible areas of difference among data from the Montana, Australia, and two quite different sets of burning tables, the similarity in particulate emission factors is very satisfactory.

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TABLE 1

"HIGH-VOLUME" DATA

Site	1	2	3	4	5
		August 1967			
Days	31	--	29	--	--
Geo. Mean*	33	--	49	--	--
		September 1967			
Days	29	30	30	30	30
Geo. Mean*	39	33	40	49	85
		October 1967			
Days	20	19	20	20	20
Geo. Mean*	29	31	39	45	61
		May 1968			
Days	8	4	8	8	7
Geo. Mean*	27	28	39	35	51
		June 1968			
Days	30	21	30	30	29
Geo. Mean*	68	65	79	79	89
		July 1968			
Days	30	15	31	30	31
Geo. Mean*	63	45	64	79	101
		August 1968			
Days	28	29	27	31	30
Geo. Mean*	51	42	72	62	83
		September 1968			
Days	29	22	28	28	30
Geo. Mean*	53	79	58	52	78
		October 1968			
Days	13	--	14	14	14
Geo. Mean*	84	--	95	87	110

*$\mu g/m^3$

TABLE 2

SUSPENDED PARTICULATE DATA

FOREST SLASH BURNING

SIGNIFICANCE TESTS

INTERVAL	FIRE DAYS			WEEK DAYS		SAT. & SUN.	ALL DAYS
			Horizontal				
Allsites	4.267***	4.421***	4.042***	0.305	-0.816	-0.964	
Site 1	1.135	1.200	1.091	0.104	-0.217	-0.285	
Site 2	1.073	0.646	0.893	-0.682	-0.503	0.354	
Site 3	2.170*	1.478	1.816	-0.799	-0.781	0.254	
Site 4	3.913***	3.540***	3.470***	0.039	-0.791	-0.625	
Site 5	2.982***	4.516***	3.156***	2.273**	0.222	-2.196**	
			Vertical				
Allsites	2.413**			3.748***		2.829***	5.147***
	2.223*			3.998***		2.061*	4.924***
	0.337			0.628		-0.587	0.317
	-1.357			-0.438		-0.442	-0.998
	-3.671			-7.758***		-3.769***	-9.154***
Site 1	0.165			0.728		-0.240	0.542
	-1.746			-2.596**		-2.681**	-3.979***
	-3.248***			-3.559***		-2.602**	-5.127***
	-4.956***			-9.702***		-5.713***	-12.033***
Site 2	-1.945			-3.057***		-2.100*	-4.102***
	-3.690***			-3.984***		-2.063	-5.211***
	-5.194***			-9.457***		-4.852***	-11.439***
Site 3	-1.689			-0.940		0.094	-1.139
	-3.702***			-7.395***		-2.638**	-8.211***
Site 4	-2.293*			-6.737***		-2.810***	-7.223***

TABLE 3

SUSPENDED PARTICULATE DATA

FOREST SLASH BURNING

SIGNIFICANCE TESTS

Horizontal

INTERVAL		FIRE DAYS		FIRE+1 DAYS		WEEK DAYS	ALL DAYS
Allsites	1.822	4.397***	3.532***	1.512	0.756	-1.527	
Site 1	-0.083	1.278	0.877	1.268	0.910	-0.664	
Site 2	0.157	1.256	0.883	0.777	0.516	-0.518	
Site 3	1.651	2.078**	1.840	0.050	-0.237	-0.575	
Site 4	1.709	4.022***	3.212***	1.620	0.922	-1.402	
Site 5	1.650	2.958***	2.472**	0.627	0.180	-0.930	

TABLE 4
ALL SITES BY MONTH
SUSPENDED PARTICULATE DATA
FOREST SLASH BURNING
SIGNIFICANCE TESTS
Vertical

INTERVAL	FIRE DAYS	WEEK DAYS	SAT. & SUN.	ALL DAYS
All Data	2.969***	4.323***	2.101*	5.502***
	0.077	3.284*	2.819**	4.791***
	3.548***	5.805***	2.327*	6.487***
	0.077	3.997***	3.782	5.518***
	-2.183	-5.728***	-1.785	-5.805***
	-1.093	-2.592**	-2.484**	-4.260***
	-0.382	-1.153	-1.265	-1.466
	-1.251	-1.145	-0.594	-1.437
	-2.698*	-5.209***	-3.025***	-6.656***
August 1967	0.116	-1.743	-0.274	-1.885
	-1.019	0.974	-0.197	-0.122
	0.116	0.556	1.823	1.360
	-7.709***	-9.200***	-3.083***	-10.034***
	-3.660***	-6.028***	-3.205***	-8.036***
	-5.485***	-4.811***	-2.473**	-6.162***
	-6.066***	-4.636***	-2.466**	-6.181***
	-8.365***	-9.187***	-4.412	-11.724***
September 1967	-0.068	2.924***	0.096	1.995**
	0.0	2.022	2.238	2.822***
	-0.168	-7.564***	-3.685***	-8.809***
	-0.084	-4.550***	-3.912***	-7.095***
	-0.161	-3.439***	-3.001***	-4.921***
	-0.145	-3.316***	-2.759***	-4.881***
	-0.171	-6.745***	-4.499*	-9.252***
October 1967	0.068	-0.325	2.569*	1.555
	-4.491***	-11.471***	-3.603***	-11.161***
	-3.928***	-7.780***	-3.803***	-9.046***
	-2.758**	-6.378***	-2.867***	-6.923***
	-3.658***	-6.142***	-2.821***	-6.919***
	-4.764***	-11.605***	-5.420***	-12.224***
May 1968	-0.168	-9.677***	-5.441***	-10.756***
	-0.094	-6.336***	-5.206***	-8.408***
	-0.161	-4.869***	-4.375***	-6.741***
	-0.145	-4.705***	-5.212***	-6.839***
	-0.171	-13.158***	-15.417***	-17.060***
June 1968	1.560	2.759***	-0.854	1.288
	2.770**	4.376***	0.326	3.952***
	1.432	4.140***	1.057	3.946***
	-1.183	-2.402*	-2.254*	-3.746***
July 1968	0.312	1.456	1.032	2.436**
	-0.555	1.350	1.773	2.422**
	-2.178	-4.200***	-1.248	-4.200***
August 1968	-1.199	-0.044	0.597	-0.004
	-3.820***	-4.980***	-2.146*	-6.236***
September 1968	-2.460*	-4.755***	-3.366***	-6.332***

TABLE 5

SITE #1 BY MONTH
SUSPENDED PARTICULATE DATA
FOREST SLASH BURNING
SIGNIFICANCE TESTS

Vertical

INTERVAL	FIRE DAYS	WEEK DAYS	SAT. & SUN.	ALL DAYS
All Data	1.176	3.100***	2.051	3.870***
	0.069	1.606	1.138	2.099*
	1.822	3.352***	1.774	4.121***
	0.069	2.618	1.575	3.112***
	-0.891	-3.462***	-1.353	-3.644***
	-0.037	-2.392*	-1.976	-2.819**
	-1.173	-0.724	0.102	-0.705
	-0.928	-0.658	-0.511	-1.093
	-1.832	-2.832	-2.118	-4.040***
August 1967	0.084	-1.482	-0.907	-1.633
	0.496	1.400	0.181	1.231
	0.084	1.489	0.757	1.871
	-2.636	-6.754***	-3.072***	-7.607***
	-1.212	-5.317***	-3.007***	-6.053***
	-2.590	-4.581***	-1.877	-4.975***
	-2.802	-4.016***	-2.864**	-5.468***
	-3.490	-8.463***	-5.602***	-10.663***
September 1967	-0.055	2.117	0.948	2.222*
	0.0	1.896	1.059	2.244
	-0.005	-4.396***	-2.018	-4.973***
	-0.071	-3.320***	-2.205	-3.936***
	-1.001	-2.214*	-0.849	-2.578**
	-0.137	-1.986	-1.530	-2.961***
	-0.002	-4.312***	-3.185*	-6.178***
October 1967	0.055	-0.045	0.890	0.513
	-2.092	-5.788***	-2.820**	-6.791***
	-1.654	-4.676***	-2.658*	-5.536***
	-1.955	-4.439***	-1.863	-4.806***
	-2.385	-3.913***	-2.925**	-5.196***
	-2.871	-6.587***	-10.272***	-8.531***
May 1968	-0.005	-5.380***	-2.197	-5.796***
	-0.071	-4.322***	-1.949	-4.547***
	-1.001	-4.474***	-1.629	-4.581***
	-0.137	-3.773***	-2.401*	-4.900
	-0.002	-17.750***	-6.893***	-13.574***
June 1968	0.923	0.661	-0.648	0.576
	-2.028	2.737**	1.143	2.656**
	0.301	2.490*	0.729	2.347*
	-1.335	-0.658	-1.241	-1.718
July 1968	-1.212	1.729	1.504	1.784
	-0.950	1.578	1.255	1.499
	-1.859	-1.159	-0.378	-1.953
August 1968	1.421	0.023	-0.568	-0.370
	-0.158	-3.527***	-2.483*	-4.508***
September 1968	-1.666	-3.004***	-2.486	-4.224***

TABLE 6

SITE #2 BY MONTH
SUSPENDED PARTICULATE DATA
FOREST SLASH BURNING
SIGNIFICANCE TESTS
Vertical

INTERVAL	FIRE DAYS	WEEK DAYS	SAT. & SUN.	ALL DAYS
All Data	0.087	2.242	0.082	2.473
	0.087	2.756**	1.309	3.260***
	1.577	2.641*	1.564	3.210***
	0.087	1.373	1.226	1.901
	-1.478	-2.604*	-0.998	-3.033***
	0.562	-0.013	0.189	0.157
	-0.212	-0.913	0.208	-0.664
	-1.830	-3.493***	-2.752**	-4.749***
	0.087	0.071	0.082	0.076
August 1967	0.0	-1.844	-0.077	-1.956
	-0.076	-0.974	-0.127	-1.616
	0.0	-8.049***	-1.004	-7.554***
	-0.007	-5.254***	-0.069	-4.499***
	-0.252	-3.685***	-0.061	-3.738***
	-0.003	-4.339***	-0.107	-4.345***
	-0.002	-3.772***	-0.175	-4.778***
	0.0	0.014	0.0	0.014
September 1967	-0.076	0.898	0.512	0.572
	0.0	0.374	0.762	0.788
	-0.007	-5.773***	-1.703	-5.975***
	-0.252	-2.143	-0.635	-2.513*
	-0.003	-4.132***	-0.974	-4.133***
	-0.002	-5.818***	-3.909***	-7.513***
	0.0	0.088	0.077	0.086
October 1967	0.076	-0.220	0.917	0.424
	-2.680	-5.063***	-2.080	-5.803***
	-1.050	-2.280	-1.117	-2.797**
	-1.331	-3.972***	-1.719	-4.318***
	-2.907	-4.753***	-6.061***	-7.078***
	0.076	0.062	0.127	0.079
May 1968	-0.007	-4.249***	-1.362	-4.284***
	-0.252	-2.280*	-0.924	-2.821**
	-0.003	-2.977*	-1.532	-3.529***
	-0.002	-3.230***	-4.398***	-4.846***
	0.0	0.354	1.004	0.397
June 1968	5.987***	2.623*	0.746	3.070***
	2.510	2.477*	1.051	2.923**
	-0.556	-0.920	-1.316	-1.562
	0.007	0.124	0.069	0.107
July 1968	-1.501	-0.831	-0.043	-0.870
	-4.550*	-2.583**	-2.477*	-4.414***
	0.252	0.111	0.061	0.116
August 1968	-2.044	-3.016***	-3.560***	-4.709***
	0.003	0.124	0.107	0.126
September 1968	0.002	0.082	0.175	0.103

TABLE 7

SITE #3 BY MONTH
SUSPENDED PARTICULATE DATA
FOREST SLASH BURNING
SIGNIFICANCE TESTS
Vertical

INTERVAL	FIRE DAYS	WEEK DAYS	SAT. & SUN.	ALL DAYS
All Data	2.098	1.164	0.184	1.619
	0.091	2.852***	2.075	3.798***
	2.173	3.053***	1.087	3.456***
	0.091	1.611	1.427	2.268
	-1.833	-3.365***	-0.885	-3.457***
	-0.343	-0.874	-0.146	-1.146
	-0.537	-1.361	-2.151	-2.332*
	-1.024	0.111	0.411	-0.008
	-1.353	-3.180**	-1.608	-3.814***
August 1967	0.006	1.182	1.139	1.517
	-0.917	1.794	0.708	1.658
	0.006	0.756	0.996	1.144
	-13.841***	-3.562***	-0.759	-3.926***
	-3.279***	-1.494	-0.237	-2.148*
	-13.068***	-1.770	-1.514	-2.779***
	-6.614***	-0.754	0.155	-1.223
	-11.252***	-3.405**	-1.333	-4.299***
September 1967	-0.102	1.343	-0.477	0.246
	0.0	0.045	0.286	0.235
	-0.007	-6.670***	-2.312*	-6.684***
	-0.127	-3.441***	-1.625	-4.480***
	-0.013	-3.594***	-2.846*	-4.377***
	-0.170	-2.367*	-1.277	-3.246***
	-0.006	-6.873***	-2.500	-7.319***
October 1967	0.102	-1.493	1.840	0.109
	-4.434***	-8.009***	-2.226*	-7.708***
	-2.913**	-4.277***	-1.475	-5.111***
	-2.698**	-4.008***	-2.670*	-5.185***
	-3.621	-3.141***	-1.110	-3.718***
	-3.768***	-14.422***	-6.071***	-12.245***
May 1968	-0.007	-5.181***	-2.385*	-5.452***
	-0.127	-2.466*	-1.853	-3.592***
	-0.013	-2.379*	-2.356*	-3.535***
	-0.170	-1.638	-1.834	-2.613**
	-0.006	-10.332***	-6.882***	-12.991***
June 1968	2.340*	2.323*	0.669	2.299*
	5.269*	1.653	-1.238	0.783
	2.175	3.206***	1.347	3.182***
	1.423	-1.330	-1.337	-1.850
July 1968	-0.493	-0.383	-1.654	-1.127
	-1.092	0.846	0.579	1.017
	-1.651	-2.997**	-1.862	-3.817***
August 1968	-0.705	1.163	2.236	1.917
	-3.003	-2.167	0.001	-2.021
September 1968	-1.103	-3.561***	-2.864*	-4.434***

TABLE 8

SITE #4 BY MONTH
SUSPENDED PARTICULATE DATA
FOREST SLASH BURNING
SIGNIFICANCE TESTS
Vertical

INTERVAL	FIRE DAYS	WEEK DAYS	SAT. & SUN.	ALL DAYS
All Data	0.116	0.286	0.089	0.404
	0.116	1.694	1.131	2.493
	1.932	2.862*	1.413	2.965***
	0.116	2.648*	2.096	3.539***
	-1.382	-3.398***	-0.737	-3.056***
	-1.279	-1.249	-2.260	-3.094***
	0.656	-0.151	-0.610	-0.236
	0.858	0.949	0.911	1.691
	-1.013	-2.739*	-1.006	-2.993***
August 1967	0.0	0.332	-0.073	0.317
	-0.082	2.694*	-0.198	0.821
	0.0	1.647	-0.005	2.077
	-0.006	-1.950	-0.089	-1.410
	-0.230	-0.914	-0.134	-1.554
	-0.111	-0.297	-0.078	-0.447
	-1.003	0.044	-0.097	0.080
	-0.008	-7.303***	-0.190	-3.627***
September 1967	-0.082	2.017	0.438	0.873
	0.0	1.992	1.322	2.402*
	-0.006	-5.027***	-1.396	-4.815***
	-0.230	-2.744**	-2.720*	-5.049***
	-0.111	-1.424	-1.210	-2.160*
	-1.003	-0.540	-0.156	-0.610
	-0.008	-4.842***	-1.587	-5.318***
October 1967	0.082	0.690	2.976	2.136
	-2.302	-7.049***	-1.946	-5.556***
	-3.121**	-4.623***	-4.559***	-5.948***
	-0.792	-2.603**	-1.702	-2.779***
	-0.090	-2.016	-0.759	-1.416
	-1.998	-13.374***	-4.440**	-7.440***
May 1968	-0.006	-5.605***	-2.428*	-5.644***
	-0.230	-3.823***	-4.716***	-6.138***
	-0.111	-2.325*	-2.129	-3.394***
	-1.003	-1.905	-1.880	-2.665**
	-0.008	-7.786***	-6.193***	-9.349***
June 1968	1.308	1.940	-1.470	-0.010
	2.460	2.567**	0.040	2.222*
	5.048	3.635***	1.365	3.970***
	1.040	-0.522	-0.497	-0.884
July 1968	2.326	0.870	1.355	2.312*
	2.618	1.784	3.106**	4.159***
	-0.603	-2.245	0.995	-0.954
August 1968	0.564	0.792	1.181	1.504
	-2.014	-2.328*	-0.477	-2.640**
September 1968	-5.197	-3.277**	-1.904	-4.439***

TABLE 9
SITE #5 BY MONTH
SUSPENDED PARTICULATE DATA
FOREST SLASH BURNING
SIGNIFICANCE TESTS
Vertical

INTERVAL	FIRE DAYS	WEEK DAYS	SAT. & SUN.	ALL DAYS
All Data	0.097	0.309	0.110	0.270
	0.097	-0.987	0.721	-0.095
	1.821	2.381*	-0.537	1.995
	0.097	1.680	2.910	2.908**
	-0.398	-1.075	0.155	-0.596
	-1.248	-0.631	-1.121	-2.066*
	0.714	0.213	-0.579	0.219
	-0.389	0.782	0.412	0.875
	-0.992	-1.601	-1.006	-2.152*
August 1967	0.0	-0.525	-0.086	-0.247
	-0.052	1.009	-0.073	0.364
	0.0	0.841	-0.014	1.295
	-0.006	-1.101	-0.142	-0.604
	-0.214	-0.733	-0.112	-0.980
	-0.014	-0.183	-0.157	-0.197
	-0.006	-0.025	-0.100	-0.022
	-0.003	-2.457*	-0.985	-1.861
September 1967	-0.052	2.485*	-0.757	1.510
	0.0	1.787	2.068	2.391*
	-0.006	-0.083	-0.480	-0.380
	-0.214	0.235	-1.306	-1.440
	-0.014	0.773	-1.005	0.218
	-0.006	1.164	-0.224	0.658
	-0.003	-0.763	-1.271	-1.708
October 1967	0.052	-0.022	2.312	1.476
	-1.157	-4.411***	0.585	-2.394*
	-2.550*	-3.496***	-0.259	-3.331***
	-0.436	-1.694	0.083	-1.429
	-1.152	-1.397	0.637	-0.959
	-1.528	-5.633***	-0.364	-3.529***
May 1968	-0.006	-3.489***	-3.744***	-4.081***
	-0.214	-2.693**	-3.535***	-4.408***
	-0.014	-1.213	-4.611***	-2.531**
	-0.006	-1.001	-2.542*	-2.117*
	-0.003	-5.417***	-30.960***	-5.792***
June 1968	-0.603	0.491	-1.191	-1.426
	4.454***	0.982	-0.786	0.690
	0.026	1.476	0.239	1.212
	-1.057	-1.496	-1.480	-2.287*
July 1968	3.027	0.626	0.509	1.827
	0.621	1.079	1.182	2.298***
	-0.621	-1.676	-0.174	-0.815
August 1968	-4.446*	0.372	0.845	0.475
	-3.248	-1.394	-0.856	-2.135
September 1968	-1.073	-1.795	-1.244	-2.457*

TABLE 10

PLUME DISPERSION AND INTERCEPT DATA, MONTANA, 1968-69

IDENT NO.	DATE	TIME	ALT Ft*	WIND DEG/mps	X km	σ_y m
1	7/ 3/68	1912	7000	350/5.9	27	896
2		1920	8200	350/5.9	40	955
3		1924	8000	350/5.9	48	1310
4		1933	8000	350/5.9	58	1520
5	7/ 5/68	2241	5800	290/2.5	5	167
6	7/ 5/68	2244	6200	290/2.5	14	454
7	7/16/68	2213	6000	180/3.0	9.5	454
8		2232	6000	180/3.0	17	990
9		2237	6000	180/3.0	5	259
10	7/24/68	2151	7000	260/6.0	18	463
11	7/24/68	2211	5500	280/2.6	17	677
12		2214	5000	280/2.6	10	700
13		2219	3000	305/1.0	20	617
14	7/26/68	2250	6200	320/2.5	21	598
15	8/ 7/68	2237	5700	235/12	13	687
16	8/30/68	1918	5500	290/11.7	47	2200
17		1924	5500	290/11.7	50	2770
18		1930	5000	290/11.7	45	2480
19		1842	4500	290/11.7	28	1240
20	6/17/69	2245	3600	005/3.3	10	346
21	6/17/69	2247	3600	005/3.3	11	570
22		2248	3600	005/3.3	12	346
23		2249	3600	005/3.3	14	766
24		2252	3600	005/3.3	15	514
25		2253	3600	005/3.3	16	570
26	7/14/69	2259	1500	270/8.0	5.3	197
27		2301	1500	270/8.0	6.2	321
28		2304	1500	270/8.0	7.5	447
29		2306	1500	270/8.0	8.9	588
30	7/18/69	2312	5100	240/6.8	29	1310
31	9/28/70	1508	4100	no obs.	32	1425
32		1512	4100	no obs.	40	2200
33		1520	4100	no obs.	37	1850
34		1524	4100	no obs.	43	2050

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*Above an average 5,000 ft terrain.

TABLE 11

PLUME DISPERSION AND INTERCEPT DATA, AUSTRALIA, 1970*

DATE	NUMBER OF INTERCEPTS	AVERAGE ALTITUDE	AVERAGE CLOUD WIDTH (km)	INTERCEPT DISTANCE (km)	σ_y (m)
10/31/70	3	3,500	18.3	57.5	4270
11/10/70	3	7,000	7.5	13.0	1750
	1	6,000	28.2	66.8	6590
12/ 7/70	3	10,000	17.0	66.8	3970
12/11/70	1	2,000	11.7	42.5	2730
12/16/70	1	2,500	19.4	38.0	4530
	1	2,500	25.9	62.1	6050

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*Ref: Vines, et al. 1971, Table 7.

TABLE 12

AVERAGE SPECIES DISTRIBUTION

	Larch	Douglas fir	True fir	Spruce	All pine
Miller Creek	25.7%	30.6%	6.5%	31.1%	6.2%
Newman Ridge	26.4%	33.6%	7.3%	2.8%	28.5%

TABLE 13
AVERAGE PREBURN FUEL SIZE CLASS

Aspect	Duff	Needles	0-1	1-10	>10
	Size classes, cm				
	tons/acre				
	Miller Creek				
North	22	1.66	1.33	8.92	107.84
East	41	1.64	1.38	11.61	94.91
South	24	1.36	1.17	10.24	107.55
West	18	1.48	1.26	8.57	94.77
	Newman Ridge				
North	52	1.39	1.06	8.56	94.76
East	56	1.00	0.83	9.10	86.10
South	48	1.78	1.36	12.99	83.17
West	42	1.39	1.20	12.22	97.81

TABLE 14
PERCENTAGE FUEL BURNED

Duff Min	Duff Max	Needles	0-1 cm	1-10 cm	>10 cm	Total
			Miller Creek			
0.1%	100%	100%	87%	69%	60%	61%
			Newman Ridge			
36.0%	52%	100%	92%	88%	55%	60%

TABLE 15

PARTICULATE EMISSION FACTORS
(Kg particulate/metric ton fuel)

	WSU	UCR
Larch Needles	5.8	
Larch Twigs 0-1 cm	9.3	
Larch Twigs 1-2.5 cm	3.3	
Larch Needles and Twigs		5.1
Douglas Fir Needles	4.8	
Douglas Fir Twigs 0-1 cm	3.8	
Douglas Fir Twigs 1-2.5 cm	3.3	
Douglas Fir Needles and Twigs		2.8
Duff	7.5	
Spruce		3.7

TABLE 16

ESTIMATED AVERAGE PARTICULATE EMISSIONS BY EXPOSURE ASPECT
(Kg/acre)

Aspect	UCR[1]	WSU[1]	WSU[2]	UCR[1]	WSU[1]	WSU[2]
		Miller Creek			Newman Ridge	
North	203	221	262	216	216	369
East	202	202	324	180	172	332
South	221	220	285	206	212	264
West	206	205	265	220	218	337

[1] without duff

[2] including duff

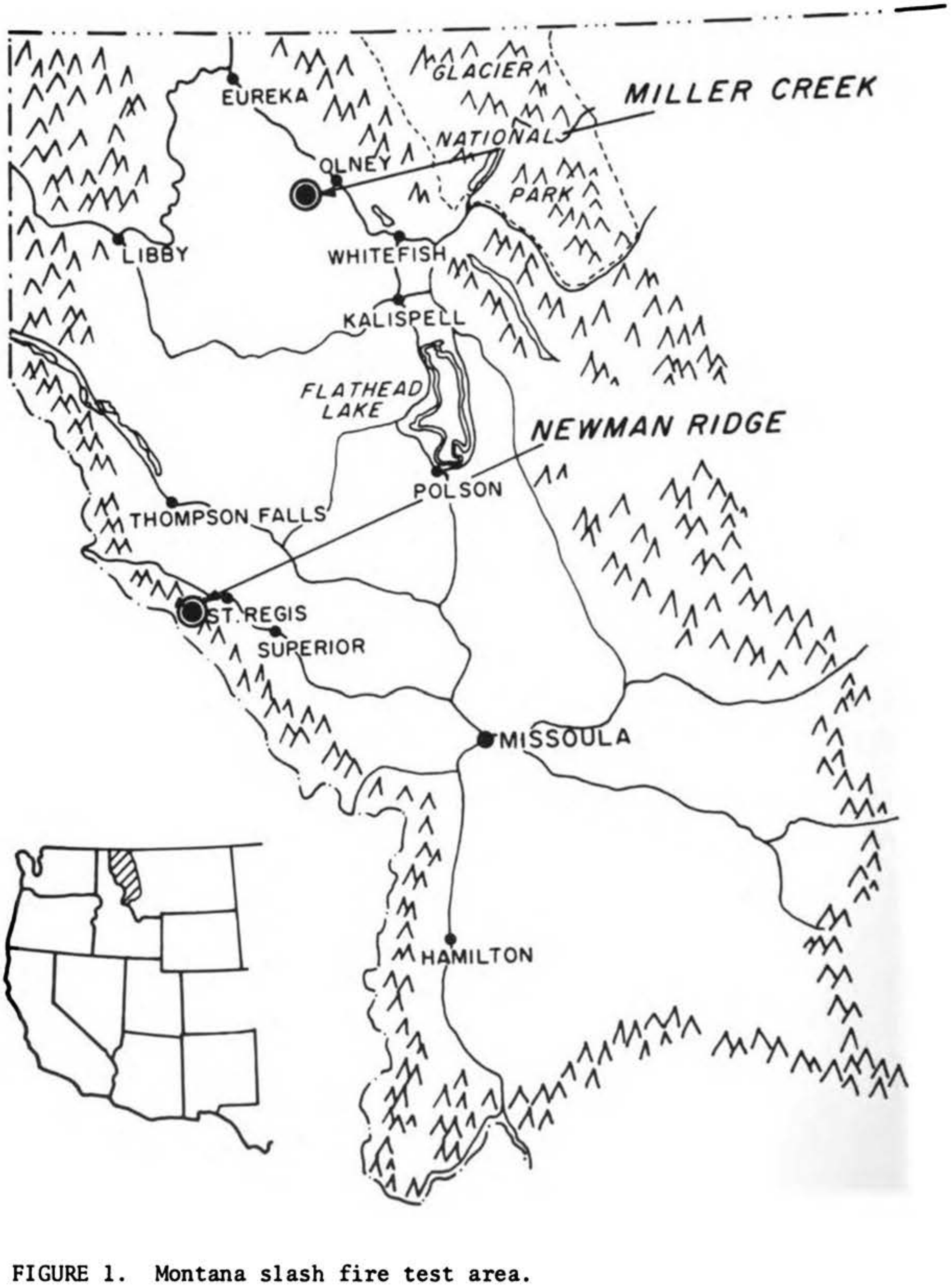

FIGURE 1. Montana slash fire test area.

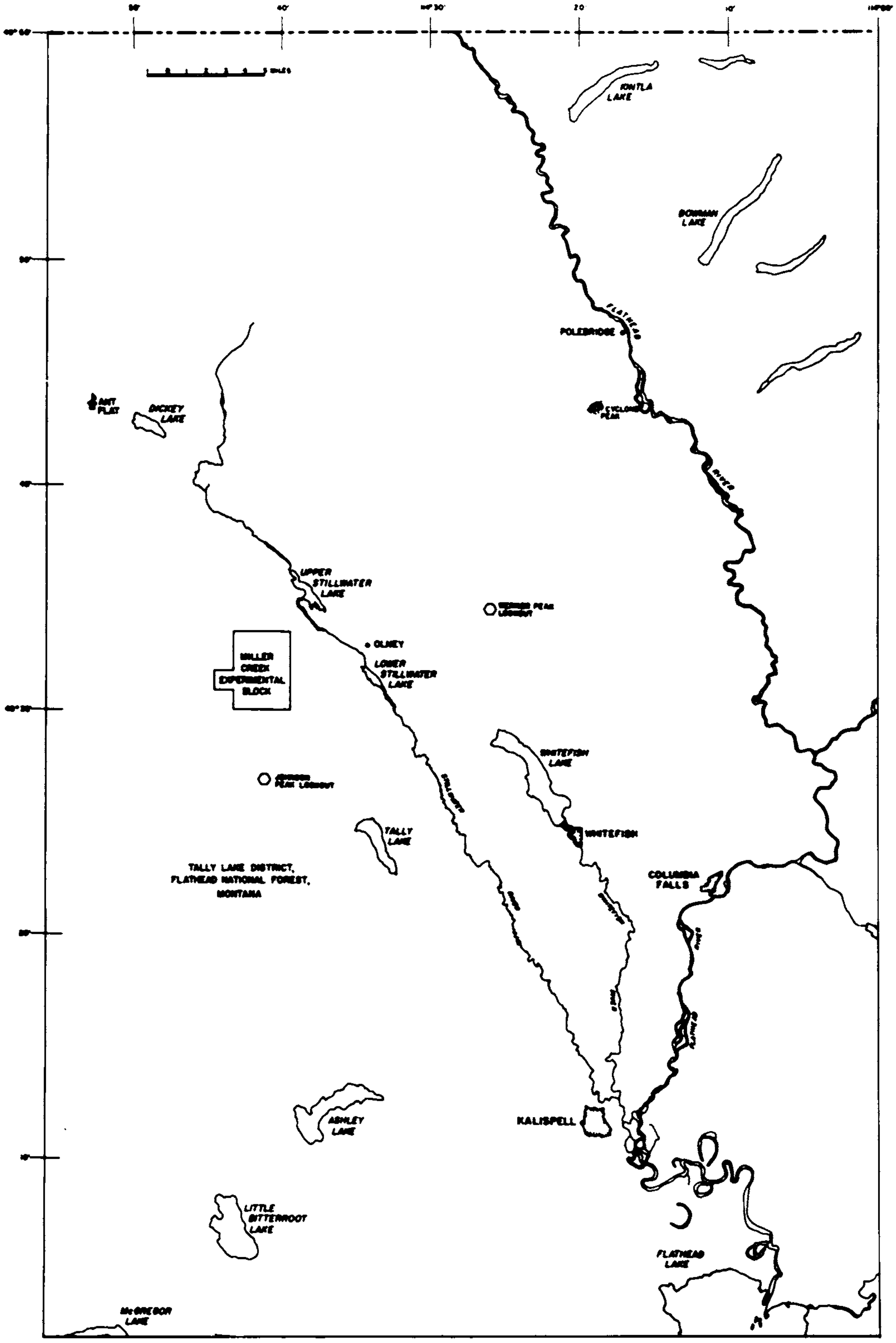

FIGURE 2. Miller Creek prescribed burn and ground sampling stations.

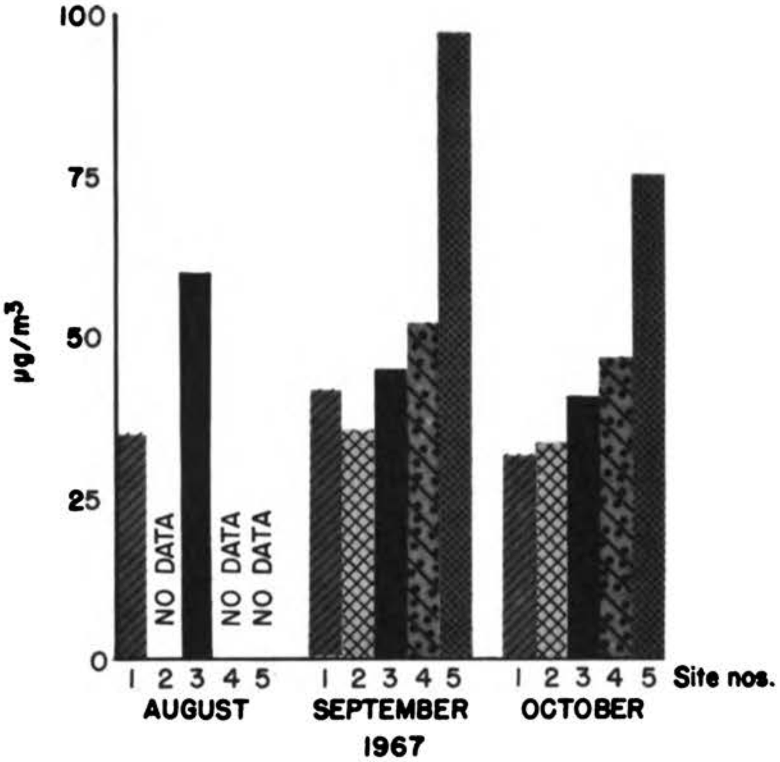

FIGURE 3. Monthly 24-hour average suspended particulate concentration.

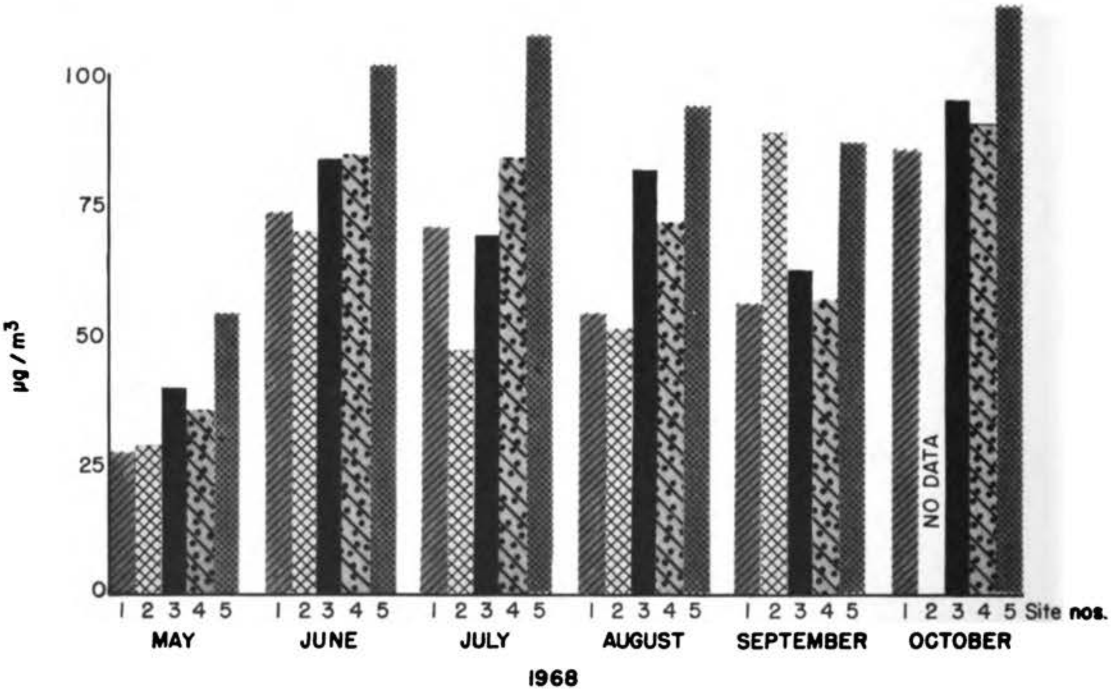

FIGURE 4. Monthly 24-hour average suspended particulate concentration.

FIGURE 5. Flathead Valley pollution sources.

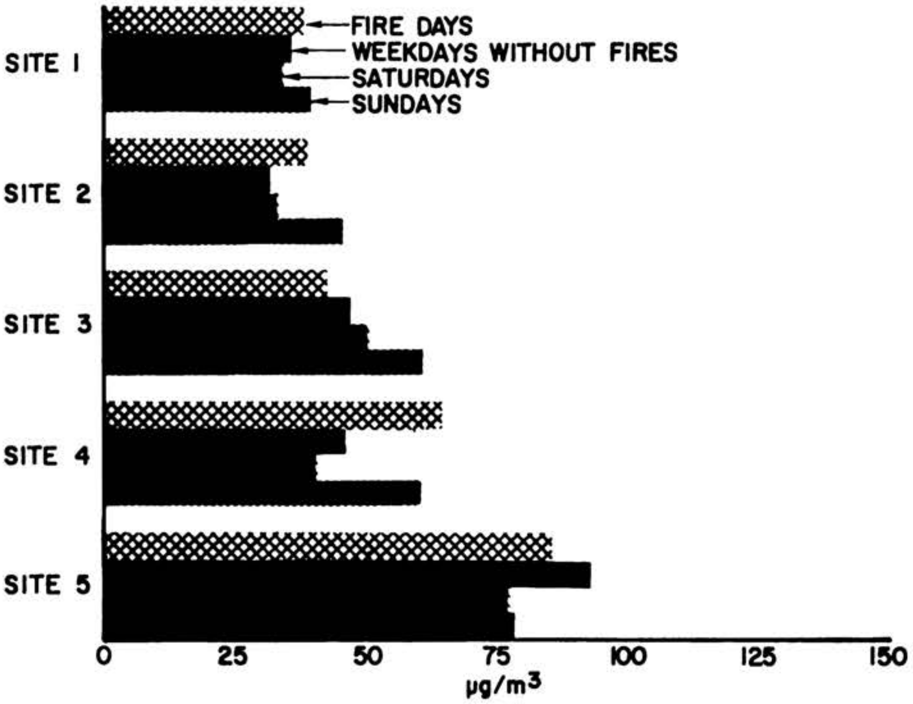

FIGURE 6. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends (August-October 1967).

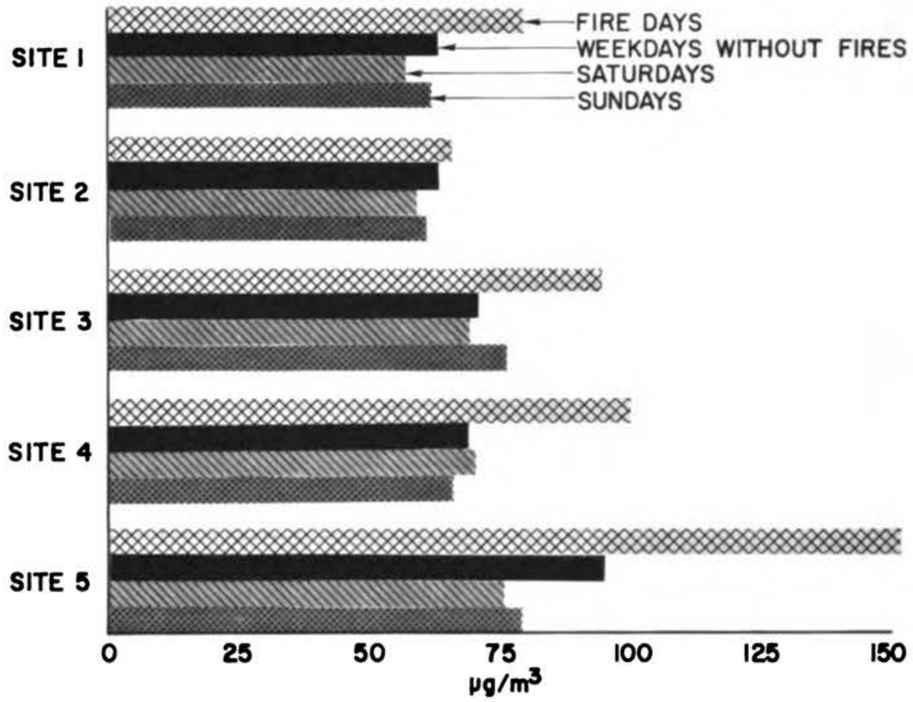

FIGURE 7. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends (June-October 1968).

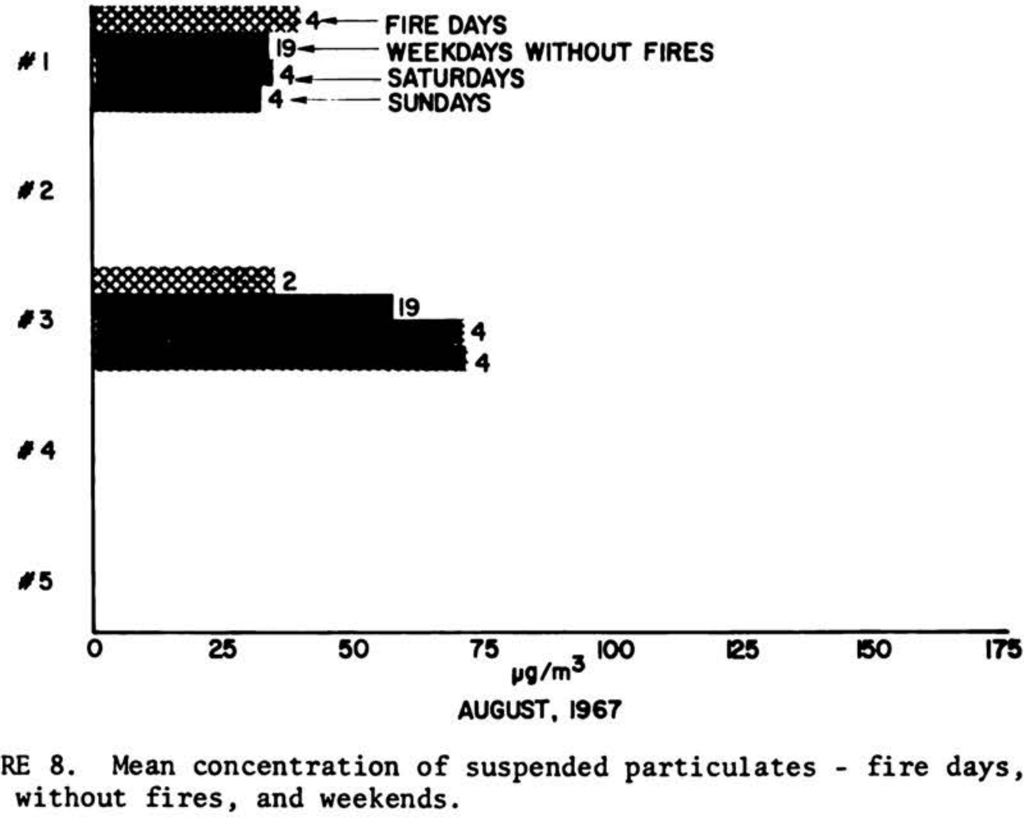

FIGURE 8. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

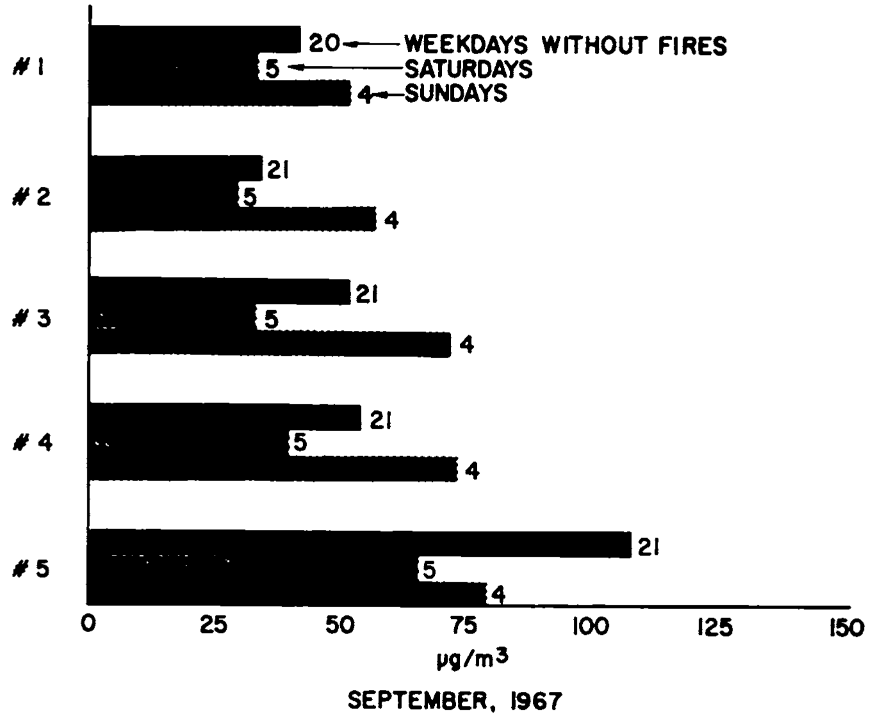

FIGURE 9. Mean concentration of suspended particulates - weekdays without fires and weekends.

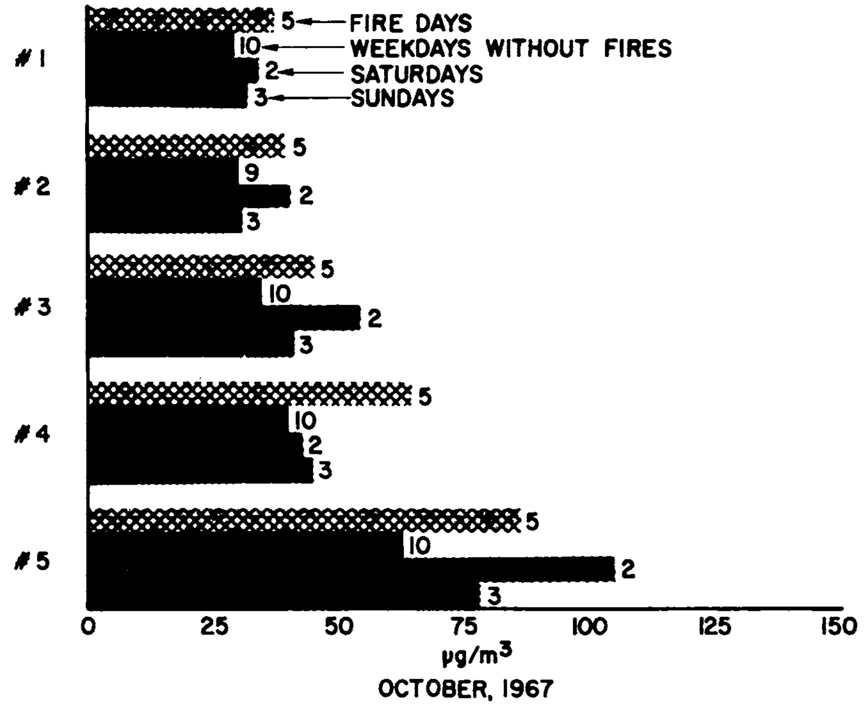

FIGURE 10. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

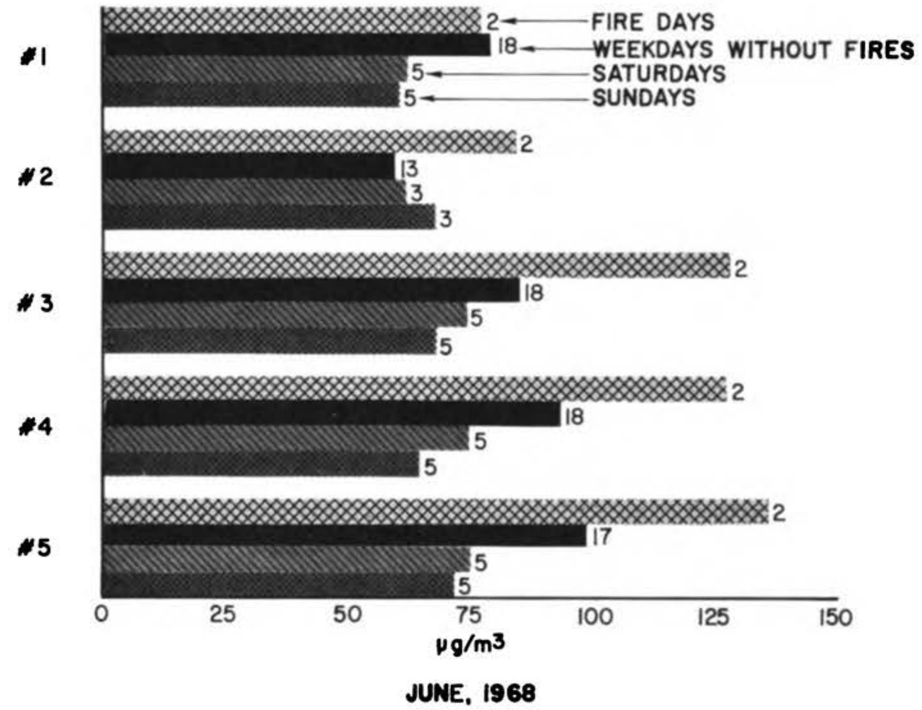

FIGURE 11. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

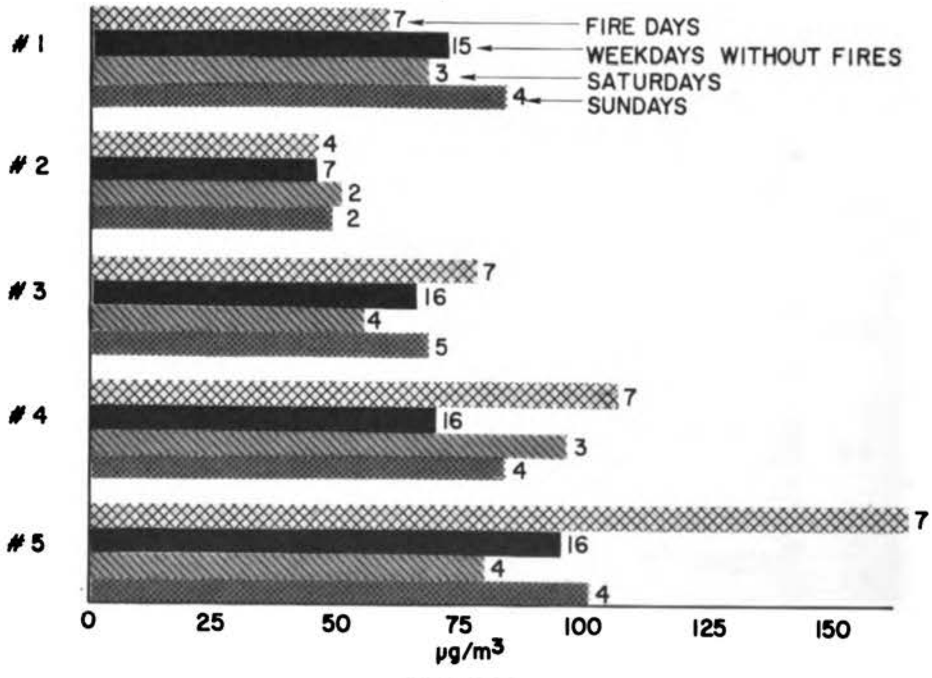

FIGURE 12. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

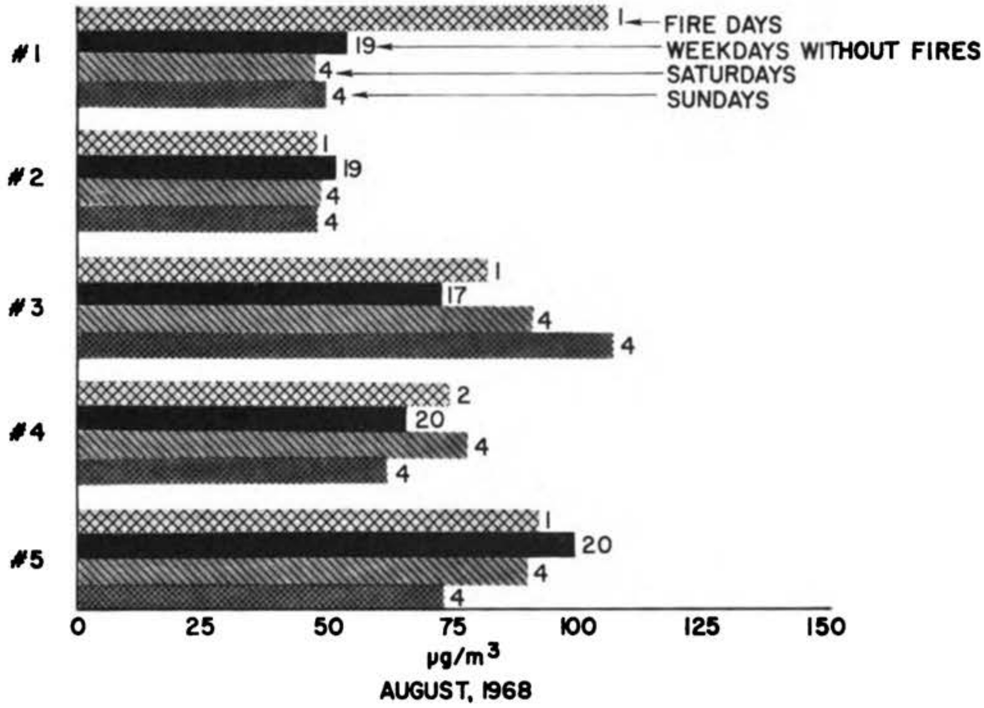

FIGURE 13. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

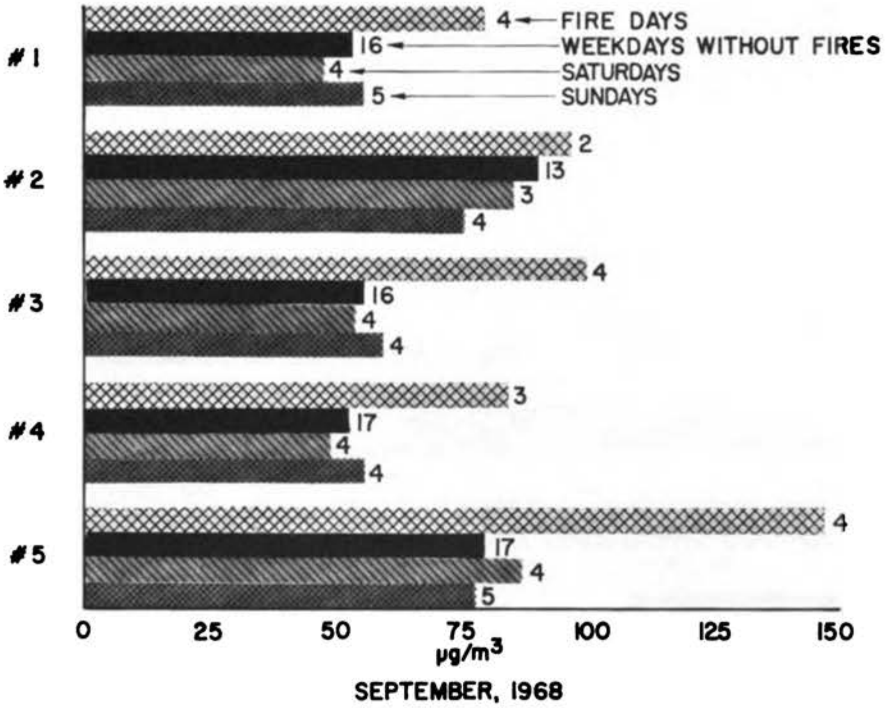

FIGURE 14. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

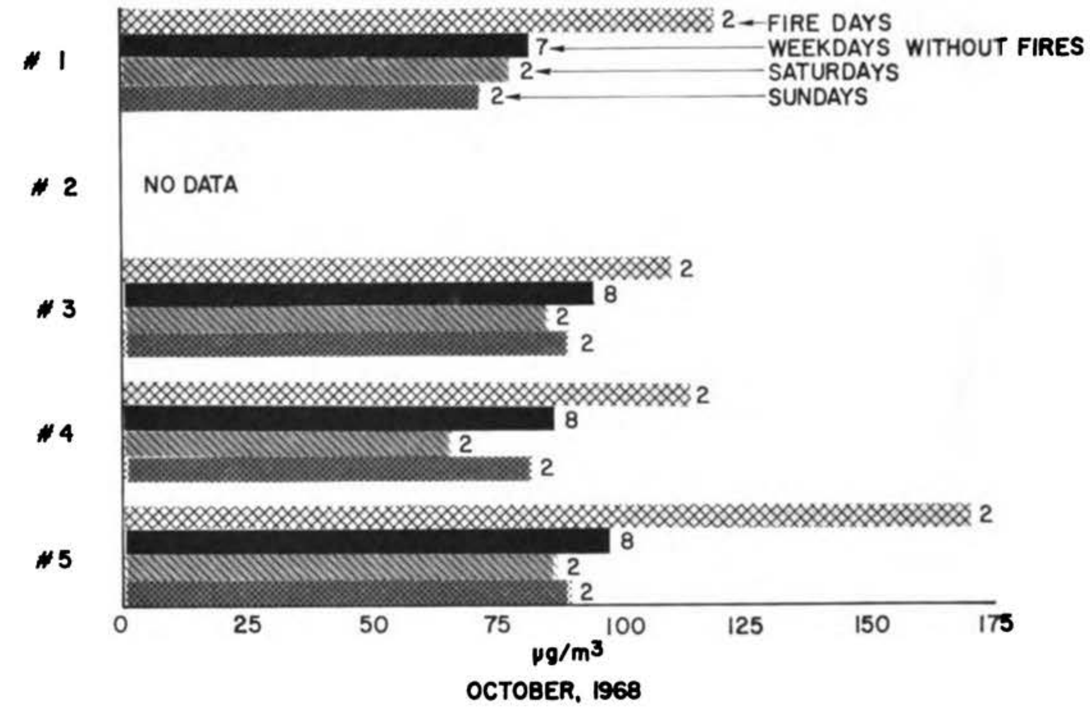

FIGURE 15. Mean concentration of suspended particulates - fire days, weekdays without fires, and weekends.

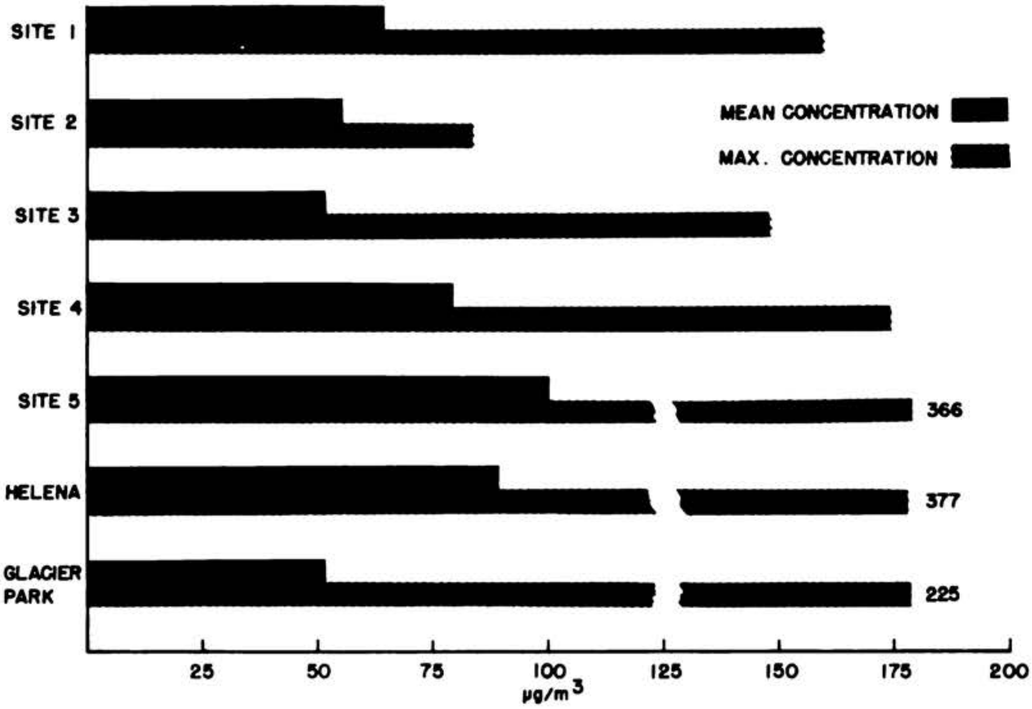

FIGURE 16. Summer comparison - concentration suspended particulates (June-August).

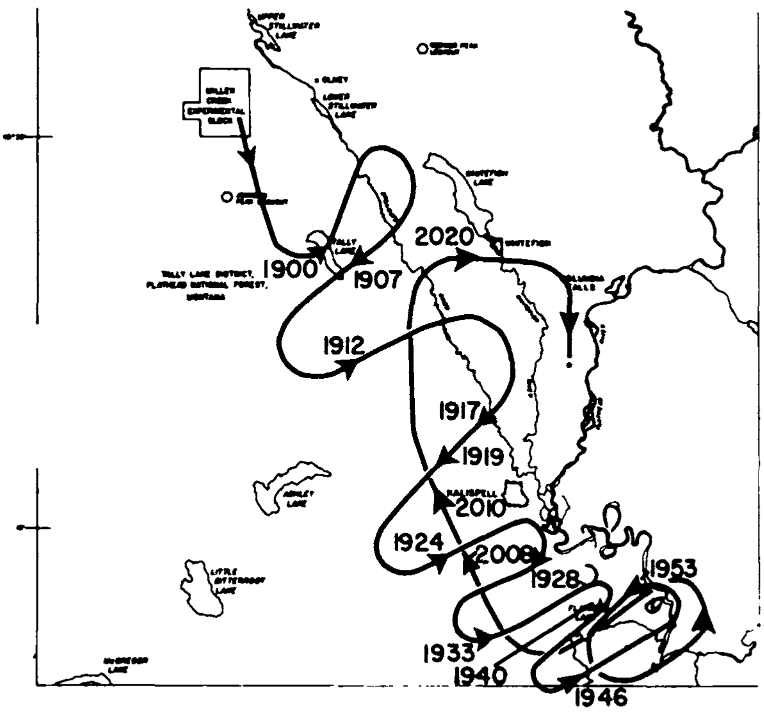

FIGURE 17. Flight #2, 7/3/68, S10 & S4.

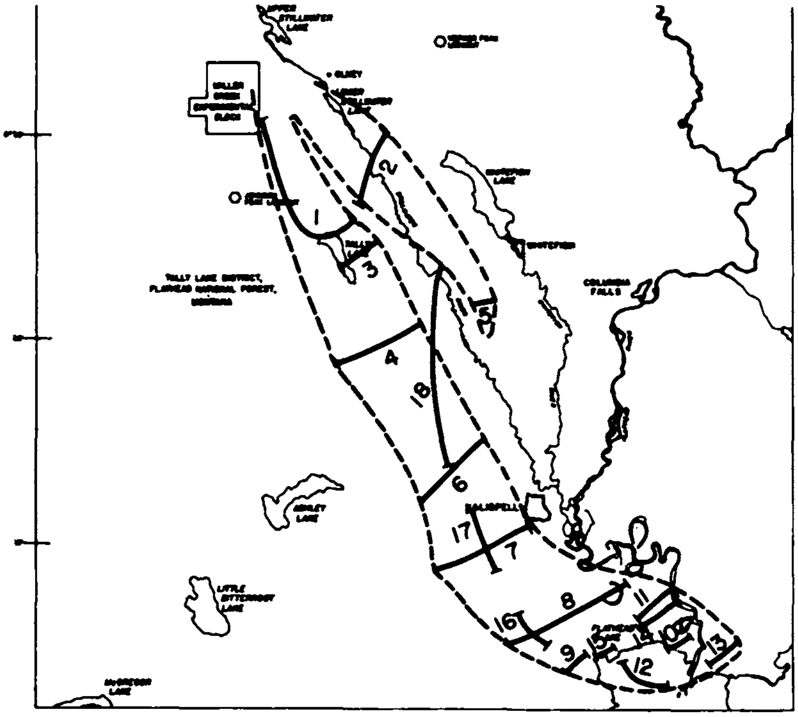

FIGURE 18. Flight #2, 7/3/68, S10 & S4.

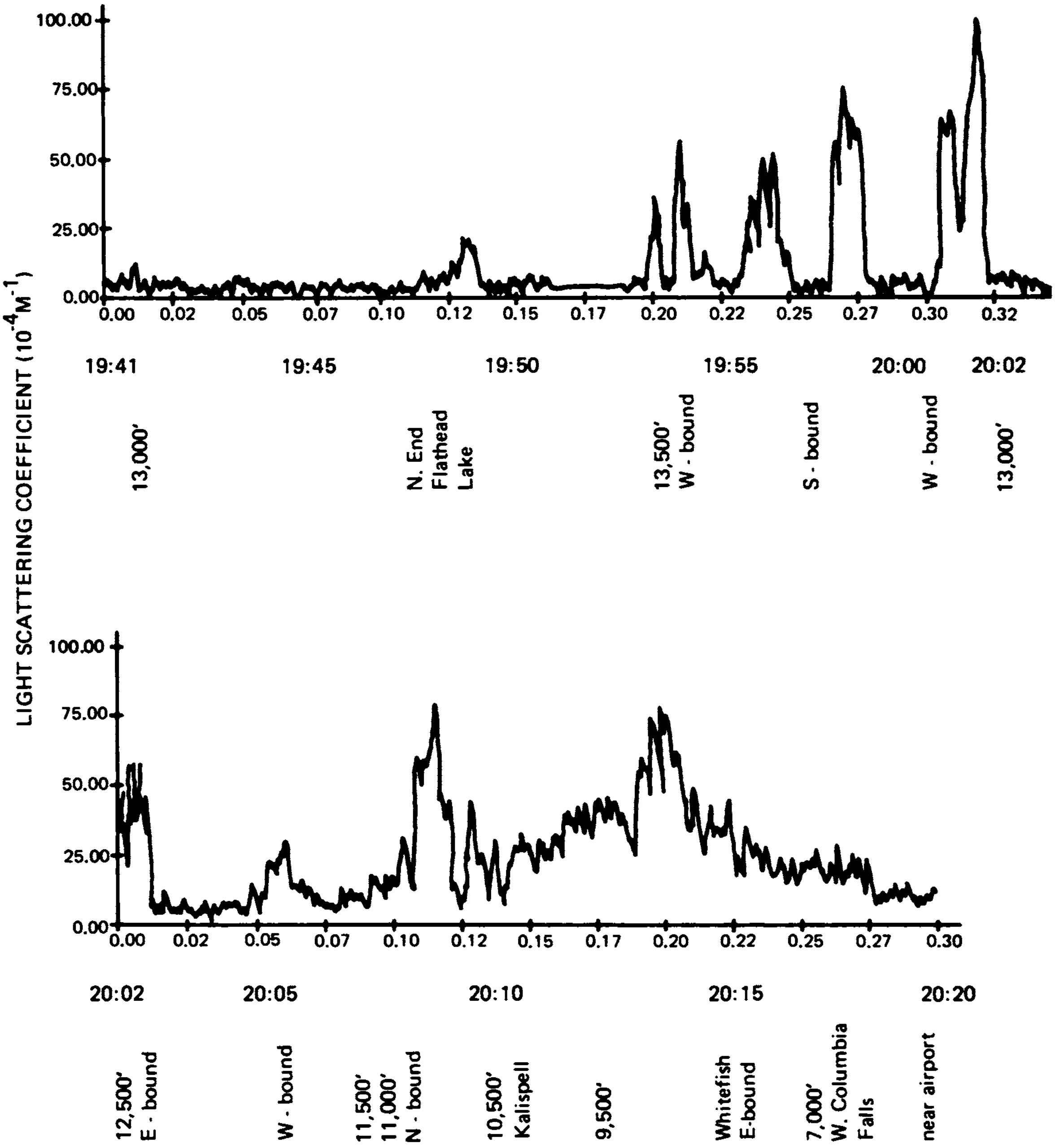

FIGURE 19. Light scattering profile - flight #2, July 3, 1968.

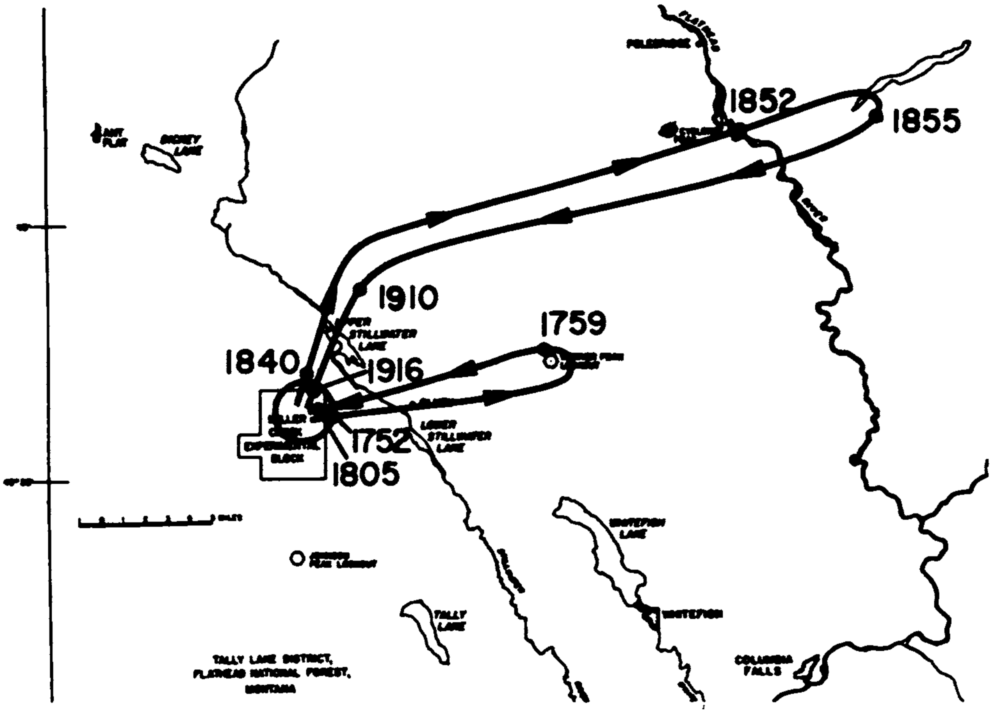

FIGURE 20. Flight #13, 9/9/68, E10 & E14.

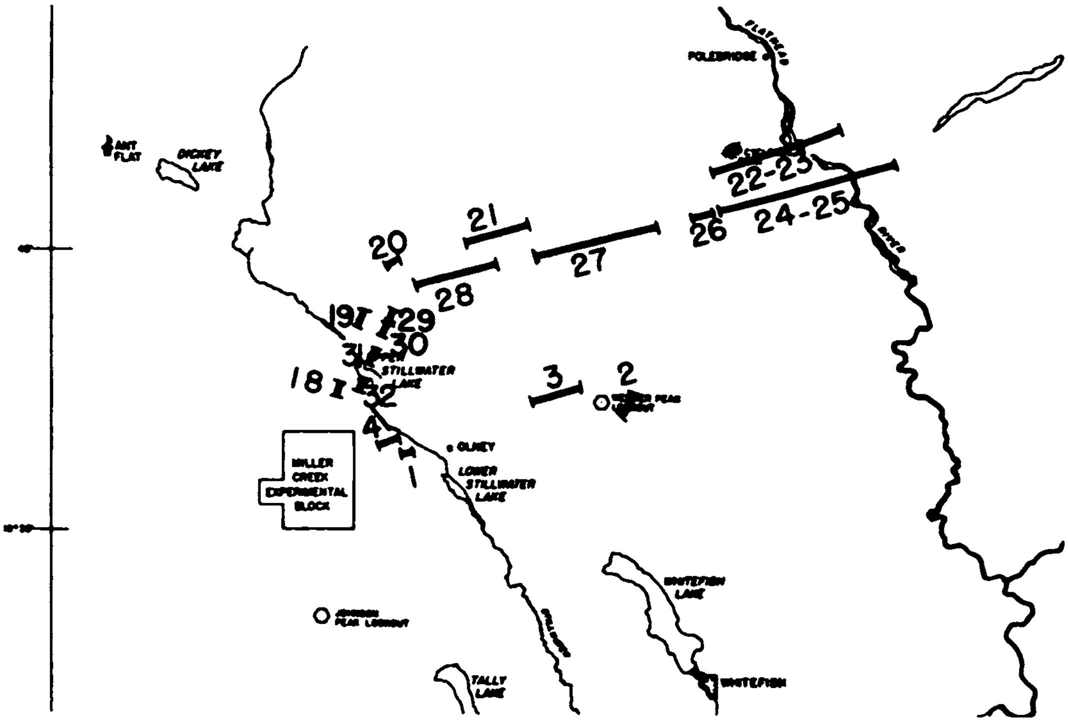

FIGURE 21. Flight #13, 9/9/68, E10 & E14.

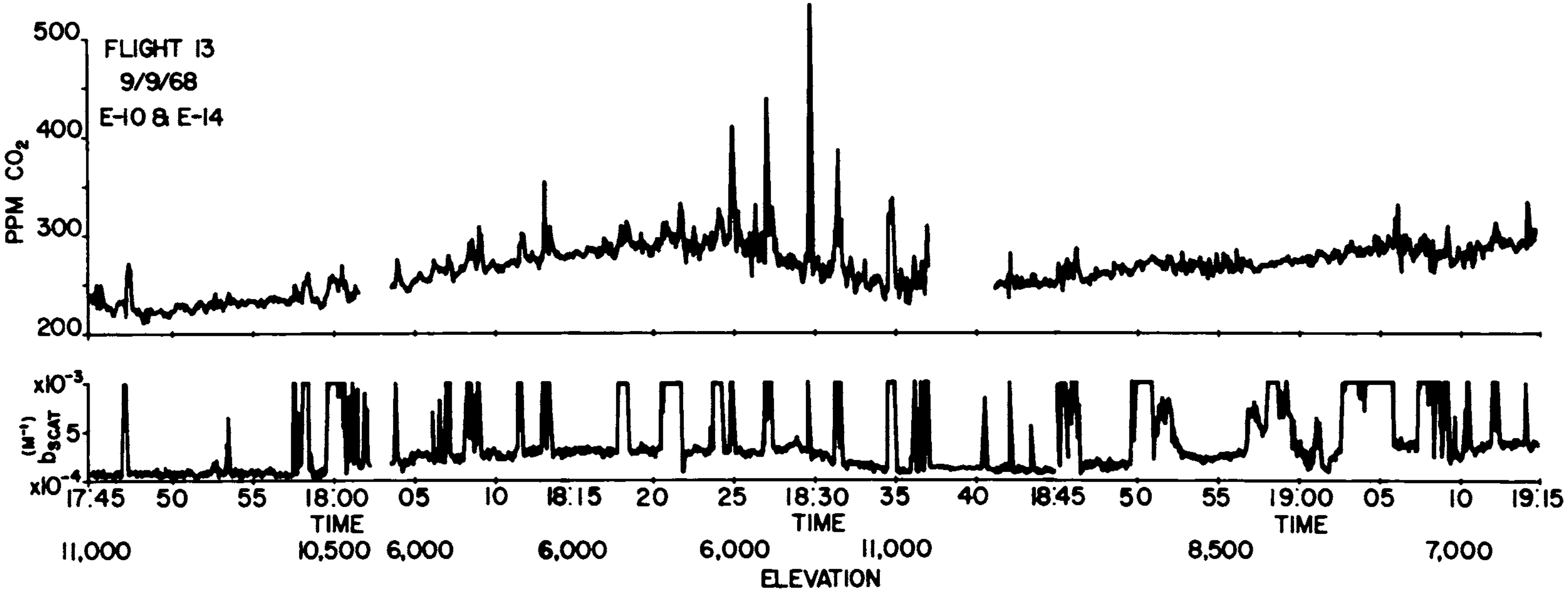

FIGURE 22. Light scattering and carbon dioxide profiles - flight #13, September 9, 1968.

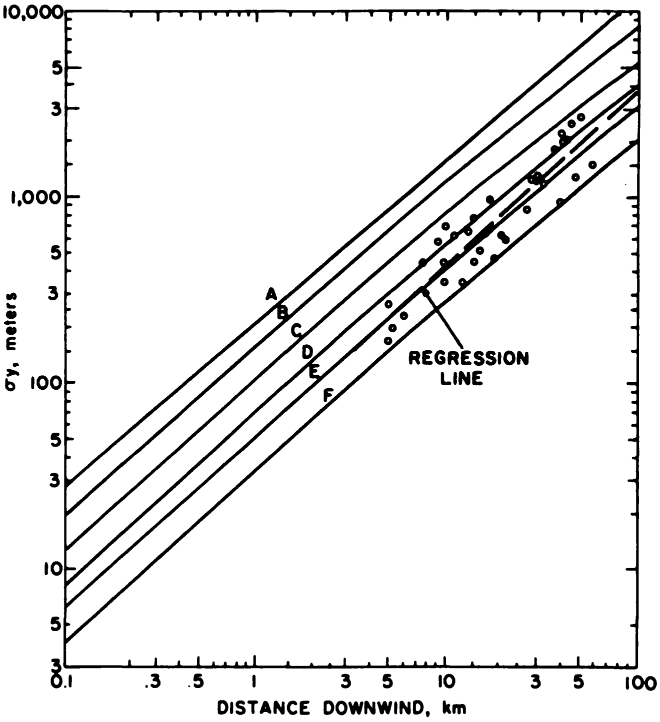

FIGURE 23. Lateral dispersion, Montana fire plumes, 1968-1970.

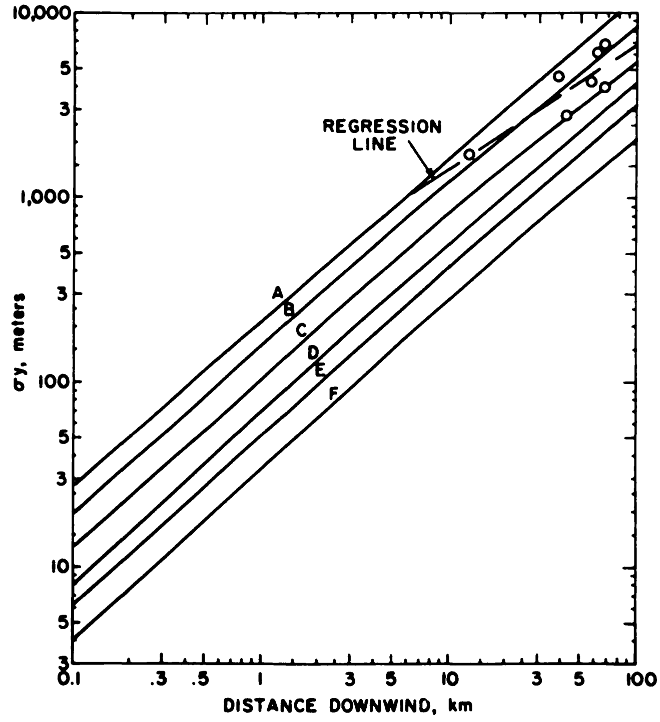

FIGURE 24. Lateral dispersion, Australian brush fire plumes, from Vines, et al.

New Technology for Determining Atmospheric Influences on Smoke Concentrations

Michael A. Fosberg
U. S. Forest Service

Introduction

The impact of man's activities on the mountain wild land environment has become, in the last few years, an item of national concern by both interested citizens' groups and public agencies responsible for management of these lands. If one were to rank the factors influencing man's activities and well being, air quality would certainly be near the top of the list. This ranking was dramatized by the strong public and legislative reaction following 1968 and 1969 summers in Oregon's Willamette valley when smoke from burning agricultural stubble and forest residues reduced visibility on major traffic arteries to dangerous levels.

Prediction and evaluation of the transport and concentrations are needed to prevent recurrence of such episodes. These predictions are fundamentally based on prediction and evaluation of the wind flow in mountains and the action of this flow, along with stability and turbulent dissipation of the smoke plumes.

One may now ask the fundamental question "What are the wind patterns in the mountain wild lands?" The answer is not readily available, simply because there are very few wind observations. One answer is to establish observation points. This solution has the drawbacks of the frequently prohibitive costs and the inaccessibility of many areas. A second answer is through extrapolation of a few data points to surrounding areas. This, too, has a drawback in that wind variations in complex topography are not readily definable. While none of the above drawbacks are insurmountable, a third solution has been developed which overcomes the strong dependence on many wind observations. This third solution, the numerical model, is based primarily on the thermal driving forces of the atmosphere, and is therefore amenable to evaluation through remote sensing of the thermal fields.

General Feature of the Model

The numerical model was derived from the curl and divergence of the Navier-Stokes equation of motion (Fosberg *et al.* 1972, Fosberg and Marlatt, 1973) and is intended to calculate the thermally driven flow patterns from the available data. Anderson (1971) and Lantz (1972) attempted similar solutions but required more assumption.

A fundamental assumption necessary to transform the equations into a diagnostic model was that the flow characteristics at some previous time were in steady state, and that they were accelerated to a new steady state by the thermal and frictional body forces. Since the time derivatives are zero at both states, the derivative will reach a maximum and then decay back to zero. Thus the mean value theorem may be used to evaluate the final equilibrium state provided we know the nature of the changes in the body forces, the time interval over which they operate, and the nature of the initial state.

This assumption contains an implication that the inertial terms in both equations have little influence on the magnitude of the final equilibrium condition. Thus the interaction of the thermal and kinematic fields are also neglected. The resultant wake effects downwind of a disturbing body force are distorted because of these implications. Except for the wake effect, these implications are of minor consequence in practical application.

Since the behavior of the time derivative is generally unavailable for local circulations, one-half of the maximum body force was used to express the time integral.

The model was adapted to mountainous terrain by transforming the flat computational plane to one that followed the natural undulations of the topography. Thus, the computational plane is a fixed height above the ground. Because the body forces involve pressure and temperature, hydrostatic equilibrium was assumed so that local buoyancy forces would not distort the pressure and temperature fields on the spatial scales of interest.

The frictional terms in the flow equations were defined by the low level wind shear and surface roughness.

The velocity derivatives with respect to the horizontal coordinates were neglected since they are of much smaller magnitude than those in the vertical. Thus assuming a constant eddy diffusivity and substituting the law of the wall into the Fickian term of the flow equations, the friction term is expressed as the shear and deformation of the friction velocity. The friction velocity was evaluated from the law of the wall, the micrometeorological roughness length, and the velocity of the undisturbed background flow. The roughness length is directly related to the nature of the underlying terrain and vegetation.

The wind velocity was calculated from the vorticity and divergence by separating the velocity into a rotational non-divergent component and a divergent irrotational component so that vorticity could be expressed in terms of a stream function and the divergence could be expressed by a velocity potential.

The boundary conditions for the solution were selected such that the divergence-produced accelerations were contained entirely within the computational domain. Boundary conditions for the stream function were chosen to allow inflow and outflow across the computational perimeter.

The integration coefficient was defined by the phase velocities of the divergence and vorticity produced disturbances and the finite difference grid size. The phase velocity was taken as the background wind for the vorticity solutions and the speed of sound for the divergence-produced circulation.

Flow across a long rough ridge under several conditions of stability, windspeed, and ridge surface temperatures were compared to an analytical solution of air drainage (Fleagle, 1950). Analyses of perturbation velocities for cases of no mean wind show excellent agreement (Fig. 1) with the analytical solution. Comparisons of the solution containing inertial terms also show excellent agreement and imply that flow superposition is valid.

Transport and Diffusion of Smoke

Application of the detailed wind calculations to smoke dispersion and management requires an additional calculation. The mass continuity of the airborne particulate matter can be calculated for every point in the domain for which the velocities are defined. The dynamical vertical motion was calculated from the divergence times the height of the turbulent boundary layer. The terrain-induced vertical motion was calculated from the wind normal to the mountain slope, and the resultant vertical motion from the sum of the two components. The vertical leakage by diffusion was approximated by a Fickian diffusion expression. The boundary layer eddy viscosity is taken to be directly proportional to height. The smoke source rate can be specified arbitrarily in magnitude and space to fit any particular application.

These calculations made with these assumptions show good agreement with classical diffusion calculations, numerical solutions, and a case study of a smoke plume (Fritschen, 1970) (Fig. 2). This numerical model shows a somewhat weaker diffusion close to the sources than do analytical solutions, but a stronger dissipation downwind. The case shown, that of a heated ridge, shows the influence of convective removal of material.

The transport equation is time-dependent and highly subject to computational stability and truncation errors.

The time steps for the diffusion calculation were defined by the maximum velocities of the disturbed flow and the grid spacing.

Application of the Model to Smoke Management

A number of case studies were analyzed with the flow model and dispersion equation. Data came from studies in the San Francisco Bay area (Fosberg and Schroeder, 1966), and in north central Colorado (Reeser and Marlatt, 1973). Both (outlined in Fig. 3) areas are characterized by complex topography: the Bay area by the coastal valleys and ridges separating the Pacific Ocean and the Sacramento-San Joaquin Valleys, and Colorado's North Park with a basin surrounded by high mountains.

Smoke emissions and resultant plumes representing possible source sites and rates were calculated for the California case of airflow.

The divergent pollution potential index (Reeser and Marlatt, 1973) was used to evaluate collection areas for the Colorado case. The airflow calculations were based on nocturnal mountain climatology (Hayes, 1941).

Calculations of the wind flow in central California were made for a day with a well-developed sea breeze with a shallow marine layer. A coarse computational grid (16 km) was used so that wind disturbances smaller than 60 km wavelength are not resolved properly. Thus flow deflections into small valleys such as the Russian River valley and the Bay breeze flowing westward to the Marin Peninsula are not resolved. Excluding these areas, the large-scale flow characteristics are depicted reasonably (Fig. 4). The anticyclonic flow just off shore, the strong inflow across the city of San Francisco, the northerly flow up San Francisco Bay, the westerly winds across the Berkeley Hills, and the northerly flow in the San Joaquin Valley are calculated with very little error. There are no directional errors in this area and less than 1 m sec^{-1} error in speed. Winds across the coast range also showed good agreement with observations. The most troublesome areas were winds through the Carquinez straits where the narrow valley increased windspeeds beyond model resolution, the Russian River valley lying across mean wind flow and narrower than model resolution, and the lower Sacramento Valley. Southerly winds would be expected in the lower Sacramento Valley rather than the westerly winds calculated.

While the first two problems can be related to grid resolutions, the wind errors near Sacramento are probably a result of the fact that the Sierra Nevada Mountains were not included in the computations.

The total errors associated with these data (including the unresolvable areas) and with data from a previously published analysis for Fort Collins give a windspeed error of ± 1.1 m sec^{-1} and a wind direction error of $\pm 20.7°$. There is a $\pm 11.25°$ uncertainty in the observations themselves, however.

Two sources of smoke were simulated in the model (Fig. 4). One, a small circular source Southeast of Mount St. Helena, had a weak disperse plume extending out to the Sacramento Valley. The other simulated a smoke source from the dead eucalyptus in the Berkeley Hills. This source was a large line. The calculated plume maintained high concentrations for 20 km before dissipating.

Data for the Colorado North Park area were defined from mountain climatology studies. The surface temperatures were defined as 0°C at the lowest point in the basin, and all temperatures along the walls were then determined from a 305 m inversion of 2.2°C/100 meters to simulate a nocturnal environment. Several flow characteristics are evident under a light south wind. The calculation (Fig. 5) predicted near-stagnation at low elevations along the southern part of the basin and along the ridge northwest of the basin. Highest windspeeds were above the inversion along the Park Range.

These areas of low windspeeds, when confined with convergence, define regions of very low dispersion potential for a smoke source. The calculation of a pollution potential index (Fig. 6) for North Park defines two areas of high concentration potential. The wind-stagnation areas along the south rim and along the northwest ridge are combined with convergent flow. Only along the higher elevations of the Park Range is the flow sufficiently strong to dissipate a smoke plume.

Summary and Conclusions

Analysis and prediction of winds are essential to smoke management programs. Unless the wind field is fully defined, plume concentrations and trajectories cannot be accurately forecast. Because few wind observations exist in mountainous areas, a diagnostic model was developed to evaluate the wind field in terms of the thermal and frictional forces driving these winds. This diagnostic model is particularly attractive for evaluation of smoke plume configurations because numerous sources may be evaluated simultaneously.

There are two principal applications of the model. It may be used to obtain detailed evaluation of current wind conditions in remote areas from representation of the thermal field. The thermal field data may come from direct ground observations or from remote sensing. The second major application is forecasting winds and smokeplume locations in detail for planning. Since temperature and pressure fields in mountainous areas are more readily forecast than is the detailed wind field, the diagnostic model tends to reduce forecast uncertainties.

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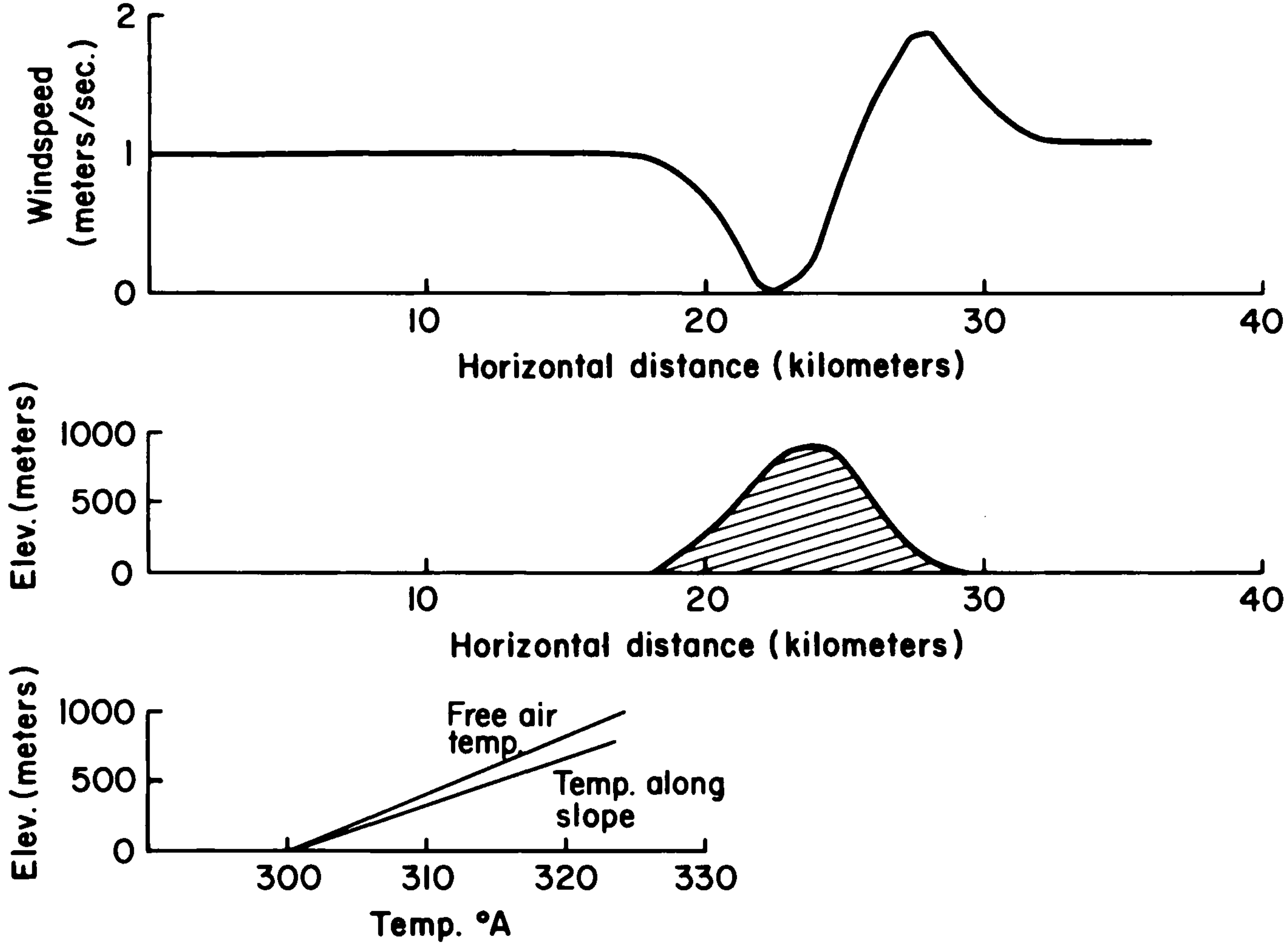

FIGURE 1. Calculated wind across an idealized long ridge. The disturbed wind field is superimposed on a 1 meter sec^{-1} background flow. Temperature profiles for the free air and along the slope show amount of surface cooling.

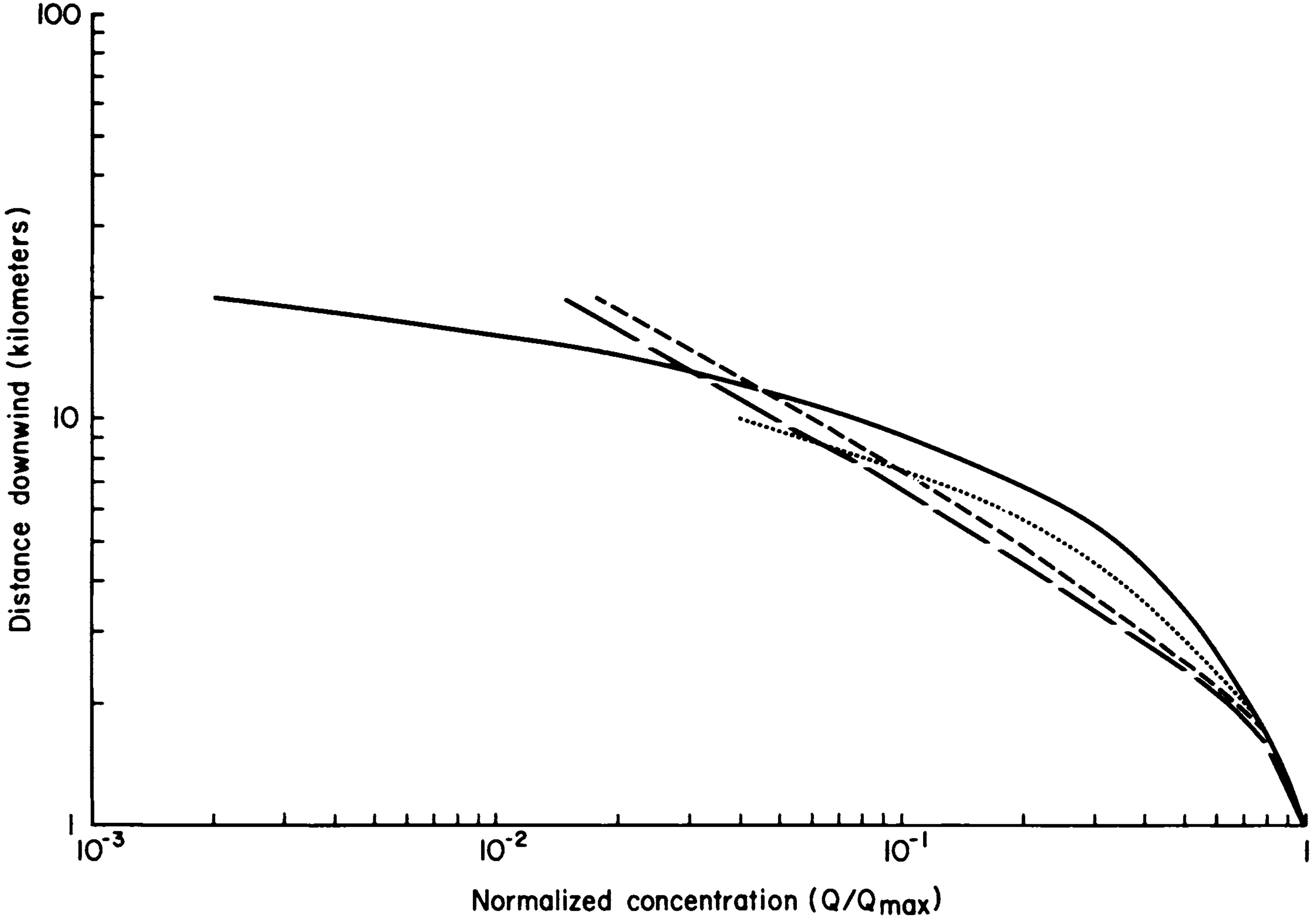

FIGURE 2. Smoke plume concentration downwind of source. Heavy dashed line--Sutton (n=0.2), light dashed line--Bosanquet-Pearson, dotted line--these calculations across a ridge, solid line--these calculations without a ridge.

FIGURE 3. Locations of data sources for test cases.

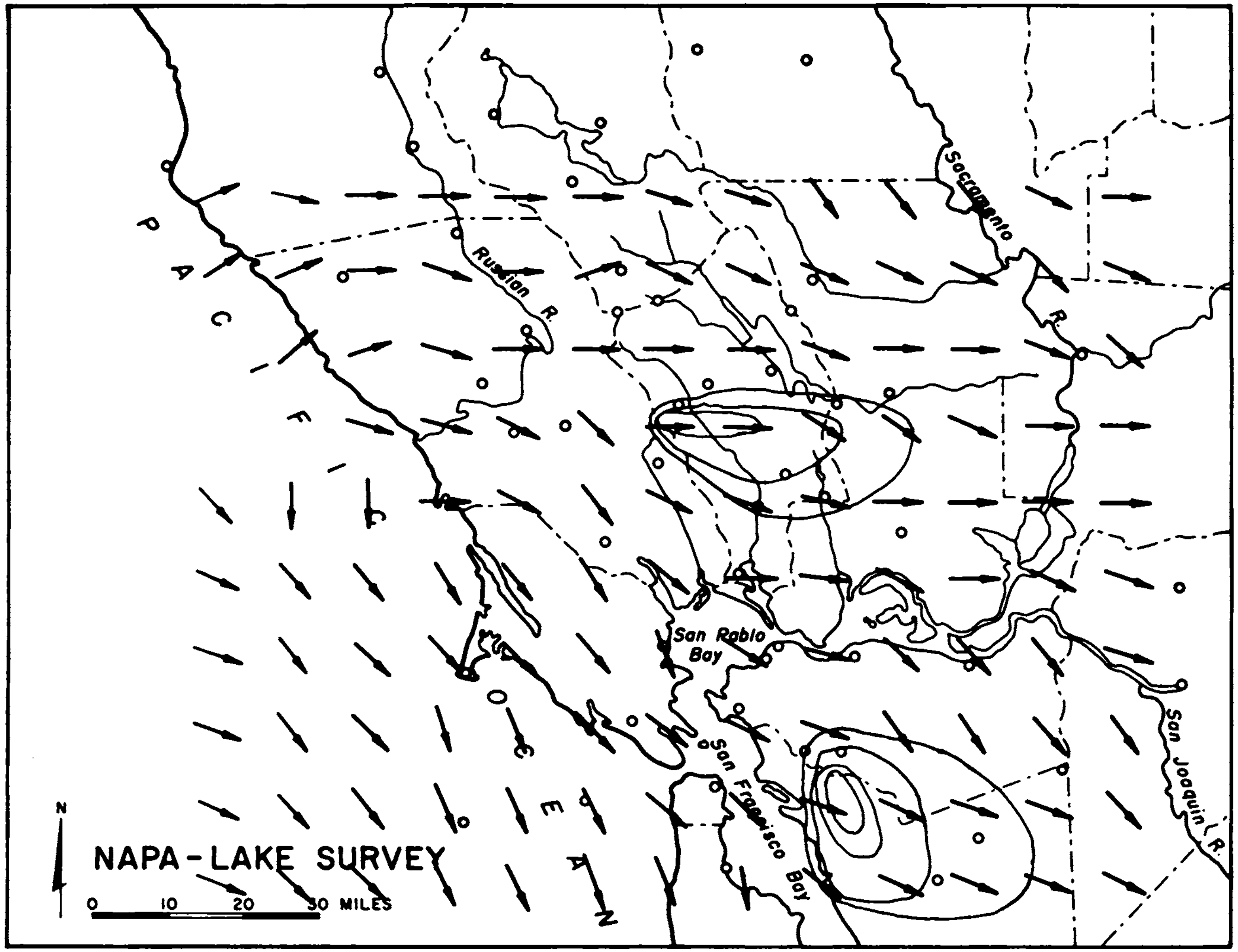

FIGURE 4. Calculated airflow patterns in central California. Simulated smoke plumes from two areas are shown. Isopleths of concentrations are in powers of 10.

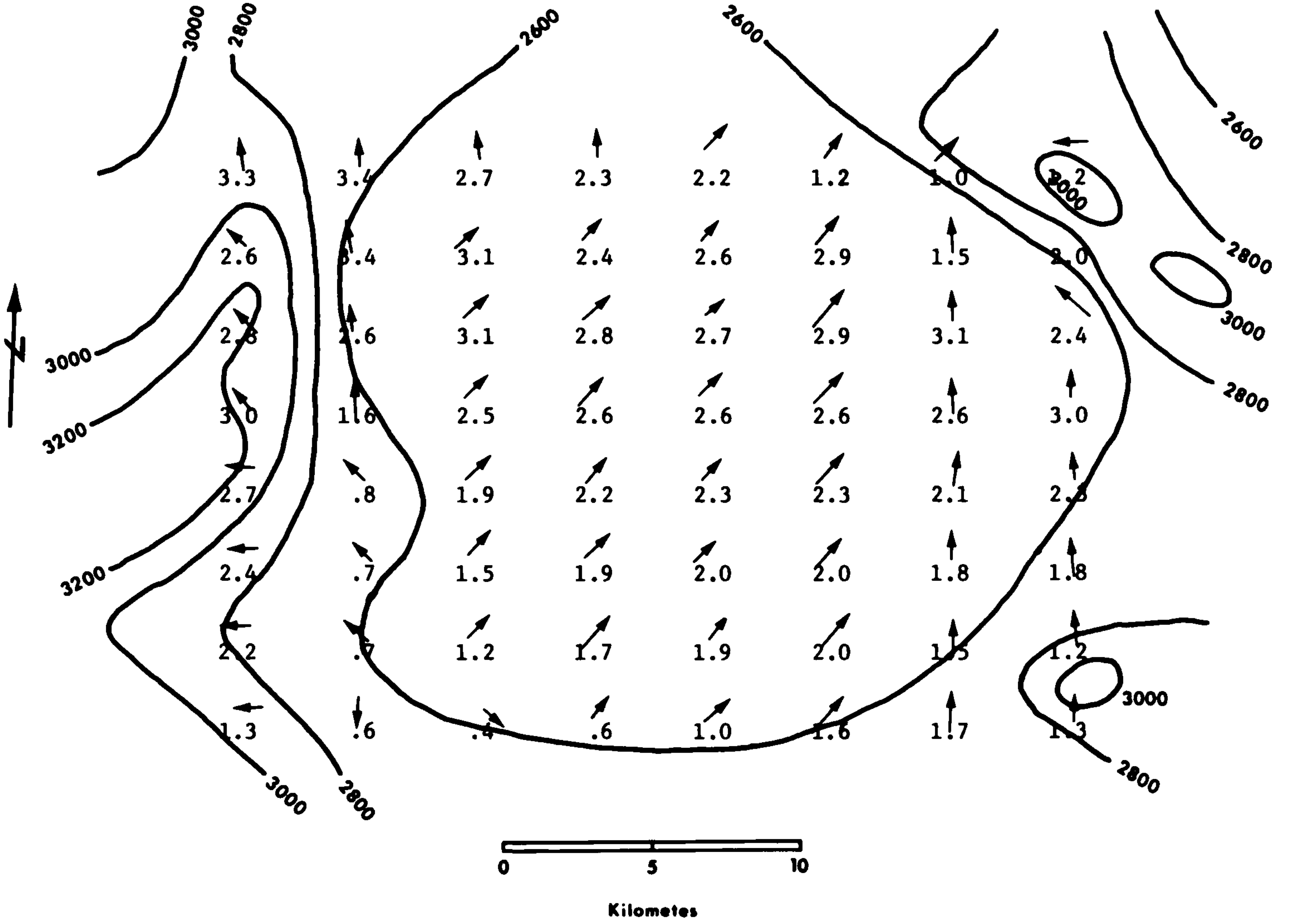

FIGURE 5. Calculated airflow for North Park, Colorado. Numbers below wind directions. Arrows are calculated speeds in meters sec^{-1}. Terrain contours are shown in meters above sea level.

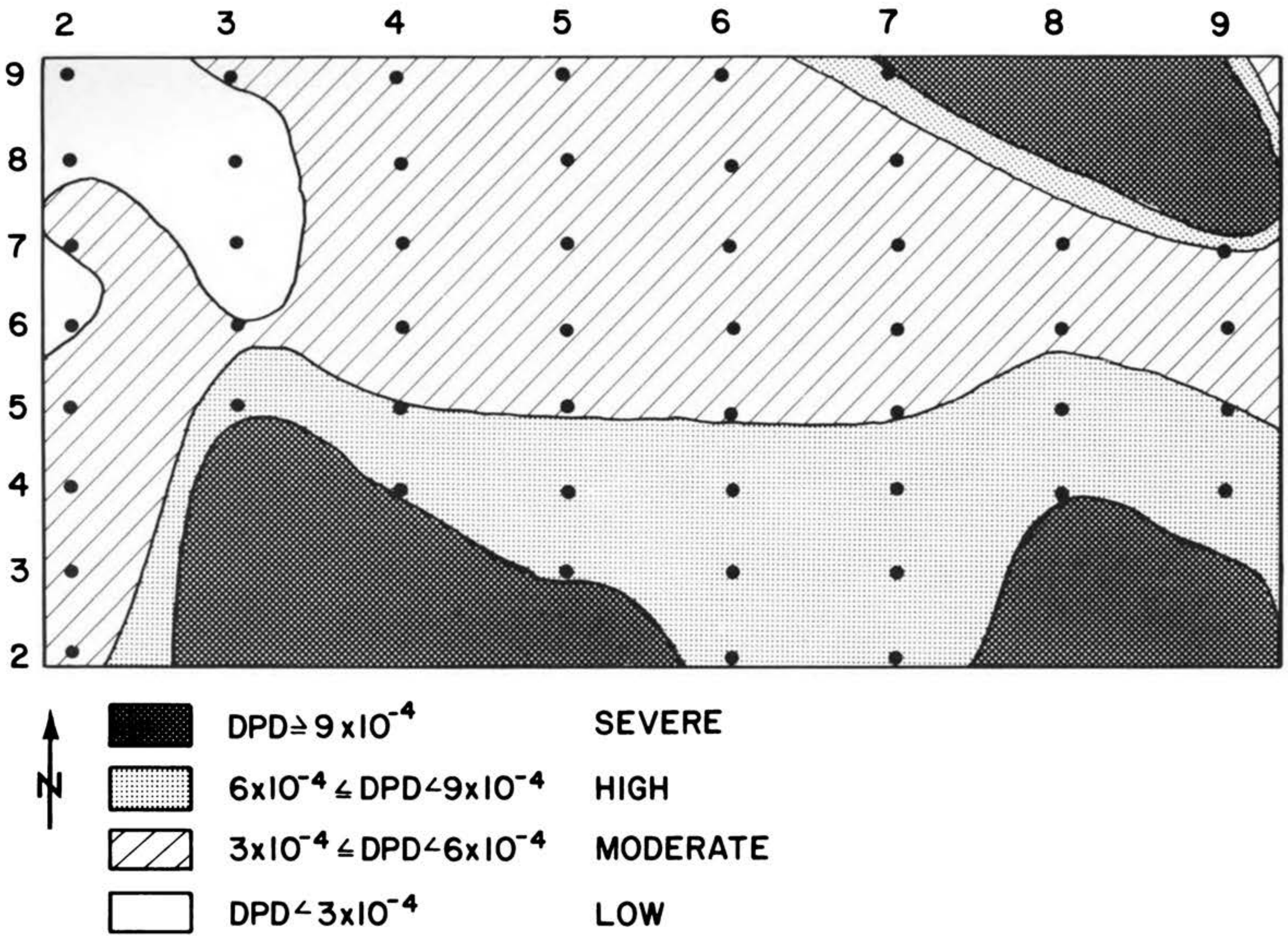

FIGURE 6. Calculated pollution potential for North Park. Dots show location of calculation grid.

SESSION II

LAWS, STANDARDS, AND REGULATIONS FOR SMOKE ABATEMENT

Moderator:

James W. Kerr
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AMBIENT AIR QUALITY STANDARDS FOR PARTICULATE MATTER IN THE UNITED STATES

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Introduction

Under the Clean Air Act of 1970 (1), EPA was given the responsibility for setting national ambient air quality standards. These standards define a level of air quality which in the judgment of the Administrator is necessary to protect the public health or welfare. Two types of ambient air quality standards are required to be set:

1. Primary standards: These standards specify the levels necessary to protect public health with an adequate margin of safety.

2. Secondary standards: These standards specify those levels necessary to protect public welfare from any known or anticipated adverse effect. The Act defines public welfare very broadly to mean effects on visibility, soils, water, crops, vegetation, materials, animals, weather, transportation, and personal comfort and well-being.

In accordance with the provisions of the Act, EPA promulgated standards for six pollutants on April 30, 1971 (2):

a. Total suspended particulate matter (TSP)
b. Sulfur dioxide (SO_2)
c. Carbon monoxide (CO)
d. Hydrocarbons (HC)
e. Oxidants (OX)
f. Nitrogen dioxide (NO_2)

The primary emphasis of my talk today will be on the particulate matter standard, but most of the ideas could be equally applied to other pollutants.

A couple of points should be made about all of the standards. First, no direct consideration is given to economics in determining the level at which the standard is set. Both primary and secondary standards are set to prevent adverse effects, and that is the only criterion used. Some consideration may be given to economics in situations where the determination of what constitutes an adverse effect is basically a judgmental decision. For example, as we will discuss a little bit later, particulate matter in the air causes a reduction in visibility. The level at which this reduction becomes adverse is judgmental and economics may and should play a part in forming that judgment. Secondly, these standards are national. That is, we set *one* number and it applies across the country. No consideration can be given to regional differences if any exist. This second point will be of some importance in our discussion today of particulate matter.

Clean Air Act

There are three sections of the Clean Air Act of 1970 which bear on ambient air quality standards. Section 108 of the Act requires that the Administrator of EPA publish what are known as air quality criteria documents for any pollutant which may have an adverse effect on public health or welfare. Furthermore, any pollutant which is emitted by numerous or diverse mobile and/or stationary sources must be included. These air quality criteria documents are to include the latest scientific information on the kind and extent of all identifiable effects on public health and welfare which may be expected from the presence of the pollutant in the ambient air in varying amounts. In addition, the criteria document attempts to quantify, to the extent that current information allows, atmospheric conditions which may influence the effect of any pollutant. It is apparent that particulate matter falls in this category. The criteria document for particulates is known as AP-49 and was published in January 1969 (3).

When the criteria or background document is published, EPA is also required to publish a document detailing the types and cost of control techniques possible for the pollutant.

From time to time as more information becomes available, EPA will publish revisions to criteria documents to update them and ensure that they are current. For example, EPA recently published a revision to the sulfur dioxide criteria document to bring up-to-date the section dealing with effects on vegetation. EPA has also commissioned the National Academy of Sciences to begin a review of all criteria documents.

Simultaneously with the publication of a criteria document, EPA is required, under Section 109 of the Act, to propose National Ambient Air Quality Standards (NAAQS) based on the criteria document. As may be expected, the process of developing the standard runs parallel with the development of the criteria document. A good deal of cross flow of information exists as to methods of presenting and quantifying data so that the end result is a standard which is consistent with the criteria.

Once a standard is set, the Act provides rather detailed instructions on how the standards are to be met. Section 110 of the Act requires states to submit plans to EPA demonstrating that the ambient air quality standards will be attained within a specified time period and maintained at or below the level of the standard after attainment. The primary standards are to be attained within 3 years after the standard is set unless a one-year postponement or two-year extension is granted. Secondary standards are to be attained within a reasonable time. A definition of reasonable time depends on factors such as type of emission control possible, the cost of this emission control, and other factors peculiar to the geographical area. Most states have elected to achieve the secondary standards in either 1975 or 1977.

NAAQS for Particulate

The National Ambient Air Quality Standards (NAAQS) for particulate which have been promulgated are:

Primary

- Twenty-four hour maximum not to be exceeded more than once per year is 260 $\mu g/m^3$.
- Annual geometric average is 75 $\mu g/m^3$.

Secondary

- Twenty-four hour maximum not to be exceeded more than once per year is 150 $\mu g/m^3$.
- Annual geometric average to be used as a guide in achieving the 24-hour standard is 60 $\mu g/m^3$.

The annual secondary number is not a standard but rather a guide to be used by the states in planning a control strategy to achieve the 24-hour standard. In general, mathematical relationships show that if an annual average of 60 $\mu g/m^3$ is attained, then the odds are that the short-term standard will be attained.

Derivation of Particulate Matter Standards

Basis for primary (4)

As with most pollutants the determination of the effect of particulates on human health is made difficult by the presence of other pollutants, especially sulfur dioxide. However, the studies cited below indicate that for protection of health, the primary standards were set at a scientifically defensible level which is adequate to protect public health with an adequate margin of safety.

The basis for the development of these standards was "Air Quality Criteria for Particulate Matter," (NAPCA Publication No. AP-49). This monograph critically reviewed all pertinent health studies discussing their individual strengths and weaknesses.

1. Evidence for the maximum 24-hour concentration not to be exceeded more than once per year.

    a. Epidemiologic studies of populations exposed to 200-300 μg/m^3 of particulates accompanied by 530-1060 μg/m^3 (.20--.40 ppm) of sulfur dioxide for 24-48 hours showed that an increase in normal general mortality levels was likely. These studies also suggested that: (1) rises in infant mortality, (2) increased admissions to clinics for treatment of upper respiratory tract illness and cardiac disease, and (3) aggravation of symptoms in patients with chronic bronchitis, would occur.

    b. Studies of populations exposed to 150-200 μg/m^3 of particulate matter accompanied by 265-530 μg/m^3 (.10--.20 ppm) of sulfur dioxide for 24-48 hours suggested that an increase above expected mortality levels would occur.

    c. No data were available on immediate health effects of exposure to less than 150 μg/m^3 of particulate accompanied by less than 265 μg/m^3 (.10 ppm) of sulfur dioxide.

2. Evidence for annual geometric mean level.

    a. Several epidemiologic studies ascertained the health effects of long-term exposure to average annual particulate concentrations of 125-175 μg/m^3 accompanied by 90-120 μg/m^3 (.035--.045 ppm) of sulfur dioxide. At these levels, increased chronic respiratory disease (chronic bronchitis and emphysema) prevalence in adults and excess chronic bronchitis mortality was well documented. Likely health effects resulting from long-term exposure to these average annual levels included an increased frequency of acute lower respiratory tract disease (pneumonia, chest colds, bronchitis) in children, an increased frequency of common colds and minor respiratory ailments, a diminished pulmonary function (measured by spirometry), and an excess mortality above expected levels. There were suggestive findings of excess mortality from lung cancer at these exposure levels.

    b. Studies of populations exposed to average annual concentrations of 75-125 μg/m^{3}of particulates accompanied by 65-90 μg/m^3 (.025--.035 ppm) of sulfur dioxide indicated a likely impairment in pulmonary function and suggested both an increased frequency of upper and lower respiratory tract disease in children and an increase above normal levels of mortality.

    c. No data on health effects from exposure to average annual concentrations of less than 75 μg/m^3 of particulates accompanied by less than 65 μg/m^3 (.025 ppm) of sulfur dioxide has been reported.

Several foreign studies as well as studies in this country have been published since the particulate criteria document was written. Results of Community Health and Environmental Surveillance System (CHESS) studies constitute the majority of epidemiologic evidence relating to health effects of particulates since that time, but these studies like most other studies reported to date, generally could not fully distinguish the individual effects of SO_2 and particulates.

Basis for Secondary Standard

A review of the criteria document for particulates indicated that for all of the welfare effects (visibility, material damage, etc.) only a reduction in visibility could be determined as being potentially adverse at levels below the primary standard or below the level of the primary standard for TSP combined with the standards for SO_2. The judgment as to when a TSP-caused reduction in visibility becomes an "adverse" effect is not easy since it is largely subjective and based on where and when the reduction takes place. The setting of a standard is further complicated by the fact that only particles in a certain size range (0.02--1.0 μ) generally contribute to a reduction in visibility. If total mass of suspended particles in the atmosphere is to be related to visibility, the size distribution of the aerosol must be known. Carlson (5), at the University of Washington, has developed a relationship between TSP and visibility which is given in the criteria document. This is as follows:

$$L_V \approx \frac{0.75 \times 10^3}{\text{Conc. } (\mu g/m^3)} ,$$

where L_V is the visual range in miles.

It assumed a relatively well aged urban type aerosol with no fresh smoke plumes. Once we have a relationship such as this, a judgment must be made as to when a reduction in visibility is adverse. FAA and other agencies consider that when visibility is five miles or less, aircraft operations are restricted. If the formula above is used, the mean value of mass particulate loading would correspond to 150 $\mu g/m^3$--the secondary standard. Thus the secondary TSP standard is based on maintenance of five mile-visibility in urban areas. In areas where windblown dust is a problem, the standard should give a considerably higher visibility. However, the standard must be applied nationally although the criterion used for the numeric standard (maintenance of five-mile visibility) varies.

Implementation of the Standard

The implementation of the NAAQS is, as was mentioned, the responsibility of the states. The plans submitted by the states generally outlining strategies to achieve the standards were developed through the example region approach. That is, the effectiveness of control regulations to attain standards was demonstrated by either a diffusion or rollback model for the most heavily polluted area of the state and the results extrapolated for the balance of the state. In general, the chief thrust of most state regulations for particulates was on the control of stationary sources of particulates such as power plants, cement plants, incinerators and other industrial sources. Many states have banned most types of open burning, but none has banned prescribed fire. Some states, as you know, have enacted rules governing its use, such as restrictions on when, where, how much and even how you can burn.

A second requirement laid on the states is to ensure that once the particulate standards are reached, they will be maintained and areas below the standards will not violate the standards. States have approached requirement by means of a permit system whereby specified sources of particulate matter must apply for a permit to begin construction. To obtain this permit the potential source must demonstrate that its emissions will meet all applicable emission limitations and not interfere with the attainment or maintenance of the primary or secondary standard.

NAAQS and Prescribed Fire

The use of fire as a forestry management tool can and does impact on ambient air quality, possibly to the extent that short-term NAAQS are threatened. However, there is little information one way or the other on which to quantify this intuitive feeling. Minimum ambient air quality data has been taken in the vicinity of fires and little work has been done on modeling the effects of a prescribed burn on ambient air. The Forest Service at Macon, under the direction of Dr. Bob Cooper, is making studies in the area of quantifying the effect of prescribed fire on air quality through modeling and measuring efforts in the south where the terrain conditions are more amenable to modeling. However, the mountain terrain in the west causes severe problems for current models. In the absence of sufficient data, the actions taken by the states to regulate the use of fire and ensure that the burning which is carried out is necessary, seem appropriate at this time. However, if more data are collected and these data show that prescribed fire in an area will cause the NAAQS to be exceeded, then some further action must be taken.

It seems prudent in removing debris from the forest that efforts on the part of foresters--public and private--concentrate on determining what the impact on air quality really is and look for ways to minimize effects of prescribed fire through good burning techniques or, even better, eliminate as much as possible by developing alternatives to burning.

Research and Development Potentially Leading to Particulate Matter Standards

The major particulate R&D program with potential impact on forestry operations is the fine particulate control program. Mounting evidence implicates fine particles (less than 3 microns) in adverse health effects. In addition, the reduction in visibility I mentioned previously is also caused by these particles. Work is under way to identify the effects caused by these particles, develop control and measurement techniques, and better define the sources of these particles. The size distribution of particles produced by forestry burning is not well known and will have to be better understood before its relation to these potential standards can be determined. A control strategy recommendation for fine particles is due in 1976. Standards of some sort should follow within 2-3 years thereafter.

Prevention of Significant Deterioration

While not directly ambient air quality standards, a recent court ruling requiring EPA to prevent significant deterioration may act to set limits on ambient concentrations of pollutants at levels which would have a direct impact on prescribed fire.

On July 16, 1973 (6), EPA proposed four alternative regulations designed to prevent significant deterioration of air quality. These regulations were in response to a suit filed in May 1972 by Sierra Club, *et al.* charging that the plans filed by the states to attain and maintain the NAAQS also had to prevent "significant deterioration" of air quality. After a lengthy litigation ending in a tie vote in the Supreme Court, the lower courts ruling was affirmed. The four proposals were: (1) a single increment in air quality for SO_2 and TSP applicable nationwide, (2) an allowed increase in emissions of SO_2 and TSP, (3) a case-by-case local determination of significant deterioration, (4) a two-zoned approach giving two increments in air quality and also allowing selected areas to increase to the secondary standard.

EPA held public hearings in five cities during late August and early September. About 160 persons gave testimony including several forestry organizations. Public comments have also been received from a large number of groups. We are still in the process of evaluating these comments to decide what possible courses of action are open to us.

The issue of prevention of significant deterioration could have a profound impact on the use of fire as a forest management tool. It appears that under three of the four alternative plans much of the current use of prescribed fire would not be allowed. The comments received from the forestry organizations I mentioned have pointed out this fact and have requested that appropriate consideration be given to the beneficial aspects of forestry burning before any final rulemaking. We will, of course, consider these factors prior to our final promulgation.

What action will finally be taken is still very much up in the air. We have not yet completed the review of the comments we have received or fully analyzed the social and economic questions raised by these comments. Any of the four proposed alternatives or possibly some combination of the four or some entirely new approach may be finally decided on.

Summary

The ambient air quality standards in the U.S. are designed to prevent two effects--adverse heath effects are covered by primary standards; adverse welfare effects by secondary standards. The levels selected for the standards must be based solely on information compiled by scientists in the *Air Quality Criteria Documents*. The impact of the standards on forestry activities is somewhat unclear due to the lack of information about the effects of a prescribed fire on ground level air quality.

References

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AIR QUALITY STANDARDS FOR SMOKE PARTICULATE MATTER IN CANADA

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Many U.S. citizens think of Canada as a copy of the U.S.A. It is true that you more at home in a Canadian city than in an equivalent city in Japan or Nigeria.

Like you we labor under a two-tier system of government, often with both tiers having a share of the jurisdiction. However, there are differences, both fundamental and subtle. Canada has a Parliamentary system of Government laid down by the British North America Act. The major power is in the hands of the Provinces with the Federal Government dealing primarily with health, money, defense, inter-provincial and international problems. Thus, in the field of air pollution control, the responsibility lies mainly with the Provincial authorities and the Federal role is one of coordination, to promote a uniform approach across Canada and to eliminate the creation of "Pollution Havens." A concurrent jurisdiction does exist when there is a danger to health and the Federal Government can intervene directly when a Province fails to take action.

It is often useful to make a "guess-timate" by dividing a U.S. statistic by ten on the basis that the population and G.N.P. of Canada is one tenth of that of the U.S.A. It is a device of some usefulness for a ballpark figure but it ignores the essential differences between our two countries. For instance, the climate of Canadian cities approximates to that of Boston, Detroit, North Dakota or the State of Washington. We have, in fact, a cold climate which increases the percentage of fuel used for heating and leads to increased persistence of inversions in winter. This lower mean temperature is proving to be a factor in the level of emissions from autos. Also, Canada has an abundance of water power and thermal generation of electricity is a comparatively late arrival on our industrial scene.

The areas of Canada north of the 60° latitude are organized as two "territories"--Yukon and Northwest Territory--governed by Councils appointed by Ottawa. The area is mainly muskeg and tundra, sparsely inhabited by Indians and Eskimos, but recent discoveries of oil and gas will hasten development. The remainder is divided into ten Provinces, analogous to the U.S. States, with pollution control sophistication varying from the most advanced in Ontario to almost non-existent in some of the poorer Provinces.

The greatest concentration of industry in Canada is found in Ontario and it is accompanied by a commensurate level of pollution control. Toronto passed its first smoke abatement by-law in 1907 and continued through the years to upgrade its control of pollution.

In 1955, the Ontario government appointed a Select Committee to study the problem of air pollution and its control. As a result of this committee's report in 1957, the Province passed the Air Pollution Control Act in 1958. This Act delegated the control function to municipalities but widened the scope considerably to provide for control of all sources of air pollution. At the same time, it provided for the entry of the Province in an advisory role. However, the results of this legislation were not satisfactory since some municipalities were loath to assume their designated responsibilities and it became apparent that if any progress were to be made in controlling air pollution, the control function had to be vested in one central agency. As a consequence the Air Pollution Control Act, 1967, was passed in June and proclaimed in October, whereby the Province assumed the total control function.

For smoke, Ontario has specified a maximum of Ringelmann No. 1, with four minutes in 30 at No. 2 for slicing fires, and No. 3 for three minutes out of 15 for starting a new fire.

To control other emissions, Ontario has set limits on the concentration of a pollutant at its point of impingement, since this is where the effect is felt, and for suspended particulate matter a 30-minute average of 100 $\mu g/m^3$ is allowed.

Recognizing that particulate matter acts synergistically with other pollutants, notably sulphur oxides, Ontario has gone one step further and devised an air pollution index for use in several industrial areas. An analysis of the levels of pollution measured during episodes resulting in increased morbidity or mortality in several cities around the world indicate that clinical symptoms can be expected when the suspended particulate matter level reaches 600 micrograms per cubic meter with 0.13 ppm SO_2 or 500 micrograms SPM with 0.25 ppm SO_2. For the purpose of the index, this threshold is defined as equal to 100.

$$\mathrm{API} = a(\mathrm{dust}) + b(SO_2)$$

$$600a + 0.13b = 100$$

$$500a + 0.25b = 100$$

This allows the coefficients a and b to be determined.

$$\mathrm{API} = 0.14(\mathrm{dust}) + 117(SO_2)$$

In practice, the SPM level is not available in real time and it is replaced by the COH value which is available in real time and correlates with SPM with a correlation coefficient of more than 0.7.

The index is then adjusted so that the arbitrary values of 1.0 COH and 0.10 ppm SO_2 give an Air Pollution Index of 32. By definition, therefore, the Air Pollution Index has a value of zero at zero pollution, a value of 32 at 1.0 COH and 0.10 ppm SO_2 and a value of 100 at the onset of clinical symptoms in susceptible members of the public.

$$\text{API} = 0.2[30.5(\text{COH}) + 1.26(\text{SO}_2)]^{1.35}$$

In practice, voluntary restrictions of major polluters are looked for when the API exceeds 32 and adverse conditions are expected to persist for at least six hours. A first alert is called when the API reads 50, a second at 75, and an "essential services only" call at a level of 100 anticipated for at least six hours.

Since the index has been in use it has exceeded 32 about 2.3% of the time but prompt voluntary action by the worst polluters has been effective in keeping the value below 50 except on very infrequent occasions.

For comparison, the value of the index would have been

		Excess Mortality
210 for New York	1953,	nil
290 for London	1959,	200
410 for New York	1962,	250
585 for London	1952,	3900.

By contrast, Toronto in 1962 had a heavy fog for four days with Index values from 125-155 but no excess mortality was demonstrated.

Quebec

The Province of Quebec, preoccupied with social and technological reforms, has only recently appointed a Minister of the Environment and has yet to pass formal pollution control legislation. However, Montreal, a cosmopolitan city of two million inhabitants, has acted at the municipal level.

Smoke equal to or greater than No. 1 Ringelmann is prohibited except for building or raking fires. No limitation is placed on emissions during building or lighting fires. However, no one may operate the motor of a parked vehicle for more than four minutes.

The limit for particulate matter is set at 80 $\mu g/m^3$ annual and 250 $\mu g/m^3$ for a 24 hour average and boilers are further limited to 0.6 lb particulates per million BTU at 10 million BTU/hr and reducing linearly down to 0.1 lb/million BTU at a nominal rating of 200 million BTU.

Incinerators must have gas cleaning equipment which is 100% effective for particulates over 20 microns.

Other modes of creating particulates such as open air storage or open cartage of sand, gravel, etc., the dry abrasive cleaning of buildings and the use of dry pneumatic drills is likewise banned.

Alberta

Alberta, in an attempt to ease the restrictions on rural areas, distinguishes between urban areas over 50,000 population, urban areas under 50,000 population and rural areas. Smoke emissions are limited to the Ringlemann Numbers as set out below.

	Urban over 50,000	Urban under 50,000	Rural
Normal operations	#2, <10 min/hr not exceeding #2	#3, <10 min/hr not exceeding #3	#3, <30 min/hr not exceeding #3
Starting, Cleaning, Fires	#2, <20 min/hr not exceeding #3	#3, <20 min/hr not exceeding #3	-- not exceeding #3

Particulate emissions are limited to 0.85 lb per 1000 lb of flue gas corrected to 50% excess air in the case of products of combustion, with less than 0.4 lb/1000 lb of flue gas retained on a 325 mist screen.

As additional guidance, the Department of Health consider a level of 100 $\mu g/m^3$ for particulates and 0.45 COH annual average for smoke to be acceptable for the ambient atmosphere.

British Columbia

British Columbia is busy defining, industry by industry, three objective levels, A, B and C. In general, Level A applies to all new installations, is based on the Best Practical Technology, and is routinely to be used as design criteria. Level C represents the minimum acceptable level of good practice and is universally applicable immediately. Level B is an intermediate level representing the best that can be achieved with the present equipment which may be outmoded by today's standards. It is planned that all controls will be upgraded to the higher levels in planned stages.

In the case of teepee burners, the C Level which is immediately effective is Ringelmann #3 except 15% of the time when Ringelamnn #4 is acceptable. However, plans are required to upgrade this performance to Level B requiring Ringelmann #2 except for 15% of the time not above Ringelmann #3. Finally, since this type of burner is inherently unacceptable, these burners are to be phased out by January 1, 1975, and Level A will be fully effective and requiring not more than 0.10 grains/scf.

Recognizing that stack testing cannot easily be carried out on a beehive burner, the regulations permit the use of a 15 day average dust fall (10 tons/sq. mile/month for Level B and 20 tons/sq. mile/month above background for Level C) to indicate a satisfactory control of the teepee emissions. In the Kraft industry, the recovery stack levels are set at 5, 10, and 20 lb per ton of air dried product for the three levels.

It is recognized, however, that the recovery furnace is not the only source of particulate matter. The emissions from the minor sources are combined and a maximum emission of 1.5, 2.0, and 3.0 lb of particulates per ton of air dried product (ADT) for Levels A, B, and C is permitted.

In most efficient wood-processing plants today, waste is consumed in specially designed boilers to raise steam. The burning of wood, especially at high rates, leads to entrainment of ash--and often smouldering wood particles--in the flue gases. Cyclones were often used on older furnaces but these were not without their problems. Modern systems now exist to get down to 0.10 grains/scf which therefore becomes the A Level.

A further source of pollution from the Forest Industry is the practice of "slash burning." This method of improving the fertility of the woodlot as well as reducing the fire hazard has traditionally been regulated by the degree of fire hazard. However the need to avoid the build-up of pollution is now acknowledged and the Province of British Columbia recognizing the importance of air movement in removing and diluting the products of combustion, withhold burning permits when adverse weather forecasts render such action advisable.

This regulation of the Forest Industry is the first of a series of industry regulations and at the present time, regulations for

(a) mining, mine milling and smelting,
(b) chemical and petroleum industries,
(c) food processing, and
(d) municipal discharges--sewage and garbage,

are planned for early publication.

Saskatchewan

Saskatchewan passed Act, The Air Pollution Control Act, to enable the Minister to control air pollution and to set up an Advisory Committee. The regulations under this Act limit the emission of particulates to 150 micrograms per cubic meter and 1.5 COH units averaged over 24 hours.

In 1971, to coordinate the pollution control functions of the Provincial Government and its agencies, The Clean Environment Authority Act was passed creating the Saskatchewan Clean Environment Authority.

Manitoba

Manitoba has also passed a Clean Environment Act creating a Clean Environment Commission. However, no regulations have yet been passed and control is effected through the Public Health Act which limits smoke to #1 Ringelmann except for 4 minutes in 30 for normal running and #2 Ringelmann except for 3 minutes in 15 when building or raking fires. The particulate level is restricted to 0.40 grains per cubic meter at S.T.P.

New Brunswick

New Brunswick has passed the enabling legislation in the form of the Clean Environment Act but has yet to pass the regulations specifying the acceptable levels of pollution emissions.

Nova Scotia, Newfoundland and Prince Edward Island have likewise passed Environment Protection Acts and set up the appropriate Ministries. No regulations setting out the permissible levels of pollution have yet been passed.

The Federal Involvement

Since pollution is mainly a provincial responsibility and until a few years ago, it was not a matter of urgency or importance to most people, the Federal Government took little heed of it except in relation to health and such action as seemed necessary was handled by a Division in the Department of National Health and Welfare's Environmental Health Unit. Expansion of the Division was commenced in 1970 and the Clean Air Act was promulgated in 1971. In the meantime, concern for the environment had grown to the extent that the Government of Canada created a Department of the Environment to look after the whole range of renewable resources--fisheries, forestry, air and water resources, meteorology, air, water, and land pollution, etc.

The Federal Clean Air Act reflects the Central Government's concern for:

1. International concerns
2. Interprovincial concerns
3. Federal installations and responsibilities
4. Areas of universal concern (i.e., motor vehicles where individual provincial legislation of auto design and manufacture is clearly inappropriate)
5. A leadership role of Canada as a whole, and
6. An advisory service for provinces.

Areas 1 and 2 are self-evident. Area 3 covers Federal and Military establishments, a wide range of inter-provincial activities such as insurance and banking and including docks, harbors and shipping, railways, airlines and pipelines, as well as the Crown Corporations. The Federal Government can exercise direct and strong control over these undertakings.

An indirect but equally effective control can also be imposed on a range of undertakings which accept federal financing or inducements to build or expand their operations. Such inducements are conditional on meeting Federal standards for pollution control.

These Federal standards, which are mandatory for Federally controlled undertakings are agreed upon by joint Federal Provincial Committees of experts and are thus generally acceptable for use as guidelines by the Provinces thus giving a uniform approach to pollution control across Canada. These standards or "objectives" can be used as a basis for regulations under provincial acts to control plants under provincial jurisdistion.

The objectives are unique in that they are planned to have three levels, known respectively as the "Maximum Desirable," "Maximum Acceptable," and "Maximum Tolerable" levels. The "Maximum Acceptable" levels correspond in concept to the secondary air quality standards recently announced by the United States and to air quality objectives in use by some provinces in Canada. This level is intended to provide adequate protection against effects on soil, water, vegetation, materials, animals, visibility, personal comfort and well-being. It represents the realistic objective today for all parts of Canada. When this level is exceeded control action by a regulatory agency is indicated.

The "Maximum Desirable" level defines the long term goal for air quality and provides a basis for an anti-degradation policy for the unpolluted parts of the country and for the continuing development of control technology. "Maximum Tolerable" levels, to be announced at a later date, are intended to indicate the onset of an "imminent danger" requiring immediate abatement action. Air pollution episodes which sometimes result when pollutants accumulate during adverse weather conditions would fall within this category and in the absence of prompt Provincial action, intervention by the Federal Government would be indicated.

In the matter of control strategy, I am sure you all recognize the two basic strategies in use today. I refer to the Best Practicable Technology and the Air Resource Management approaches. Proponents of the Best Practicable Technology are accused of risking an unacceptable air quality especially where the control levels are not precisely defined. The Air Resource Management group believe that the assimilative capacity of the atmosphere should be utilized and would therefore condone an increase in pollution in areas where the air quality is still good. The Canadian Government, recognizing the advantage of both strategies has adopted an approach of Preventive Management based on:

- The control of new stationary sources based on the best practicable technology,
- The control of existing stationary sources within a negotiated period of time based on the best practicable technology,
- The control of urban air pollution by adopting the air resource management approach.

In this way, progress can be made towards the widespread use of the best practicable technology and funds are available to assist the installation and the demonstration of the latest technology where experience of commercial exploitation does not exist. However, the use of the resource management techniques with their associated objectives ensures that even in urban areas, adverse conditions will be recognized whether the best practicable technology has been installed or not.

The control of particulate matter is covered by an objective of 60 $\mu g/m^3$ annual geometric mean for suspended particulate matter at the Maximum Desirable Level and 70 $\mu g/m^3$ annual geometric mean *or* 120 $\mu g/m^3$ maximum 24 hour concentration at the Maximum Acceptable Level. No objectives for smoke or deposited dust have been set neither have values been published for the Maximum Tolerable Levels.

In addition to the Objectives cited above, the Federal Government is active on the following endeavors:

1. National Emission Standards for Hazardous Pollutants

It is proposed to establish standards for such pollutants as may constitute a significant danger to health and Canada is examining the need for such standards for beryllium, asbestos, mercury, and lead.

2. National Emission Guidelines

Government/Industry Task Forces are establishing guidelines based on the best practical control technology available which it is hoped the Provinces will adopt as Provincial regulations.

3. Automobile Emissions

In Canada, automotive emission controls are the responsibility of the Ministry of Transport acting with the technical advice of the Department of the Environment. To date, the Canadian Government has acted in parallel with the United States Government with regard to Automotive Emission Standards. However, Canada has opted for less stringent requirements than those in the United States for the 1975 vehicles. Testing of new vehicles to ensure compliance is carried out by the Department of the Environment on behalf of the Ministry of Transport. It should be noted that once a vehicle has been sold by the manufacturer the Federal Government has no authority to ensure the continued maintenance and operation of the emission control devices.

4. Fuels Regulations

The Department of the Environment has made proposals regarding a limitation of the lead content of both "leaded" and "unleaded" gasolines. The proposal regarding "leaded gasolines" is in keeping with the concern of most industrialized nations over the buildup of lead in the urban environment.

5. Pollution Data

The Federal Government coordinates a Federal-Provincial National Air Pollution Surveillance Network which provides monthly reports on Ambient Air Quality Levels in 38 cities across Canada.

Conclusion

We have now come the full circle with smoke control. The Industrial Revolution first drew attention to the aesthetic objections to smoke and all our interest in Air Pollution Control has grown out of the nineteenth century fight for smoke abatement. Inevitably, this gave way to concern for new pollutants, primarily the gases, but now a concern for the synergistic effect of smoke in the presence of such gases as sulphur dioxide has developed. Smoke and particulates can still contribute to a health hazard when adverse weather conditions lead to a buildup of atmospheric pollutants.

STATE ACTIONS FOR SMOKE CONTROL

MONTANA

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Department of Health and Environmental Sciences
Helena

OREGON

Harold M. Patterson
Division of Air Quality Control
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GEORGIA

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Department of Natural Resources
Atlanta

SUMMARY OF STATE REGULATIONS AS THEY AFFECT OPEN BURNING

Hugh E. Mobley
U.S. Forest Service

LAWS, STANDARDS, AND REGULATIONS FOR SMOKE ABATEMENT IN MONTANA

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Helena

Open burning in the state of Montana is controlled by Regulation 90-010. Essentially, it states that no open burning shall be done without a permit. Air Quality Control Officers are situated throughout the state for enforcement and for the convenience of the people in obtaining a permit if burning is necessary. The program is aimed at being reasonable and livable with the objective of reducing burning to an absolute minimum.

Montana Standards for Total Suspended Particulate Matter: Same as Federal Secondary Standards:

60 micrograms per cubic meter, annual geometric mean
200 micrograms per cubic meter not to be exceeded more than one percent of days a year.

Measurements are by hi-volume sampler. It can be seen from these values that it would be rather difficult to apply on a short term basis. Measurements have to be made and checked, averaged and analyzed over a long period of time, and then there is the problem of determining source of the pollution and method of enforcement. This is a rather difficult and lengthy procedure.

The air in Montana is predominantly good. If the visibility is less than 50 to 100 miles, we begin to wonder about the cause. If it is 15 to 20 miles and the cause is not hydrometeors connected with weather, it is time to investigate the cause. It is quite likely that burning should be curtailed to prevent more serious problems. The amount of smoke in the atmosphere for the control of open burning is determined mostly by visibility. In a situation of air stagnation, visibilities seem to go quickly from the 15 to 20 mile range down to the 2 to 3 mile range and hi-volume samples then show an excess of smoke in the atmosphere. Our aim is to prevent the excess of smoke in the atmosphere and, therefore, take action when it seems eminent that this would occur.

Guidelines have been set up and incorporated into the State Implementation Plan defining what is acceptable to burn and what is not to be burned under any conditions. Camp fires or recreational fires of less than 3 feet in diameter are acceptable and do not require a permit. Barbecues and fireplaces are not classed as open fires and are, therefore, acceptable. Tires, railroad ties, waste oil, linoleum, roofing, car bodies, or anything that burns with dense black smoke or toxic gases are not to be burned in any open fire. In between these two extremes comes a great many items that may or may not be burned according to certain conditions. I will explain a few.

In urban areas, where a collection service is available, no burning is permitted. In rural areas, a burning barrel is permitted for the burning of dry organic material such as leaves and weeds and including loose dry papers. The burning of garbage or a slow smoldering fire that creates a public nuisance is not permitted. Some burning seems essential to good agricultural practices such as the clearing of ditch banks or an unusually heavy growth of stubble that would clog a plow or the clearing of land. A permit is necessary for each burn.

Now the important item of slash burning: Under the Clean Air Act, federal agencies must comply with state and local regulations. At the present time, slash burning is still permitted in Montana; however, there are some controls. Basically, all burning is to be conducted according to principles and technical information currently available for good smoke dispersion. A memorandum of agreement was drawn up and has been signed by Montana Department of Health and Environmental Sciences, Air Quality Bureau; Montana Department of Natural Resources and Conservation, Division of Forestry; USDA Forest Service Region 1; Bureau of Land Management; Bureau of Indian Affairs; Burlington-Northern Timber and Western Lands; U. S. Plywood Company and St. Regis Paper Company.

The objective of the agreement is to minimize or prevent the accumulation of smoke when prescribed burning is necessary for conduct of accepted forest practices such as hazard reduction, regeneration, and wildlife habitat improvement. The development of alternative methods is to be encouraged when such methods are practical. A system has been set up for reporting and coordinating burning operations in the state. All burning is coordinated closely with special weather forecasts for good smoke dispersion made by the National Weather Service for this purpose. Forecasts are for good, fair or poor smoke dispersion. During periods of good smoke dispersion, agencies can burn all they have manpower to control. During periods of fair smoke dispersion, very limited burning is done with special permission for each burn. An example is in the back country above an inversion layer. During periods of poor smoke dispersion no burning is permitted. No permits for agricultural burning are valid during such a time. In the event an Air Stagnation Advisory is issued by the National Weather Service, all burning in the state is stopped until the Air Stagnation Advisory is lifted. Part of the memorandum of agreement is a Cooperative Smoke Management Plan setting up communication systems whereby all organizations in an affected area can be notified of the moratorium on burning until an Air Stagnation Advisory is lifted.

The Forest Service plans to burn 71,000 acres of slash in Region 1 this fall, 41,692 acres in the state of Montana. The Forest Service is the largest organization doing burning but far from the only one. The vast clouds of smoke do not mysteriously disappear by what we call good smoke dispersion. The smoke travels great distances gradually diffusing but materially increasing the pollution load of the atmosphere. Many of the gains made in air pollution control in the state are nullified by the burning of slash. These gains have been made at considerable expense. Another very serious detrimental effect on the air pollution efforts is the resolve of the people. Many feel justified in burning a small pile of leaves in their backyard when they see the large clouds of smoke from the burning of slash. Of course many small fires contribute much smoke.

The finger should not be pointed at the Forest Service. There is the Bureau of Land Management, Bureau of Indian Affairs, COE, BP--State Forest, and the many private and industrial organizations, U. S. Plywood, Burlington-Northern Timber and Western Lands, St. Regis Paper and many others. In the past we have had good cooperation from all organizations and all seem dedicated to doing the best possible job of smoke management. During the fall of 1972, four Air Stagnation Advisories were issued and by stopping all open burning, the air quality remained good throughout the time.

Montana Department of Health and Environmental Sciences is dedicated to clean air. This means reducing burning to an absolute minimum. Clearing for new state highways has gone to high heat incineration for slash disposal. Clearing of drift on Lake Koocanusa by COE was done in Air Curtain Destructors. This reduces smoke. Any burning will cause smoke. The only way to eliminate burning is through an extensive fuel management program. In this day of energy shortage, why should we go on burning slash? Each year a tremendous amount of energy is destroyed by slash burning and all we get out of it is dirty air. Is all this burning necessary? We know of the many reasons slash is burned. Hazard reduction, disease, insect infestation, windfall and others, but isn't there a better way?

The Montana State Board of Health has authority to stop all burning of slash in Montana. They do not want to drop the axe and cause possibly an even worse result. It will take additional research to get the final answers. Most programs and research today assume burning is the way to go. We would like to see more research on the elimination of open burning. We of the State of Montana would like to see this symposium dedicate a major effort toward the better utilization of forest material and the reduction of open burning to an absolute minimum.

LAWS, STANDARDS, AND REGULATIONS FOR SMOKE ABATEMENT IN OREGON

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Oregon's program for air pollution control was initiated by the 1951 legislative assembly. To understand why initial state directed action was taken, one has to recall that Oregon is not a heavily populated state, Oregon had a successful state operated water pollution control program, the problems existing at that time were fluorides from aluminum plants, odors from kraft pulp mills, deposition of cinders and fly-ash from boilers and dusts from the production of cement located in various areas of the state and not effectively controlled by local government.

In order to more fully understand visual problems resulting from Oregon's two smoke management programs, slash burning and agricultural field burning, some background information relative to the Oregon economy, its population and the geographic, climatic and meteorological features will be helpful.

Topography, Climatology and Meteorology

The land area of Oregon, 97,000 square miles, can roughly be divided into two distinct geographic and climatic regions. Western Oregon consists of that area west of the Cascade Mountains extending about 100 miles to the Pacific Ocean, and except for the mountain areas, elevations are generally less than 1000 feet. It has an annual rainfall of about 40 inches and contains about 85% of the state's population. The Willamette Valley, lying immediately west of the Cascades, extends from the northern border, where Portland, the largest city, is located, south about 135 miles to the city of Eugene.

Eastern Oregon is located east of the Cascade range and extends to the Idaho border on the east, the eastern portion of which contains a third major mountain range, the Blue Mountains. It occupies about two-thirds of the state, elevations are in excess of 1000 feet, contains 15% of the population, and except for the mountain areas is semi-arid.

Portland, at an elevation of 77 feet, has visual markers upon which local citizenry gauge "air pollution." Mount Hood, elevation 11,245 feet, is 45 air miles to the ESE. Mount St. Helens, elevation 9,677 feet is 48 air miles to NNE. Mount Adams, elevation 12,307 feet, is 65 air miles NE. Mount Ranier, 14,410 feet, is 91 air miles between the latter two peaks.

Similar smaller peaks or mountain ranges lie sufficiently close to all major cities to act as an index as to the visual clarity of the air.

Lumber, agriculture and tourism, in that order, are the leading economic industries in Oregon.

The climate of the state of Oregon is governed by the temperate maritime air masses crossing the state as they are affected by the mountain-valley topography of the area. Since Oregon's population is concentrated in the western valleys, notably the Willamette Valley and Lower Columbia drainage, the atmospheric ventilation and dispersion conditions in these areas have been extensively studied.

The so-called "box model" has been used with some success to describe the atmospheric conditions in the Willamette Valley. This model visualizes mountain ranges forming the side of a box with river cuts and passes forming doors and windows in the box. The application of this concept can easily be visualized for other confined valleys of western Oregon such as the Medford Valley in the Rogue Basin.

The model visualizes the valley air mass becoming relatively stagnant and decoupled from the upper air circulation when an adiabatically warmer air mass lies over the air within the box, thus forming an effective "lid" to the box. From mid to late summer, this condition commonly exists in the Willamette Valley when cool marine air spills over the Coast range and settles onto the valley floor. This well-known sea breeze usually occurs about mid-afternoon during August and September and can be considered to be the result of mid-day heating in the interior valleys.

During the fall months, before the onslaught of the usual winter storms, the sea breeze effect becomes less operative because of the decreasing maximum altitude of the autumn sun and the resulting decrease in daily heating. It is during this time of the year that atmospheric stagnation becomes most pronounced in the western valleys. October and November exhibit the greatest frequency of periods of stagnation relative to air circulation.

Management of agricultural and slash burning practices have attempted to utilize features of the local climatology to lessen the impact of smoke on the population of the state. During periods of pronounced stagnation and poor valley ventilation burning is curtailed or prohibited. Burning is permitted during other times when smoke can be ventilated away from population centers or smoke sensitive areas.

Smoke Problems

Smoke problems in Oregon by classification are not significantly different than those of many other states. Historically and currently, except for timber industry sources and in particular wigwam waste burners, urban problems are typical of other industrial and commercial areas.

Non-urban sources of smoke in addition to wigwam waste burners have included agricultural field burning, orchard heating, open burning in uncontrolled areas and slash burning.

Statutory and Regulatory Control of Air Pollution (Smoke)

While statutory control of air pollution sources was granted early, exemptions in the statutes prevented direct administrative or regulatory control of certain sources by the Department, and some exemptions still exist including agricultural operations and the growing of crops or the raising of fowl or animals, agricultural land clearing and barbecue equipment.

Enforcement for air pollution control purposes has been accomplished by prohibiting an activity. For example, open burning at solid waste sites and at all industrial and commercial establishments in "special control areas" in Oregon is prohibited. For other source categories subject to control, specific comprehensive rules containing emission limitations, compliance schedule dates and monitoring and reporting requirements were developed for major source categories, including wigwam waste burners, rendering plants, hot mix asphalt plants, kraft pulp mills, sulfite pulp mills, and board product industries. General emission limitations relative to particle size, grain loading, and visible emissions have been adopted by control agencies.

The visible emission limitations were recognized as a needed control tool and the states of Washington and Oregon cooperatively initiated a training program in 1967 to train smoke observers or smoke inspectors to accurately evaluate visible emissions. Classroom training has been conducted in Portland State University and field training in both Portland, Oregon, and Redmond, Washington, and a certificate is issued to an applicant satisfactorily passing both phases.

The visible emission limitation rule has been particularly effective in minimizing (smoke) emissions from wigwam waste burners. The total number of waste burners has been reduced from over 300 to about 200 of which only 77 are active, and these have largely been modified to burn within the regulatory emission limitations.

The visible emission rule in Oregon was Court-tested when Lloyd A. Fry Roofing in Portland appealed in the Court of Appeals of the State of Oregon, April 7, 1972, and the conviction was subsequently upheld by the Supreme Court.

Enforcement of air pollution regulations, when voluntary cooperation fails includes: legal proceeding on violation of a rule which when proven constitutes a misdemeanor; summary abatement or compliance proceedings before the Commission or Hearing Officer and affirmative findings by the Commission resulting in issuance of an order by the Commission; and a more recent legislatively authorized tool--the civil penalty wherein the Department may levy up to a $500 civil penalty for each offense, and each day may constitute a separate offense, for violation of a rule, order or permit condition.

Two control programs are statutorily directed in Oregon--agricultural field burning and slash burning--and will be further discussed.

Slash Burning Smoke Management System

In the fall of 1968, fire control agencies worked with a citizens' committee on air pollution set up by the Chairman of the Oregon State Sanitary Authority, now the Department of Environmental Quality, to prepare legislation to control smoke from agricultural and forestry burning. The objective in relation to forestry was to provide a legislative authorized system which would prevent slash smoke from further aggravating an already polluted condition in a number of urban-industrial areas of the state, and particularly the Willamette Valley. A fire action council was formed to prepare a smoke management system. The council consisted of fire control administrators from the Oregon State Department of Forestry, Oregon Forest Protection Association, U.S. Bureau of Land Management, U.S. Bureau of Indian Affairs, and the U.S. Forest Service.

The effort resulted in the signing of a memorandum of agreement by the State, Federal, and private fire control agencies operating in Oregon, and by the Department of Environmental Quality. It placed in effect a cooperative Smoke Management Plan to minimize or eliminate slash smoke accumulation in designated areas of high population density. The system itself was issued as part of the operating instructions of each of the participating fire control organizations. The State Forester served as coordinator. He holds legal authority of the state to control open burning on forest lands by issuance of permits. Each day's burning plans are communicated to the Department of Environmental Quality for overall coordination with overall air quality considerations.

As indicated, this effort was largely a voluntary management program and operated that way until the 1971 Oregon Forest Practices Act became law. A portion of these 1971 statutes required the State Forester and the Department of Environmental Quality to approve a "Smoke Management Plan" for the purposes of maintaining air quality. It required that the plan be developed by the State Forestry Department in cooperation with State and Federal agencies, landowners, and organizations which would be affected by the plan. The plan was required to be approved by the State Board of Forestry and the Environmental Quality Commission and filed with the Secretary of State.

In 1971, a reported 1.686 million tons of slash was burned on 43,268 acres by way of 1,103 prescribed burns. In 1972, a reported 2.648 million tons of slash was burned on 84,147 acres by way of 9,909 prescribed burns.

The evaluation of the slash smoke management program is largely subjective in nature. In terms of reduction of the presence of smoke in smoke sensitive areas, the program is believed very successful. The attitude of, the cooperation of, and the working relationships with forestry personnel has been excellent. The State Forester provides an evaluation of the program annually. Quoting from a summary portion of the 1972 season report: "Smoke moved into a designated area 86 times on 43 different days. In 77 of the 86 cases, the smoke in a designated area was a minor amount. There were several burns which were accomplished without the consideration of a smoke management forecast and on several occasions an old forecast was used instead of a current one." It should be further noted, and I quote: "Operators remarks often indicated that they were only assuming smoke from a prescribed burn entered a designated area because smoke was moving in the direction of a designated area at the time of the burn. This was not a valid assumption because in several cases total smoke dispersal occurred before smoke could have been advected into a designated area."

A case evaluation is made by the Department of Forestry when an actual or alleged entrance of smoke into a designated area occurs. A partial review of two of the evaluations might illustrate the technical and human problems associated with the management program.

Case #6

Salem Forecast	9-19-72 0800
Surface winds	SSW to WSW 7-15, variable and gusty vicinity of showers
Winds aloft	3000 ft SW to W 15-20 5000 ft SW to W 15-20
Mixing	Good

Burn occurred 9-19-72, ignition time 1000, elevation 750 ft.

Operator's Observation: Clear, steady wind from the W at 3 mph. Smoke plume rose to 2000 ft, laid over and unexpectedly moved to the W. Minor smoke in designated area...unexpected.

Summary: Operator apparently made error in entry on direction of smoke movement. All available data indicates a moderate to strong SSW to W flow which would have resulted in smoke moving to NE or E. Forecast verified. Operator should have expected resulting smoke behavior. Although mixing was good, the wind flow was such that the proximity of burn to a designated area resulted in smoke blowing into the designated area. Smoke should have been minimal and aside from this, it was actually a very good burn day with only minimal effects on air quality.

Case #1

Salem Forecast NA

Operator indicated forecast used was the 0900 forecast issued 5-14-72. This was impossible since forecast was not issued over that weekend. No special requests for weekend forecasts had been received.

Burn occurred on 5-14-72, ignition time 1100, elevation 1800 ft.

Operators Observation: Clear, steady wind from the SW at zero. Smoke drifted to the NE at 3000 feet. Smoke behavior not expected.

Summary: Burn was accomplished without the consideration of a smoke management forecast.

A plot of the total days per month in which visibility, as measured at weather service facilities, is less than seven miles at Portland, Salem and Eugene clearly indicates that degradation of visual clarity, on this basis in 1972, occurred during the period August through November. A plot on this same graph, Fig. 1, of the acres of agricultural field burning and slash burned illustrates that these activities are conducted during this same period. This burning, not too surprisedly, results in such news releases as occurred in the Eugene paper on September 23, 1973, which in part states: "Smoke filled the Willamette Valley Friday from Eugene to Portland, and the cause, according to the Dept. of Environmental Quality (DEQ), was forest slash burning. The forest people weren't so sure. The DEQ reported 183,000 tons of slash was on the burning schedule of forest agencies west of the Cascades Friday. Forest agencies, meanwhile, conceded to only limited responsibility for the smoke."

Agricultural Field Burning

Field burning in the Willamette Valley was initially practiced for straw disposal and for field sanitation relative to grass seed and cereal grain crops after harvesting. It was estimated that over one-half million acres in the Willamette Valley were burned annually usually during the period from the middle of July to early October.

1969 legislation directed the Environmental Quality Commission to establish a meteorological control program to regulate the type and extent of burning done on various classifications of days. Wording of the statute and burdens relative to consideration of economics, weather conditions, and public health and welfare made attempts to implement the program difficult. The program initially implemented with only meteorological criteria proved inadequate. Early conclusions were that any time more than 2,000 acres of fields were burned in the South Willamette Valley, there was an 80-90% chance that visibility in Eugene would be reduced to one to six miles. Changes in the program were immediately incorporated adding acreage quota restrictions and a north-south valley quota concept.

1971 legislation clarified questions relative to the conduct of a priority-quota restriction program and a legislative phase-out date was adopted by which there shall be no open field burning after January 1, 1975.

To give some concept of the program, the following tabular summary is provided:

The normal agricultural field burning season is late July through early October, and normally 90% or more of the acreage shown below is burned each year. The total straw tonnage burned is over one million tons per year.

Willamette Valley Grass Acreage:		280,000
South Valley (Benton, Linn & Lane counties)	183,000	
North Valley (Polk, Marion, Washington, Clackamas, Yamhill and Multnomah counties)	97,000	

Representative Acreages and Straw Amounts

Grass Type	Acreage*	Straw Production (tons/acre)
Annual rye	117,000	5
Perennial rye	40,000	4
Tall fescue	16,000	2.5
Orchard	12,000	3
Blue	17,000	2.5
Fine fescue	32,000	3
Bent	33,000	2

*These vary from year to year.

Emissions:		
	Particulate	16 lb/ton (mostly 1 micron and smaller)
	CO	101 lb/ton
	HC	6.2 lb/ton (saturates and acetylene, olefins and ethylene)

Generally under the currently operated programs only 10-11 days in the field burning season occur when fields in the South Valley can be burned. Winds prevail from the N-NW in the summer period and normally only when a storm front moves in do winds from a southerly direction occur allowing south valley burning quotas to be issued. On more than one occasion acreages in excess of 30,000 have been burned in one day. While reasonably successful for the Western urban population, on one occasion significant visibility reduction occurred in Central Oregon and on two occasions State Forestry personnel advised of expressed concern relative to smoke in the forests. As the result of the reduced visibility, it would have been impractical, if not impossible, to observe an initiated forest fire if one had started.

Smoky days in Eugene and Salem during August and September of 1972 were 13 and 17 respectively (visibility reduced to six miles or less).

Summary

Oregon has a working, and in most respects, a successful smoke management plan. (A copy of the Smoke Management Plan is attached as Appendix A.) Much of the success of the plan is attributed to cooperation and diligence of people involved in carrying out the plan.

Based upon the conclusion that long term improvements will come as a result of a reduction in the necessity to burn current tonnages and improved technology and alternatives are an objective in that regard, the following comments are offered in the short term.

It has been the conclusion of the Department that from an air quality standpoint so long as these smoke producing programs continue using present techniques, agricultural field burning and slash burning, degradation of the visual air quality will continue. The smoke management programs alleviate or minimize the impact on designated areas.

Based upon my experience, air quality staffs generally have an insufficient number of measurement techniques or methods to technically evalute the operating results of slash burns for the purpose of making constructive specific recommendations to improve the program. The day-to-day type contact suggests that we are not yet in agreement as to the criteria of the program. Some field operation people are inclined to identify "smoke in a designated area" as an identifiable smoke plume entering a designated area in that form, whereas air quality personnel consider a reduction in visibility as a result of smoke in either diffuse or plume form resulting in unacceptable reduced visibility. Until we are able to resolve some of the questions relating to air quality objectives and the day-to-day measurement of effect, progress will be difficult to measure.

Be assured that, if the agricultural field burning problem is resolved in Oregon, the public may well become more critical of any smoke in any sensitive areas of the state, designated or not designated.

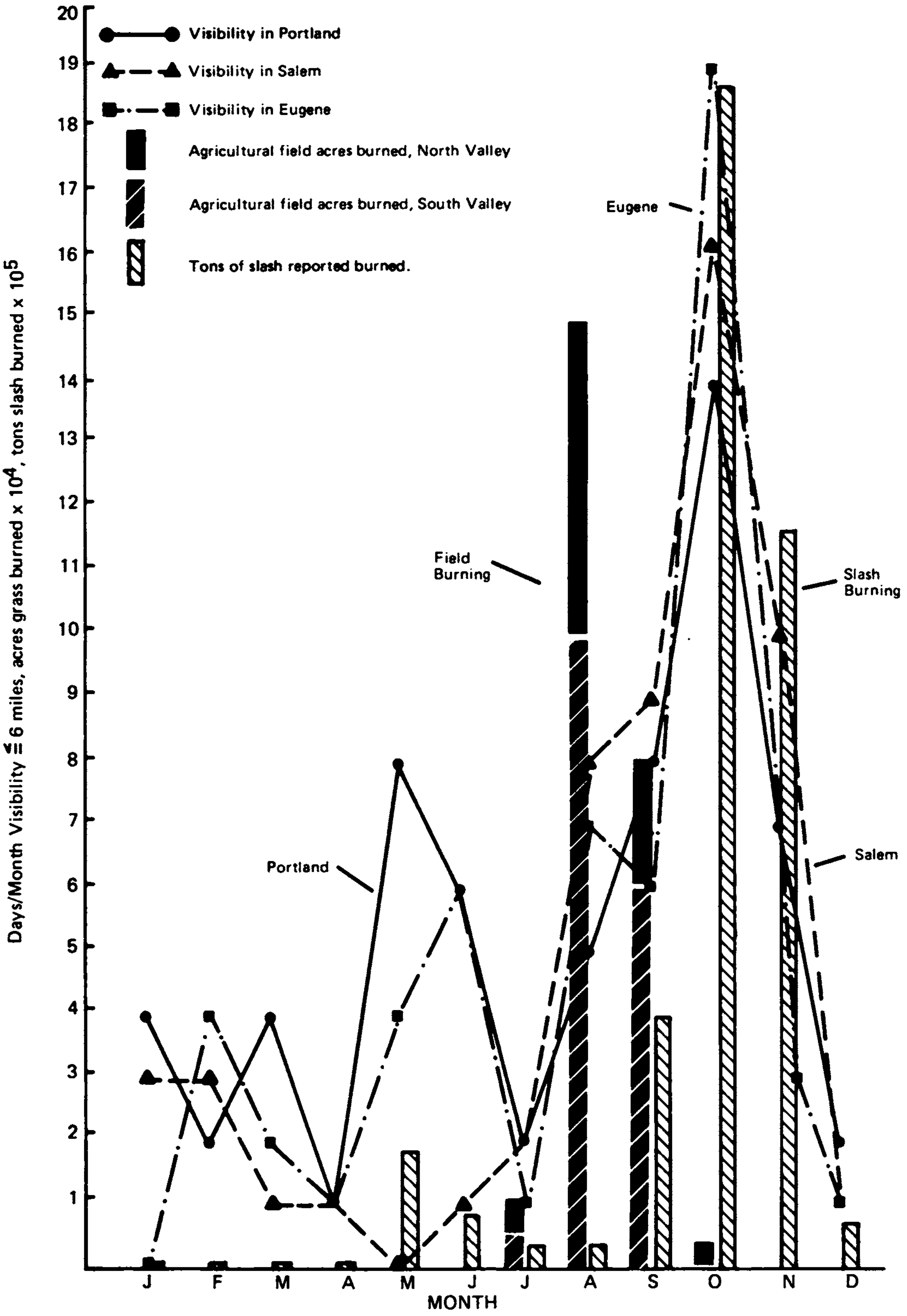

FIGURE 1. 1972 Grass field burning, slash burning and visibility restrictions.

SMOKE MANAGEMENT PLAN

Approved by Oregon State Board of Forestry, January 5, 1972

OBJECTIVE:

To keep smoke resulting from burning on forest lands from being carried to or accumulating in designated areas (Exhibit 1) or other areas sensitive to smoke.

DEFINITIONS:

Deep mixed layer - extends from the surface to 1,000 feet or more above the designated area ceiling.

Smoke drift away - occurs where projected smoke plume will not intersect a designated area boundary downwind from the fire.

Smoke drift toward - occurs when the projected smoke plume will intersect a designated area boundary downwind from the fire or when wind direction is indeterminate due to wind speed less than 5 mph at smoke vent height.

Smoke vent height - level in the vicinity of the fire at which smoke ceases to rise and moves horizontally with the wind at that level.

Stable layer of air - a layer of air having a temperature lapse rate of less than dry adiabatic (approximately 5.5°F per 1,000 feet) thereby retarding either upward or downward mixing of smoke.

Tons available fuel - an estimate of the tons of fuel that will be consumed by fire at the given time and place. Low volume is less than 75 tons per acre, medium volume 75 to 150 tons per acre, and high volume over 150 tons per acre.

Residual smoke - smoke produced after the initial fire has passed through the fuel.

Field administrator - a forest officer who has the direct responsibility for administering burning permits on a unit of forest land within the boundaries of an official fire district.

Restricted area - that area delineated in Exhibit 1 for which permits to burn on forest land are required year round, pursuant to Rule OAR 43-041.

Designated area - those areas delineated in Exhibit 1 as principal population centers.

Heavy use - unusual concentrations of people using forest land for recreational purposes during holidays, special events, etc.

Major recreation area - areas of the state subjected to concentrations of people for recreational purposes.

CONTROL:

The State Forester is responsible for the coordination and control of the smoke management plan. The plan applies state-wide with full interagency cooperation with the U.S. Forest Service, Bureau of Land Management, Bureau of Indian Affairs, private forest industry and the Department of Environmental Quality.

Certain "designated areas" are established in consultation with the Environmental Quality Commission. The major objective of smoke control efforts will be to keep smoke from forest land burning out of these designated areas (Exhibit 1).

During periods of heavy use, major recreation areas in the State shall be provided the same consideration as "designated areas."

ADMINISTRATION:

Each Field Administrator issuing burning permits under this plan will manage the prescribed burning on forest land in connection with the management of other aspects of the environment in order to maintain a satisfactory atmospheric environment in designated areas (Exhibit 1). Likewise this effort may be applied in special situations where local conditions warrant and that are not defined as designated areas but nevertheless are sensitive to smoke. Accomplishment will entail a consideration of weather forecasts, acreages involved, amounts of material to be burned, evaluation of potential smoke column vent height, direction and speed of smoke drift, residual smoke, mixing characteristics of the atmosphere, and distance from the designated area of each burning operation. Designated areas are outlined and vertical extents or ceilings are indicated in Exhibit 1.

Each Field Administrator will evaluate down-wind conditions prior to implementation of burning plans. When a field administrator determines that visibility in a designated area, or other area sensitive to smoke is already seriously reduced or would likely become so with additional burning, or upon notice from the State Forester through the Division of Fire Control or upon notice from the State Forester following consultation with the Department of Environmental Quality that air in the entire state or portion thereof is, or would likely become adversely affected by smoke, the affected field administrator will terminate burning. Upon termination, any burning already under way will be completed, residual burning will be mopped up as soon as practical, and no additional burning will be attempted until approval has been received from the State Forester.

REPORTS:

Field Administrators will report daily at such times and in such manner as required by the State Forester covering their daily burning operations. Any wildfire that has the potential for smoke input into a designated area will be reported immediately to the State Forester's office.

KEY TO SMOKE DRIFT RESTRICTIONS:

1. Smoke drift away from designated area

   a. No specific acreage limitation will be placed on prescribed burning when smoke drift is away from designated area. Burning should be done to best accomplish maximum vent height and to minimize nuisance effect on any segment of the public.

2. Smoke drift toward designated area

   a. Smoke plume height below designated area ceiling. Includes smoke that for reasons of fire intensity, location, or weather, will remain below the designated area ceiling. Also included are fires that vent into layers of air, regardless of elevation that provide a downslope trajectory into a designated area.

      (1) Upwind distance less than 10 miles outside designated areas. No new prescribed fires will be ignited.

      (2) Upwind distance 10-30 miles outside designated area boundary. Burning limited to 1,500 tons per 150,000 acres on any one day.

      (3) Upwind distances 30-60 miles outside designated area boundary. Burning limited to 3,000 tons per 150,000 acres on any one day.

      (4) Upwind distances more than 60 miles beyond designated area boundary. No acreage restriction unless otherwise advised by the Forester.

   b. Smoke will be mixed through deep layer at designated area. This section includes smoke that will be dispersed from the surface through a deep mixed layer when it reaches the designated area boundary.

    (1) Upwind distance less than 10 miles from designated area boundary. Burning limited to 3,000 tons per 150,000 acres on any one day.

    (2) Upwind distance 10-30 miles from designated area boundary. Burning limited to 4,500 tons per 150,000 acres on any one day.

    (3) Upwind distances 30-60 miles outside designated area boundary. Burning limited to 9,000 tons per 150,000 acres on any one day.

    (4) Upwind distances more than 60 miles beyond designated area boundary. No acreage restriction unless otherwise advised by the Forester.

c. Smoke above a stable layer over the designated area. Smoke in this group will remain above the designated area, separated from it by a stable layer of air.

    (1) Upwind distance less than 10 miles outside designated area. Burning limited to 6,000 tons per 150,000 acres on any one day.

    (2) Upwind distance 10-30 miles outside designated area. Burning limited to 9,000 tons per 150,000 acres on any one day.

    (3) Upwind distances 30-60 miles outside designated area. Burning limited to 18,000 tons per 150,000 acres on any one day.

    (4) Upwind distances more than 60 miles beyond designated area boundary. No acreage restriction unless otherwise advised by the Forester.

d. Smoke vented into precipitation cloud system. When smoke can be vented to a height above the cloud base from which precipitation is failing, there will be no restrictions to burning.

3. Changing conditions

When changing weather conditions, adverse to the Smoke Management objective, occur during burning operations, aggressive mop-up will be initiated as soon as practical.

ANALYSIS AND EVALUATION:

The State Forester will be responsible for the annual analysis and evaluation of state-wide burning operations under this Plan. Copies of the summaries will be provided to all interested parties.

Oregon Administrative Rule 43-041 - Pursuant to Chapter 297, Oregon Laws, 1971, burning on forest land within the boundaries of a forest protection district and lying within a restricted area as set forth in the plan for managing smoke, on file with the Secretary of State on the date of October 1, 1971, shall be subject to the following conditions:

1. A permit to burn from the forester shall be required for all slash burning during any time of the year within the restricted area as set forth in Exhibit 1 of the above referenced plan.
2. A permit to burn from the Forester shall be required for all burning on forest land during any time of the year in areas within Columbia, Washington, Yamhill, Polk, Benton, Lane, Linn, Clackamas, Marion, and Multnomah counties, which the Forester determines to be in the public interest to require such burning.

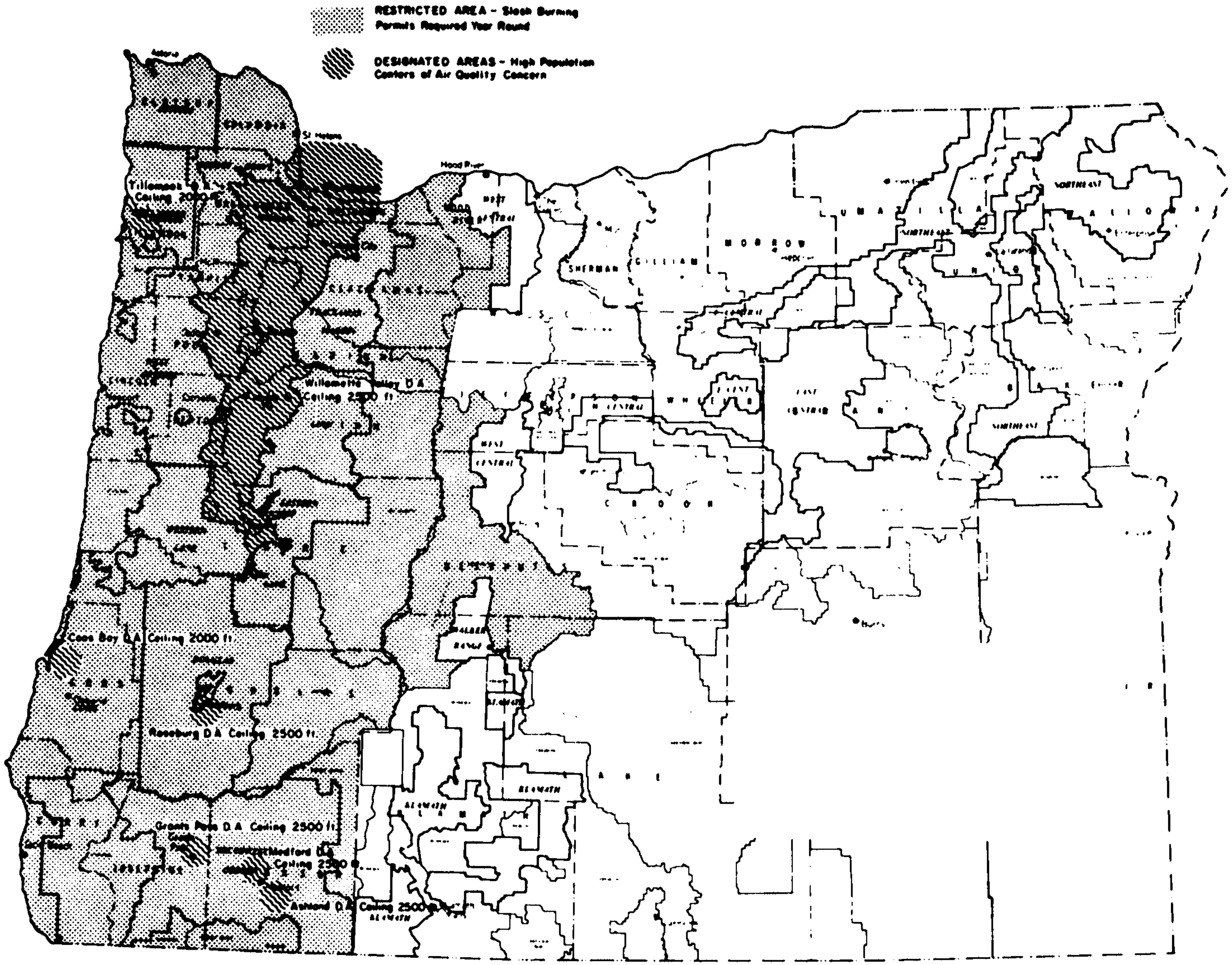

EXHIBIT 1. The Restricted Area includes all forest lands west of the summit of the Cascades and the forest protection areas of the Mt. Hood and Deschutes National Forests east of the Cascades.

GEORGIA'S OPEN BURNING REGULATIONS

Robert H. Collom, Jr.
Department of Natural Resources
Atlanta

As you all are aware, many of the legal controls placed on open burning come from state government air pollution control agencies. Therefore, I am sure you would wish to have a better understanding about the kinds of considerations and decision making which go into the development of those state laws and regulations which affect the practice of open burning either in urban areas or over rural forest lands. With this in mind, I will give you a chronological development of the present open burning regulations and program activities in the State of Georgia.

The first state law in Georgia which was effective was adopted in 1967. In this law there were certain limitations placed on the authority to control and regulate air pollution. One of these limitations applied to the limiting or restricting of owners of any forest land from burning over their own land. Those who drafted the legislation were cognizant of the important nature of Georgia's pulp wood and pulp and paper industry. Therefore, they wished to make sure that prescribed burning which has normally been used in managing pulp wood forests would not be effected. Thus far we have not found that this limitation on our authority has in any way diluted our efforts to control significant air pollution within the state. This will be brought out by further comments.

Following the adoption of the law in 1967, a number of meetings were held with industry, government and citizen groups in order to develop the first regulations to implement the Act. These regulations were adopted in 1968 and did include limitations on certain kinds of open burning. In 1971, ambient air standards were adopted in Georgia following closely the recommendations and requirements under the federal Clean Air Act. The federal Act specified that criteria documents published by the federal government should be the primary basis for establishing ambient air standards, particularly those aimed at preventing health effects. In 1972, the state regulations were further amended to provide for additional emission restrictions in order to meet the ambient standards which had been adopted. This series of amendments also placed further restrictions on open burning, primarily due to the pressure and interest expressed by the general citizenry.

Some of the reasons for the concern and control of smoke from open burning are obvious. Health, of course, is the primary reason and is a consideration against which no one can argue. Since the early sixties documented cases have indicated that smoke from the burning of such things as garbage and other waste materials can cause very severe health damage, primarily to those with pre-existing lung disorders. In New Orleans a situation developed in which many asthmatics were hospitalized for treatment, and in fact a few died from an unknown cause. Upon investigation it was determined that the source of this smoke, which adversely affected these asthmatic individuals, was underground smoldering fires of old landfills assumed to have been buried and covered over. Fissures in the ground opened and spontaneous combustion gave rise to smoke whose constituents were proven to cause allergic reactions in these individuals.

Visibility is another adverse effect often cited and attributed to smoke. The effects of visibility are not only aesthetically displeasing, but have been known to cause accidents and death. A good example of this is the situation on the New Jersey turnpike where a number of people were killed on October 24, 1973, due to a heavy concentration of smoke from an open burning dump, accompanied by fog.

Heavy quantities of smoke are basically unpleasant to most individuals, particularly those who reside in urban areas. In Georgia the majority of our citizens' complaints involve smoke from open burning. These complaints naturally occur primarily in urban areas where the greatest population density is located. In such situations smoke from land clearing, burning dumps, etc., can readily affect a number of individuals due to the close proximity to residential and commercial areas.

An overall inventory of emissions in the State of Georgia, which was complied in 1970, indicated that 8.5% of the particulate matter emissions came from the burning of garbage in open dumps. We did not include any estimates from smoke from forest fire or prescribed burning since we had no legal authority to regulate such. However, it is fair to say that including such smoke would bring the overall estimate of particulates from open burning to within 10 to 15% of the total particulate emissions in the state. With increased control of industrial emission the percentage of particulates from open burning will continue to rise in relation to industrial emissions, so that in the future open burning will command closer and closer scrutiny.

There are other considerations which went into our thinking before we adopted regulations on open burning restrictions. First of all, are there other alternative means to dispose of the waste products which had normally been burned? In many areas of the state there are no readily available alternative disposal methods at this time. Secondly, we had to consider the habits of the general citizenry, particularly those in more rural areas for whom burning of small quantities of waste in the back yard or some nearby field has been a way of life for centuries, and in fact may not affect anyone, since people are quite distant from one another. A third very pragmatic consideration on our part was our ability to enforce an open burning regulation on a statewide basis. We were determined not to adopt haphazardly a regulation which sounded good but which we could not effectively enforce, or was not even necessary.

Considering enforceability, we decided that it was only necessary or advantageous for us to control open burning in the strictest manner in those areas which are more urbanized and had a greater population density. We finally decided that the stricter regulations need only apply in those counties having a population over 65,000. Of 159 counties in Georgia this limitation included only 12 of the more urban counties in which our larger cities are located. However, these 12 counties included over 50% of the state's population and involved areas that had greater than 300 persons per square mile. It was our opinion that such areas required additional controls on open burning as compared to more rural areas of the state, and the areas involved were not too numerous to adequately enforce and inspect violations as necessary.

Therefore, the present form of our regulations on open burning do allow such burning for specified reasons which mainly involve small amounts of materials for unavoidable reasons. In those counties having a population over 65,000, no open burning is allowed unless it can be adequately demonstrated that adequate disposal for the particular materials in question is not available. If this is the case then burning is allowed, but only certain amounts within a given area, and only if the smoke densities are kept down through the use of good "boy scout" practices. We have found that it is possible to burn a number of materials, particularly wood waste, in a clean manner if the person conducting the burn is knowledgeable and pays attention to how the material is piled so that good air flow is enhanced giving good combustion. Georgia's present regulations are as follows:

(5) Open Burning:

(a) No person shall cause, suffer, allow, or permit open burning in any area of the state except as follows:

1. Reduction of leaves on the premises on which they fall by the person in control of the premises, unless prohibited by local ordinance and/or regulation;

2. Carrying out recognized agricultural procedures necessary for production or harvesting of crops;

3. Destruction of combustible demolition, or construction materials either on site or transported to a burning facility approved by the Department, unless prohibited by local regulations;

4. Supervised removal of undesirable growth from forest and woodlands;

5. For recreational purposes or cooking food for immediate human consumption;

6. Fires set for purposes of training public fire-fighting personnel when authorized by the appropriate governmental entity and the guidelines set forth by the Department are strictly observed;

7. Disposal of tree limbs, etc., resulting from storm damage;

8. For weed abatement, disease, and pest prevention;

9. Operation of devices using open flame such as tar kettles, blow torches, welding torches, portable heaters, and other flame making implements;

10. Setting and maintenance, by contractors and tradesmen, of miscellaneous small fires necessary in such activities as street paving work, installation or repair of utilities, etc., provided, that such fires are kept small in size, no smoke of a shade darker than a No. 2 on the Ringelmann chart is produced, and that local ordinances and regulations do not prohibit such action;

11. Open burning in other than predominantly residential areas for the purpose of land clearing for construction or right of way maintenance provided the following conditions are met.

    (i) Prevailing winds at the time of the burning are away from the major portion of the area's population;

    (ii) The location of the burning is at least 1,000 feet from any dwelling located in a predominantly residential area;

    (iii) The amount of dirt on or in the material being burned is minimized;

    (iv) Heavy oils, asphaltic materials, items containing natural or synthetic rubber, or any materials other than plant growth are not being burned;

    (v) No more than one pile 60' X 60' or equivalent is being burned within a 9 acre area at one time.

(b) In those counties whose total population, as listed in the latest U.S. Census, exceeds 65,000 the only legal exceptions of open burning shall be items 5., 6., 9., and 10. under section (5) (a) above, provided however, that if adequate disposal facilities for the particular combustible materials involved are not reasonably available, the other items under section (5) (a) shall also be permitted except that in no event shall the open burning of more than 100 cubic yards per day of material described in item 11 of section (5) (a) be permitted unless the person performing such burning shall have first given two days written notice of the time and place of such burning to the Department.

(c) A written notification to a person of a violation at one site shall be considered adequate notice of the Rules and Regulations and subsequently observed violations by the same person at the same or different site will result in immediate appropriate legal action by the Department.

(d) Except for a reasonable period to get a fire started, no smoke of a shade darker than a No. 2 of the Ringelmann Chart or equivalent opacity, shall be emitted by any source of open burning listed in sections (5) (a) and (b) above.

(e) During an air pollution episode declared by the proper authorities, no open burning of any kind shall be permitted unless open burning is required in the performance of an official duty of any public office if fire is necessary to thwart or prevent a hazard which cannot be properly managed by any other means or is necessary for the protection of public health.

Open burning in urban areas comes under five major categories. Examples of these kinds of burning, the reasons for them and methods for handling them are presented in the following comments.

Disposal of stumps and limbs by land developers who wish to build shopping centers, residential areas, and the like is a constant problem in urban areas. Quite often these areas are very close to residential areas and as such the smoke allowances must be watched closely. We have found that some tracts of land lend themselves readily to disposing of the waste by landfilling and covering it over. Of course, no structure with any weight can be placed over these areas, but they can be used after a number of years for a number of useful purposes. In some small areas the shredding of this material has been done satisfactorily, with the mulch being used for landscaping and other beneficial purposes. However, a great amount of the material is either hauled off to governmentally operated "stump dumps," or disposed of by burning in an air curtain destructor. These air curtain destructors or "trench burners" will do an adequate job if large stumps or a lot of green leafy material are not burned. There is an art to the proper operation of these burners, but if watched closely and constructed properly they can dispose of many tons of materials in a day's time with very little or no smoke. Also, it is possible with some materials to open burn small piles in a clean fashion, as long as the wind direction does not carry the small amount of smoke into residential or commercial areas nearby.

The open burning of garbage dumps operated by local governments is still a severe problem in the state. It is estimated that between 300 and 400 such burning dumps still exist. The state's Solid Waste Management Program is actively pursuing the reduction and elimination of such burning by converting most municipal disposal areas to properly operated sanitary landfills. There are problems of providing adequate tax money at the local level and securing the necessary equipment. However, the present state law requires that acceptable plans be made by January 1975 and that they be followed shortly thereafter.

The salvaging of scrap metal from junk autos, and some copper wire, produces copious amounts of dense, black smoke when open burning is employed. Open burning of such materials is expressly prohibited statewide. Shredding of junk automobiles in a shredder expressly designed for this purpose is a very satisfactory method of disposal and handling. However, such machines are very costly, running up to a million dollars or more total expense. Such a shredder installation requires hundreds of cars per day to provide an economical and profitable operation. Normally, it is only practical to haul such junk auto bodies into a shredder from a radius of 100 to 200 miles distance. The smaller junk car salvage operator is able to use a batch incinerator designed for the burn-out of such automobile hulks. Such an incinerator will handle up to eight cars per hour and will cost between 30 and 50 thousand dollars. Each such burning unit must be custom made, and does require proper operation and maintenance after construction.

The open burning of industrial waste has presented few problems to us and for the most part this practice has been discontinued statewide. Normally an industry has enough money and a good enough organization to find some disposal means other than piling it up and letting it burn. Of course, the burning of leaves, limbs, and garbage by individuals is at times a problem, but normally if conducted on a small scale and in rural areas does not really affect anyone. The state regulations make allowances for such practices.

The problem of smoke from prescribed fires in forest areas has not caused a major air quality problem. Such prescribed fires have been utilized in the South for many years for the proper management of woodlands. If we continue to receive the kind of cooperation from woodland operators, U.S. Forest Service, and the State Forestry Commission as we have in the past, we do not feel that it will be necessary to amend the state law and require additional, stricter controls on this practice. At present we are quite interested in the Burning Index system being researched and developed through the auspices of the U.S. Forest Service. Such an index system would relate to proper and adequate weather conditions for burning in a given area.

Smoke from prescribed fires normally occurs in less populated areas and is not of a continuous nature. Normally such a burn will require no longer than 24 hours and is sometimes conducted in less time. I do feel however that research should be continued and expanded into finding alternative disposal means for as much wood products and residues as is possible. In the South much of the tree is already utilized for either wood pulp, fuel, particle board manufacture, landscaping, mulch, poultry litter or production of carbonaceous char. For the most part, only the sawdust and bark remain a disposal problem, and I feel that within the next three to five years these so-called waste products will be put to useful purposes. I am encouraged by the type and quality of research which is now going into the analysis of smoke and its impact on air quality. Such knowledge of particle concentration, size distribution, composition, and effects will be essential in order to make adequate decisions in the future.

The overriding consideration for air quality control is the achievement of the ambient air standards. These standards have been set in order to protect certain public health and welfare considerations. At the present time EPA is conducting some research into the feasibility of adopting ambient particulate standards on the basis of certain particle sizes. Such a standard would certainly relate more easily to specific effects than the one presently in use, which relies strictly upon a total mass loading. There is some amount of discussion among control agencies at present as to where the ambient air standards must be met. Some feel that the standard must be achieved in all locations throughout the country. Others feel that a given standard should only apply where it is reasonably expected that individuals would be exposed for the time period covered by the standard. As yet this question has not been adequately resolved or dealt with, but will soon have to be in order for the states and local governments to know if they are achieving their own and the federal ambient air quality standards by the mid-1975 deadline, which most of us must meet.

As in the past most of the air monitoring sites will continue to be in the more urbanized areas where the greatest percentage of the population is located and the more adverse effects occur. Some emphasis is being placed on locating samplers in more rural areas in order to get a better understanding of the values occurring in these areas, and the effect that urban pollution is having on rural areas. However, this kind of sampling is still lacking and I feel will continue to be in the next few years.

As far as the future is concerned, there is a definite need for continuing research in relating specific particle sizes, densities, chemical reactions and synergistic effects to the adverse effects of a health or welfare nature which must be prevented. It is hoped that ambient standards can be better defined by relating particle sizes to specific effects, so that an overkill of emission restrictions would not be placed where it is unnecessary.

The recent Supreme Court tie vote upholding a lower court ruling requiring regulations to prevent significant deterioration will have a decided effect on all state regulations in the near future. The significant deterioration regulations which will be first adopted by the federal government, and then by the states, will have the most decided impact on presently clean areas such as those in rural forest lands. The setting of such deterioration regulations will in effect amount to the setting of new, lower ambient air standards than presently exist, solely for maintaining clean air in presently clean areas. Although this philosophy sounds good to most of us, I think we all realize that it cannot be pushed to its ultimate or we would be unnecessarily affecting many of man's activities for no good reason. However, unless Congress or the Courts have a change of heart it appears that such restrictions will be put into effect and enforced.

There is one final thought I would like to leave with you. Government agencies do not attempt to unduly restrict industrial or forest land operations for no apparent reason. Attempts have been made to relate emission and regulatory restrictions to those activities which directly affect human health and welfare. Those individuals with technical knowledge and experience in the operation of forest lands should make their knowledge known and available to these agencies, so that further regulatory action can be predicated upon the best available knowledge and not be unnecessarily restrictive or troublesome, either to the agency in its enforcement work or to the forest land owner and operator in the conduct of his daily business.

SUMMARY OF STATE REGULATIONS AS THEY AFFECT OPEN BURNING

Hugh E. Mobley
U.S. Forest Service

Prescribed fire has been an essential tool in forestry for more than 60 years throughout the South. Its use is prescribed on over two million acres annually. It has been used in the Northwest since 1910 for logging slash disposal, and is vital in reducing the potential of catastrophic wildfires, as well as other uses.

In the burning of forest fuels, however, certain products of combustion are put into the atmosphere and, consequently, come under the open burning regulations of the various states. As you know, the state air pollution control agencies are responsible for the regulating of air pollutant emissions in their respective states to meet and maintain federal standards. As a result, the regulations vary between all the states and are constantly changing. An attempt to summarize these various regulations has definite limitations.

I will highlight the principal rules and regulations by three geographic areas:

The Northeast, including the 17 Northeastern and Lake States from Wisconsin to Maine;

The West, including the 18 states of the Pacific Coast, Rocky Mountain, and Midwestern States west of the Mississippi;

The South, which includes the Southern States from Texas to Virginia.

The Northeast

In the Northeastern and Lake States, fires are used for clearing land, slash disposal, hazard abatement, blueberry production, and improvement of pastureland.

Prescribed fires for forest management, including wildlife, are not used to any extent except in Maryland, Delaware, and New Jersey.

When state air pollution regulations were first passed, open burning was banned completely in certain areas. In other areas, the regulations were in conflict with existing fire control laws. In some states, a person desiring to burn had to first secure *two* permits--one from the air pollution agency and the other from the fire control agency. These conflicting items have now been resolved in most states.

Some restrictions apply to open burning in all Northeastern and Lake States. It is completely prohibited in some sensitive areas or certain air sheds. Permits are required in most states. Generally fires for cooking, training, and recreational purposes are exempt from any statewide restrictions. Most regulations are worded so that all open burning is prohibited except for specific listed items. Open burning of salvage materials, trade wastes, dumps, garbage, petroleum products, and plastics is prohibited in most states.

In New Jersey, open burning is not permitted except for prescribed burning in the prevention and control of wildfires. It has to be in accordance with a plan approved by the Bureau of Forestry.

In Pennsylvania, air basins have been established in which no open burning is permitted.

Generally, open burning is allowed in the Northeastern and Lake States *when* certain specific restraints are met. Let us use Illinois as a typical example.

Permits for open burning are required. They are issued when:

- Atmospheric conditions will readily dissipate contaminants
- Such burning does not create a visibility hazard on roadways, railways, or airfields
- Done in other than restricted areas
- Burning is more than 1,000 feet from residences
- No reasonable alternative method of disposal is available.

The regulations are generally stringent but good. They are flexible in that each application is judged on its own merit.

The West

In the Western and Midwestern States, open burning is used for reduction of fire hazard, conversion of brush to timber or grass, preparation of site for planting or seeding, improvement of wildlife habitat, reduction of fungus infection on grass fields, and improvement of livestock range.

In the Northwest, old-growth forests produce large accumulations of unusable, highly flammable debris. From the air, a mosaic of forest patterns can be seen--tracks of past wildfires. Other techniques of slash control, including mechanical methods and greater utilization, are being tried, but burning remains the most widely used method. Hot fires are used which produce well-defined convection columns that lift the smoke up to 5,000 feet or even more above the fire. Most debris is consumed within four hours. These logging areas are generally remote from populated areas and usually have less stable air--a desirable characteristic for dispersion of smoke.

The Southwest is also faced with a serious wildfire problem, especially in the flashy brush fuels. Fire is used in these areas to reduce the fuel, resulting in a reduction of wildfire hazard. Fire is also used to establish and maintain firebreaks and for type conversion of brush to timber or grass, as well as range improvement.

In the Midwestern States where fire is not used to a great extent, regulations are usually less restrictive.

Open burning is restricted in all the Western States--except for Wyoming, Nebraska, and Kansas. New regulations are now being prepared in Wyoming and Nebraska.

Regulations in the West generally follow the pattern in the Northeast. Restrictions are based on the amount of pollutants given off by the material when burned, meteorological conditions, how essential it is to remove the material, and alternative ways to dispose of material other than burning. The regulations discourage open burning and complete elimination of nonessential burning is sought.

Open burning of the more polluting materials is usually prohibited. These are petroleum products, salvage operations (both cars and wire), garbage, plastics, and dead animals. The burning of less toxic woody materials is not as restrictive.

In Montana, all burning is prohibited unless specifically excepted. A public officer, or an individual who has a permit from a public officer, can use open fire for eliminating a fire hazard, instructing in firefighting, and removing hazardous material.

Agricultural and forestry practices are permitted provided no public nuisance is created and a permit is secured. Guidelines for issuing permits are:

- Meteorological conditions are such that good smoke dispersion shall prevail
- Material shall be dry, piled, and free from foreign debris when possible
- Burning shall be between 10:00 a.m. and 4:00 p.m.
- Burning shall be confined to those materials specified in the permit.

California uses a different approach. A "Burn" or "No-Burn" Notice, based on meteorological criteria, is issued each morning by 7:45 a.m. for 11 air basins. Except for the Lake Tahoe Basin, elevations above 6,000 feet are exempt from the "No-Burn" Notice. A permit is required by the county air pollution control district and is valid only on "Burn" days. Each district develops its own rules and regulations to cover its own particular conditions. The permits generally regulate the total volume of fuel that can be burned. Fuel has to be dried and prepared so as to reduce smoke. Only approved ignition devices can be used, and the wind direction is specified.

In New Mexico all burning, except for agricultural purposes, must take place between 10:00 a.m. and 4:00 p.m.

Open burning for agricultural and forestry purposes is permitted in Idaho when it can be shown that such burning is necessary and that no fire or traffic hazard will occur.

In Oregon, burning of grass fields is used extensively by the grass-seed industry to control disease. Most field burning occurs in populated valley bottoms where air pollution is already a problem from urban-industrial sources. The purpose of present regulations is to phase out open field burning in such areas when a feasible alternative method of field sanitation becomes available.

Permits are required year round in western Oregon. Prior to issuing a permit, each county collects a fee of up to 50 cents per acre. These funds are used for administering the program and for research development and demonstration of alternatives or better techniques of open field burning.

For forest areas, a smoke management plan was developed by all forest managers--including private forestry industry, U.S. Forest Service, Bureau of Land Management, Bureau of Indian Affairs, and the Department of Environmental Quality. The objective of this plan is to keep smoke resulting from forest lands burning from being carried to, or accumulating in, designated areas or other smoke-sensitive areas. The Division of Forestry is responsible for the coordination and control of the forest smoke management plan. Smoke must be vented up and away from smoke-sensitive areas. Fuel conditions must be conducive to good combustion. Criteria for issuing permits are very restrictive and have resulted in a marked reduction in the number of days when open burning is allowed. Considerations are weather forecasts, acreage involved, amount of material to be burned, potential smoke-column vent height, direction and spread of smoke drift, residual smoke, distance from designated areas, and mixing characteristics of the atmosphere.

No specific acreage limitation is placed on prescribed burning when smoke drift is away from designated areas. Smoke drift toward a designated area is restricted according to the following situations:

- Smoke vented into precipitation cloud system - no restrictions
- Smoke above a stable layer over the designated area - limited to a certain tonnage per area according to distance
- Smoke mixed through a deep layer at designated area - still further limited
- Smoke plume height below designated area ceiling - rigid restrictions.

Washington has much the same type of regulations as Oregon. Forestry burning is regulated by a cooperative agreement by all forest landowners and agencies. This agreement is administered by the Washington Department of Natural Resources. These agreements are strictly enforced in both states.

The South

Fuels are an inherent part of the southern forest, accumulating to the point where they become serious fire hazards. These fuels eventually burn--either as wildfires or prescribed fires. Prescribed fire is used to reduce the potential damage by wildfire. It is also used to improve the various resource benefits--accomplishing more than one objective at the same time. Some of these resource benefits are wildlife habitat improvement, site preparation, disease control, control of understory species, and to improve forage and accessibility.

Over two million acres are prescribed burned annually in the South, most of which are under an overstory of timber. They are low-intensity backing fires that produce little smoke. Some high-intensity fires are used to dispose of logging slash.

Initial state air pollution control plans emphasize reduction of air contaminants resulting from fixed and continuous emission points, such as incinerators and industrial operations, because they contribute a major share to air pollution. Agricultural and forest burning seldom raise the level of contaminants to the air quality standard set by the states, except in the immediate vicinity of the fire.

Visibility reduction on roads and airports, however, is a special hazard. Serious highway accidents causing loss of lives have occurred previously due to smoke from prescribed fires, as well as wildfires.

All Southern States have restrictions on open burning. Generally, the regulations prohibit all open burning with specific listed exceptions. The principal concern in agricultural and forestry burning is reduced visibility in smoke-sensitive areas. Practically all states prohibit the "high-polluting" sources of open burning--such as petroleum products, salvage, and commercial operations. When burning is the only feasible method, however, some states will issue permits for these special cases.

All states restrict open burning in or near smoke sensitive areas. In a few states, rural forest-type burning is exempt from any restrictions. Some use visibility as the criterion while others use distance from smoke-sensitive areas. Land-clearing restrictions are generally more stringent.

In Virginia, the State Forester has overall responsibility for statewide control of forest management burning and his office has to be notified prior to any burning. All open burning must be terminated upon declaration of any of the following four stages of an air pollution episode: (1) watch, (2) alert, (3) warning, and (4) emergency. No open burning is permitted that will create a traffic hazard.

In Florida, open burning for all industrial purposes is prohibited except when it is the only feasible method and a permit is first secured. The following types of open burning are exempt from any regulations--brush from homes, campfire or other recreational purposes, instruction in firefighting, and flaring of waste gas for reasons of safety.

Burning for agricultural and forestry operations is allowed under the following stipulations: Does not constitute a hazard to air traffic, does not reduce visibility to less than 500 feet, restricted to the hours between 9:00 a.m. and one hour before sunset, meteorological conditions conducive to smoke dispersion, and permission secured from Division of Forestry.

Permits can be suspended if conditions change so that prescribed burning becomes deleterious to health, safety, or general welfare--or which obscures visibility of vehicular or air traffic.

The Florida Division of Forestry (which administers the program) can issue permits for early morning, late afternoon, or night burning when certain specific meteorological conditions are met. An Air Stagnation Index has been developed that is used as a guide for the field people. On the other hand, if fire danger is high, permission is refused even though smoke dispersion would be excellent.

In North and South Carolina, open burning is restricted to the hours between 9:00 a.m. and 3:00 p.m.

The North Carolina Forest Service has, under test operation, a system much like Oregon and Washington for controlling smoke drift into smoke-sensitive areas. It is based on total allowable burning tonnage in each designated area according to weather conditions and distance from smoke-sensitive areas.

In Texas, open burning is authorized in rural areas when no nuisance is or will be created, wind direction is away from smoke-sensitive areas, burning is between the hours of 9:00 a.m. and 5:00 p.m., and certain meteorological conditions exist.

Air pollution laws are not a hindrance to practicing forestry. In fact, many state forestry agencies have found that the new air pollution regulations on forest and agricultural burning are wildfire prevention tools that restrict the indiscriminate burning previously done by some landowners without regard to neighbors, smoke-sensitive areas, air pollution, or possible escape.

Summary

In the beginning, some air pollution control regulations worked an undue hardship on the forest industry and forestry agencies. This was primarily due to a lack of knowledge of the forestry program and the problems encountered. Even though new and zealous to do their job, the various pollution control agencies have been understanding and most agreeable in working out common solutions to common problems.

It is important that the state forestry agencies work closely with the state pollution control agencies. Where this has been done, the response has been most positive in working out programs and administrative procedures that are most beneficial to the user--John Q. Public.

SESSION III

SMOKE MANAGEMENT

Moderator:

Karl Wenger
Rocky Mountain Forest and Range Station

METEOROLOGICAL PROBLEMS IN SMOKE MANAGEMENT

Charles F. Roberts
U.S. Forest Service

It has been estimated that the burning of forest fuels by both wild and prescribed fires produce in excess of three million tons of particulates annually over the United States (1). Since at one time or another every ounce of these particulates is generated, transported and deposited in its ultimate location by the atmosphere, it is important to consider the meteorological factors involved in efforts to rationally manage the concentration of particulates over a given area.

The need for rational smoke management programs is both clear and urgent. Everyone is aware of the increasing concern of the public about the issues of environmental pollution. While the problems of air pollution have been most acute in urban areas, the smoke generated by prescribed fires has on occasion raised the hackles of residents of rural areas also. A recent decision of the courts has held that new emphasis must be given to the preservation of air quality and the maintenance of air quality standards in rural areas. At the time of the writing of this paper, the form which this new emphasis will ultimately take is not yet clear. However, none of the proposals being considered appear to be especially troublesome to forest managers so long as reasonable precautions are observed and the proposed rules are correctly interpreted. Regarding the air quality aspects of prescribed fire, it is the design and the application of these "reasonable precautions" that leads us into the meteorological problems of smoke management. In the course of this paper I shall consider the meteorological problem and the state-of-the-art in three areas: (1) Considerations in the generation of smoke from prescribed burning, (2) problems in the transport and dispersion of smoke, and (3) problems in predicting the ultimate fate and effects of smokes.

Smoke Generation

The generation of smoke is the direct result of the combustion process. For that reason, those meteorological factors which influence combustion will clearly have important effects on smoke generation and will therefore need to be emphasized in rational smoke control and management. The primary meteorological elements that appear to be involved in smoke generation are those which govern fuel moisture and the burning conditions. We shall need to consider the problems of measuring, specifying and predicting those atmospheric variables involved in each situation.

Fuel Moisture

While as yet there are no completely definitive studies relating fuel moisture and smoke production, it is obvious to anyone who has ever attempted to light a campfire that the association is strong and positive; that is to say, the higher the fuel moisture the slower and cooler the fire will burn with an attendant greater smoke output per unit weight of fuel consumed. Fuel moisture then becomes one of the controlling elements in assessing the rate and total amount of smoke production for a given prescribed fire.

Considerations of fuel moisture require one to distinguish between living and dead fuels. For the dead fuels, it is well known that the vapor phase moisture absorption is controlled by ambient temperature and relative humidity. Wood will absorb water vapor by a diffusion process until an equilibrium point called the "equilibrium moisture content (EMC)" is reached. This factor is expressed as a ratio of the weight of water absorbed to the weight of the dry wood, and is a function of atmospheric relative humidity and temperature, although the primary dependence is on relative humidity.

Liquid phase absorption depends on the porosity of the wood and the period of time in which the wood remains in contact with a liquid water film. This latter process depends on the duration of precipitation in excess of some threshold amount. Fosberg (2) has found that the threshold amount is 1 mm per hour.

The absorption of water in both the liquid and gaseous phase is a rate process which takes place across finite intervals of time. Since ambient conditions are never constant for any long period of time, proper specification of fuel moisture will require data on temperature and relative humidity over fairly long periods, the actual length of the period depending on the rate of response of the fuels, a factor generally described by a characteristic time constant. The problem of determining dead fuel moisture for use in prescribed burning then becomes one of obtaining temperature, humidity and rainfall measurements with the required precision, accuracy and frequency. An alternative and certainly preferable procedure involves the use of what has come to be called the fuel moisture analogue. This device has been a gleam in the eye of those concerned with fire danger and fire behavior for many years. The concept of the fuel moisture analogue is one of exposing an element composed of material and fashioned in geometry with the response to variations in ambient equilibrium moisture that is nearly identical to the response of wood under the conditions which replicate forest fuels. Fuel moisture is then established by direct measurement of some property of the analogue such as weight, electrical resistance, capacitance, and so forth. I will not attempt to report on the current status of the development of the fuel moisture analogue since others who are present at this conference are in much closer contact with this work than I. However, the important things to note are that the emission factors for forest fuels are highly dependent on the moisture content of the fuels and as yet there is no ideally suited method for determining the moisture content of those fuels that will take part in combustion.

The green fuel moisture determination is an even more difficult problem since there is no known universal stable relationship between green fuel moisture content and the current or antecedent environmental condition. Although a relationship must exist, it is most unlikely to be universal in its applicability. This problem appears to me to fall more within the purview of the plant physiologist than the meteorologist so I would propose that we pass this problem to our botanist colleagues with the suggestion: "Why don't you fellows work on this one?"

Vertical Dispersion and Transport

The problems of dispersion and transport are concerned with the removal of the smoke from the combustion zone and the manner and state in which it arrives at its ultimate resting place far distant from the fire area. Although smoke actually is comprised of both gases and particulates I am only going to consider the particulate component, since the gases are involved in complex chemical reactions which would tend to invalidate the purely meteorological analysis of their transport and dispersion.

The first phase of the transport and dispersion phenomenon consists of a rapid vertical exit of the smoke in the form of a buoyant plume or jet. To describe quantitatively the rate of transport and the variation of smoke density with altitude and time requires a specification of both the mean and the fluctuating motions in the convection column. Over the years a very large literature has developed for predicting the rise of a heated plume in an atmosphere in varying states of thermal stratification and horizontal motion. These studies have resulted in a variety of what have come to be known as "plume rise models," most of which unfortunately are for application to smoke columns emitted from tall stacks or chimneys associated with power plants.

Briggs (3) has provided an excellent summary of the state-of-the-art in plume rise models and has found that some of the models do give excellent results under field conditions that approximate those assumed in the derivation of the model. The results of Briggs' review produced the conclusion that the "two-thirds law" is a valid approximation to plume rise under any stability condition. His formulation of the two-thirds law is:

$$\Delta H = 1.6\ F^{1/3} \times X^{2/3}/U \qquad (1)$$

Where ΔH is the height of the plume center line, X is the distance downwind from the source, U is the average speed of the horizontal wind and F is $(g/\Pi_\rho C_\rho T)Q$, the buoyancy term, with Q the energy release rate. For strictly neutral stability conditions, a different plume rise formula must be employed for horizontal transport distances: $X_* > 0.52\ F^{2/5} h^{3/5}$. In this formula, h is stack height, which, for a ground source, must be replaced by an artificial parameter such as "effective stack height." There are at present no good guidelines for assigning the value of effective stack height to open burning fires of finite size.

To illustrate the characteristics of smoke columns from prescribed fires that can be treated by plume theory, I have made some rough calculations using Briggs' best equations.

First I assumed a nominal prescribed fire, one acre in size, with a 100 BTU/ft^2/min energy release rate. The buoyancy factor F, is then 7.93×10^4 in units of ft^4 and sec^{-3}. Under these conditions the range of validity for the simple formula for neutral stability conditions with a 50 ft "stack height" is about 500 ft. For an extreme case of a 500 BTU fire, of 10 acres, the range of validity for the short formula is increased only to about 2,300 ft. Hence it is clear that in prescribed burning the long range plume formula will have to be used on most occasions since one will be concerned with transit distances in excess of 2,000 ft.

Briggs gives a long range plume rise formula as:

$$\Delta H = 1.6\ F^{1/3} U^{-1}\ X_*^{2/3} [2/5 + 16/25(X/X_*) + 11/5(X/X_*)^2][1 + 4/5(X/X_*)]^{-2} \qquad (2)$$

Calculations with this equation on a 10 acre fire with a 500 BTU specific output yields a value for X_* of 2,362 feet and for a distance downwind at which $X = X_*$ the parameter $\Delta H \times U$ has a value of 44,800 ft^2/sec. For a windspeed of 10 feet per second this yields a rise speed of 19 feet per second. This value can be compared with that obtained by other methods.

An alternative method for describing smoke column behavior is through the use of convection models that have been developed to simulate the behavior of cumulus clouds. These models are derived from the same theory underlying the development of the plume rise formulas discussed above, but they have the added virtue of being able to take account of vertical variations in static stability as well as providing information on features of the convection column other than the height-distance profile. The former features of the convection models are important for their use in treating smoke from prescribed fires since these convection columns will frequently penetrate the atmosphere to levels where there are marked variations in static stability.

The development of models of convection has been concerned with correctly specifying the rate at which bouyancy and momentum are exchanged between the rising, hot plume and an environment which is either motionless or in a uniform, horizontal flow. The mixing or the entrainment process is generally described in terms of the fraction of the mass or volume of the column which is exchanged with the environment per unit distance of vertical displacement, $M^{-1}dM/dZ = \mu$. In this formula, M is mass and μ is called the entrainment factor. Various laboratory studies have concluded that μ has an inverse dependency on updraft radius so that entrainment is generally formulated as $\mu = \alpha/R$, where α is a constant, the value of which is assigned somewhere between 0.2 and 0.6. Cumulus cloud models Davis-Weinstein (4), for example, assume that $\alpha = 0.2$.

The proper specification of the mixing process is one of the crucial meteorological problems in the prediction of convection column properties and behavior. The growth of column volume through turbulent exchange with the environment provides the mechanism for the dilution of particulate concentration. Since heat and momentum are also exchanged in the mixing process, both the vertical and horizontal motions are strongly influenced by the mixing process which acts in combination with the motion of the environmental air itself.

If we assume entrainment rates characteristic of those used in most cumulus models, then $\mu = 0.2/R$. For a column 400 ft across, the environmental air is entrained at the rate of about 0.1% of the original volume for each foot of vertical rise. For increments of 1,000 ft, the volume will have approximately doubled and the radius will have increased by a factor of 1.4, neglecting of course the volume expansion arising from vertical accelerations. Given the validity of the parameterization of the mixing process the vertical profile of concentration of the various combustion products in a convection column can be specified quite well; however, to define the rise speed and the height which the column will ultimately obtain requires information about the temperature structure along the vertical in the environmental air mass.

To demonstrate the influence of various parameters on convection column behavior I have computed a profile of vertical speed and column top for three characteristic air mass structures: (1) the ICAO standard atmosphere and (2) an adiabatic atmosphere and (3) an isothermal atmosphere.

The computations are based on a crude linear model derived from the Davis-Weinstein cumulus model. The development is as follows:

For convective processes the third equation of motion can be written as:

$$WdW/dZ = \beta - \mu W^2 \qquad (3)$$

Where β, the buoyancy term, equals $g/T_e/(T_p-T_e)$, T_p being a temperature representative of the parcel making up the convection column. T_e is the environmental or ambient temperature, and g is the gravitational acceleration. μW^2 is the drag which is determined by the mixing process itself. Since the primary source of the vertical variations in updraft speed lies in the rapid decay along the vertical of specific buoyancy, any satisfactory approximation of vertical speed requires a specification of the vertical variation in the buoyancy term.

We differentiate the temperature terms in the buoyancy expression and make allowance for parcel temperature change that arises from both mixing and adiabatic expansion yielding the following equation:

$$d\beta/dZ = -\mu\beta/(1 + \eta) + g(\delta_a - \delta_e)/T_e - \beta\delta_e/T_e, \qquad (4)$$

is a linear differential equation that can be integrated from parameters obtained with conventional radiosonde observations. The solution is,

$$\beta = (\beta_o - J/k)\exp(-kZ) + J/k, \qquad (4a)$$

where

$$J = g(\delta_a - \delta_e)/T_e,$$

and

$$k = \mu/(1+\eta) + \delta_e/T_e.$$

I have approximated the temperature change due to mixing as,

$$\Delta T_p = (T_e - T_p)/(1 + \eta) - T_p.$$

One can make use of the equation for the vertical variation in buoyancy arising from the stratification of the air mass, adiabatic expansion and mixing to integrate Eq. 3 for the vertical velocity.

$$W^2 = [2(\beta_o - J/k)/(2\mu - k)]\exp(-kZ) + J/k\mu$$
$$- [W_o^2 - 2(\beta_o - J/k)/(2\mu - k) + J/k\mu]\exp(-2\mu Z), \qquad (5)$$

where Z is the height above some reference level at which $W^2 = W_o^2$. Note that we have computed the mixing temperature by taking account of the volume of environmental air that is entrained by the rising parcel. By similar reasoning, we can compute the concentration of the various constituents of the rising plume that are conserved in the field of motion if that information is required.

A difficulty encountered in calculating convection column behavior with a model of the type described above is the necessity of prescribing an initial plume temperature at the fire front in order to initiate the convection. There is no obvious method for arriving at a representative temperature. In those calculations presented in this paper I employed the following scheme for determining initial plume temperature.

For a slab of gas of unit thickness participating in the combustion process I assumed a combustion temperature of 1500°K. I computed the vertical acceleration of the vertical speed, dW/dZ, resulting from the buoyancy associated with this temperature. From this factor I computed the horizontal convergence with the relationship $dW/dZ = -(\mathrm{div}\ V)$. Replacing (div V) with its geometrical equivalent, $\mathrm{div}\ V = A^{-1}dA/dt$, I computed the rate of inflow into a cylinder of unit height sitting on top of the fire zone. The resulting temperature of the mixture of gases making up the convection column as it leaves the fire is determined from mixing the two volumes in the same manner as that described for determining plume temperature resulting from entrainment at higher levels. An example of the calculation follows.

$$T_e = 300°K$$

$$\text{Buoyancy} = g/T_e/(T_p - T_e)$$

$$= g/300/(1500-300) = 4g$$

$$\frac{dW}{dZ} \simeq \frac{W_1 - W_0}{\Delta Z} = 2\sqrt{2g}$$

$$\frac{dA}{dt} = -(2\sqrt{2g})A = -8.85(HR^2)$$

Hence, the ratio of the two mixing volumes is 8.85.

$$\text{Plume Temp.} = \frac{8.85 \times 300 + 1500}{1 + 8.85}$$

$$= 422°K$$

If the column rises above the condensation level we ought to take account of the effects of condensation on the change in the buoyancy force. This can be done by replacing the dry, adiabatic lapse rate γ_a by the moist ascent rate γ_m in the J-term of equations (4) and (5), and by allowing a mass increase factor to take account of the presence of liquid water in the ascending parcel. I have not attempted these revisions for the simple reason that most of the fires which we are concerned about in controlled burning will not be used under conditions in which the plume from the fire would induce significant cumulus development.

Horizontal Transport and Dispersion

We now turn attention to the problem of horizontal transport and dispersion of the smoke plume. While there has developed a very large literature on diffusion formulae bearing the names of Sutton, Pasquill and others, these methods yield satisfactory results only for relatively short distances compared to those of concern in smoke management. For dispersion it is important to recognize that the motion of the atmosphere which we describe as the "wind" is a composite of a large number of eddies of varying sizes and durations. If one makes very detailed measurements of windspeed and direction it will be found that there are variations in the vector wind of periods ranging from a fraction of a second to several tens of minutes (Fig. 1). For a given site, the periods of dominant variations in the wind will vary with both the strength of the flow and the temperature structure of the air layers near the ground. On bright, sunny days with light winds, the most important variations will have

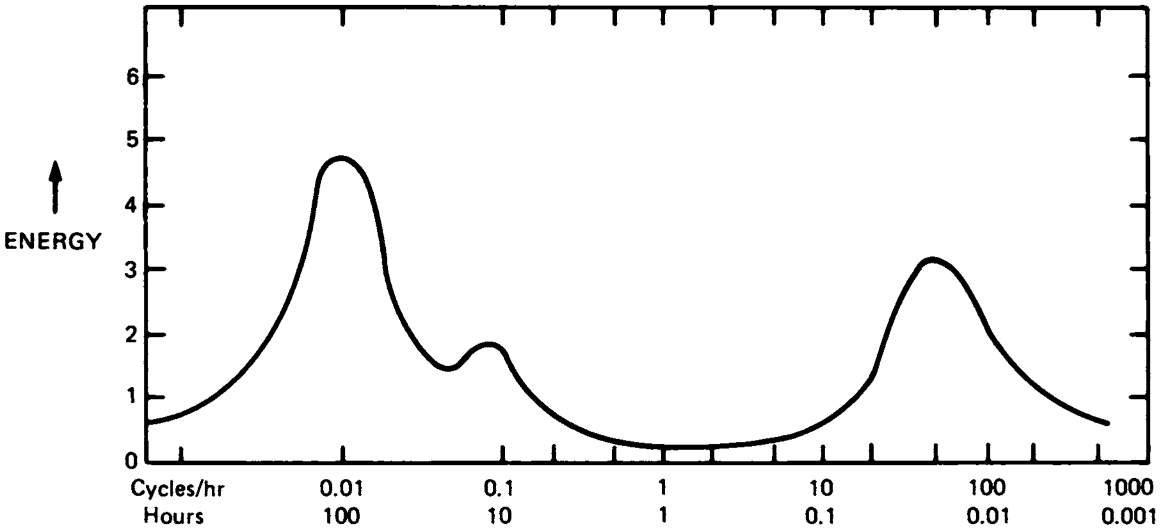

FIGURE 1. Van der Hoven's Wind Speed Spectrum.

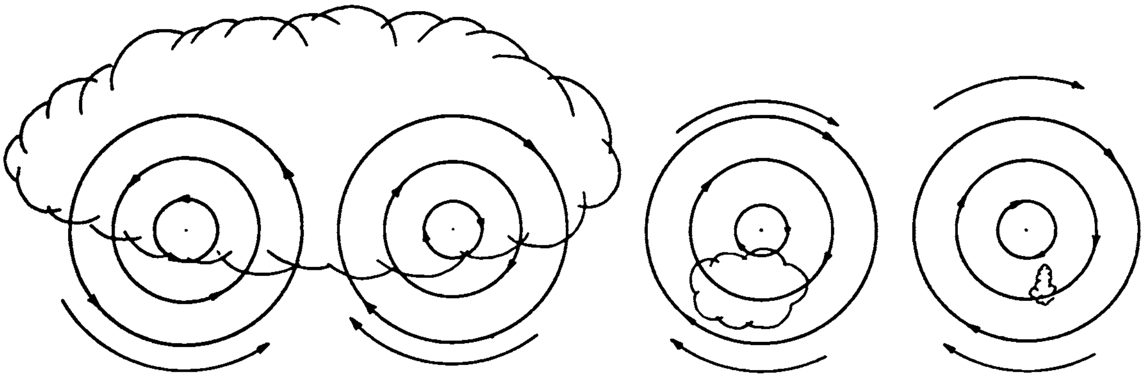

FIGURE 2. Relationship between eddy dispersion and plume size.

periods of around 15 to 20 minutes. On cloudy, windy days, the periods will be on the order of a couple of minutes or less.

If the windspeeds and directions measured at discrete intervals of time are accumulated over periods which are longer than the dominant periods of the variations, one can define a "mean flow" which is quite steady from one averaging period to the next. The transport of smoke generally can be quite adequately described by the mean flow from a properly selected averaging period while the fluctuating motion with their varying periods will accomplish the dispersion or dilution of horizontally moving plumes.

To predict or specify the transport and dispersion characteristics on any given occasion requires an accurate description of the properly defined mean flow, along with both the intensity and characteristics of the turbulence. The effectiveness of the turbulence in diluting the smoke depends in a very important way on the scale or the characteristic size of the eddies. We shall now examine qualitatively, at least, how these problems may be approached. First, we need to establish some relationship between the scale or the size of an eddy and its period or frequency. For the domain of eddies that can be regarded as turbulence one ordinarily makes use of the so-called frozen turbulence hypothesis of G. I. Taylor which assumes that eddies move along without much change at some constant speed determined by a basic current. We may regard an eddy as a small vortex type circulation, then it can be seen that the transformation between scale and frequency is given by the formula, Frequency = $C/2\pi S$, where C is the basic current speed and S is the scale or size of the eddy.

While looking at the geometric representation of an eddy (Fig. 2) it will be helpful to consider the relationship between eddy size and its dispersive power with respect to horizontally moving smoke plumes. For this purpose, we superimpose smoke plumes of three different sizes on our picture of the eddy circulation. In the first instance, the size of the plume is very small compared to the scale of the eddy and the plume is simply advected around the vortex with its structure remaining pretty much intact. For the second case, in which the plume approaches the size of the eddy itself, one can see that the eddy flow requires that different parts of the plume move in slightly different directions. In the other case, the plume is being effectively torn up in the spatial variations in the flow. If you can imagine that instead of a single eddy, there exists a large number of eddies of continuously decreasing size, it is obvious that the distortion and the separation of the plume will be greatly increased. In general, the number of eddies operating in the plume increases with plume size.

If our picture of the dispersion process is correct, the proper specification of dilution will require that we have information on both the magnitude and the size of the eddy circulations. This information is conveniently provided by the spectrum of turbulence. The spectrum represents the distribution of energy (or velocity variance) in terms of wave number or eddy size. The spectrum when expressed in Lagrangian frame of reference provides a direct indication of the magnitude of the wind fluctuations that move along with the plume. Hence, an accurate turbulence spectrum will permit a good statistical description of plume dispersion as it moves downwind.

Theoreticians who have worked with turbulence over the years, have found that only certain properties of the spectrum can be specified from local, external conditions. The most useful finding has been that resulting from applications of the Kolmogorov theorem which indicates that the functional form of the turbulence spectrum in the so-called inertial subrange is determined by the energy dissipation rate and a certain universal constant. The actual statement of the Kolmogorov theorem which has come to be called the "minus five thirds law" is $E = \alpha k^{2/3}\varepsilon^{-5/3}$. Where E is the spectrum (a function of wave number, k) ε is the energy dissipation rate and α is a universal constant. The size of the eddies making up the inertial subrange depends on stability and height above ground. Generally the sizes range from about one tenth of the height above ground to sizes of the order of a centimeter. It would appear that under most conditions, the structure of the inertial subrange will govern the rate of dilution of smoke plumes.

Briggs (3) in his monograph has, from dimensional analysis, suggested that the relationship between dilution rate and energy dissipation rate is

$$dr/dt = \beta\varepsilon^{1/2}r^{1/3},$$

where r is plume radius and β is a dimensionless constant. Observational data suggests that β is between 0.80 and 1.0 when best estimates of energy dissipation are used. The range of validity of this relationship is not clear, but inasmuch as it has been found that the similarity hypothesis produces a satisfactory approximation for the low-wave number portion of the spectrum, the Briggs formula should be capable of predicting smoke column dispersion for large transport distances.

Horizontal Transport

The horizontal transport as contrasted to the dispersion of combustion products is controlled by the speed and the direction of the mean wind in those layers nearest the ground. Since, on most occasions, there is a fairly deep layer in which both the speed and the direction change rapidly along the vertical, the problem of specifying the horizontal transport is more complex than it seems at first. However, if one is interested in the transport of the smoke through some altitude zone, then there is a need for wind flow information only in that particular zone.

In smoke management it would seem that the primary consideration is with the smoke transport in the first few hundred feet of the atmosphere. This means that the problem requires one to determine the wind in the so-called Ekman layer where, fortunately, the theory governing the vertical variation in wind is fairly good, at least for practical applications such as those involved in smoke management.

The problem of wind variation in the vertical under the influence of a horizontal pressure gradient, surface friction and the Coriolis acceleration has commanded the attention of a large number of highly competent theoriticians over several decades. Each has derived solutions to the problem that bears his name: Ekman, Taylor, Lettau, Blackadar and Rossby, just to name a few. Some have allowed for effects other than those three basic forces mentioned above. For example, Lettau (5) allowed for baroclinic effects in his solution and Rossby and Montgomery took account of both stable and unstable conditions of flux.

Again it is fortuitous for the practitioner that all solutions have a strong similarity. Each describes the vertical variation in a form which approximates a logrithmic spiral, approaching the geostrophic wind asymptotically at an altitude depending on surface windspeed, the angle between wind and pressure gradient force, surface roughness and vertical stability, if the stratification is non-adiabatic.

The horizontal transport of smoke is described by the vertically averaged wind through the Ekman layer, the wind profile being defined by the surface wind, the geostrophic wind and the depth of the friction layer. Both the geostrophic and surface winds can be obtained from wind and pressure measurement over the local area. The depth of the friction layer is not easily determined; however, various formulae have been suggested for its estimation. Hanna (6), in a comparison of the several existing methods for specifying the thickness of the boundary layer, found that Laikhtman's formula worked best. The Laikhtman formula is

$$H = 0.75U_g(g/T\gamma_\theta)^{-1/2},$$

where U_g is the surface geostrophic wind speed, γ_θ is the average lapse rate of potential temperature in the boundary layer and the other notation is standard. Hanna reports a 0.89 correlation between the predictions of the Laikhtman formula and observations of boundary layer depth. Clearly, however, Laikhtman's formula is not applicable in a completely adiabatic atmosphere.

Fate and Effects

The ultimate concern in smoke management is with fate and effects of the particulates and gases which are released in the combustion process. The gaseous components of the plume involve problems in atmospheric chemistry, and these I am going to exclude from this paper which deals only with the meteorological aspects of smoke. The particulates in the smoke plume, however, influence and are influenced by purely meteorological processes and hence, we shall discuss the fate and effects of these components in that context.

Fate

Vines (7) and others have shown that the particulates produced by combustion are made up primarily of tar and ash, covering a wide range of sizes. Measurements have shown that the size distributions vary from a few tenths of a micron to several tens of microns. This wide dispersion in sizes leads to widely varying fates for the different particulate classes. Obviously, those particulates which are much larger than one micron in diameter commence to settle relative to air currents on which they are suspended immediately after release. As soon as the vertical motion dies away as a result of the disappearance of buoyancy, these larger particles begin to "fall out" and slowly settle to the ground. The fate of the large size particulates is rather clear: they leave the atmosphere and return to the surface of the earth within a few hours after release. The smaller, submicron size, particulates present an entirely different problem, however. Their fall speeds are so slow that they remain in the column above the fire until they are exchanged with the ambient air through the mixing process. From this point, they are further transported and diffused throughout the entire atmosphere.

The total residence time for the submicron size particles is not adequately known, but it is virtually certain that the only really effective removal mechanism is precipitation scavenging. The rates of fall of smaller particles in still air is so slow as to imply residence times of the order of years at the altitudes normally reached by the convection column. Even the effectiveness of precipitation scavenging remains in doubt. The work of Engleman (8) and others clearly shows that the raindrop capture process for particles below one micron in size is not very efficient. The only effective wholesale removal process requires that the particulates serve as condensation nuclei for cloud and precipitation formation. There is growing evidence that this is the most important mechanism for the removal of small particles from the atmosphere.

While it is not likely that any of the components of forest fire smoke are as hygroscopic as those that make up industrial smokes, it is still well known that wildfires produce vast quantities of very efficient condensation nuclei, the type and amount depending in some yet unknown way on fuels and fuel conditions. If forest fire smoke represents a significant source of condensation nuclei smoke management must take account of this fact, and prescribed fires ought to be scheduled and planned to take advantage of this method for reducing the particulate loading on the atmosphere.

Effects

What are the effects of the particulates and gaseous products in the smoke columns of forest fires? The most difficult and certainly the most controversial aspect of the meteorology of smoke management lies in the area of effects. Of the principal components making up the column, CO_2, CO and particulates, only the particulates are a major concern in meteorological processes and weather. CO_2 content has a very pronounced influence on the atmospheric radiation, but the prescribed burning of forest fuels only changes the rate of CO_2 release. It does not affect the total amount produced since, sooner or later, those fuels that are burned would decompose anyway, and the net contribution to the carbon dioxide content of the atmosphere is unchanged by burning.

There are no known important influences on meteorological processes resulting from CO inputs to the atmosphere, although there is some concern over the possibility that significant amounts of CO could enter the stratosphere where a chemical reaction with ozone might alter the radiation received in the lower atmosphere and create long term shifts in the earth's climate.

Particulates in smoke represent the major meteorological concern. The most obvious effect of these particles is the reduction in atmospheric visibility that comes about from the drastically altered visual range in an atmosphere that is contaminated by particles. While reduced visibility may be the most immediate result of the presence of the smoke, it is probably not the most serious, in spite of the potential hazard which it poses for both ground and air transportation. The more subtle, long term effects of the growing concentration of particulates in the atmosphere provides the real basis for concern regarding smoke effects. It is a concern which may eventually become a real problem to the whole of human society.

There is substantial evidence that the particle content of the atmosphere is increasing steadily and rather rapidly. J. Murray Mitchell (9), in his analysis of the effects of particulate loading cites a number of sources for the evidence on increasing contamination: measurements of alpine glaciers, changes in atmospheric electrical conductivity over the ocean, turbidity measurements at Mauna Loa observatory in Hawaii, and starlight extinction data from astronomical observatories. These data show clearly a significant increase in particle loading during the last century but leave in doubt the magnitude of the increase and the extent to which it is global or regional in nature.

Mitchell's analysis of particulate loading trends, summarized in Fig. 3, provides a strong argument for smoke management programs in which small particle production is minimized, especially if the effects of particulate loading on the global climate are those which have been hypothesized by the various investigators. Mitchell assumes from past data an annual growth rate for man produced particulates of 4%. The curve labelled $f = 0.2$ is the projected total loading on the atmosphere if man contributes 0.2 (20%) of the total. The curve labelled $f = 0.3$ assumes man's contribution as 30%. The best data available suggest that anthopogenic particulates make up between 20% and 30% of the total. If higher percentage contributions are assumed the total growth rate approaches that indicated by the curve labelled $f = 1.0$, which is the projection based on the assumption that all particulates are man made and growing at the rate of 4% per year.

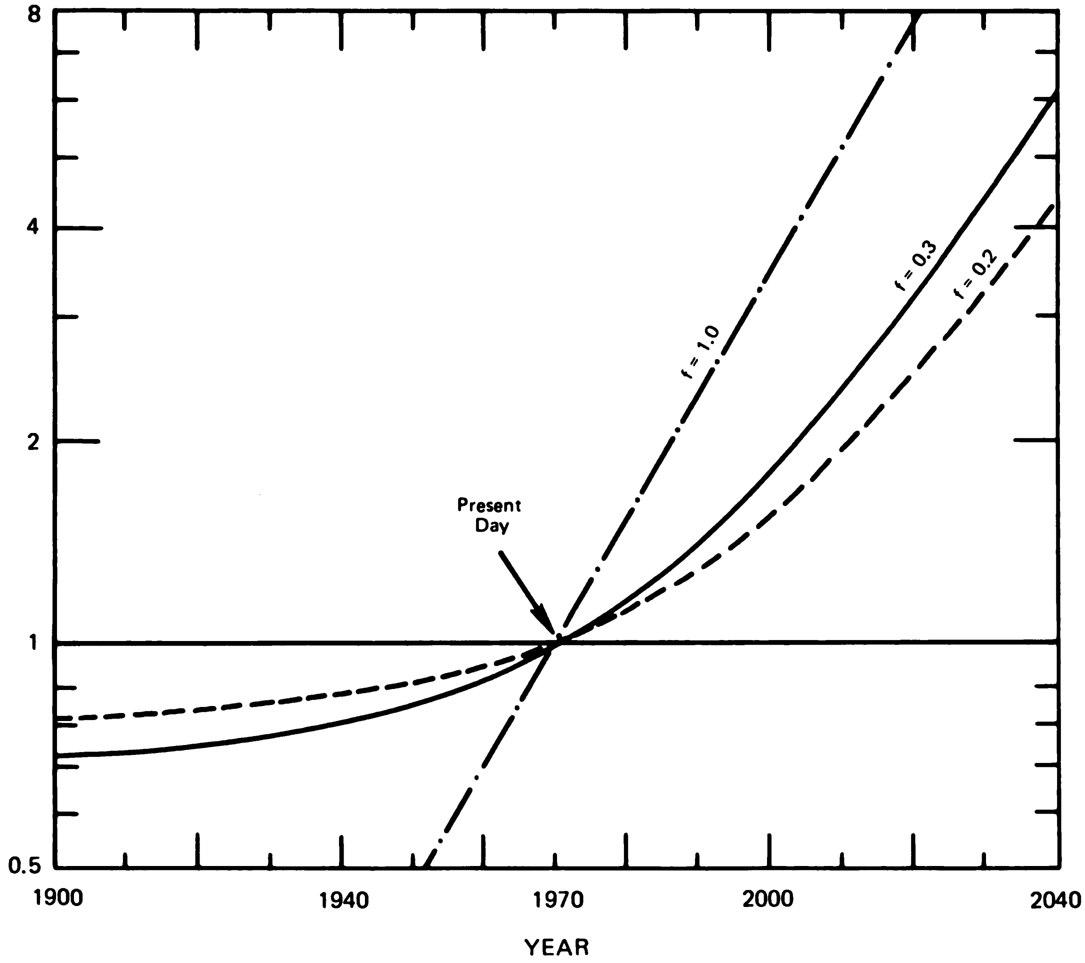

FIGURE 3. Projections of atmospheric particle loading (from Mitchell -9-).

One of the more definitive studies on the effects of particulates was reported in a recent paper of Braslov and Dave (10) who integrated the radiative transfer equations for several model clean atmospheres and atmospheres polluted by particles with precisely defined scattering and absorbing properties. Their results appear to indicate that atmospheric particles have a major influence on the earth's albedo only at sun angles below 45°. Unfortunately the Braslov-Dave study is not able to project the fate and effect of the absorbed radiation. The importance of this factor is a major source of the disagreement regarding climatic impact.

Actually, the picture on climatic impact of particulates is totally ambiguous at present. One can obtain either a warming or a cooling effect on the earth's climate from a given particulate loading depending on assumptions regarding the vertical distribution of particulates and their optical properties. This is a problem which urgently needs a solution to provide sound guidelines for environmental management. I am hopeful that our work in the Smoke Management R&D Program will contribute to the resolution of this complex issue.

Summary

The meteorological problems in smoke management can be grouped in the general areas of (1) smoke production, (2) transport and dispersion and (3) fate and effects. The principal problems in smoke production are those requiring specification of fuel moisture for both living and dead fuels, and wind conditions on the time and space scales to which prescribed fires respond.

For transport and dispersion the major problems lie in the adaptation of models simulating atmospheric convection to fire convection column behavior. A major obstacle in this effort lies in parameterizing fire energy input to initiate and sustain the convection. Prediction of dispersion of smoke plumes requires the derivation of complete statistical descriptions of wind fluctuations on the small scales.

The major concern in fate and effects involves the impact of the submicron particles in the earth's radiation balance.

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TABLE I

CONVECTION COLUMN RISE THROUGH MODEL ATMOSPHERES

A: US Standard Atmosphere, Tp = 475^{o}K

Ht	Ta	R = 115m		R = 200m		R = 50m	
(Meters)	(^{o}K)	Tp	W (mps)	Tp	W (mps)	Tp	W
0	288.00	*	*	*	*	*	*
10	287.97	470.1^{o}K	11.0	473.2^{o}K	11.1	465.8^{o}K	10.6
50	287.84	468.6	22.2	471.0	23.4	461.3	13.3
100	287.67	446.2	27.6	457.3	30.7	418.7	20.1
500	286.37	422.2	23.1	441.3	38.4	380.8	5.4
1000	284.74	339.8	12.5	369.0	28.9	305.8	-0.4
1500	283.10	300.9	6.2	322.7	19.9	285.3	*
2500	279.80	285.6	*	298.7	5.2	279.8	*
3500	276.47	273.7	*	278.3	*	*	*
5000	273.10	*	*	269.3	*	*	*

B: Adiabatic Atmosphere

0	288.0	475.0^{o}K	.0	475.0^{o}K	*	475.0^{o}K	.0
10	287.9	470.7	11.0	473.3	11.1	470.1	10.6
50	287.5	468.6	22.2	471.0	23.4	461.0	18.8
100	287.0	446.1	27.7	457.0	30.8	418.7	20.1
500	283.0	422.1	23.4	441.3	38.8	380.7	5.7
1000	278.0	339.5	13.5	368.7	30.0	305.3	1.9
1500	273.0	298.6	8.2	320.9	21.9	282.5	0.8
2500	263.0	280.5	2.2	294.4	10.1	273.9	0.05
3500	253.0	264.7	1.1	270.1	5.8	263.1	0.02
5000	238.0	253.4	0.2	255.4	2.2	253.0	0.00

C: Isothermal Atmosphere

0	280.0	475.0^{o}K	.0	475.0^{o}K	.0	475.0^{o}K	.0
10	"	470.1	11.4	472.7	11.5	469.5	11.0
50	"	468.3	23.0	471.1	25.2	460.4	19.4
100	"	444.9	28.6	456.5	31.8	416.3	20.3
500	"	420.0	23.7	440.0	39.5	376.7	5.4
1000	"	334.5	12.5	364.9	29.5	299.1	-2.2
1500	"	294.9	5.4	317.4	19.7	278.8	*
2500	"	280.0	*	274.6	-2.1	274.8	*
3500	"	270.1	*	*	*	*	*
5000	"	*	*	*	*	*	*

FACTORS INFLUENCING SMOKE MANAGEMENT DECISION IN FOREST AREAS

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U.S. Forest Service

Forest ecologists tell us that fire, hence smoke, has always been a part of the forest environment. It probably always will be. But in this day of managed environment, both fire and smoke from forest fuels are subject to increasingly strict controls. In this paper, we will look at forest smoke--first, as it has been covered in a current effort by forest scientists to design environmentally sound guidelines for management of forest residues, and second, we will examine the components of a smoke management system.

Preparation of Interim Guidelines for Residues Management

The Forest Residues Reduction Program, for which we work, is currently preparing interim guidelines for the management of forest residues. All environmental effects of these residues and of their treatments must be considered. Wildfires are fueled by residues, and many residue treatments use fire, so smoke from such fires must be considered as one important effect.

In our work, *forest residue* is considered to be the woody material, living or dead, that tends to accumulate in the natural forest or that is left following cultural operations and which may be a fire hazard or impediment to the management of the forest environment.

We approached residue management not only as it affects water, air, or scenery, which seem to get most of the attention, but also as such management may affect the total forest environment--soil, plants, animals, and influences such as fire, insects, and disease. We think our approach is a sound one, since it considers these factors together, instead of separately. Consideration of all aspects of the forest environment is the essence of good forest management and is required by the Multiple-Use Sustained-Yield Act and National Environmental Policy Act.

The first step in formulating guidelines was the preparation of 18 papers, each summarizing the state-of-knowledge of the effects of forest residues and their treatments on a component of the forest environment. These papers were written by researchers from the Pacific Northwest and will be published as a compendium.

Later steps involved integrating such research knowledge, as well as the field experience of practicing specialists and administrators, into interim residue management guidelines which were both scientifically sound and administratively workable. The process for achieving this meeting of minds, many with opposing viewpoints, was designed and directed by the Forest Residues Program Manager, John M. Pierovich.

We set three requirements for residue treatment guidelines. First, they had to be based on the best available scientific information. Second, particular geographic regions of application had to be indicated for each guideline. And finally, no conflicts between guidelines would be tolerated. Any conflicts arising during formulation were to be resolved, if possible, by requiring different methods of performing residue treatment jobs. If this was not sufficient or possible, then an administrative decision favoring one environmental component would be needed.

The requirement for scientific soundness was accomplished in two ways. First, citations of specific residue and treatment effects were abstracted from the 18 manuscripts. Each citation was categorized by applicable geographic area, residue type, treatment method, and environmental component affected. This categorization was used as the basis for computerized cross referencing and retrieval documentation for the resulting guidelines. Second, from Federal and State forestry agencies, top researchers and administrative staff scientists familiar with Northwest resource problems were formed into nine technical panels covering the environmental components:

Soils
Silviculture
Terrestrial Habitat
Fire Management
Forest Insects
Forest Diseases
Water Quality & Aquatic Habitat
Air Quality
Forest Recreation

All panel members were provided with the cross-referenced citations and encouraged to provide any additional pertinent references. Each panel produced a set of statements backed up by citable authority, specifying the degree of residue removal and limitations on treatment method required for acceptable management of the particular environmental component. Where requirements varied by type of residue or geographic area, the necessary restrictions or specific exclusions formed part of the statement. For example, the Soils Panel specified: Where fine and medium textured soils are present, crushing of residues will be avoided whenever soil moisture in the surface 10 inches exceeds 10%.

In the next step, the statements prepared by the technical panels were carefully compared to identify conflicts either within or between environmental components. There were many. The chairmen of the nine technical panels met to resolve those conflicts of a technological nature; for example, the Forest Recreation Panel wanted to remove all man-caused residue, but the Terrestrial Habitat Panel pointed out that slash residue was necessary for nesting and cover for wild animals that recreationists would enjoy seeing. This was resolved by specifying that appropriate residue be left where wildlife habitat was a consideration.

When the technical conflicts had been resolved, two additional panels of experienced forest managers met. One, chaired by Deputy Regional Forester Robert Torheim, performed the arbitrations necessary to apply the residue management specifications to public lands. The other, composed of private forest managers and chaired by Western Forestry and Conservation Association Forest Counsel Steele Barnett, made similar adjustments for application of the specifications to private forest lands. The final products, somewhat different sets for public and for private forest lands, are a far cry from simple directives such as *never clearcut*, *never burn*, or *chip all residue*. The guidelines recognize the multiple components of the environment, and they reflect the variations in the environment; they are scientifically as sound as present knowledge will permit, and they are administratively achievable, though possibly not without some revisions in present practice.

Air Quality Panel Recommendations

Some of the primary recommendations of the Air Quality Technical Panel were:

1. Methods of residue treatment other than burning are preferred. However, where the residue treatment required for acceptable resource management can best be accomplished by burning, such burning will be done in compliance with an approved smoke management plan. (A model smoke management plan was provided, similar to that in Cramer and Graham.[1])

2. To minimize the amount of smoke produced, emphasize methods of fuel preparation and burning procedures that produce hot fires, strong convection columns, and clean burns with minimum smoldering.

3. Special safety measures must be taken wherever smoke from burning operations may interfere with vehicular or air traffic.

4. To facilitate establishment of priorities for use of burning or alternative residue treatments, each land manager should determine for his area the average number of days annually when smoke dispersion and burning conditions are such that burning can be accomplished within air quality standards.

5. Large concentrations of forest residues that constitute a potential threat of important smoke nuisance from wildfire should be abated.

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[1] Owen P. Cramer and Howard E. Graham. Cooperative management of smoke from slash fires. J. For. 69(6): 327-331, illus. 1971.

6. When burning can be accomplished without visible or otherwise objectionable emissions (such as with air curtain-type equipment), no air quality limitations apply.

The two forest management panels accepted most of the specifications suggested by the Air Quality Technical Panel. Other technical panels were explicit in defining where fire should not be used or where certain kinds of burning would be unacceptably damaging to soil. More attention was given to the amounts and sizes of materials that should be removed (or left) than to how the reductions to these levels would be achieved. Of all treatments, fire was most restricted. Many other restrictions were aimed at the use of heavy equipment--soil compaction, soil disturbance, and slope limitations.

Components of a Smoke Management System

Though the interim environmental guidelines for treatment of forest residues indicate many limitations on the use of fire, other limitations on the accumulation of residues as obstructions, fire hazards, and potential smoke hazard must also be met by some form of residue treatment. Equipment and cost limitations will continue to favor the use of fire in some situations. But, once the decision has been made that the residue and environmental situation in which it lies are such that burning is the best treatment, all aspects of the environment considered, then it still becomes necessary to make some additional decisions to get the burning accomplished with minimum pollution. And this is where the smoke management plan comes into play (see footnote 1).

Pollution is the presence of substances in a concentration and for a duration that causes or tends to cause undesirable effects. The objective of smoke management is to minimize the amount of smoke produced by the burning of forest residues and to prevent it from contributing to pollution, particularly in areas sensitive to smoke. One of the first steps in setting up a smoke management system is to identify Smoke-Sensitive Areas (SSA). These are defined as high use or heavily populated areas that are susceptible to excessive accumulation of atmospheric emissions because of climatic and topographic restraints on ventilation, such as in natural basins. Their boundaries may be defined in terms of the confining terrain, distance from heavy population, and a ceiling or horizontal boundary 2,000 feet above mean terrain level.

The smoke management plan is built around the characteristics of forest residue burning operations. Some of these characteristics are:

1. Forest fuel smoke sources come in a variety of forms and sizes from the campfire that produces the tangy aroma of wood smoke to the forest conflagration. Smokes from prescribed burning are in between. Some are large and burn hot producing a strong convection column that may lift the smoke plume thousands of feet above the usual air pollution sources. But we also have prescribed underburning which produces comparatively little heat; hence, its smoke tends to remain in lower air

layers. Each type of burning operation has characteristics that in turn place special requirements on the smoke management system.

2. Each type of burning has its own requirements for weather and fuel moisture for producing the desired burn result. Consequently, there has to be flexibility in scheduling to meet these requirements. Smoke management makes additional requirements both on the weather and on the condition of the fuel. Under smoke management, prescribed burning of forest residues is done on the basis of a fire-weather forecast and on-the-ground observations that fulfill the exacting weather requirements.

3. Geographically, forest residue smoke sources are frequently vertically and horizontally remote from SSA and metropolitan air quality problems.

4. Because each smoke lasts only a few hours and can be carefully scheduled to meet the necessary dispersion conditions, the emissions from forest burning need not be in air that becomes involved in pollution problems.

5. Smoke from the burning of forest residues is the same as the smoke that has gone into the air naturally for as long as such fuels have been flammable. Its components do not accumulate in the air but have limited residence times in response to various cleansing systems. Though smoke contains various chemicals that in concentration may be considered undesirable, the greatest impact appears to be from impairment of visibility. As long as visibility requirements are met, the other smoke components will be well within ambient air standards.

Processes in Smoke Dispersion

Smoke that goes into the air does not become a pollution problem if the weather forecasts are accurate and if the smoke management plan functions properly. The plan is keyed to how the smoke will disperse, and dispersion is governed by weather-related processes that we call diffusion, diversion, avoidance, and washout. The capacity of these processes determines the amount of residue that may be burned, or more properly, time, place, and the amount of particulate that may be released into the atmosphere.

Diffusion--In many forest situations the area needing treatment by fire is in the same elevation range as the sensitive areas nearby. If a strong convection column cannot be assured, as in the case of periodic light underburning, then burning must be delayed until the depth of the mixing layer is adequate to provide the necessary dilution within the available downwind distance. Convective rise plus diffusion of smoke plumes in the layer of air in contact with the surface are the bases for an existing smoke management system[2] for Georgia. These are also in the systems used by forest protection agencies in Oregon and Washington, and by the Forest Service in California. The basic parameters are wind, stability, and distance to an SSA.

Diversion--In many forest burning situations, it may be possible to await a wind direction that will cause the smoke generated to be blown away from sensitive areas. This is particularly applicable to burns that will produce at least a partially elevated plume that will not cause a problem at the surface in the vicinity of the fire. This principle is used in the West where forest areas are remote from sensitive areas. It is not appropriate for low energy fires in populated areas or where there are other sensitive areas close by downwind, unless combined with diffusion requirements.

Avoidance--Under conditions of stable air, as at night and during the colder part of the year, air strata form that are thermally, hence physically, prevented from mixing vertically. While such a condition tends to hold metropolitan area emissions in the surface layers, it also prevents any emission or smoke plume in a higher layer from descending into lower layers. Mountainous terrain often extends into air strata that are thus separated from valley air. Terrain elevation plus the additional elevation gained by a hot convective column provide a means for complete avoidance of smoke contamination in lower elevation sensitive areas in certain stable airmass situations.

Washout--One of the most effective devices for satisfying air quality requirements of prescribed burning is venting the convective column directly into a precipitating cloud system. Of course, this immediately limits burning to heavy accumulations of fuel, usually in prepared piles. It also requires good weather forecast support to assure that the smoke plumes will actually enter precipitating cloud layers. The theory is that the hygroscopic smoke particles will act as condensation nuclei around which droplets will form. These in turn will tend to coalesce and precipitate. The theory needs further checking, but precipitation processes do require particle nuclei for sublimation or condensation. Much of the burning in Pacific coast forests is of large piles that can be ignited after the autumn rains or of smaller piles that have been covered.

Supplemental Aids

To be completely successful in carrying out the intent of the smoke management plan, the fieldman who plans the individual burn needs guides

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[2] J. A. Pharo. An interim smoke management guide for the South, Part I: head and backfires. Unpublished manuscript on file at USDA For. Serv. Southeast. For. Exp. Stn., Asheville, N.C. 1972.

that will indicate smoke production characteristics. These might include aids for estimating:

1. fuel loading of an area in amounts that will be actually consumed;

2. emission factors for various forest residues as they are affected by:

    a. type of burn and fuel arrangement,

    b. condition of fuel including moisture content,

    c. type of fuel;

3. convective column energy and plume buoyancy in terms of height to which the column may be expected to ascend under varying conditions of wind and stability; and

4. timetables of smoke production characteristics for burning various kinds of fuel complexes--differentiating between periods of start-up, full fire, and die down.

The smoke management plan is only a tool. Use of it requires administrative coordination of which areas in a given administrative unit will be selected for burning on any given day. Besides factors already mentioned, this involves regulating the physical separation of plumes in time and space with respect to each other and also with respect to burning in both upwind and downwind forest areas. In Oregon, the State Forester's Office has this responsibility, though most actual coordination is handled within the individual National Forests and State districts.

A new feature this fall in Oregon and Washington will be automation of much of the decision making process including computer determination of burn quotas for a predicted weather situation. All fire control agencies are expected to participate. Designed by Howard Graham of Region 6 Division of Fire Management, the computer program will keep track of areas listed for burning. For a predicted weather situation, the individual areas eligible for burning will be listed for each National Forest, State district, or county. And the total allowable burn will be specified for each of several categories of distance from an SSA. The designation of the eligible areas to be burned is left to the field administrator. Any special limitations imposed by the State such as "no burning below 3,000 feet" or "all burning quotas reduced 50%" would also be distributed in the computer message.

Most of the details of residue burning restrictions for smoke management are shown in the Table at the end of this paper. In addition, burning practices are suggested for minimizing smoke production and impact. These cover:

1. time of ignition to take full advantage of afternoon deep thermal mixing of the atmosphere and to avoid accumulation of smoke in nocturnal drainage winds,

2. rapid firing to develop maximum heat output for the strongest convection column and highest plume, and

3. chunking-in of remaining large pieces to maintain an actively burning fire and reduce smoke from smoldering remnants.

Conclusions

With several years of experience in smoke management behind them, the fire management agencies of Oregon, Washington, and California[3] have reached some conclusions on the success of the system.

1. Smoke management is believed to have definitely improved air quality in areas where prescribed burning caused or added to air quality problems. Smoke management is considered a success from that standpoint.

2. No obvious changes appear to be needed in the smoke management system, but some feel there is a definite need for more aggressive use of prescribed fire. Others expressed a need for more accurate weather forecasts and more efficient system implementation.

3. All agencies except the Washington Department of Natural Resources agree that the accumulation of untreated forest residue is growing in their areas, especially from harvest operations in old-growth forests.

4. The growing hazard constitutes not only an increasing threat of large fires but also an increasing threat of accompanying smoke episodes from wildfire.

5. The air quality limitations on burning either have actually handicapped burning, have served as an excuse for not burning, particularly near the heavily populated, smoke-sensitive Willamette valley, or have resulted in extending slash burning to less favorable seasons of the year.

6. Though air quality limitations may have stimulated use of residue treatments other than burning, some are vastly more expensive and should receive economic scrutiny.

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[3] Washington Department of Natural Resources, Washington Forest Protection Association, Oregon Forestry Department, Oregon Forest Protection Association, Bureau of Land Management--Oregon State Office, Bureau of Indian Affairs, U.S. Forest Service Pacific Northwest and California Regions.

The idea of permitting open burning of unwanted forest residue, thereby placing great amounts of combustion products in the air, may be unacceptable to a lot of people. But permitting these residues to accumulate--thereby inhibiting the reproduction of needed trees and at the same time increasing the risk of a severely damaging fire or of a smoke episode at some chance time--is also quite unacceptable. Accomplishing the residue removal job by methods other than burning may also have environmental and economic consequences that are unacceptable to a lot of people. So we must examine the possibility that the carefully regulated use of fire may be less unacceptable than other alternatives, in some situations. But where fire may be a plausible alternative, it is likely to remain viable only on the basis that the resulting smoke represents the alternative treatment with the least undesirable effects. This requires full attention to fuel preparation, burning practice, and to flexibility permitted in scheduling to achieve the optimum diffusion, diversion, avoidance, and washout of each smoke from each particular source; i.e., by *smoke management*.

Table 1.--Summary of Forest Residue Burning Restrictions for Smoke Management

Dispersion conditions	Daily quotas[1] of forest fuels that may be consumed in each 150,000-acre administrative area (or quotas of particulate from burning these amounts)[2]			
	Upwind distance from SSA[3] boundary			
	I More than 60 mi.	II 30-60 mi.	III 10-30 mi.	IV Less than 10 mi.
	Tons of fuel (Tons of particulate)[2]			
1. Smoke plume into precipitating cloud system	No restriction	No restriction	No restriction	No restriction
2. Smoke plume moving away from SSA at 5 mph or more[4]	No restriction	No restriction	No restriction	No restriction
3. Smoke plume moving toward SSA [5][6][7]				
a. Plume above stable layer and above SSA ceiling (day and night)	36,000 (252)	18,000 (126)	9,000 (63)	6,000 (42)
b. Plume mixed through deep layer. Mixing level more than 1,000 ft above SSA ceiling (day only)	18,000 (126)	9,000 (63)	4,500 (31.5)	3,000 (21)
c. Plume below SSA ceiling (day only)	9,000 (63)	3,000 (21)	1,500 (10.5) Complete burning any ignited excess acreage as rapidly as possible and mop up residual fire.[8]	No new fires. Complete burning ignited fuel as rapidly as possible, and mop up residual fire.[8]

[1] Except as noted, an additional half of quota may be burned at night.

[2] Based on emission factor of 14 lb. of particulate from 1 ton of forest fuel. Burning quotas may be based on particulate emission factors for the given fuel complex and burning method.

[3] Smoke Sensitive Area.

[4] Plume dispersal winds less than 5 mph are considered too light to be of dependable direction, hence, are assumed to be toward SSA.

[5] No burning when visibility (visual range) is less than 11 miles except under condition 1.

[6] Amounts decrease for windspeeds slower than 16 mph at plume dispersal height: 10-15 mph, 75% of quota; 5-10 mph, 50%; under 5 mph, 25%.

[7] Total quota for a 1-million-acre administrative area may not exceed 150,000 tons per day under condition 3 (smoke toward SSA).

[8] Due to deterioration of earlier, more favorable conditions.

PRESCRIBED FIRE TECHNOLOGY FOR MINIMIZING SMOKE HAZARDS

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The southern pineries have had smoke drifting through them for many, many years. From colonial years up to the 1890's when lumbering was beginning on a large scale, light, annual burning was used for a number of different reasons--some were fantasy, but most of the reasoning was based on fact. Since cattle were usually grazed under the mature longleaf pine, fire's most common use was to keep a good grass cover.

As the use of burning was modified, due to the harvest of the "original" longleaf forests of the Coastal Plain, it was found to have many more uses in pine silviculture than strictly grazing benefits. Prescription burning has been a controversial subject for as long as man has tried to manage the land to any significant degree. In the past, however, not many people disagreed with controlled burning because of the smoke it created. Wood smoke, I suppose, has been in the air for so long in the Southeast it has become a folkway.

In the recent past, all environmental issues have drawn public awareness and attention. Only good can come from this awareness, but a great deal of caution and common sense has to be applied to the findings regarding the quality of our surroundings. Too often facts are taken out of context, things applied that don't relate, extrapolated beyond the data, or repeated incorrectly. Heaped on all of these inaccuracies and half-truths that develop, human emotions get intermingled. At that point all logic and reason come to a screeching halt.

From the previous papers and the ones to follow, we find that there is considerable data already available concerning wood smoke. At the Southern Forest Fire Laboratory work is well underway to establish the contents of smoke from prescription fires in our fuels and under common weather conditions, using techniques normally applied to our conditions in the Southeast. Gearing up to such a task is difficult at best, and there will be a timelag before our Research and Development program can come up with firm answers. Until that time we have to use some good old common sense, past experience, and the findings already available to us to direct our burning and manage our smoke.

We know for sure that our prescribed fires, no matter how good they are, produce smoke. I know our fires produce smoke because Mr. Cooper, Mr. Mobley, and I were all asked to present papers on smoke at this Symposium. Furthermore, I know that it can cause some problems. Smoke is sometimes hard to see through when it is drifting across a highway. More difficult than that is landing an airplane on a smoke-filled runway. These can be dangerous situations to be sure, but I would not like to be in charge of a burn where a housewife's sheets got smoky hanging on the line. Now that is not funny--that is serious business.

All kidding aside, I think we all realize that most of the prescribed burning smoke problem is of a visual nature. Right now, we just do not know all the chemical and physical characteristics and interactions of smoke. We do know large quantities of dense smoke can be a visibility hazard; and to reduce this hazard, we can do a number of things. From here we will explore, together, some prescribed burning techniques for minimizing the hazards of smoke.

First of all, most of the prescribed fires in the piney woods are ignited with a backfire. Backfires are easy, slow, and safe. They are used because most areas are not burned more often than once every five years for hazard reduction. In five years' time, litter buildup and vegetative regrowth (particularly in the South) are so heavy that headfire applications are often tricky and dangerous. Five years has, for some time, been a magic time period for hazard reduction burns, but I do not think it has much to do with minimizing risk; it is probably more a function of manpower and days available to burn.

The backing fire, then, is our most common technique for igniting the pineries. It burns deep and with great efficiency provided it has a moderately strong, steady wind. Because of the good efficiency with which it burns, the smoke is not very dense. If the litter is damp, the heat of the fire must drive off moisture to sustain combustion and, in so doing, heavy water vapor smoke is produced. Visibility in the vicinity of the burn is often significantly reduced. If the wind is adequate for good combustion efficiency and the litter is dried out well, smoke is not a problem. The wind can get too strong, however, and keep the smoke low for its entire journey downwind. Generally, backfires are not hot enough to produce high-ranging columns. The prevailing weather takes over as the smoke breaks through the crowns or even before at the fire site and influences its movement almost totally.

Burning efficiency also affects the amount of smolder smoke in a natural fuel fire. Once the fire front of a backfire passes a given point, there is generally very little smolder smoke behind it. High litter moisture can cause greater amounts of lingering smoke.

Head fires or strip-head fires can be used in light fuels very effectively. They are fast, inexpensive with regard to time, but more difficult to keep under control. With adequate preplanning, fires moving with the wind can be very useful.

Smoke from head fires is generally greater from given amounts of fuel than from backfires (3). But, head fires are used in fuels with much lighter loadings, hence reduce total smoke production. Usually these lighter roughs are one, two, or three years old and dry out much faster than old roughs. This increases opportunity time, and also reduces smoke because of the drier conditions. In our vegetative fuels, head fires produce more smoke than in litter fuel. And, they also leave a burned area with more smolder smoke for a longer period of time. The big plus for head fire comes from its speed. Sites must be burned at an interval where head fires will not damage the overstory, or else we are kidding ourselves about the fireproofing we do with regular burning. If it takes a backfire to do the job, then we are only insuring ourselves for a part of the burning rotation.

With head fires then, we are usually burning light, dry fuels at a rapid rate to produce moderate amounts of smoke but usually with a rising plume. Adequate long-range planning is absolutely necessary to use heading fires as a regular part of a burning program.

In the Southeast, most of our burning is done during the winter after the passage of a cold front. Because of short, winter days, it is important to get as much burning done as possible in as little time as possible. Along about 3:30 or 4:00 p.m. in mid-winter, the temperature starts to drop and the humidity starts to rise. In the past, we just let our fires burn until the humidity got so high they just went out. With our growing awareness of the environment, it is obvious to us now that mixing smoke with a damp atmosphere near the surface is not conducive to good visibility. Close to the fire area we might even say it is lousy visibility. All this means we had better cut our fires off earlier in the day--say 4:00 p.m. By doing that we either have to get more days to burn or burn faster when we can.

I am not quite sure how we are going to get more days to burn; we could refine our prescriptions to do more burning on the margin. In most cases burning on the margins will only increase the smoke problem when the fuels are too wet by starting a day early, or when the relative humidity is not as low as the prescription calls for. When fuels are too dry on the other end of the weather spectrum, fire escape becomes a problem. Adding days in the summer, or any time other than winter, is usually only possible for site preparation burns when we can develop a good convection column to vent the smoke out of the generally stagnant summer air system. No, we cannot effectively increase the number of days to any great extent.

What can we do? Well, we just mentioned the added speed of heading fires. With proper preplanning, use of natural fire breaks, and knowing what kind of wind to expect, we can use head fires much more than we do now. Getting the smoke out of an area quickly may be just as beneficial as having less dense smoke for a long period of time.

Burning vast areas in a short time is a common practice to our Australian counterparts (6). They have sophisticated the aerial spot-burning technique to a very fine point (1, 4, 7). Smoke is a problem to their environment also, but not for the exact reasons it would be for us here. They burn gigantic blocks of unbroken forest lands, producing a tremendous volume of smoke from a single area. Our blocks are usually broken up in small segments and scattered more on a given burning day. They also burn under more moist conditions and in hardwood fuels.

The Everglades National Park uses prescribed fire quite extensively, and many areas where fire is applied are not conducive to foot travel. The only way to fire some areas is from helicopters. Shotgun ignitors work well as an ignition system for spot fires. Smoke from the spot fires does not appear to be a problem, but no measurements have yet been made to know what the visibility reduction really is.

More progress is underway to refine the aerial ignition technique here in the States (5). It may be a way more areas can be burned out quickly with the few optimum days we have available.

Slash burning (other than in windrows and huge piles) in the Southeast has never been a big problem like it is in the West. Our fuel loadings are not too great, and getting rid of the fine fuels is relatively easy. Planting machines all have "V" blades to move the large limbs that remain unburned. Many large industrial landowners have gone to mechanical means of site preparation using rolling choppers, discs, and bedders. This helps the smoke problem since there is no smoke. Another smoke reducer is the whole tree utilizer. Some southern companies are now operating these highly mobile chippers, right on site.

Although mechanical methods are common, fire is still used. High-intensity burns in dry slash not only eliminate a good portion of the problem, they also make for a high-rising plume. Smoke transport at a high release point eliminates most of the ground-level visibility problems. However, greater awareness of airport locations becomes imperative.

There are companies that combine mechanical site preparation methods with fire. We find, however, that fire should be used first. Not only does it aid tractor operators later with better visibility, but fuel arrangement in an uncrushed state produces less smoke and more efficient combustion.

Wildlife openings are often used in southern game management. Small acreages are clearcut, dried, and burned with center-firing techniques--dubbed locally as a keyhold burn (2). With the inner ring of fire drawing the outer ring in, plume rise can be greatly increased due to the higher burning intensity. In a very short time, virtually all fuel is reduced and the smoke is lifted up and out.

Simultaneous ignition of a ridge end or mound can be achieved in the Piedmont using the "Chevron" technique (8). Fire behavior from the spoke-like lines of fire is in a range between a back and flanking fire. The added length of active firelines provides a faster burnout time than a straight backfire, yet produces an efficient fire with less smoke. This technique has limited use, but adds to our arsenal of alternatives--especially where topography is an added problem.

In some situations topography should not be looked at as a problem, but as an aid to modifying burning techniques. Two-stage burning in the Piedmont is an example. Ridgetops and upper slopes dry out faster than lower slopes and bottoms. Fires set along these ridgetops will back down the sides until they hit the point where the fuel is too moist to burn and go out. A few additional drying days will permit the use of upslope strip fires to burn out the bottom and lower slopes. This system eliminates the need for lots of plowlines, aiding the erosion problem, but may be detrimental to air quality. As the fire burns into the more moist fuels, efficiency is lost and more smoke is produced. The duration of the denser smoke may not be long enough to be a problem, but more study is needed in this area.

We have discussed some of the techniques available for prescription burning in the Southeast. All of them were not covered since there are many modifications. We have a long way to go before we can predict, with any accuracy, what kind of smoke is produced in common burning situations and where it will go when it leaves the fire site. With the information available now and good common sense, prescribed burners can do plenty today to eliminate most of the smoke hazards that may have existed in the past.

A few short guidelines may be applicable at this point.

1. Choose the technique that will accomplish your objective and minimize burning time--do not burn for the sake of burning.

2. Obtain weather forecasts and know what they mean--bone up on basic weather knowledge.

3. Do not burn during pollution alerts--it is lousy burning weather anyway.

4. Burn during good smoke dispersion weather--usually after a cold front passage.

5. Be careful when burning upwind or near smoke-sensitive areas--you may have to drive home in your own smoke.

6. Burn in small blocks. If more than one is to be burned, select widely separated units--cut down on local concentrations.

7. Use test fires to confirm smoke behavior as well as fire behavior--make it big enough to be representative.

8. Burn at night only when conditions are similar to daylight hours--nighttime is for sleeping anyway.

Smoke from site preparation burns may soon be a thing of the past, but regular burning through the growing rotation does not seem to have a suitable alternative. Prescribed burning is still a viable, necessary silvicultural, range, and wildlife management tool. But it will not matter how good it is if the public decides it is degrading the environment. With this thought in mind, we would do well to encourage anyone who burns his woods to use some good common sense and information we have available to us right now. Armed with this and having a firm grasp of the idea that now the public (or at least the environmentalists) is looking very closely at what everyone is doing and how they are doing it, we should be able to do a more efficient burning job with fewer visibility problems.

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PROBLEMS OF PRESCRIBED BURNING AND SMOKE IN WILDLAND-URBAN AREAS OF CALIFORNIA

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Hundreds of towns and cities in California adjoin parks and reserves where critical fire hazards present a serious threat to people and property. Those people usually are not aware of the hazards, nor do they know about the dangers involved. The wildfire problems are steadily growing worse as flammable fuels continue to build up and open spaces are more widely used, thus creating greater risk of fires. Large wildfires usually occur late in the dry summer period--July to October 15--when the problems of air pollution are greatest.

In many parks and reserves, prescribed burning can be an excellent means of reducing fuels and lessening critical fire hazards. Smoke will result from such activity, true, but by regulating the time and amount of burning, and the techniques, and by selecting suitable meteorological conditions and wind direction, the smoke can be kept below that normally coming from wildfires. Cooper (3), working in the southeastern United States, has aptly said that prescribed burning, with a little smoke in the right place at the right time, may be the best way to avoid the consequences of wildfires with their big smokes.

The principal objective of burning in wildland-urban areas is to reduce critical fire hazards. A close look at the problems may help explain how essential it is to prescribe burn in such areas.

One of the foremost problems with respect to prescribed burning is informing people of the need for it. As an example of this, take cognizance of the situation in the Berkeley-Oakland hills. Those cities are adjoined by regional parks, public utility lands, wildlands of the University of California, and some other relatively large undeveloped areas in private ownership. Several large wildfires have occurred there, but only two have been particularly bad. On September 17, 1923, a hot, dry, northeast wind brought a fire out of Wildcat Canyon, just over the ridge east of Berkeley, an area that is now Tilden Park. The fire spread quickly through grass into a large eucalyptus grove along the crest of the ridge. It moved quickly through the trees, and suddenly burst out into the residential area far below, apparently having reached this remote area by firebrands from the eucalyptus grove. Within forty minutes after the first house caught fire at 2:20 p.m., burning shingles were sailing over the rooftops throughout an area of Berkeley a half-mile square. Within another two hours or so, 625 houses and buildings were destroyed. Fortunately--and almost unbelievably--the flames took no human lives. The fire was controlled after a sudden wind change brought in damp ocean breezes. The story of this fire is dramatically narrated by Gilliam (6) in his chapter, "The Burning of Berkeley."

In 1970 another wildfire--dubbed the Fish Fire--destroyed 36 residences and damaged 37 others in the Oakland hills (10). This fire was also controlled only after the humidity increased and wind direction shifted from eastward inland to gentle ocean breezes from the west. After the 1970 incident, some of the fire-control officials said they could never have controlled the blazes had the winds not died down. This was obviously true of the 1923 fire as well. What would have happened, one wonders, if the wind at the time of the 1970 fire had blown at 60 miles an hour all day and night, as it did on September 17, 1965? Fortunately, during that day in 1965, no big fires developed. It is frightening to think about what might have happened if several big wildfires had started, or what might happen in the future should such weather conditions prevail again. And of course they will, but we do not know when.

During the 1970 wildfire in Oakland, many other wildland-urban fires were raging in California. From September 22 to October 5, a total of 773 separate wildfires burned nearly 580,000 acres of grass, brush, and timber-covered wildlands throughout the state. These fires completely destroyed 722 homes, either burning isolated residences or spreading from the hills into urban communities. Sixteen lives were lost, attributed directly to the fire activity. Suppression and damage were estimated at 233 million dollars. Somewhat similar disasters have occurred over California many times in the past, and the potential for further heavy losses in life and property continues to exist throughout the state. It is extremely important therefore to reduce fuels and critical fire hazards in the wildland-urban areas so that wildfires can be more easily controlled.

All factors favorable for wildfires are found in the Berkeley-Oakland hills. Many of the slopes are steep. Extremely strong winds from the north and northeast normally blow for a few days each summer, during which both humidity and fuel moisture are extremely low. Fuels are abundant. The principal wildland fuels are debris from eucalyptus and conifers, dry annual grasses (ungrazed by livestock), and soft chaparral. Most of the houses in area are made of wood, with cedar shake roofs which are highly flammable. Once the houses catch fire they burn like tinder in strong dry winds. There are many people in the area, and fires may be started either accidentally or even deliberately. The Oakland fire, for example, was started intentionally by one man with a match.

The worst type of fuel in the Berkeley-Oakland hills is debris from eucalyptus trees. Thousands of seedlings were planted in this area around the turn of the century, and the trees grew fast. The eucalyptus is particularly bad because it sheds its bark each September, much of which drapes over the limbs or hangs loosely on the trunks. Up to 50,000 pounds of loose debris per acre may be found on the ground under eucalyptus along with another 50,000 pounds of partially decomposed material (1). The fuels are oily, and burn with great intensity. A fire on the ground can create convection currents and send flaming bark high into the atmosphere. In strong winds, firebrands can set fires far in advance of the main fireline. In eucalyptus forests in Australia, firebrands during wildfires commonly set fires 10 miles ahead of the main fire, and there is an authentic case of a spot fire occurring 24 miles in advance of the main fire (5). It seems possible, therefore, that a big fire in eucalyptus in the Berkeley-Oakland hills could shower firebrands over large areas of residential sections and trap many people in the narrow and crooked streets that are common in this area.

The severity of the wildfire potential was well emphasized by A. B. Mount, Forest Research Officer from Australia, in "An Australian's impression of North American attitudes to fire" (8):

> Recently there was much fear expressed (and dispelled) about the San Andreas Fault. Nothing has been said of the far greater threat that exists above the ground in the Berkeley area. Here there is the "ideal" fire situation: a combination of topography, climate, vegetation and houses buried in the vegetation. There is apparently no fear of fire in spite of the past fire records; in spite of fuel accumulations under the eucalyptus, up their stems, in their crowns (a continuity of fuel not seen in the same species in Tasmania); in spite of the perfect intermixing of openings with tall dry grass surrounded by heavy forest fuels (both pine and eucalyptus). Very little imagination is required to foresee a catastrophe in this area far worse than the Hobart fire of 1967 (53 people perished in that fire). Just how big a catastrophe depends on how soon the public can be made aware of the fuel situation. Without this education it is possible that 500 to 1,000 people will die in a single afternoon within the next five years.

The severity of the wildfire problem in the Berkeley-Oakland hills was heightened in 1972 when a heavy freeze in December killed the tops or heavily damaged many eucalyptus trees. The freeze may have been a blessing in disguise, because the sight of dead leaves and stems, combined with publicity in the newspapers and on radio and television, made people aware of the fuels and the danger.

The governor declared the Berkeley-Oakland hills a disaster area in the summer of 1973. Since then, many eucalyptus trees have been felled and removed for lumber, pulp, and fuel, in an effort to reduce fire hazards. This has helped a great deal. But the hazards were critical long before the freeze (2), and will continue to be so because of the remaining eucalyptus trees and other fuels, such as dry, ungrazed grass, which burns in a strong dry wind as though it were sprayed with gasoline.

A program of prescribed burning on a five or six-year rotational basis, with about one fifth of the area burned each year, could be highly worthwhile in reducing critical fire hazards and maintaining them at a lower level. Enough burning has been done in the Berkeley-Oakland hills in the past two years to demonstrate how it can be done and its value in controlling wildfires (Fig. 1A,B; 2A,B).

The fuels under eucalyptus and conifers can be broadcast-burned in late winter and early spring while the surrounding grasses are still green. Later on, in spring, and until about July 1, the annual grasses and soft chaparral can be burned. Normally no burning need be done after that date.

In carrying out a prescribed burning program in wildland-urban areas certain problems will be encountered. First, the people, including both the average citizen and professional land managers, must be made aware of the seriousness of the wildfire potential and be convinced that strong measures must be taken. Controlled fire is a good means. It removes the fuels yet leaves most of the nutrients over the soils. Some nitrogen is driven off, but this is restored through greater bacterial activity, nitrogen-fixing plants, and rainfall. Furthermore, fire is a force natural to most wildland environments in California, where the weather and fuel conditions are extremely dry in late summer.

Everyone likes to see the atmosphere free of pollution and the sky crystal clear. We must use reason, however, and we must understand that a little smoke in the atmosphere at certain times may be better than critical fire hazards capable of producing much more smoke.

It can be minimized by burning frequently enough, perhaps every five years, to keep the duff shallow and thus reduce the smoldering period. Green materials produce more smoke than do dry materials, and any management technique that can keep green fuel production low is desirable. In certain places it may also be desirable to follow a broadcast burn by piling and burning the remaining large fuels. This is done by starting a fire and adding fuel gradually. A hot fire with visible heat waves results, but with very little visible smoke. This sort of burning was carried out under Monterey pine in the Berkeley hills, and hardly anyone knew about it because they could not see smoke.

Studies show that prescribed fires produce much less smoke than do wildfires burning over an equal area. In southern forest fuels, for instance, a prescribed fire put 17 pounds of particulates into the atmosphere per ton of fuel burned, while a wildfire produced 58 pounds, or more than three times as much (4). The findings are similar for carbon monoxide and hydrocarbons, two of the other principal constituents of wood smoke.

Prescribed fires can be set in winter, spring, and early summer when smog problems are not particularly bad, but wildfires occur mainly in late summer when the smog problems are greatest. Sandberg (11) reported to me that March has more days suitable for burning, for meteorological reasons, than any other month of the year. July and August are the worst months for smog, but in the Berkeley-Oakland hills prescribed burning is not planned for those months.

Smoke from the burning of forest fuels is usually regarded as undesirable. It may, however have value in protecting plants against diseases (9). Spores of western gall rust fungus failed to germinate on materials exposed to smoke for as little as five seconds, and spores of other fungi were similarly inhibited on substrates exposed to smoke for longer periods. Komarek (7) has suggested that wood smoke may be important in the atmosphere as a cleansing mechanism for maintaining an equilibrium in ecosystems.

Too much smoke is often given as a reason for not burning. The alternatives to burning are few. Some people suggest that the fuel be raked, gathered, and removed from the landscape. This can be extremely difficult, expensive, and, in fact, nearly impossible on the steep slopes, especially in areas of poison oak. Such activity would also drain the soil of its nutrients. Of course, large materials suitable for home heating should be removed and utilized where economically feasible. Soil sterilants have been used in vacant lots and on firebreaks, but are not recommended because they create bare soil, with ensuing erosion problems, as well as an unsightly landscape.

A well-developed and managed program of prescribed burning over a period of years has not been tested in the Berkeley-Oakland hills. It is time that this be done. The existing critical fire hazards are too threatening to life and property. It would seem better to have a little smoke in the atmosphere during certain days of spring and early summer than take the chance of big wildfires creating heavy destruction later. Somewhat the same situation applies to hundreds of towns and cities in California.

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FIGURES 1a and 1b. Before and after prescribed burning of a heavy peel of bark around the base of this eucalyptus.

FIGURES 2a and 2b. Before and after burning more than 100,000 lbs. of bark and other debris beneath the trees.

THE MAINTENANCE OF NATURAL ECOSYSTEMS: SMOKE AS A FACTOR

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Introduction

Recent symposia, including the present one, have focused on the emerging interest in the role of wildland fires in a variety of environments (12,26,27). White (31) noted that in moving into this environmental period the forest manager joins with all who seek harmonious use of land and water and plants in achieving a more subtle and more nearly permanent mode of stewardship. He enumerated some of the consequences of embarking into this new era in which technology ceases to be the principal reliance:

> A modified system of social assessment is required in sorting out the possible adjustments in managing fires. The aim then becomes maximum net social benefits rather than minimum monetary costs. A new set of consequences including changes in ecosystem diversity and esthetic enjoyment, must be identified but do not lend themselves readily to quantitative measurement. This effort places fresh demands upon investigation of natural processes, collection of basic data, methods of determining consumer preferences, and the distribution of benefits and costs among different sectors of society. Smoke must be weighed against visual landscapes and national wood products supply.

At the same symposium, Rappaport (21) argued that the problem of how we may live in harmony with our forests is the problem of controlling men's narrow and *linear* purposes so that they will not destroy the *circular* ecosystems to which they are bound. He indicated that if we are to live in harmony with our forests and other ecosystems, we must restore and maintain their circular ecological structure. We must understand the interrelationships among factors that contribute to ecosystem stability if we are to effectively maintain the circular structure of such systems (19,20,9). Such understanding is important to the successful management of the diverse systems found in national parks and wildernesses. Usage of "national park and wilderness" in the text refers to wilderness lands under the jurisdiction of both the National Park Service and the Forest Service.

White (31) called for a state of deepened knowledge and of genuine freedom from conventional modes of thought to achieve the wise management of fire. Jackson (13) admitted that in our conventional approach to ecology we have, perhaps, overemphasized the direct determination of vegetation by climate. He reported that general surveys of the distribution of major plant communities in Tasmania indicate that the many apparent anomalies to such a conventional view result from the failure to understand the interactions between such deflecting influences as fire and soil fertility on vegetation types. Not only does the vegetation, as determined by soil fertility and climate, affect the fire frequency but fire frequency affects the vegetation directly and indirectly (through changes it produces in soil fertility). Thus, Jackson described an elemental ecology of Tasmania based on fire, air, water, and earth. Similar fire-dependent relationships have been established for many biotic communities in the United States (7,1,30,11,8,15).

What does an elemental ecology that includes fire, air, water, and earth as basic processes mean to the management of national parks and wilderness ecosystems? The Congressional Act of 1916 which created the National Park Service stated one of the purposes of parks was "to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations." At that point in history, protection was an obvious management goal and the variety of park habitats was protected from wildfire. But, by 1963 the Leopold Committee posed some interesting questions to the Park Service:

> Today much of the west slope (of the Sierra Nevadas) is a dog-hair thicket of young pines, white fir, incense cedar, and mature brush--a direct function of overprotection from natural ground fires. Within the four National Parks--Lassen, Yosemite, Sequoia, and Kings Canyon--the thickets are even more impenetrable than elsewhere. Not only is this accumulation of fuel dangerous to the giant sequoias and other mature trees but the animal life is meager, wildflowers are sparse, and to some at least the vegetative tangle is depressing, not uplifting. Is it possible that the primitive open forest could be restored, at least on a local scale? And if so, how? We cannot offer an answer. But we are posing a question to which there should be an answer of immense concern to the National Park Service.

One year later, in 1964, Congress passed the Wilderness Act which defined wilderness as an area of undeveloped Federal land retaining its primeval character and influence without permanent improvements or human habitation and managed so as to preserve its natural conditions. Wilderness was further defined as an area generally appearing to have been affected primarily by the forces of nature with the imprint of man's work substantially unnoticeable. In meeting these purposes, National Forest Wilderness resources are to be managed to promote, perpetuate, and where necessary, restore the wilderness character of the land and its specific values of solitude, physical and mental challenge, scientific study, inspiration, and primitive recreation. Thus, one of the objectives of wilderness management is to allow natural ecological succession to operate freely to the extent feasible (25).

How have the management directions posed by the Leopold Report and the Wilderness Act been achieved in national parks and wildernesses? The purpose of this paper is to describe specific fire management programs in Sequoia and Kings Canyon National Parks and the Selway-Bitterroot Wilderness that have the common objective of perpetuating natural ecosystems.

Fire Management Program in the Selway-Bitterroot Wilderness

Background

The White Cap Study in the Selway-Bitterroot Wilderness of northern Idaho was designed in 1970 to provide valid methods for the development of fire management prescriptions (2,3). This study was the outgrowth of a Wilderness Workshop that had, in effect, recommended a new policy that "fire be allowed to more nearly play its natural role" in the wildernesses of Idaho and Montana. The key to implementing this new role for fire in wilderness today is based on the preparation and approval of preplanned prescriptions.

At this workshop strict fire control was recognized as an unnatural action in wilderness. This recognition was based on the passages from the Wilderness Act cited earlier. However, Special Provisions of the Act state that "such measures may be taken as may be necessary in the control of fire, insects, and diseases, subject to such conditions as the Secretary deems desirable." Necessary has been defined as "needed for meeting the wilderness definition and for protecting life and property in the wilderness or resources outside."

The White Cap Study

The 100-square-mile area selected for intensive study was in the southern end of the Selway-Bitterroot Wilderness on the West Fork District of the Bitterroot National Forest. The Bad Luck and White Cap Drainages were chosen for this study because they represent a diversity of plant communities and landforms. The fire suppression history of these drainages provided an excellent outdoor laboratory for studying effects of suppression on fuels and plant communities. There have been 212 fires over a 45-year period. Fire suppression efforts have been effective; 154 fires were suppressed at 1/4 acre or less in size. Fifty-eight fires over 1/4 acre in size burned 1,247 acres, for an average of 21 acres per fire.

Objectives of the study were to:

1. Develop inventory methods that relate fire management to the wilderness resource.

2. Determine relationships between fire and wilderness ecosystems.

3. Determine strategies for a more natural incidence of fire in wilderness.

Specific components of the study included fire history, fuel inventory and appraisal, plant community dynamics, landforms, soils, and fisheries.

The Fire Management Plan

Based on study results, 18 land types and 15 habitat types were identified and combined into five ecological land units (or fire management zones): (1) shrubfield, (2) ponderosa pine savanna, (3) ponderosa pine/Douglas-fir, (4) north slope communities, and (5) subalpine. These zones are recognizable subdivisions of the landscape that are ecologically equivalent in terms of topography, vegetation, fuels, and fire potential. Ecological land units have been defined as linkages between vegetation and land systems, providing the opportunity for interdisciplinary communication about ecosystems and their management (6). These perceivable units of the landscape permit the prediction of function and response to management activities.

The ecological land unit description is a labeling process that permits us to subdivide landscapes into different potentials for vegetation, fuels, and fire and also serves as a frame of reference for extending knowledge and prescriptions to other planning units. The final prescriptions reflect the differences observed in the data base for each of the land units (Table 1). As prescriptions were completed, the units were termed fire management zones. The Fire Management Plan was approved by the Chief of the Forest Service in August 1972.

Wilderness Management Fires

A lightning-caused fire on August 18, 1972, in the shrubfield zone was the first fire to be handled under the new prescriptions. The fire occurred on a 65% south slope at an elevation of 4,100 feet. Four days later the aerial patrol reported that the fire had gone out naturally; final size was approximately 24 by 24 feet.

The 1973 fire season in the Pacific Northwest was another story. Extremely dry conditions contributed to accelerated burning rates in many areas. Extended summer droughts were the rule at most locations, but June-July precipitation in the southern portion of the Selway-Bitterroot Wilderness maintained the White Cap Fire Management Area at a lower fire danger level (Table 2). The total number of fires occurring in the White Cap Fire Management Area in 1973 and the action taken are presented in Table 3.

A thunderstorm on the morning of August 10 ignited fuels in the ponderosa pine savanna fire management zone. Prescriptions called for this fire, the Fitz Creek Fire, to be observed; and to prevent the spread of the fire into the ponderosa pine/Douglas-fir zone below an elevation of 4,500 feet. Suppression action was taken, starting on August 13, to contain the east flank of the fire within the pine savanna on this side. The remainder of the fire was permitted to burn naturally. The Fitz Creek Fire burned for 43 days in the ponderosa pine savanna, shrubfield, and a small portion of the ponderosa pine/Douglas-fir zone. The final size of the fire on September 21 was 1,200 acres.

On the afternoon of August 15, the Fitz Creek Fire apparently spread south of White Cap Creek. This fire was called the Snake Creek Fire to distinguish it from the Fitz Creek Fire and to avoid confusion in radio communications and fiscal accounting. The Snake Creek Fire burned 1,600 acres and was controlled on August 21. It was suppressed because it was outside the approved area for the fire management plan.

Wilderness Fire Management and Smoke

There are no easy solutions to wilderness management. Stankey (23) has indicated that the very term *wilderness management* "is in many ways a paradoxical term, for wilderness connotes an image of a landscape untouched and an opportunity for free and unconfined use, while management suggests control and planned direction. It is perhaps because of the inherently contradictory nature of the term that wilderness management is one of the more challenging and difficult tasks facing resource managers today."

Some argue that a fire should be permitted to burn in a completely unconfined manner in wilderness. Then, when fires escape outside wilderness, the public would support a return to the policy of complete suppression. This seems to be a negative approach with ill-conceived consequences. Stankey (23) again makes the pertinent observation that "although the wilderness experience is typified as free and spontaneous and the physical environment in which it takes place as wild and natural, there is considerable evidence that opportunities for such experiences might gradually disappear without some managerial controls. The issue is not whether management action is needed, but what the specific nature of the management goal should be."

The specific management goal for fire in wilderness is that fire should play a more nearly natural role in the perpetuation of ecosystems. The term "more nearly" indicates that management constraints are considered for a variety of reasons (*e.g.*, human safety, property, or undesired fire effects outside wilderness). The White Cap Fire Management Plan (3) recognized three major outside factors that might be influenced by wilderness fires:

1. the anadromous fishery of the Selway River,

2. air quality, and

3. adjacent non-wilderness management units.

Wilderness fires will obviously result in smoke plumes within wilderness and beyond wilderness boundaries. This production of smoke is just as inevitable as the occurrence of fires in the environment of the Northern Rocky Mountains and elsewhere. The success of wilderness fire management programs will depend largely on the public's understanding of wildland smoke, as well as fire, as a part of natural systems. Much time was spent during the course of the White Cap Study with other Government agencies, conservation groups, schools, and individuals regarding the role of fire (and presence of smoke) in wildland ecosystems.

What were the specific smoke factors related to the fire management program in the Selway-Bitterroot Wilderness during the summer of 1973--a summer characterized by dry weather, numerous fires, and considerable smoke in the Pacific Northwest? The two fires in the subalpine zone (Table 3) were self-extinguishing in a short time span due to sparse ground fuels and they produced little smoke. The Fitz Creek Fire, however, burned over a period of 43 days with smoke production controlled largely by changes in fire weather (Fig. 1). Smoke containment was controlled primarily by the frequent occurrence of an inversion condition in the drainage (Fig. 2). Down-canyon air drainage, combined with the inversion, accounted for observation of the smoke plume during morning hours at least 10 miles down the Selway River from the mouth of White Cap Creek. On the morning of August 15, the slope south of White Cap Creek was not visible from the vicinity of Bad Luck Lookout, a distance of one airmile. This condition was repeated on several other mornings. Surface heating dissipated the inversion between noon and 2:00 p.m. The onset of this afternoon instability (and prevailing southwesterly winds) produced a smoke plume that on several occasions was visible over the Bitterroot Valley, about 28 airmiles east of the fire.

Precipitation that occurred during the 43 days that the Fitz Creek Fire burned slowed the burning rate and cleansed the atmosphere of particulate matter. For example, on Labor Day only one small smoke was observed from the entire Fitz Creek Fire (this followed 0.69 inch of precipitation on August 31). But a few days later, as a dry airmass again dominated the area, the fire picked up and burned another 50 acres. It is important to recognize that there was not a constant rate of smoke production during the 43 days that the Fitz Creek Fire burned. The rate of smoke production was as variable as the behavior of the fire, with the smoke and fire imprinting the atmosphere and the plant communities with a mosaic of treatment patterns.

Effects of Smoke on the Living Community

Little is known about the effects of wildland smoke on the life processes of organisms, although the personal communication from Dr. John Parmeter cited by Biswell (5) raises a host of questions.

Parmeter demonstrated that the germination of spores of several rusts and fungi is inhibited on substrates exposed to smoke from burning pine needles. One of the questions early in this paper emphasized the need to experimentally determine the biological significance of smoke on plants and animals. Perhaps naturally occurring fires in wilderness will provide one basis for studying such interactions.

Deer, elk, and black bears were observed within the perimeter of the fire while the fire was still burning. Large numbers of grouse were also seen within the burned area almost daily, sometimes under quite smoky conditions (Fig. 3). Some of the grouse apparently were feeding on seed heads of grass in the ashes.

During the 43-day history of the Fitz Creek Fire, human encounters with smoke were numerous, including backpackers, trail riders on an American Forestry Association trip, resident landowners in the Selway-Bitterroot, campers, big game hunters, guests at a wilderness ranch, and residents of the Bitterroot Valley. Two backpackers from Louisville, Kentucky, were met one evening as fire burned on both sides of the White Cap Trail. They had been hiking for 15 miles that day in smoke, returning from a trip to the upper portion of the White Cap Drainage. They indicated that when they reached the fire area, they were on the lookout for falling rocks and trees but were not unduly concerned about fire. The two hikers responded favorably to an explanation of the wilderness fire management program. One of the landowners in the Selway-Bitterroot Wilderness expressed concern over the obscuration "of a favorite view" by smoke for several days but was supportive of the overall program. When concern arises over the role of fire in wilderness, as it did on two occasions, this concern does provide a focal point for further interchange of ideas on the wilderness resource and the alternatives available for its management.

A large majority of the letters received from groups and individuals during and following the fires in the Selway-Bitterroot Wilderness favored the concept of wilderness fire management. A typical letter to the Regional Forester in Missoula stated that:

> Efforts by the Forest Service and others in this tinder-dry year to extinguish the innumerable forest fires in the Northwest have been valiant, and certainly all persons involved in this effort should be commended.
>
> However, fire in the forest is not unequivocally evil. Forests got along quite well during the millions of years when there were fires and no firefighters to put them out. Fire is obviously part of the ecology of the forest.
>
> I understand that in some wilderness and *de facto* wilderness areas the Forest Service has allowed some fires to burn out naturally. This would seem to me to be an especially wise policy as far as encouraging the regeneration of elk browse in designated wilderness areas.

Fire Management Programs in Sequoia and Kings Canyon National Parks

Sequoia and Kings Canyon National Parks have two fire management programs: (1) Prescribed burning in the generally lower elevation forests between approximately 4,500 feet and 7,000 feet elevation, and (2) a zone generally above 8,000 or 9,000 feet elevation through timberline where naturally occurring fires (*i.e.*, lightning-caused) are allowed to run their course without suppression. A strict monitoring of these fires and a plan to suppress them if required are part of the latter program. All man-caused fires in the Parks are suppressed. A summary of conditions, research and policy behind the establishment of the above programs, with their results through the 1971 fire season, was published by Kilgore and Briggs (16).

In 1963, the Leopold Report (17) recommended restoring park forests to pre-European-man conditions with emphasis on more openness. The report indicated, "Much of the west slope (of the Sierra) is a dog-hair thicket of young pines, white fir, incense cedar, and mature brush--a direct function of overprotection from natural ground fires...A reasonable illusion of primitive America could be recreated, using the utmost in skill, judgment, and ecologic sensitivity." In effect, the Leopold Report summarized what had long been apparent to many, including professionals in fire control with extensive experience in fire behavior; scientists involved with research on wildfire and its effects on forest vegetation; and many others who, though not involved professionally in the management of natural resources, were nevertheless astute observers of nature's ways. The galvanic effect of the Leopold Report was evidenced by a change in National Park Service Policy (29) relating to fire which states:

> The presence or absence of natural fire within a given habitat is recognized as one of the ecological factors contributing to the perpetuation of plants and animals native to that habitat. "Natural fires" are recognized as natural phenomena and may be allowed to run their course when such burning can be contained within predetermined fire management units and when such burning will contribute to the accomplishment of approved vegetation and/or wildlife management objectives.
>
> Prescribed burning to achieve approved vegetation and/or wildlife management objectives may be employed as a substitute for natural fire.

As early as 1965, experimental prescribed burning was undertaken in the Redwood Mountain Grove of giant sequoias in Kings Canyon National Park. Objectives included abating the fire hazard through removal of accumulated fuels and, through this process, returning the area to the pristine condition required for natural regeneration and perpetuation of sequoia groves. Prescribed burning, of course, is not a new idea; it has long been used as a tool in forest management in many areas. However, using it to restore pristine conditions was new.

During the same year (1965) a "Report of Backcountry Conditions and Resources with Management Recommendations for Yosemite National Park"* recommended "departure from the policy of suppressing all fires when reconnaissance and evaluation show a fire is contained by natural firebreaks, where there is little fuel, and where no damage will result." Although this recommendation did not become policy until 1972, one such fire was permitted to burn naturally in 1965 with only minor control action.

Allowing naturally occurring lightning fires to run their course was a new concept in land management. Undoubtedly small isolated lightning fires occasionally had been allowed to burn out without suppression, but the manager was taking considerable chances in the event such a fire burned beyond his expectations, because past fire policy had required complete and immediate suppression of all fires without exception.

In 1968, Sequoia and Kings Canyon National Parks experimented with allowing lightning fires to burn naturally in the Middle Fork Drainage of the Kings River within Kings Canyon National Park. In 1970, a Naturally Occurring High Elevation Fire Management Zone was established, which included the Middle Fork Drainage (16). Expanded in 1971 and 1972, this zone currently includes nearly 71% of the area within these two parks. Generally, the zone boundary has been set between the 8,000 and 9,000 foot elevation; however, fuel types, exposure, zone configuration, and other factors are also considered.

The ultimate objective of the fire management programs within Sequoia and Kings Canyon National Parks is to allow naturally occurring fire to play its primeval role as a determinator of ecosystems. If all natural fires could be allowed to burn, nature would indeed be playing its natural role. This process has already begun in the high elevation fire management zone.

At lower elevations, strict fire suppression policies over many years have contributed to an immense buildup of fuels on the forest floor and a thick, rank growth of understory trees.**The first fire management action in these areas was prescribed burning to eliminate the fire hazard posed by such accumulated fuels. The program has been limited in scale; however, we have had good success (14,15). Satisfactory burning prescriptions, adapted from those developed by Harry Schimke of the USDA Forest Service, have been worked out. Recently, some funds to carry out this important work have been allocated on an emergency basis out of Park Service reserves. Currently, a project request for continuing funds is number one on the Parks' priority list for new funding.

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* Unpublished report by G. S. Briggs, National Park Service.

** J. L. Vankat. Vegetation change in Sequoia National Park, California. Unpublished Ph.D. dissertation, University of California, Davis. 1970.

The Parks have found that prescribed burn units can be established and burned to eliminate the majority of the smaller understory and to remove accumulated dead and down forest litter of all types. The cost is approximately $25 per acre in a mixed conifer forest. The procedure is to allow fire to do the whole job. Except for some snag falling and, of course, line construction, no other manipulation of the vegetation cover is required prior to burning. Most of the prescribed burning effort has been confined to the Redwood Mountain Grove of giant sequoias in Kings Canyon National Park (Fig. 4). Since 1969, some 400 to 500 acres have been burned under carefully controlled prescriptive conditions. Much of what has been done so far is on or near the exterior boundaries of the Grove on defensible ridge lines. Within the next two years, as the exterior boundaries are secured, larger blocks can be burned which will reduce cost per acre and increase the acreage burned.

In the high elevation fire zone since 1968, 80 naturally occurring fires have been allowed to burn (Fig. 5). Generally, the fires remain small. Three have required some action to keep them within the zone or to protect visitors. Of the 80 fires occurring since 1968, 80% have been smaller than 1/4 acre. There have only been four fires larger than 300 acres, 5% of all fires--one occurred in 1970 and three in 1973. Considerably more acreage burned in 1973 than in all previous years together--4,770 acres. Table 4 summarizes fires occurring in the high elevation fire zone.

Naturally occurring fires allowed to run their course are continually monitored. Such fires are usually detected by Park reconnaissance aircraft. From the time of detection, a daily report is made through aerial, and if feasible, ground surveillance, for any day fire size increases more than two acres. The fire situation is continuously evaluated by members of the Park Wildfire Committee composed of wildland fire experts and Park administrators. The committee, or a quorum thereof, may order a fire suppressed or limit its size, or may recommend other appropriate activity to keep the fire within the zone boundaries.

Crowning or hot-burning has never characterized any of the naturally occurring fires in these parks, although some localized crowning may occur in the larger fires where draws, winds, weather, and fuels all favor that condition.

The average rate of spread on the largest naturally occurring fire was roughly one chain (66 feet) an hour. That rate of spread was fairly consistent throughout the day and night and was not very much affected by slope unless winds and burning conditions contributed to move a front at a greater rate. The fire was characterized by slow, steady state burning, as were other natural fires, remaining predominantly on the ground but consuming small trees up to six to eight feet in height and burning lower limbs on other trees up to six to eight feet above the ground.

Trees over 10 to 12 inches in diameter are seldom killed in natural fires. Larger green trees that are killed usually exhibit scars and pitch, which allow the fire to be led into the crown or to burn the interior of the tree, weakening it, causing it to fall and be consumed by the fire on the ground. Most snags are burned down and then consumed. The shrub layer may or may not be consumed, depending upon the intensity of the fire in a given microsite. For the most part, such close-grown shrubs as manzanita (*Arctostaphylos* spp.), mountain whitethorn (*Ceanothus cordulatus*), and bush chinquapin (*Castanopsis sempervirens*) are either consumed completely by the fire or are scorched enough to kill them. However, we generally find rapid regeneration and regrowth of shrubs and a higher diversity in herbs present after the fires.

This year a few plots were set out in which the vegetation and gross amounts of down material were qualitatively recorded before and after the fire burned the plot (Fig. 6). The plots were filmed before, during, and after burning. This coming spring, vegetation on the plot will again be recorded to determine successional changes. The film captures the effect of a natural fire on the environment and we hope to make it available to interested professional natural resource managers, wildland administrators, and conservation groups.

Public acceptance of the fire management programs in Sequoia and Kings Canyon National Parks has been most encouraging. We use press releases; feature newspaper articles; presentations to civic groups, schools, and colleges; handout material at visitor contact points within the Parks; and interpretive park programs to keep the public informed. Procedures vary with conditions. For example, in 1972 a fire crossed a major trail in one area and burned along its length for a considerable distance in another. A small bulletin board was placed at either end of the fire along the trail, explaining the Park program, with a map showing the approximate extent of the fire. The Park Ranger stationed in the area explained the program to hikers and also insured no safety hazards existed.

Another reason for public support and acceptance may be that the evidence of past fires is everywhere. There is no place within these Parks where there is forest vegetation where one cannot see bits of charcoal on the surface or in the ground, remnants of burned stumps, standing burned snags, or live trees with burned "catfaces." Such signs are strong evidence of the fact that fire has been a major factor in determining the vegetative patterns and associated fauna of the Parks. This is so obvious that most visitors are aware of the relationship; others quickly grasp the idea when it is pointed out to them.

The Parks are charged to perpetuate naturally operating ecosystems and it follows that naturally occurring fires, in other words lightning fires, be allowed to play their ancestral roles as ecosystem determinators. Although smoke from the larger fires may temporarily obscure a view, the visitor can be more than compensated by being able to observe a process of nature functioning unmodified. The chance to observe such activity is an experience of the highest order.

Smoke produced by the fire management program at times affects areas outside Park boundaries. Prescribed fires at the lower elevations and naturally occurring fires at the higher elevations are observed daily from Park reconnaissance aircraft. Observations include direction of smoke drift and density and elevation of the column.

Smoke generated by the fires in the high elevation fire management zone mostly remains within Park boundaries. The terrain in these areas, valleys and deep canyons surrounded by ridges and 11,000-foot and higher peaks, tends to contain smoke. Seasonal winds normally do not drift smoke toward the populated San Joaquin Valley. Winds and terrain cause smoke to dissipate over these Parks. Smoke production patterns also favor local dissipation.

High elevation fires develop slowly over relatively long periods--larger fires may burn for periods up to two months. Only portions of the perimeters are active at any one time though patches of heavier fuels may burn in the interior for several days. A 2,000-acre fire can be expected to have 200 acres or less actually burning at any one time. Smoke emissions from a 2,000-acre fire in the high elevation fire management zone are therefore many times less, in a given period, than from a similar size fire in more highly flammable fuels at lower elevations. The latter type of fire usually develops in a brief period of a few hours or as long as a few days. Much smoke is produced in a shorter period of time.

Most prescribed burning is done at the lower elevations on the west slope of the Sierras and not within the higher mountainous areas of the Parks. For this reason, there is a greater chance for the smoke to be carried in the direction of populated areas, but smoke generated in our prescribed fires can be controlled. Burns are planned to correspond to times when winds and other conditions favor dispersal of smoke over the Parks.

Our prescribed fires are designed, with the limited manpower we have to utilize in this program, to burn a maximum of about 50 acres a day. Fifty acres is the maximum of multistoried mixed conifer forest with large accumulations of dead fuels that approximately 12 men can burn and control in a day even when firelines have been preconstructed. Most current burning is done at elevations of 6,000 feet. Prescribed fires are designed to be ignited as early in the morning as the prescription will permit so the burn can be completed as early in the day as possible. However, ignition usually continues well into the afternoon. By the end of each day plots have been burned and smoke generation has reached a maximum. Usually, fire temperatures are high enough to carry the smoke column well up before it begins to be dispersed. Commonly, smoke columns climb to about 9,500 feet and then dissipate in a northerly or easterly direction over the Parks. By late afternoon most fuels have been consumed; however, smoke continues to be generated as large fuels are consumed. In the evening, smoke settles to the ground as increased humidities, poor burning conditions, and quiet air contribute to smoke buildup in the fire area. Smoke is found near burn sites on the mornings following burn days but is usually cleared out as upslope winds pick up and dissipate smoke to the east over the Parks. Practically no smoke is produced the day following a burn.

Although smoke is generated in both fire management programs, it is also generated by wildfires, and there have been many of them over the years in Sequoia and Kings Canyon. Some wildfires in the Parks have been much larger than any fire occurring under the fire management programs.

Because wildfires are inevitable and will always be uncontrollable some of the time they are burning, quality, volume, and timing of smoke emissions will also be uncontrollable. These disadvantages are avoided in prescription burning. In the higher elevation forests, a more severe climate has not produced the quantities of fuels found at lower elevations, so prescribed burning to remove dangerous fuel accumulation is not necessary. In a few high elevation areas, however, where fuel accumulations are considerable, prescribed burning may be necessary before any naturally occurring fires are allowed to burn without control. If the Parks continued to suppress all wildfires in these high elevation areas, they too eventually might build up dangerous fuel accumulations like those now found at the lesser elevations. This can be avoided by allowing natural processes to prevail (Fig. 7).

Withal, the Parks are quite concerned about smoke no matter how generated--wildfire, high elevation naturally occurring, or prescribed. Research on the various facets of the smoke problem is very high on the Parks' priority list. The research biologist there is designing a project to be pursued by qualified scientists. Nevertheless, fire managed under existing programs should result in fewer problems with smoke production than if the Parks had continued to suppress all fires and not use prescribed burning. Further, the fire management programs are seen as practical and logical means of reducing hazardous or potentially hazardous fuel accumulations, and for perpetuating the structure of the Parks' vegetative communities.

Summary

The fire management programs in Sequoia and Kings Canyon National Parks and the Selway-Bitterroot Wilderness generally have been well received by a variety of publics. Even the observation of smoke and the burned area immediately after a fire has not been a problem. In fact, the opposite reaction has often occurred. One individual, who had spent several seasons fighting forest fires, admitted that he had never been on a fire long enough to see the after effects. He was amazed at the rapidity that ponderosa pine needles covered the forest floor on the Fitz Creek Fire, and his opinions underwent an equally rapid change. Another person who viewed the Fitz Creek Fire in mid-September remarked that, "weren't forest fires supposed to be black?" She, too, was amazed at the rate of change within the burned area as pine needles covered the soil and plants sprouted almost before the ashes were cold.

Why should the role of fire in wildland ecosystems be widely understood and appreciated today? Most people are able to accept fire as a natural and renewing force in many ecosystems. Estella Leopold recognized this function of fire and called on agencies to direct their efforts toward meeting the ecological requirements of the Wilderness Act (1969). People today are beginning to appreciate the role fire plays in giant sequoia groves, high elevation forests, ponderosa pine stands, and food chains. Perhaps as White (31) and Rappaport (21) suggested, we are developing the capacity to think in terms of circular systems.

What are the warning signals we have been reading concerning wildland fires? Beaufait (4) reported that man can never completely prevent wildfires. Man merely postpones the inevitable release of energy stored through photosynthesis when he extinguishes wildfires (22). It is true that fuel accumulation is not the same on every acre, but is regulated by environmental factors; and that some fires result in an increase of fuels for a period of time. But of paramount concern should be the need to understand the function, structure, and requirements of fire-adapted biological systems in the conduct of management programs. National parks and wildernesses provide opportunities for not only challenging recreational experiences but also for naturally evolving baseline communities from which we can derive measures of water quality, air quality, species diversity, and habitat mosaics.

The inevitability of fire in parks and wildernesses is followed by the inevitability of smoke. Hall's (10) summary of the literature indicated that the importance of smoke from woody fuels is limited almost entirely to the obstruction of visibility. A forest is a factory in the sense that it manufactures its own food and releases dead organic matter as a by-product (and the living and dead organic matter burns, periodically, producing smoke as a by-product). But the forest is not a factory in the sense that emission control devices can be installed to control or eliminate the particulates in smoke. So our options are complex and will not be solved by simple linear solutions.

Changing public attitudes and the National Environmental Policy Act require that man's impact on his environment be carefully assessed. But what kind of assessment is made as we remove man's high profile from national parts and wildernesses, and move toward the perpetuation of *natural* systems with all environmental processes operating within certain constraints? The real solution may not be conformity with particular statutory requirements, but thoroughly presenting the various alternatives for informed public choice.

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TABLE 1.--WILDERNESS FIRE MANAGEMENT PRESCRIPTIONS FOR WHITE CAP CREEK AND BAD LUCK CREEK DRAINAGES

Management Zone	Suppression	Observation	Observation & Suppression
1. Shrubfield	a. Hunting season: BUI[1] >170 b. Along study boundaries	a. Prehunting season b. Hunting season: BUI <170	a. Fires approaching Wapiti Creek Ridge
2. Ponderosa pine savanna		a. BUI <170	a. BUI >170
3. Ponderosa pine/ Douglas-fir	a. <4,500 feet elevation	a. >4,500 feet elevation, BUI <170	a. >4,500 feet, BUI >170
4. North slope	a. Along study boundaries b. BUI >170: Peach Creek Drainage	a. West of Peach Creek Drainage b. Upper White Cap unit	a. BUI >170: fires approaching Peach Creek buffer
5. Subalpine	a. Along study boundaries b. BUI >170: Bitterroot Crest passes	a. Season-long	a. BUI >170: fires approaching Bitterroot Crest passes

[1] BUI = Buildup Index from the 1972 National Fire-Danger Rating System. BUI is being used as an interim fire management index only until a similar index is incorporated into the new danger-rating system.

TABLE 2.--JANUARY-AUGUST PRECIPITATION, 1973, AT NORTH STAR RANCH (SELWAY RIVER); DARBY, MONTANA; AND MISSOULA, MONTANA

Month	North Star Ranch[1]	Darby, Montana	Missoula, Montana
	- - - - - - -	-Inches-	- - - - - - -
January	1.75	0.52	0.44
February	1.14	0.47	0.17
March	1.17	1.28	0.23
April	0.96	0.25	0.33
May	1.15	0.57	0.54
June	2.74	1.59	1.57
July	0.58	0.35	0.09
August	0.31	0.40	0.31
Total:	9.80	5.43	3.68

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[1] Weather station 10 miles down Selway River from White Cap Creek.

TABLE 3.--FIRES IN THE WHITE CAP FIRE MANAGEMENT AREA, 1973

Fire name	Date Origin	 Out	Cause	Fire size	Fire management zone	Action taken
				Acres		
Peach Creek	8/10	8/14	Lightning	<1/4	North slope	Delayed suppression[1]
Fitz Creek	8/10	9/21	Lightning	1,200	Ponderosa pine savanna, ponderosa pine/Douglas-fir, and shrubfield	Suppression and observation
Lookout Creek	8/10	8/16	Lightning	<1/4	North slope	Suppression[2]
Cub Lake	8/11	8/12	Lightning	<1/4	Subalpine	Observation
Mt. Paloma	8/14	8/15	Lightning	<1/4	Subalpine	Observation
Peach Ridge	9/6	9/13	Lightning	<1/4	North slope	Observation

[1] Suppressed because fire near area boundary.

[2] Suppressed because this fire at first assumed to be a spot fire from Snake Creek Fire.

TABLE 4.--NUMBER OF LIGHTNING FIRES IN THE NATURALLY OCCURRING HIGH ELEVATION FIRE MANAGEMENT ZONES, SEQUOIA AND KINGS CANYON NATIONAL PARKS, 1968-1973

Year	Size class by acres					Total No. fires	Total acres burned
	<1/4	>1/4 to 9	10 to 99	100 to 299	300+		
1968	1	1	0	0	0	2	8.0
1969	2	0	0	0	0	2	0.3
1970	20	1	2	0	1	24	494.5
1971	23	1	0	1	0	25	115.0
1972	11	2	2	1	0	16	161.8
1973	7	1	0	0	3[1]	11	4,772.7
Total:	64	6	4	2	4	80	

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[1] South Sentinel Fire burned 2,486 acres; Moraine Creek Fire burned 1,760 acres; and Chagoopa Fire burned 525 acres.

FIGURE 1. The observer at Bad Luck Lookout measures humidity as the Fitz Creek Fire burns in shrubfield fire management zone.

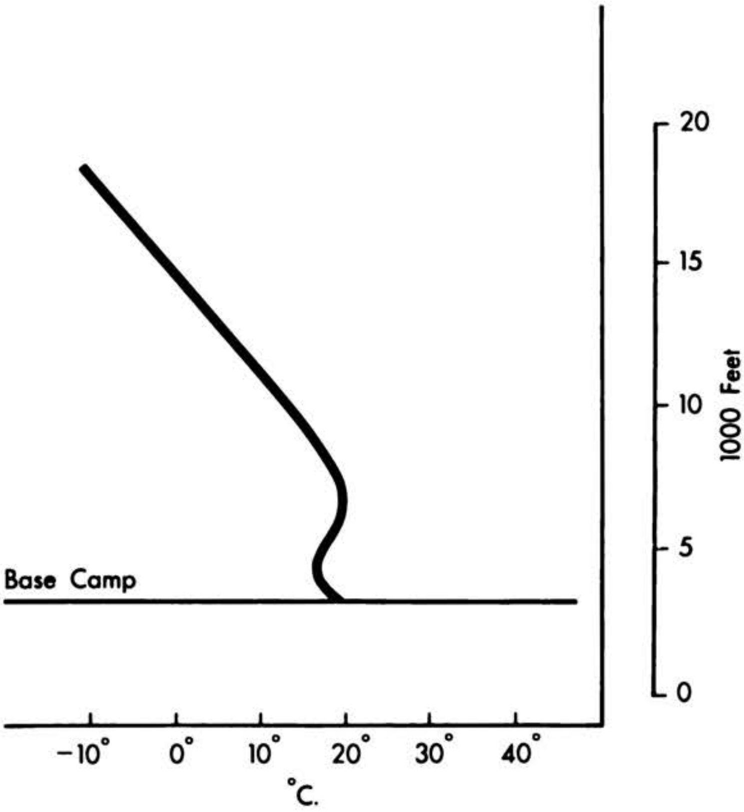

FIGURE 2. Temperature inversion recorded on the morning of August 27, 1973, near the Fitz Creek Fire.

FIGURE 3. Grouse walking up the White Cap Creek trail during early stages of the Fitz Creek Fire.

FIGURE 4. Prescribed burning in Sequoia and Kings Canyon National Parks is returning fire to fire-adapted giant sequoia groves and reducing fuel accumulations.

FIGURE 5. A portion of the 2,486-acre South Sentinel Fire that burned in the High Elevation Fire Management Zone in Sequoia and Kings Canyon National Parks in 1973.

FIGURE 6. An inventory crew records vegetation and fuel data while the South Sentinel Fire burns in pine needle litter.

FIGURE 7. Fire consuming large fuels in the South Sentinel Fire, 1973.

SESSION IV

RESEARCH AND OPERATIONAL PROGRAMS FOR PROTECTION OF ENVIRONMENTAL QUALITY

Moderator:

Robert Dils
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GOALS OF A NATIONAL PROGRAM IN SMOKE RESEARCH

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Introduction

A primary basis for a National program in smoke research is the Clean Air Act as amended. The intent and purpose of this law is:

> "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." (1)

Both primary and secondary national ambient air quality standards have been established for six criteria pollutants. National primary ambient air quality standards are those which, in the judgment of the Administrator of the Environmental Protection Agency, based on the air quality criteria and allowing an adequate margin of safety, are requisite to protect the public health. National secondary ambient air quality standards are those which, in the judgment of the Administrator, based on the air quality criteria, are requisite to protect the public welfare from any known or anticipated adverse effects associated with the presence of air pollutants in the ambient air.

Attention is now being directed toward the "non-criteria" pollutants. These include various metal compounds, polynuclear hydrocarbons, and synthetic chemicals such as polychlorinated biphenyls (PCBs). There are many divergencies of opinion as to the proper interpretation of available data on public health and welfare effects. These divergencies of opinion in part reflect the complexity of the problem, particularly with regard to acute and chronic health effects. In an effort to make the problem of compliance with the Clean Air Act tractable, we attempt to treat individual pollutants (by definition) as separate entities. This, of course, does not represent actual exposure; therefore, in most cases, this does not permit quantitative evaluation of effects with a high degree of certainty. At some point in our deliberations judgment must be exercised. The overall goal of our research effort should be to provide an adequate data base upon which knowledgeable and reasonable individuals can make prudent decisions regarding debatable questions. Specific goals will change depending upon the adequacy of our data base and our ability to identify meaningful boundaries to specific segments of the overall problem. It is at this point that we run into difficulties in our efforts to state the goals of a smoke research program. We can propose an impressive list of individual pollutants; however, in the ambient atmosphere, they represent a portion of a single medium. Each of these individual constituents are usually coupled, either directly or indirectly, through chemical or dynamic mechanisms. Smoke is an excellent example of such a complex mixture.

Historically, the first and foremost objections to atmospheric pollution were due to soiling and visibility reduction from smoke, haze, or smog. Emissions from forest fires, and from open burning of agricultural refuse and land clearing debris have long been recognized for their effects on air quality. A 1912 Forest Service bulletin stated--"forest fires are the most frequent causes of widespread pollution of the atmosphere" (2). This of course would not be true today, at least, in some local areas. Some interesting data were presented recently by Smith, *et al.* (3), (Scripps Institution of Oceanography) regarding the annual carbon fallout from forest fires. They analyzed the amount of carbon in ocean sediments deposited over the past million years, except that the most recent 5,000 years were excluded. Based upon these analyses, they conclude that forest fires and energy production are now contributing comparable amounts of carbon to the atmosphere.

Despite the fact that the problem of atmospheric pollution from smoke has been recognized for many years, and that considerable effort has been devoted to it, a number of important questions remain to be answered. However, before we discuss the goals of a research program, it will be necessary to state a working definition of smoke. The American Society for Testing and Materials (ASTM) defines smoke as:

> "small gas-borne particles resulting from incomplete combustion, consisting predominantly of carbon and other combustible material, and present in sufficient quantity to be observable independently of the presence of other solids." (4)

The Federal Register (5), dealing with rules and regulations for new motor vehicle engines, defines smoke as:

> "matter in exhaust emissions which obscures the transmission of light."

If we are to be responsive to the provisions of the Clean Air Act, our smoke research program should address not only the physical, chemical, and dynamic properties of smoke, but also the effects upon human health and welfare. In this regard, the invisible emissions may be most important; therefore, we must be concerned with all products of incomplete combustion. A research program limited in scope to visible emission would cover only a portion of the problem. Therefore, for the purpose of discussion, we will include both gaseous and particulate emissions. Important factors which must be considered are atmospheric pollutant loading and its effects upon health and welfare.

Smoke Constituents - Current Pollutants

Pollutants resulting directly from incomplete combustion for which national ambient air quality standards have been promulgated include:

(1) Nitrogen Oxides

(2) Sulfur Oxides

(3) Hydrocarbons

(4) Carbon Monoxide

(5) Particulates

(6) Oxidants formed by photochemical processes in the atmosphere.

It should be noted that these combustion products are not unique to forest fuels.

Nitrogen oxide (NO) is the major nitrogen compound emitted during combustion processes. Reaction of NO with oxygen during the cooling of combined gases converts a small fraction (approximately 10%) of the NO to nitrogen dioxide (NO_2). The major conversion of NO to NO_2 is due to photochemical processes in the atmosphere. The principle welfare effect from NO is its role in the reduction of visibility. NO is not considered to have adverse effects on human health at concentrations normally found in the ambient atmosphere. Its toxic potential at ambient concentrations results from its oxidation to NO_2. The toxic effects of NO_2 have been demonstrated in animal experiments.

Controlled experimental human exposures to NO_2 have not been conducted. However, epidemiological studies have indicated three adverse effects on human health: (1) increased susceptibility to acute respiratory disease, (2) increased severity of lower respiratory disease in children, and (3) increased risk of chronic respiratory disease by reduced ventilatory function in children (6).

Sulfur compounds are emitted from combustion processes in the form of sulfur dioxide (SO_2), sulfur trioxide (SO_3), and corresponding acids and salts (sulfites and sulfates). Sulfur dioxide (SO_2) is emitted in appreciable quantities from the burning of coal and fuel oil which contain inorganic compounds. Other oxides of sulfur are not emitted in such appreciable quantities as compared to sulfur dioxide. Sulfates are formed primarily by oxidation of atmospheric sulfur dioxide. The sulfuric acid and other sulfates formed by this transformation account for about 5% to 20% of the suspended particulate matter in urban air. Suspended sulfates, ranging in size from 0.1 μ to 1.0 μ in radius, are very effective in reducing visibility. The potential toxic effects from sulfur dioxide are increased when it occurs synergistically with particulate matter under conditions which would promote the conversion of sulfur dioxide to sulfuric acid (7). Sulfur dioxide is not ordinarily a constituent of wood smoke; nevertheless, it may be necessary to consider the combined effects of particulates emitted from forest and agricultural burning, and sulfur dioxide emitted from other sources (8).

Hydrocarbons are emitted into the atmosphere from sources such as transportation, organic solvent evaporation, industrial processes, solid wastes disposal, and fuel combustion from stationary sources (9). The primary source of hydrocarbon pollution is from the incomplete combustion of motor vehicle fuels such as gasoline (9,10,11). A few of the hydrocarbon compounds such as toluene, benzene, m-xylene, and ethylene react with ozone in the presence of nitrogen oxides and sunlight to form photochemical smog (8). A component of photochemical smog is peroxyacyl nitrate, or PAN, an eye irritant, which also is highly toxic to plants (8). Of thousands of hydrocarbon compounds, only a few may be extremely toxic. In this respect, two groups of hydrocarbon compounds of importance in air pollution are: (1) olefin and ethylene series which may cause a general reduction in plant growth; although, in small concentrations, they appear to have no direct effect on animals; and (2) the aromatic, or benzene series of which some are known to be carcinogenic. Benzo(a)pyrene is thought to be the most potent carcinogen of these compounds (10). Forest fires and agricultural burning are sources of these compounds.

Carbon monoxide (CO) is the most widely distributed and most commonly occurring air pollutant. Total emissions of CO into the atmosphere exceed those of all other pollutants combined (12). The largest man-made source of carbon monoxide is the incomplete combustion of organic fuels used for motor vehicles and heating. Industrial processes, refuse burning, agricultural burning, and forest fires are collectively the next largest source (1). In the higher animals, carbon monoxide (CO) is absorbed exclusively via the respiratory tract. Most of its toxic effects are the result of its reaction with hemoglobin to form carboxyhemoglobin which reduces the oxygen carrying capacity of the blood (12).

Particulate matter is a diverse assemblage of multimolecular components varying in chemical composition ranging from salt crystals and acid droplets to heterogeneous liquid and solid aggregates and living cells. Most physical properties of particulates, such as electrical and optical, are size dependent. Combustion products and photochemical aerosols make up a large fraction of the particles in the size range of 0.1 μ to 1 μ diameter. The increase over natural levels of particles below 0.1 μ diameter seems to be due entirely to combustion. Particles in the size range between 1 μ and 10 μ in diameter generally include local soil, fine dusts emitted by industry and maritime locations, and airborne sea salt. Particles greater than 10 μ in diameter result from highway construction, wind erosion, grinding, etc. The bulk of the particulate mass in the atmosphere ranges in size from 0.1 μ to 10 μ diameter. These particulates may exert a toxic effect by one or more of three mechanisms:

1. Intrinsic toxicity of the particle due to its inherent chemical and/or physical characteristics.

2. Interference with one or more of the clearance mechanisms in the respiratory tract.

3. Particles may act as a condensation nuclei on which a toxic substance such as sulfur dioxide may be adsorbed (12).

Welfare effects produced by particulates in the atmosphere include soiling, and effects on visibility, weather, and climate.

The products of incomplete combustion include a number of pollutants other than those for which national ambient air quality standards have been established. These include a variety of metallic components which may be present in fuels as impurities, and a variety of polycyclic organics. Most important, from the standpoint of forest fires and agricultural burning, would be the category of polycyclic organics. A number of the trace metals are known to be toxic, and some of the polycyclic organics are known to be carcinogenic such as benza[a]pyrene (BaP). BaP emissions in the U.S. from forest fires and agricultural burning are estimated at 140 tons per year (14).

Problem Areas

Promulgation of national ambient air quality standards and implementation of some control programs provides guidelines by which a national research program must follow. What are the remaining problem areas which should be addressed in a national research program? The following is quoted from the introduction of a book entitled *Smoke* published by Cohen and Ruston in 1925 (15):

> "...Thus matters are at a standstill. But if it can be shown beyond any question that the effects of smoke are distinctly injurious to health, or clearly pernicious in other ways, and that its removal can be effected without serious expense or discomfort, then the authorities have not only the right, but a positive duty to interfere and enforce more drastic means for its suppression. The question, then, arises: Have we any trustworthy information on the subject? What is the nature of soot? What is the quantity emitted from domestic and from factory chimneys, and what is the quantity temporarily and permanently deposited? What is the quantity suspended in the air, and to what extent does it affect health? Does it corrode as well as discolor masonry, brickwork, and metalwork, and how far is it destructive to vegetation? Do its effects extend beyond the immediate vicinity of the town; to what extent does it shut out daylight, induce or aggravate fog? And, finally, what is the increased cost of cleaning?"

We have devoted considerable effort to the problems of air pollution since 1925, and progress has been made. Major questions which remain unanswered are: Is our data base adequate? What is the characterization of air pollutants? What is the atmospheric loading and how does it vary in space and time? To what extent does air pollution contribute to acute and chronic diseases? What are the effects of air pollution on the ecosystem? What are the effects of air pollution on materials? What are the geophysical effects of air pollution; the effects on visibility, weather, and climate? What are the socio-economic effects of air pollution?

The questions are indicative of the complexity of the problems; they suggest the requirement for long-term goals and objectives.

Goals of Past and Present Smoke Research

Much of the early research was devoted to coal smoke. The objectives were related to soiling, reduction in visibility or sunlight, damage to vegetation, and general health. Efforts were made to quantify atmospheric loading of soot in England in the late 1800's (15). Analyses were made to determine the composition of soot, and values were obtained for carbon, hydrogen, tar, and ash from domestic and factory sources. Studies were conducted to determine the effects of soot on vegetation.

The association between the development of cancer and excessive contact with an environmental contaminant was first made in 1776 when the British physician Percival Pott noted the high incidence of cancer of the scrotum in the chimney sweeps of London and correctly attributed the disease to their continual contact with soot (16). These early studies focused attention on the carcinogenicity of polycyclic aromatic hydrocarbons and guided toxicological laboratory research in that direction.

Although many descriptive accounts of air pollution from forest fires and agricultural burning may be found in the literature, most of the quantitative studies specifically related to smoke from these sources have been conducted since 1960. Early work by Yocom and Hein (24), Feldstein, *et al.* (17), and Darley, *et al.* (18) was devoted to obtaining quantitative estimates of emission under various fuel loadings and burn conditions. Data were obtained using burning towers and single and multiple chamber incinerators specifically designed to simulate open burning. Gerstle and Kimnitz (19) have used the same tower design to obtain emission data from open burning of municipal refuse, landscape refuse, and automobile components. These studies have provided initial estimates of emissions from the open burning of various fuels under range burning conditions which provide a basis for estimating comparative contributions to atmospheric loading and some insight as to the role of these pollutant sources in the formation of photochemical smog and reductions in visibility.

Analysis of samples from some of the above mentioned studies has provided important new information on the composition of the products of incomplete combustion from open burning of the various fuels. These studies have revealed significant variations in emissions and principal constituents as a function of atmospheric conditions, fuel characteristics, and flame temperature.

Studies currently being conducted by Darley, *et al.* (20), using an improved burning tower data acquisition system, are providing important new information on smoke composition, and particulate emissions and size distribution.

Many other studies are currently underway which will add significantly to our data base. Emission problems are being studied at Washington State University, Oregon State, and the University of Washington at Seattle. Also, the University of Washington, in cooperation with the USDA Forest Service, has been conducting research on air quality aspects of burning heavy forest fuels in the Pacific Northwest. The results of their work have yielded both specific and general information on the effects of prescribed burning in that area (21). Weather influences on smoke dispersion are being investigated in the Forest Fire Meteorology Project at the Riverside Forest Fire Laboratory. The aim of this project is to predict smoke movement in terms of commonly experienced weather patterns. Project Fuelbreak at the Riverside Forest Fire Laboratory was designed to study alternative methods of disposing of woody materials. Forest fire behavior is being studied at Riverside in the Mass Fire Systems and Fire Behavior Project. Research to find ways of minimizing the impact of smoke from prescribed burning on local communities is represented by the combined efforts of Washington State University, and the Northern Forest Fire Laboratory at Missoula. Light instrumented aircraft have been employed by Washington State University and the University of Florida to study the effects of wildfires and prescribed fires on air quality. In addition to the above projects, the U.S. Forest Service Fire Search Laboratory at Macon, Georgia has been organizing and implementing a research project to investigate forest burning and air pollution. The specific goals of the research project as stated in the report *Prescribed Burning and Air Quality* by John H. Dieterich (21,22,23), are to:

1. Bring together and publish all existing information pertinent to the impact of fire, prescribed or wild, on southern environments;

2. Identify and measure the products released into the environment when forest fuels are burned, and contrast these releases to the slower processes of natural decomposition;

3. Determine the effects of the various products of combustion on air quality; and

4. Prepare interim guidelines on smoke management for immediate use by action agencies.

Goals of Future Research

Where do we go from here?

The goals of the Southern Forest Fire Laboratory and other research groups provide a starting point for future research but should be broadened to include prescribed burning in other sections of the country, especially slash burning in the west. Guidelines for prescribed burning should be adopted on a nationwide basis taking into account area variations in types of fuel, amount consumed, and meteorological conditions. In addition, we need to know more about the long range transport of pollutants from slash and prescribed forest burning and their influence on visibility, weather, and climate. Also, much needs to be done to determine the effects of forest fire particulates on the behavior of pollutants from urban sources. Improving that portion of the nationwide emissions inventory which pertains to wildfires and prescribed burning provides documentation but does not allow us actual on-the-spot coverage of pollution episodes. Emissions inventories are based on emissions factors which are applied to the total measurable quantities of combustible materials to give predictions of atmospheric loadings of pollutants. Immediate impact studies require monitoring equipment and technology, along with the transport and diffusion modeling capabilities of high-speed computers, to aid in legislative activities to reduce atmospheric pollution. The behavior of smoke from prescribed burning and wildfires is dependent on many physical and chemical properties--from the types of fuel being burned and the heat of the fire to the structure and dynamic state of the atmosphere. Forest fires in the proximity of urban areas may contribute to urban air pollutant concentrations by intermixing with pollutants from urban sources. The degree to which this causes an urban problem is dependent on the fire's location with respect to wind direction, the intensity of the fire, and the temperature of the air above the fire. Urban problems may be intensified, especially in areas of high industrialization, if a forest fire is located directly upwind of the area and the air is stable enough to hold particulates in the smoke close to the ground. On the other hand, smoke from a fire downwind of the urban area may blow directly away from the area or, due to unstable atmospheric conditions, the smoke may be vented to a higher elevation separated thermally from the polluted urban air. These are essentially local problems that must be considered in the trade-offs between prescribed burning and urban pollution. Widespread problems may be caused by forest burning. Even after a visible plume of smoke has diffused, microscopic dusts, droplets, and gases often subsist in concentrations great enough to cause area-wide reduction in visibility. These aspects of the problem should be investigated.

Current research at EPA is oriented toward monitoring and controlling atmospheric pollution from all sources and, at the same time, assessing damage to human health and welfare. No in-house activities are specifically aimed at the forest fire problem. However, some of the projects currently underway in meteorological research and control technology may have a definite role in the research of smoke from forest fires. For instance, in meteorological research, plans are underway to study the interactions of pollutants and thermal emissions and how they affect visibility, weather, and climate. The information obtained will be used in the development of simulation models, land-use planning, and control strategy implementation. New and improved concepts and methodologies are being developed for implementing and evaluating air quality simulation models having a broader, more comprehensive capability to predict air quality distribution under various emission, topographic, and meteorological conditions.

In view of the number of government and other agencies involved in research directly or indirectly bearing on the problems of forest fire smoke, consideration should be given to forming a national committee or steering group to coordinate the planning of smoke research related to forest burning. This might be considered the first goal in a national program of smoke research. Fortunately, research has progressed to the point where a great many of the problems have been identified. Now, a unified effort--a national program--must be put into action to solve these problems. But, in the meanwhile, not having all the answers cannot justify failure to take action based on the scientific knowledge currently available.

Summary of Goals

1. Development of adequate open burning source emission inventories, related to controlling variables, and the contribution of these sources to the total atmospheric loading as a function of space and time.

2. Obtain a more complete characterization of the composition and particulate size distribution of incomplete combustion products from open burning.

3. Provide the necessary input data for air quality simulation and prediction models; and develop the monitoring equipment and technology required to obtain quantitative input data.

4. Develop guidelines for the management of controlled burning to ensure minimum impact upon air quality in compliance with the provision of the Clean Air Act.

5. Determine the extent to which the incomplete combustion products from open burning may contribute to adverse human health and welfare.

6. Obtain a reliable data base for comparing benefits of controlled burning (as a management tool) versus the benefits of improved air quality.

7. Develop alternative (non-burning) methods for slash disposal, fuel reduction, and site improvements.

8. Form a national steering group to coordinate the planning of smoke research related to open-burning.

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PANEL DISCUSSION

PRIORITIES FOR SMOKE RESEARCH

Moderator:

Craig Chandler
U.S. Forest Service

SMOKE COMPOSITION

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Environmental Protection Agency

The literature on a breakdown of the chemical composition of smoke reflects to a large degree our capability to sample and analyze trace constituents. The *method defines the measurement.* Practical, or working definitions of the various atmospheric pollutants usually represent that which we collect, or sample, and that to which our analytical methods respond. Biota and materials are exposed to the total burden, which may differ significantly from our measured values.

Smoke is a complex mixture which contributes to an even more complex mixture of gases and aerosols in the atmosphere. If an element or compound has not been reported as being a product of combustion, this may mean that it is not one, or the concentration is below our detection capability, or it has not been looked for.

Combustion products, either directly or indirectly, account for most of our criteria air pollutants for which national air quality standards have been promulgated. These include:

Carbon Monoxide
Particulates
Hydrocarbons
Nitrogen oxides
Sulfur oxides
Oxidants

Measurable amounts of sulfur oxides have not been found in burning forest fuels. High concentrations of sulfur are emitted from the burning of coal. Products from forest fires may contribute indirectly to oxidant levels through photochemical processes.

If we confine our discussion of the composition of smoke to the criteria pollutant categories as indicated, it should be brief and not necessarily very provocative. If, however, we wish to examine in more detail the categories of hydrocarbons and particulates, plus other potential non-criteria pollutants, then we have a new ball game. It is at this point that the unknown becomes greater than the known, and the number of important variables increase significantly. Even in the case of the criteria pollutant categories, it is difficult to quantify emission factors due to the variation in burn conditions, fuel type, fuel loading, moisture, etc. The problem is even more complicated when we talk about specific hydrocarbon or particulate compounds.

For the purpose of opening the discussion, I will confine my remarks to some of the constituents of smoke or combustion products, which have been identified. Since many of the sources of my information are attending the symposium, we should not have difficulty in filling in the details.

Figures 1 through 3, and Table 1 through 3 were extracted from a paper by Gerstle and Kemnitz (1). These results indicate the variation in constituent concentrations with burn time and conditions, and with the various material burned. A breakdown of some polynuclear hydrocarbons is given in Table 3.

Tables 4 through 6 are due Feldstein, *et al.* (2). These results provide a breakdown of some gases and particulates by fuels and burning sources. Again the variation between fuels and burn conditions is significant.

Tables 7 through 12 are from the work of Darley, *et al.* (4). The data were obtained from agricultural waste using a burning tower.

Gibbard and Schoental (5) analyzed various woods for aldehyde content. The results are given in Table 13. Some of the aldehydes have been reported to be carcinogenic in animals (6).

Fritschen, *et al.* (7) analyzed smoke samples from a broadcast burn and from laboratory fires. These results are shown in Tables 14 through 16.

Combustion products from automobiles, trucks and incineration processes have been analyzed by Hangebrauck, *et al.* (8,9). These results are shown in Tables 17 through 22.

The references cited here do not represent a bibliography on the subject of the composition of smoke, or the product of combustion. However, they do illustrate the complexity of the problem and identify some of the compounds thought to be most important--specifically the polynuclear hydrocarbons.

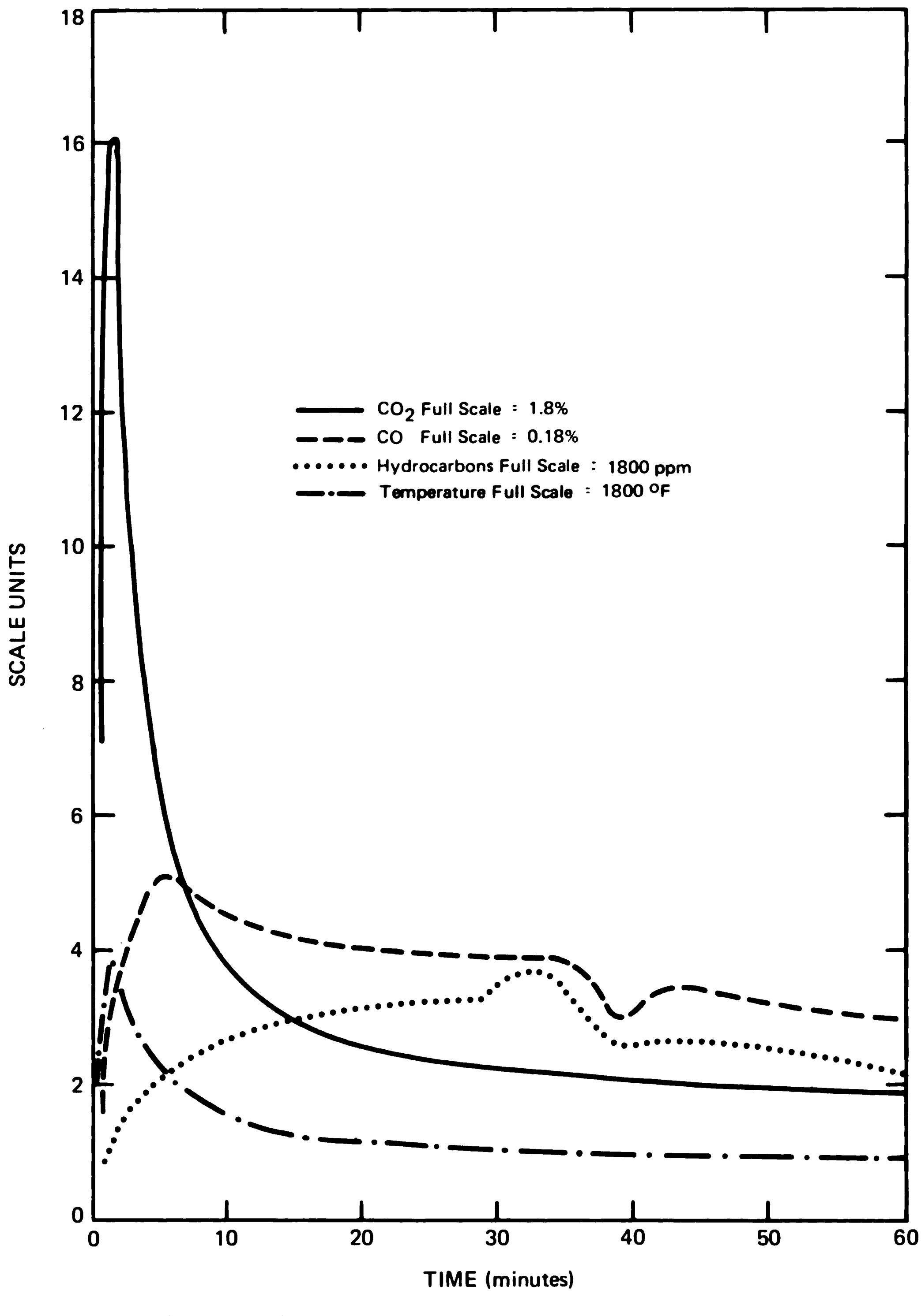

FIGURE 1. Variations in CO_2, CO, hydrocarbons, and temperature with time during burning of municipal refuse (Gerstle and Kemnitz).

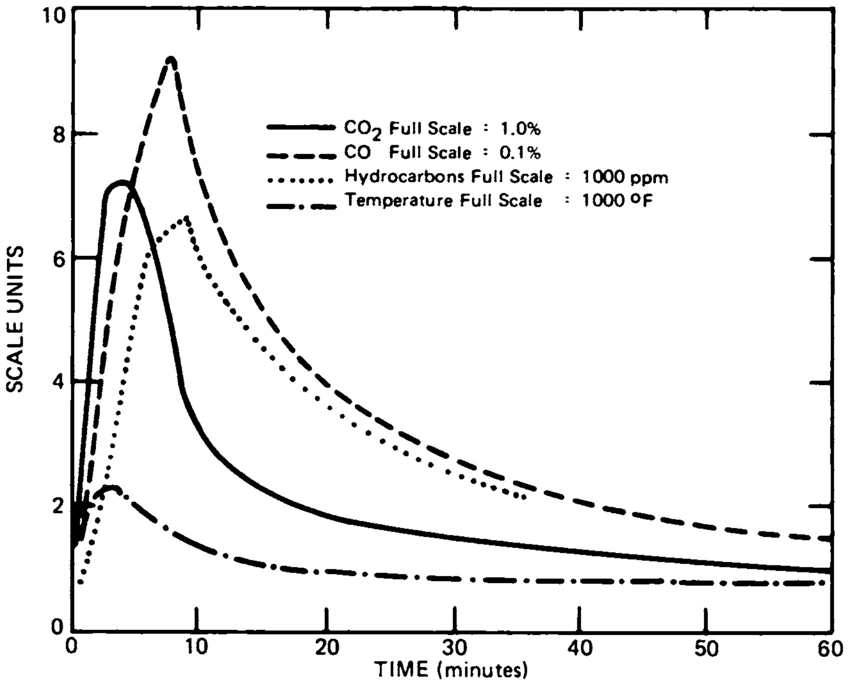

FIGURE 2. Variations in CO_2, CO, hydrocarbons, and temperature with time during burning of landscape refuse (Gerstle and Kemnitz).

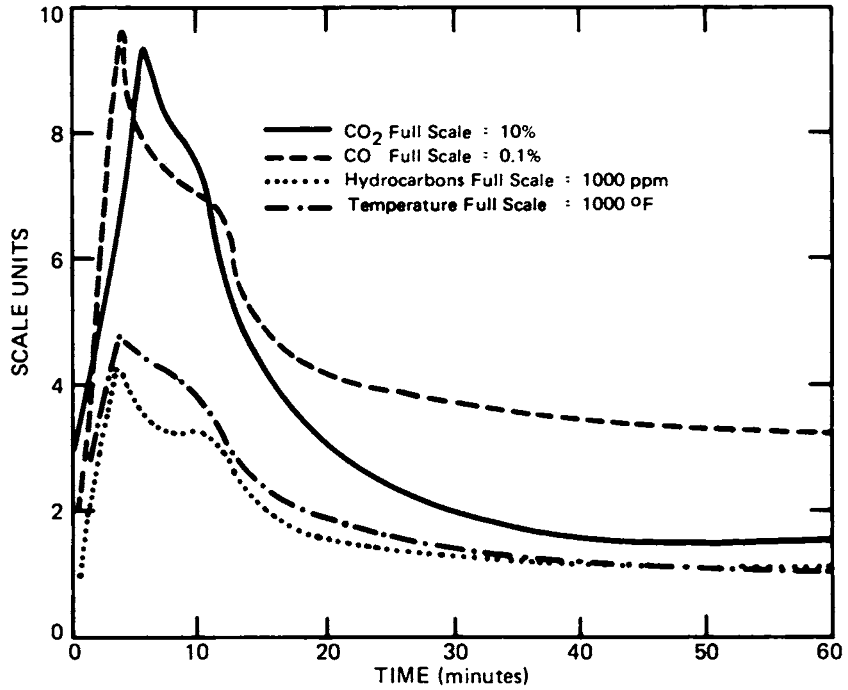

FIGURE 3. Variations in CO_2, CO, hydrocarbons, and temperature with time during burning of auto components (Gerstle and Kemnitz).

TABLE 1. GASEOUS EMISSIONS FROM OPEN BURNING

		Gaseous Emissions -- Pounds per Ton of Material Initially Present				
Test No.	Material Burned	CO_2	CO	HC[a]	Formaldehyde	Organic Acids[b]
1	Municipal refuse	1250	90	30	0.095	14
2		1210	80	30	0.094	16
Avg.		1230	85	30	0.095	15
3	Landscape refuse	860	80	35	0.005	18
4		550	50	25	0.006	8
Avg.		700	65	30	0.006	13
5	Automobile components	1500	125	30	0.030	16

[a] Gaseous-hydrocarbons expressed as methane.

[b] Organic acids expressed as acetic acid.[1]

TABLE 2. NITROGEN OXIDE EMISSIONS

Test No.	Material Burned	NO_x Emissions ppm	Pounds per Ton of Material Burned[a]	Time Elapsed After Fire Started, min.
1	Municipal refuse	9	8	33
		7	6	54
		8	9	75
2		127	27	3
		11	9	43
		2	4	83
3	Landscape refuse	20	4	3
		2	1	27
		1	1	48
		16	4	2
4		<0.5	<0.5	40
5	Automobile components	84	17	0
		5	5	24
		1	2	52

[a] Calculated on the basis that all of the nitrogen oxides are nitrogen dioxide.[1]

TABLE 3. POLYNUCLEAR HYDROCARBON EMISSIONS FROM OPEN BURNING, GRAMS PER TON OF MATERIAL INITIALLY PRESENT

	Municipal Refuse 1	2	Landscape Refuse 3	4	Automobile Components 5
Anthracene	--[a]	--	--	--	1.9
Phenanthrene	--	--	--	--	13.2
Fluoranthene	0.78	1.19	0.77	0.64	33.4
Pyrene	0.89	1.28	1.31	0.87	46.9
Crysene	0.25	0.34	1.01	0.42	14.5
Benz(a)anthracene	0.17	0.21	0.26	--	19.4
Benzo(a)pyrene	0.19	0.22	0.31	0.13	17.8
Benzo(e)pyrene	0.13	0.16	0.12	0.08	9.0
Perylene	--	--	0.05	--	1.6
Benzo(g,h,i)perylene	--	0.19	0.21	--	12.2
Anthanthrene	--	--	0.03	--	1.4
Coronene	--	--	--	--	1.5

[a] Indicates that the compound was not detected.[1]

TABLE 4. COMPARISON OF EMISSIONS FROM THE BURNING OF VARIOUS FUELS (POUNDS OF MATERIAL PER TON BURNED)

Component	Multiple Chamber Incinerator	Backyard and Single Chamber Incinerator*	Gasoline Engine Operations
Total Organic Gases	0.8	250	110
Total Organic Gases (excluding Methane)	0.75	166	98
Saturated HC (excluding Methane)	0.15	30	37
Total olefins	0.1	36	28
Total oxygenates	0.35	59	1
Total aromatics	0.1	11	20
Methane	0.05	85	12
Ethylene	0.05	30	11
Acetylenes	0.05	30	12
Carbonyls	0.3	35	1
Other Oxygenates	0.05	24	0
Nitrogen Oxides	2	0.1	40
Carbon Monoxides	0.05	600	1060
Particulates	--	24	4

*Calculated from work of Yocom and Hein[3] by Feldstein et al.[2]

TABLE 5. COMPARISON OF GASES AND PARTICULATES PRODUCED BY VARIOUS FUEL BURNING SOURCES

		Gases and Particulates Emitted (Tons/Day)			
Source	Tons of Fuel Consumed per Day in the Bay Area	Total Organic Gases Excluding Methane	Total Olefins	Ethylene	Particulates
Daily Gasoline Engine Operations	10,000	490	140	55	20
Daily Comm. S. C. Incineration	1,700	140	31	26	20
Daily Backyd. S. C. Incineration	2,200	180	40	33	26
Daily Comm. M. C. Incineration	40	0.02	0.002	0.001	--
Total Daily Emissions	--	810	211	114	66

Feldstein, et al.[2]

TABLE 6. ESTIMATED TONNAGES OF GASES AND PARTICULATES EMITTED BY LAND CLEARING OPEN BURNS

		Gases and Particulates Emitted (Tons)			
Open Burn	Tons of Fuel Burned	Total Organic Gases Excluding Methane	Total Olefins	Ethylene	Particulates
Martin Ranch	2850	240(168)	51 (36)	43 (30)	34 (24)
Eichler 1959	1000	83(168)	18 (36)	15 (30)	12 (24)
Eichler 1960	2000	166(166)	36 (36)	30 (30)	24 (24)
Briones	7500	620(170)	134 (36)	112 (30)	90 (24)
L. C. Smith 4/19/62	1500	124(166)	27 (36)	23 (30)	18 (24)
L. C. Smith 3/29/62	1000	83(166)	18 (36)	15 (30)	12 (24)
L. C. Smith 3/22/62	250	21(168)	4.5(36)	3.7(30)	3 (24)
L. C. Smith 3/20/62	200	17(170)	3.6(36)	3 (30)	2.4(24)
L. C. Smith 3/1/62	50	4(160)	1 (40)	1 (40)	.6(24)

(#/ton) Feldstein, et al.[2]

TABLE 7. YIELD OF HYDROCARBON, CO, AND CO_2 IN POUNDS PER TON OF WASTE MATERIAL FROM THE BURNING OF VARIOUS AGRICULTURAL WASTES COLLECTED IN THE SAN JOAQUIN VALLEY AND SAN FRANCISCO BAY AREA OF CALIFORNIA

Waste Material	% Moisture	Total Hydrocarbon as C	CO	CO_2
		San Joaquin Valley		
Rice straw	--	9.1 ± 2.4	73 ± 17	2091 ± 305
Barley straw	--	14.5 ± 3.7	83 ± 23	1708 ± 389
Native brush				
Dry	--	4.7 ± 2.5	70 ± 8	2733 ± 410
Dry and green	--	15.2 ± 4.3	81 ± 6	1990 ± 237
Green	--	27.4 ± 8.8	134 ± 41	1528 ± 464
Cotton	40 ± 14[a]	3.1	73	2532
		Bay Area-1965		
Fruit prunings	11 ± 4[a]	4.2 ± 1.3	46 ± 14	2258 ± 238
Native brush	5 ± 1	4.7 ± 2.1	65 ± 30	2620 ± 204
Fir chips	5	2.8	35	1522
Redwood chips	--	2.2	70	3742
		Bay Area-1966		
Fruit prunings	35 ± 15	9.7 ± 4.2	66 ± 21	1995 ± 347
Native brush	13 ± 7	4.4 ± 2.3	55 ± 19	2374 ± 204

[a] Figures are given with standard deviations. Entries without deviations represent one or two fires only.

(Darley et al.[4])

TABLE 8. YIELD OF ETHENE, OLEFINS, AND PARAFFINS PLUS ACETYLENES IN PERCENT OF TOTAL CARBON FROM THE BURNING OF SEVERAL AGRICULTURAL WASTES COLLECTED FROM THE SAN JOAQUIN VALLEY AND SAN FRANCISCO BAY AREA OF CALIFORNIA

Waste Material	Ethene	Olefins	Saturates Plus Acetylenes
	San Joaquin Valley		
Rice straw	9.6 ± 5.4[a]	16.7 ± 4.6	4.2 ± 2.1
Barley straw	9.6 ± 2.5	14.3 ± 4.9	4.5 ± 1.5
Native brush			
Dry	6.9 ± 3.3	10.7 ± 5.6	4.3 ± 2.6
Dry and green	12.6 ± 5.1	19.9 ± 7.0	4.1 ± 1.5
Green	10.3 ± 4.9	16.4 ± 7.6	3.8 ± 1.9
Cotton	9.1	16.0	5.2
	Bay Area--1965		
Fruit prunings	8.8 ± 5.1	15.7 ± 8.0	5.5 ± 2.9
Native brush	10.3 ± 7.3	16.2 ± 10.0	5.7 ± 2.7
Fir chips	7.0	11.7	3.8
Redwood chips	8.0	11.7	3.3
	Bay Area--1966		
Fruit prunings	14.1 ± 5.2	22.4 ± 7.1	6.8 ± 2.7
Native brush	10.2 ± 3.4	16.9 ± 4.9	6.9 ± 2.6

[a] Percents are given with standard deviations. Entries without deviations represent one or two fires.

(Darley et al.[4])

TABLE 9. MAXIMUM YIELD OF ETHENE, OLEFINS, AND PARAFFINS PLUS ACETYLENES IN POUNDS PER TON OF WASTE MATERIAL FROM THE BURNING OF VARIOUS AGRICULTURAL WASTES COLLECTED FROM THE SAN JOAQUIN VALLEY AND SAN FRANCISCO BAY AREA OF CALIFORNIA

Waste Material	Ethene	Olefins	Saturates Plus Acetylenes
	San Joaquin Valley		
Rice straw	1.7[a]	2.5	0.7
Barley straw	2.2	3.5	1.1
Native brush			
Dry	0.7	1.2	0.5
Dry and green	3.5	5.2	1.1
Green	5.5	8.7	2.1
Cotton	0.3	0.5	0.2
	Bay Area-1965		
Fruit prunings	0.8	1.3	0.5
Native brush	1.2	1.8	0.6
Fir chips	0.2	0.3	0.1
Redwood chips	0.2	0.3	0.1
	Bay Area-1966		
Fruit prunings	2.7	4.1	1.3
Native brush	0.9	1.5	0.6

(Darley et al.[4])

TABLE 10. MAXIMUM YIELD OF TONS OF HYDROCARBON PER DAY FROM BURNING THE THREE PRINCIPAL TYPES OF AGRICULTURAL WASTES OCCURRING IN THE SAN FRANCISCO BAY AREA

Waste Material	Lbs. HC/ton	Tons Waste Burned/Yr	Tons HC/Yr	--Max. tons HC/day-- Burning Season	Calendar Yr 365 Days
Fruit prunings	9.7 ± 4.2	121,115	587 ± 254	5.6[a]	2.30
Barley straw	14.5 ± 3.7	1,632	12 ± 3	0.7[b]	0.04
Native brush	4.4 ± 2.3	28,140	62 ± 32	47.0[c]	0.25

[a] 150 days from December through April.

[b] 120 days November-December, and June-July.

[c] 2 days in August.

(Darley et al.[4])

TABLE 11. COMPARISON OF YIELD OF HYDROCARBONS IN POUNDS PER TON OF FUEL BETWEEN THE BURNING OF THE THREE PRINCIPAL TYPES OF AGRICULTURAL WASTES OCCURRING IN THE SAN FRANCISCO BAY AREA AND FROM THE EXHAUST OF GASOLINE ENGINES

	Agricultural Wastes			
Hydrocarbon	Fruit Prunings	Barley Straw	Native Brush	Gasoline Engine
Total	13.9	18.2	6.7	130
Ethene	2.7	2.2	0.9	7.8
Olefins	4.1	3.5	1.5	20.8
Saturates plus acetylenes	1.3	1.1	0.6	14.3

(Darley et al.[4])

TABLE 12. SATURATES, OLEFINS, AND ACETYLENES ANALYZED FROM BURNING OF AGRICULTURAL WASTES

Saturates	Olefins
Propane	Propene
Isobutane	Butene-1
Butane	Isobutene
Isopentane	*Trans*-butene-2
Pentane	*Cis*-butene-2
Hexane	3-methyl butene-1
	Butadiene-1,3
Acetylenes	Pentene-1
Acetylene	2-methyl butene-1
Methyl acetylene	*Trans*-pentene-2
	Cis-pentene-2
	2-methyl butene-2
	2-methyl butadiene-1,3

(Darley et al.[4])

TABLE 13. YIELDS OF ALDEHYDES(μg/g) IN WOOD

	Sinapyl	Syringic	Coniferyl	Vanillin
Eucalyptus sp.	3000	3000	150	100
Fagus Sylvatica L. (Beech)	800	800	250	250
Tectona Grandis (Teak)	700	500	600	450
Santalum Album L.	600	500	300	200
Quercus Robur L. (Oak)	500	600	250	200
Chinese Incense	500	600	250	250
Indian Incense	100	200	100	50
Cocos Nucifera L.	300	500	300	300
Juniperus Procera Hochst	0	0	450	600
Larix Decidua (Larch)	0	0	600	600

(Gibbard and Schoental.[5])

TABLE 14. INFRARED SPECTROPHOTOMETER ANALYSES OF SMOKE SAMPLES, BROADCAST FIRE AT PACK FOREST, JUNE 25, 1968

	Sample Location				
Component	PB-1	PB-3	G-11	G-4	G-2
	Parts per million				
Carbon dioxide	490	820	580	330	320
Carbon monoxide	24	58	40	0	0
Methane	4	10	5	2	2
Ethylene	1	1	1	0	0

(Fritchen et al.[7])

TABLE 15. COMBINED GAS CHROMATOGRAPH-MASS SPECTROMETER ANALYSIS OF SMOKE SAMPLES FROM BROADCAST BURN, PACK FOREST, JUNE 25, 1968

		Sample Location						
Component	Activated Charcoal	A-3	1-1	E-1	PB-1	G-11	G-4	G-2
	Parts per million							
Ethylene	0.03	0.07	0.05	0.01	0.99	1.05	0.04	0.09
Ethane	.01	.02	.02	0	.50	1.25	.02	.05
Carbonyl sulfide	0	1.00	.50	.50	0	0	0	0
Propene	.13	.02	.01	0	.34	.70	.60	.01
Propane	.09	.01	.01	0	.21	.60	.01	.02
Methanol	0	3.07	1.92	1.60	1.03	2.86	.45	.34
Freon 12	.01	0	.90	0	0	0	0	0
Acetaldehyde	0	.04	.02	.03	0	0	0	0
Isobutane	.01	0	.21	0	0	0	0	0
Butene-1	.16	.05	0	.08	0	0	0	0
Ethanol	0	.18	.26	.06	.14	.10	.06	.15
Furan	.04	0	0	0	.12	.45	0	0
Aceton	0	.01	.05	.01	.24	.37	.02	.23
Dichloromethane	.01	.65	.48	.11	0	0	0	0
Dichlorethylene	.01	0	0	0	0	0	0	0
N-pentane	.01	0	.04	.01	0	0	0	0
Pentene-2	0	.02	.02	0	0	0	0	0
Methylfuran-2	0	0	0	0	.03	.17	0	0
Ethyl acetate	0	0	0	0	.39	.80	.03	.12
Benzene	.07	.04	.03	.03	.09	1.79	0	.01
2,4-dimethyl 2-pentene	0	.02	.02	0	0	0	0	0
N-heptane	0	0	0	0	.01	.72	.01	.01
1,1,2 trichloroethane	0	3.42	.44	.21	0	0	0	0
Toluene	.01	.07	.40	.03	.11	.09	.04	.02
Xylene	0	.04	.07	0	0	0	0	0

(Fritschen et al.[7])

TABLE 16. GAS CHROMATOGRAPHIC ANALYSES OF SMOKE SAMPLES FROM FIVE LABORATORY FIRES, BY NUMBER OF MINUTES AFTER FIRE START

Gas	Western hemlock sample no.1			Western hemlock sample no.2			Douglas-fir			Western redcedar sample no.1			Western redcedar sample no.2		
	2 min.	7 min.	17 min	1.5 min.	7 min.	18 min.	1 min.	5 min.	16 min.	2 min.	5 min.	16 min.	2.5 min.	8 min.	19 min.
	Parts per million														
Methane	3.2	--	13.2	3.2	4.8	8.3	2.0	0.7	9.3	3.5	5.2	11.2	10.0	4.3	7.8
Ethene	1.0	--	1.4	1.2	.6	.6	.6	.9	1.0	1.3	.8	.9	5.2	.5	.6
Ethane	.1	--	.6	.1	.2	.3	.6	.3	.5	*	.3	.4	.7	.2	.3
Acetylene	.6	--	.1	.7	.3	.2	.3	.3	.2	.7	.3	.3	2.5	.1	--
Propane	*	--	.4	*	2.7	*	*	.1	.2	*	.1	.3	.2	*	*
Propene	.2	--	.5	.3	.1	.1	.1	.3	.5	.3	.2	.3	1.1	.2	.2
Isobutane	--	--	*	*	*	*	*	*	*	*	*	*	*	*	*
N-butane	*	--	*	*	*	*	*	*	*	*	*	*	*	*	*
Acetylene	.7	0.1	.5	.8	.2	.1	.5	.3	.2	.8	.3	.3	2.9	.3	.2
1-butene	*	*	*	*	*	*	*	*	*	*	*	*	.2	*	*
Isobutene	*	*	*	*	*	*	*	*	*	*	*	*	.1	*	*
Trans-2-butene	*	*	*	*	--	--	--	*	*	*	*	*	*	*	*
Isopentane	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Cis-2-butene	*	*	*	*	--	--	--	*	*	*	*	*	*	*	*
N-pentane	--	--	--	--	--	*	--	--	--	--	--	--	--	--	--
3-methyl butene-1	*	*	*	*	*	--	*	*	*	*	*	*	*	*	*
1,3-butadiene	*	*	*	*	*	*	*	*	*	*	*	*	.3	*	*
1-pentene	*	*	--	--	--	--	*	*	--	*	*	*	*	--	--
2-methyl butene-1	--	--	--	--	--	--	--	--	*	--	--	--	*	--	--
Trans-2-pentane	--	--	*	--	--	--	--	--	--	--	--	*	--	--	
2-methyl butene-2	--	--	--	--	--	--	--	--	*	--	--	--	--	--	--

*Less than 0.1 p.p.m. Methane, ethane, ethene, and acetylene were analyzed by use of a 5-foot Poropak N column at 60°C. All others were analyzed by use of a 36-foot, 10-percent DMS column at 0°C.

(Fritschen et al.[7])

TABLE 17. EXHAUST EMISSION DATA

Vehicle			H_2O	CO_2	CO		Total Gaseous Hydrocarbons		NO_x		Particulate Matter			
	Year	Mileage	(%) (wet basis)	(%) (dry basis)	(%) (dry basis)	gm/ mile	ppmC by vol (dry basis)	gm/ mile[a]	ppm by vol (dry basis)	gm/mile (as NO_2)	gm/ 1000 scf (dry basis)	gm/ mile	Benzene-Soluble (%)	Water Soluble[b] (%)
Automobiles Make A	1962	19,000	10.5	13.7	1.76	34.9	2320	2.28	2120	6.91	4.98	0.299	58.5	14.5
	1962	26,000	10.4	13.5	1.86	37.9	2130	2.15	2380	7.98	4.51[c]	0.279[c]	38.6[c]	
	1959	49,000	12.0	13.6	2.13	40.1	2600	2.43	1630	5.05	4.22	0.241	29.8	20.9
	1956	58,000	10.3	13.8	2.02	35.9	2970	2.61	1520	4.43	10.45	0.563	90.8	7.8
	Four-car Avg.		10.8	13.6	1.94	37.2	2510	2.37	1910	6.09	6.04	0.346	54.4	14.4
Automobiles Make B	1964	14,000	12.1	13.2	1.81	40.8	3550	3.96	2710	10.04	5.37	0.367	26.1	14.1
			10.4	13.1	1.99	44.7	3520	3.91	2700	9.95	5.08	0.346	31.8	11.9
	1962	19,000	11.2	13.3	2.34	55.0	3820	4.43	1210	4.67	3.77	0.268	24.7	15.3
			11.3	12.7	2.21	49.3	3770	4.16	1260	4.61	2.99	0.202	29.6	22.6
			12.1	13.4	2.43	57.4	4080	4.78	946	3.67	2.95	0.211	26.8	13.4
	1959	53,000	10.4	13.3	2.12	50.0	3240	3.78	1630	6.34	3.53	0.253	44.0	26.5
	1957	67,000	13.0	13.2	3.33	64.7	3760	3.62	1370	4.37	4.36	0.257	24.7	15.0
	Four-car Avg.		11.6	13.2	2.42	52.9	3610	3.95	1710	6.26	4.09	0.273	31.2	17.9
Trucks Make A	1963	17,000	12.4	12.7	2.97	54.5	6120	5.56	2040	6.16	3.68	0.205	37.4	19.9
	1956	50,000	12.1	9.6	7.63	165	8270	8.87	244	0.87	15.90	1.044	59.2	5.3
	Two-truck Avg.		12.3	11.2	5.30	110	7190	7.22	1140	3.52	9.79	0.625	48.3	12.6
Trucks Make B	1964	6,000	12.6	12.9[d]	2.88[d]	75.9[d]	4860[d]	6.34[d]	1730[d]	7.51[d]		0.619	23.7	19.3
	1963	17,000	11.2	13.1	1.13	35.3	4180	6.46	2190	11.25	7.36	0.697	34.8	20.1
			11.1	14.0	1.61	48.6	5210	7.78	2670	13.27	6.55	0.599	38.9	18.2
	Two-truck Avg.		11.8	13.2	2.13	58.9	4780	6.73	2080	9.88	6.96	0.634	30.3	19.2

[a] Based on a hydrogen-to-carbon ratio of 1.86.

[b] Water-soluble portion recovered for evaporation of condensate.

[c] Not including water-soluble portion.

[d] Proportional sample taken over first 10.5 miles of route only.

(Hangerbrauck, et al.[8])

TABLE 18. POLYNUCLEAR HYDROCARBON EMISSION DATA

Vehicle				Benzene-Soluble Organics		BaP		Group 1							Group 2		
								BaP	P	BeP	Per	B [ghi] P	Anth	Cor	A	Phen	Fluor
		Year	Mileage	(gm/ mile)	µg/gm Φ sol[a]	µg/gal[b]	µg/10^3 M^3[c]	g/vehicle mile									
Automobiles	Make A	1962	19,000	0.175	32	91	3,300	5.6	81	9.5	0.28	26	2.30	9.6	5.8	d	39
		1962	26,000	0.120	35	72		4.2	70	8.1	0.78	35	0.64	10.7	3.6	27	39
				0.108	27	43	1,660	2.9	12.9	4.7	0.34	34	0.33	17.2	3.9	46	6.7
		1959	49,000	0.072	55	62	2,400	3.9	27	8.6	0.57	14.3	0.30	4.1	d	4.4	39
		1956	58,000	0.511	42	380	14,100	21.5	119	23.5	1.38	77	3.17	32.2	d	d	102
		Four-car Avg.		0.218	40	147	5,400	8.6	67	12.0	0.70	38	1.56	15.0	2.4	10.3	51
	Make B	1964	14,000	0.0956	e	60[f]	e	4[f]	76	e	d	6.7	d	7.2	1.34	53	42
				0.1098	e	60[f]	e	4[f]	67	e	d	9.4	d	7.7	1.04	36	32
		1962	19,000	0.0662	160	137	5,300	10.6	142	13.9	1.72	65	0.36	19.9	7.6	92	67
				0.0597	88	80	2,700	5.3	125	9.6	0.78	49	0.37	18.5	5.7	32	65
				0.0566	66	49	1.800	3.7	58	6.3	0.54	28	d	8.5	3.6	8.5	32
		1959	53,000	0.1112	94	162	5,200	10.5	103	17.8	1.89	41	0.68	11.1	11.1	49	76
		1957	67,000	0.0633	530	470	20,100	33.5	341	31.6	3.54	144	4.56	63.9	12.7	75	223
		Four-car Avg.		0.0703		190		14	156		1.7	60	1.37	25	7.7	53	98
Trucks	Make A	1963	17,000	0.077	>32	>40	>1,560	>2.5	410	>3.5	0.84	94	d	61	10.0	260	220
		1956	50,000	0.618	210	1,450	70,000	130	1,500	105	20	480	118	240	270	1,030	980
		Two-truck Avg.		0.348	>120	>750	>36,000	>66	960	>54	10	290	59	150	140	650	600
	Make B	1964	6,000	0.159	120	216		19.2	440	39	2.55	92	d	38	23.0	340	310
		1963	17,000	0.243	52	149	4,700	12.6	640	48	1.02	153	d	102	13.6	290	440
				0.233	27	68	2,400	6.3	600	42	1.12	94	d	61	7.0	290	330
		Two-truck Avg.		0.199	80	160		14.4	530	42	1.81	108	d	60	16.7	320	350

[a] Micrograms per gram of benzene-soluble organics.

[b] Micrograms per gallon of fuel input.

[c] Micrograms per 1000 cubic meters of dry exhaust at 68°F and 29.9 inches Hg.

[d] Compound not detected in sample.

[e] Interference prevented determination.

[f] Estimate based on average pyrene-to-BaP ratios for tests 57, 58, and 59.

(Hangerbrauck, et al.[8])

TABLE 19. POLYNUCLEAR HYDROCARBON EMISSION SUMMARY - HEAT GENERATION SOURCES

			Group 1									Group 2			
			Benzo(a)pyrene[a]												
Source No.	Fuel Used	Firing Method	µgm per 1000 M3[b]	µgm per Lb Fuel		Pyrene	Benzo(e)-pyrene	Perylene	Benzo (g,h,i)-perylene	Anthan-threne	Cornene	Anthra-cene	Phenan-threne	Fluor-anthene	Benz (a)-anthra-cene
					Micrograms Per Million Btu Heat Input										
1	Coal	Pulverized	42	0.22	19	150								180	19
2			75	0.43	32	240	92					370		550	
3		Chain grate stoker	71	0.44	37	390	130							680	
4		Spreader stoker	49	0.35	26	590	350				26			360	
5		Underfeed stokers	7,900	140	10,000	16,000	7,900	1,600	4,500	290	330	850	10,000	38,000	3,900
6			61	1.6	120	1,700	230						1,000	3,200	
7			3,400	52	3,800	7,700	5,400		580		1,200		29,000	47,000	560
8		Hand-stoked	340,000	6,000	400,000	600,000	100,000	60,000	300,000	90,000	30,000	400,000	1,000,000	1,000,000	
9	Oil	Steam-atomized	<38	<0.3	<20	49								56	
10			40	0.89	47	300							1,800	270	27
11		Low-pressure air-atomized	1,900	18	900	6,100			300		2,100	3,900	3,500	1,900	
12		Centrifugal-atomized	<26	<0.9	<40	1,800							8,900	5,000	
13			<27	<1	<60	15								76	
14		Vaporized	<34	<2	<100	1,200								15,000	
15	Gas	Premix burners	<29	<0.4	<20	160					14			100	
16			350	4.6	200	18,000	490		1,800	200	5,300			2,900	
17			<23	<0.5	<20	170								320	
18			<30	<0.6	<20	120	18						77	110	

[a] "Less than" values for benzo(a)pyrene were calculated for those samples having concentrations below the limit of quantitative determination (approximately 0.6 microgram per sample). Similar calculations were not included for the other polynuclear hydrocarbons (indicated by blanks in the table).

[b] Micrograms per 1000 cubic meters of flue gas at standard conditions (70°F, 1 atmosphere).

(Hangerbrauck, et al.[9])

TABLE 20. POLYNUCLEAR HYDROCARBON EMISSION SUMMARY - INCINERATION SOURCES[a]

				GROUP 1							GROUP 2			
				Benzo(a)pyrene	Pyrene	Benzo(e)-pyrene	Perylene	Benzo (g,h,i)-perylene	Anthan-threne	Coronene	Anthra-cene	Phenan-threne	Fluoran-thene	Benz(a)-anthra-cene
Source No.	Type of Unit	Sampling Point	µgm per 1000 M3[b]	Micrograms Per Lb of Refuse Charged										
	Municipal													
20	250-Ton/Day Multiple chamber	Breeching (before settling chamber)	19	0.075	8.0	0.34				0.24			9.8	0.37
21	50-Ton/Day Multiple chamber	Breeching (before scrubber)	2,700	6.1	52	12		34		15		18	4.6	
		Stack (after scrubber)	17	0.089	2.1	0.58		0.63		0.63			3.3	0.15
	Commercial													
22	5.3-Ton/Day Single chamber	Stack	11,000	53	320	45	3.1	90	6.6	21	47	140	220	4.6
23	3-Ton/Day Multiple chamber	Stack	52,000	260	4,200	260	60	870	79	210	86	59	3,900	290

[a] A blank in the table for a particular compound indicates it was not detected in the sample.

[b] Micrograms per 1000 cubic meters of flue gas at standard conditions (70°F, 1 atmosphere).

(Hangerbrauck, et al.[9])

TABLE 21. POLYNUCLEAR HYDROCARBON CONTENT OF PARTICULATE MATTER EMITTED--INCINERATION AND OPEN BURNING SOURCES[a]

			Group 1							Group 2			
Source No.	Type of Unit	Sampling Point	Benzo(a)-pyrene	Pyrene	Benzo(e)-pyrene	Perylene	Benzo(ghi)-perylene	Anthanthrene	Coronene	Anthracene	Phenanthrene	Fluoranthene	Benz(a)-anthracene
			Micrograms Per Gram of Particulate										
	Municipal incinerators												
20	250-Ton/Day Multiple chamber	Breeching (before settling chamber)	0.016	1.9	0.08				0.06			2.2	0.09
21	50-Ton/Day Multiple chamber	Breeching (before scrubber)	3.3	28	6.5		19		8.2		9.8	2.5	
		Stack (after scrubber)	0.15	3.6	0.97		1.1		1.1			5.5	0.26
	Commercial incinerators												
22	5.3-Ton/Day Single chamber	Stack	58	350	49	3.3	98	7.1	23	51	150	240	5.0
23	3-Ton/Day Multiple chamber	Stack	180	2,600	180	36	540	45	130	53	62	2,400	210
	Open Burning												
24	Municipal refuse	In smoke plume	11	29	4.5					4.7		13	
25	Automobile tires		1,100	1,300	450	72	660	53	81	110	450	470	560
26	Grass clippings, leaves, branches		35	120	21		5.4			4.7		110	25
27	Automobile bodies		270	670	120	33	150	12	15	220	160	450	40

[a] A blank in the table for a particular compound indicates it was not detected in the sample.

(Hangerbrauck, et al.[9])

TABLE 22. POLLUTANT EMISSION SUMMARY--HEAT GENERATION SOURCES

						Dry Basis		Total Particulates Lb Per			% Benzene-Soluble Organics	CARBON MONOXIDE Lb Per		HYDROCARBONS (as Methane) Lb Per		OXIDES OF NITROGEN (as NO_2) Lb Per		OXIDES OF SULFUR (as SO_2)			FORMALDEHYDE Lb Per	
Source No.	Fuel Used	Firing Method	Flow, scfm	Temp, °F	H_2O, %	CO_2 %	O_2 %	1000 Lb[b]	Million Btu	Ton of fuel[c]	Organics	Million Btu	Ton of fuel[c]	Million Btu	Ton of fuel[c]	Million Btu	Ton of fuel[c]	Ppm by Vol.	Lb Per Million Btu	Lb Per Ton of fuel[c]	Million Btu	Ton of fuel[c]
1	Coal	Pulverized	415,000	260	5.4	12.3	6.9	0.50	0.59	14.0	0.7	0.004	0.1	0.007	0.16	0.47	11	1490	3.72	88	1.3×10^{-4}	30×10^{-4}
2			32,300	235	6.2	12.3	6.1	1.90	2.23	61.6	0.3	0.10	2.8	0.004	0.11			405	1.00	28	0.9×10^{-4}	26×10^{-4}
3		Chain grate stoker	45,000	430	6.7	12.1	7.7	0.99	1.31	31.0	0.3	0.51	12	0.005	0.11			2030	6.14	146	1.4×10^{-4}	33×10^{-4}
4		Spreader stoker	18,000	405	6.9	10.6	8.5	0.66	0.82	22.6	1.4	<0.1	<3	0.006	0.16						2.2×10^{-4}	60×10^{-4}
5		Underfeed stokers	3,340	380	2.1	3.0	17.2	0.68	0.62	17.0	1.1	0.16	4.5	0.116	3.2						21×10^{-4}	590×10^{-4}
6			3,290	235	2.1	2.5	18.1	0.24	0.25	7.0	3.6	0.14	3.9	0.036	1.0	0.30	8.3	205	2.3	62	3.8×10^{-4}	100×10^{-4}
7			43	345	2.2	2.6	17.1	0.52	0.44	12	1.2	1.1	31	0.12	3.3	0.36	9.8	178	1.2	32		
8		Hand-stoked	78	220	2.1	2.8	17.7	1.80	1.29	37	17	3.5	99	0.73	21	0.11	3.2	80	0.54	15		
												<0.1	<4	0.013	0.51			1250	3.0	116	0.63×10^{-4}	24×10^{-4}
9	Oil	Steam-atomized	5,200	530	8.5	9.0	8.2	0.32	0.306	11.7	1.0					0.31	12	188	1.3	48	2.4×10^{-4}	89×10^{-4}
10			10,000	340	5.4				0.267	10.0	2.7	0.055	2.2	0.004	0.17			125	0.35	14	1.6×10^{-4}	62×10^{-4}
11		Low-pressure air-atomized	195	230	7.4	8.8	9.0	0.049	0.051	2.0	60											
12		Centrifugal-atomized	145	170	3.0	2.9	16.9	0.041	0.046	1.8	39	0.038	1.5			0.44	17	14	0.12	4.5		
13			115	175	2.6	1.8	18.3	0.070	0.080	3.1	9.4	0.075	2.9	0.021	0.82			35	0.46	18	6.4×10^{-4}	250×10^{-4}
14		Vaporized	49	185	1.9	1.2	19.3	0.067	0.071	2.8	11	0.25	9.8	0.030	1.2	0.03	1.3	4	0.08	3	5.8×10^{-4}	230×10^{-4}
15	Gas	Premix burners	3,640	380	8.4	3.6	14.3	0.026	0.021	1.0	11	0.013	0.6	0.003	0.14	0.14	6.4				0.89×10^{-4}	41×10^{-4}
16			325	210	11.4	5.9	10.0	0.030	0.032	1.5	8.0	3.00	140	0.082	3.8	0.16	7.3				2.2×10^{-4}	100×10^{-4}
17			92	170	4.8	2.4	16.9	0.010	0.006	0.3	33	0.02	0.9			0.35	16	0	0	0	2.4×10^{-4}	110×10^{-4}
18			82	140	4.1	2.2	17.3	0.011	0.007	0.3	23	0.026	1.2	0.022	1.0	0.09	4.1	0	0	0	1.1×10^{-4}	53×10^{-4}
19			11	295	4.4	2.0	17.5	0.027	0.026	1.2	19	0.030	1.4	0.016	0.74	0.06	2.8				26×10^{-4}	1200×10^{-4}

[a] Blanks in the table indicate that no test was made.

[b] Pounds of particulate per 1000 pounds of dry flue gas adjusted to 50% excess air.

[c] API gravities of the fuel oils are given in Table; the density of natural gas = 0.0443 lb per cu ft (60°F, 1 atm).

(Hangerbrauck, et al.[9])

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FUELS--THE SOURCE OF THE MATTER

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Whether we are concerned for the urban or the wildlands fire situation, we need to know the total fuel available, the fuels consumed, and the conditions controlling the burning. Differences in fuel complexes must be recognized and fuel inventories prepared that will allow accounting for the fuels to be consumed. Emission factors for the combustion products of those fuels must be developed as functions of the burning conditions imposed to achieve management objectives but assure minimum impact on air quality.

During this symposium we have discussed the type of material emitted and dispersed from urban fires and forest fires. The sources of this material are the man-made products and natural vegetation that become fuels and, under the right conditions, burn. Fuels, then, are the source of the matter that affects air quality. Our challenge is to determine the effects of fuels and fire on environmental quality and to provide some well-defined alternatives for managing fuels.

The problems reducing environmental impacts of our activities are expressed by Milne and Milne (4) in their book, "The Arena of Life":

> The goals of civilization seem incompatible; on one hand we try to reduce pollution in the forms of dust, gases, soluble substances, slow decomposing materials, radioactivity, and heat. Our aim is to get those wastes from mankind down to a level at which the great biogeochemical cycles could dispose of them with no dangerous accumulation. To stop pollution altogether is clearly impractical and unnecessary--our chemists invent substitutes for wood since it is scarce, they produce plastics that are not biodegradable, we make waste plastics disappear by incinerating them using fossil fuel for heat and then with our concern about polluting the air we install scrubbing equipment to clean the smoke from the incinerators and then have polluted water to deal with. We see that fossil fuels are getting scarce and costly and press for nuclear reactors to generate our electricity. But electric power accounts for one-fifth of the uses to which we put heat from fossil fuels...

Whether we are concerned about urban fires or wildland fires, we need to know the fuels being consumed and the conditions controlling the burning. It must be recognized and appreciated that urban fuels and forest fuels are not the same, nor are their products of combustion. Urban fuels range from petroleum products to cellulosic materials and generally produce more NO_X, SO_X, and hydrocarbons than wildland fuels produce. Forest fuels, however, usually produce more particulate and water vapor, which are highly visible (5). Research indicates that aside from reducing visibility, forest fires have little impact on air quality (3).

Work in Australia (10) shows that the smoke-to-fuel ratio is about .02:1.00. This characteristic is probably linked to the fuel quantity, its size distribution, and spatial arrangement besides the environmental factors surrounding the site. It has been demonstrated that the quantity of smoke decreases when the combustion zone temperature increases and that there is a direct relationship between combustion rate and temperature (7). In turn, the reaction intensity of the combustion zone is a function of fuel size and packing ratio (9). Fire research has to define the effects of fuels on fire behavior and smoke generation so benchmarks can be established to assess the consequences of man's activities.

Just as urban fuels and wildland fuels can be markedly different from each other, wildland fuels alone can vary greatly. We have to consider grasslands, brushfields, and forests where precommercial thinnings and harvest slash add to the existing fuel load. There are alternatives to using fire to meet our land management objectives, but they may cost 10 times as much in manpower and equipment (1), and in addition may be biologically unsound. As was noted by Wilson and Dell (11), fuel treatment planning must precede activities that change vegetation so that fuel situations are in harmony with environmental objectives. This requires that fuel management become part of resource use planning.

Recognizing fuel complexes as storehouses with irregular annual additions and withdrawals of energy provides a basis for fire and smoke management. Part of the management job is controlling fuel loadings (8). To achieve control, research should (1) provide methods for measuring and quantifying the fuels; (2) identify portions of fuels that will be consumed in a fire by fuel type, location, time, and climatic considerations; (3) discover if certain fuels or treatments release significant quantities of critical effluents (6); (4) provide reliable emission factors for those fuels considered to be pollutant sources (2); (5) develop the operational guidelines for using fire or its alternatives to achieve management objectives and maintain a quality environment; and (6) coordinate research efforts so results are applicable to the total management job. We must remember that the demands of mankind must be balanced against the carrying capacities of the land and the environment.

A review of past research can lead to an interesting conclusion about what we, in fuel research, must do in the future. We have learned, for example, that minimum emissions occur at high rates of combustion and high temperatures in the combustion zone. Such combustion is likely to occur when fuel beds are loosely packed and fuel moisture is low. We also know that an unstable atmosphere with winds aloft disperses smoke and minimizes impact on air quality. Most of these conditions prevail at a time of year all too familiar to us--fire season. Fire season is nothing more than nature's response to changes in fuels and weather. We should recognize and appreciate this phenomenon and accommodate it in our research. Knowing what the fuels are, where they are, and how they respond to weather is part of the research that must be done so we can show forest managers when and how to use fire as a tool.

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SMOKE AND FOREST FIRE BEHAVIOR

David E. Williams
Canadian Forestry Service

Because so little has been done in Canada on the subject of smoke from forest fires, my main objective in being here is to learn all I can about what has been done and what is being planned here in the United States. I would first like to make a few observations about the problem in Canada and then attempt to summarize what I have heard here, particularly as it relates to fire behavior.

The forest fire smoke problem in Canada comes essentially from three sources:

(a) Wildfires -- The solution here, of course, is the control of wildfires--something we have been striving to do for a long period of time. The one exception to this is the question of fires, mainly in remote areas, where the "let burn" policy is being observed. This has not yet become a serious problem in Canada because of the remoteness of most of the areas concerned.

(b) Slash Burning Operations -- These are mainly on the west coast and at the present time are the major source of complaint re air pollution. The fact that at least three people are attending this Symposium from British Columbia attests to the seriousness of the problem there. Attempts are being made to schedule burns when atmospheric conditions are such as to reduce the pollution effects, but this presents a difficulty because there are only a small number of days available for effective slash burning. It may be that slash burning is only an interim measure and that the eventual solution may well be higher utilization and the disposal of residues through other means than fire. However, a number of speakers here have indicated that we can expect to have to live with slash burning for some time to come and air quality regulations will have to be developed to recognize this situation.

(c) Use of Fire to Modify Vegetational Types -- Although there has been a considerable amount of experimental work in Canada, very little of this type of burning is being done operationally. Experimental burns have naturally enough stressed the relationship between fire danger indices and fire behavior in the fuel types concerned. If further advances are to be made in this area of fire use, it is obvious that studies of smoke production should be included to determine ways of reducing the possibility of smoke problems from such fires. One way we have found to reduce the impact of such pollution, if not the pollution itself, is through a well-planned advance publicity program. We have found that if the objectives of the burn are clearly explained in advance, there is very little public reaction to the smoke that results. This is in agreement with the findings of Bob Mutch and George Briggs.

It is difficult to summarize in a short time the many excellent papers given at the Symposium and their relation to forest fire behavior. First the smoke problem itself; there seems to be general agreement that it is fundamentally a visibility problem. It does not have the serious health implications as does industrial smoke pollution, but it is nevertheless a problem in relation to transportation and tourism. An example of this is the recent serious accident situation that existed on the New Jersey turnpike. The next point to look at is the relationship between the smoke problem and fire behavior, particularly the behavior of our prescribed burns. It was pointed out quite clearly by both Vines and Cooper that in prescribing conditions for a fire we begin by defining the behavior we want. It should therefore be our objective at the same time to predict how much smoke will be produced and where it will go. More research is needed to enable us to do this for the various intensity levels and fuels. Obviously it becomes more complicated when you consider mountainous country. In effect another dimension is added. However, both Fosberg and Cramer have indicated how that problem can be handled.

In summary it seems obvious that, in further research in the use of fire we should attempt to identify what the smoke production will be, how long it will persist, and where it will go so that a forester in applying a prescription to a particular fuel type under a set of conditions will be preselecting his smoke conditions as well as fire behavior.

PANEL DISCUSSION

GOVERNMENT AND INDUSTRY PROGRAMS FOR SMOKE CONTROL

Moderator:

W. R. Tikkala
U.S. Forest Service

THE NATIONAL FOREST VIEW

Henry W. DeBruin
U.S. Forest Service

I am indeed pleased to present a brief resume of National Forest Managers' concerns for smoke and its control. I will illustrate our case for scientific smoke management and mention our efforts for better forest products utilization and fuel management, which is the key to lowering the flammability of forest lands. This, coupled with scientific smoke management, will reduce smoke from forest burning operations.

First, I want to present you four challenges related to the problems of smoke management:

- Fires by prescription are much better than wildfires.
- We must reduce the flammability of forests.
- We must relate to many *new* groups interested in our work.
- We are doing much and we have more to do.

Let us set the stage for *change*. We must be innovative and foresighted in our management thinking. Options for various management decisions must be kept open to accommodate change. Change is indeed with us whether it be our concern for smoke or women on firelines and in fire camps.

Only slight attention has been paid to the impact of smoke on the local economy and community. We were concerned about visibility when smoke blanketed a highway or where smoke spotted freshly laundered clothes on a line. We were aware of smell, minor skin irritation and general nuisance of certain smokes.

But now we must concern ourselves with wood smoke and air quality as responsible citizens and members of a concerned public. Times have changed and we recognize the greater impacts on the economy and community and this response may have been generated more from outside stimuli than our own.

The Clean Air Act of 1970 required establishment of ambient air quality standards for both gaseous and particulate pollutants. To achieve and maintain these standards, most efforts are on the more permanent sources of pollution, reflected in the U.S. Environmental Protection Agency annual estimates of nationwide emissions for the five major pollutants and of sulfur oxide, carbon monoxide, hydrocarbons, nitrogen oxide and particulates.

Since 1970, the Forest Service has given much attention to smoke management in symposia and publications. To list a few:

Hall's - *Forest Fuels Prescribed Fire and Air Quality 1972* - a Pacific Northwest Research Station publication,

Fire in the Environment Symposium 1972 - Denver, Colorado, and

Prescribed Burning Symposium 1971 - Charleston, South Carolina.

Continued research is being carried out to determine more exactly:

What are the products of forest fuel combustion?

Where do the smokes go and how do they behave under a variety of atmospheric conditions?

What happens to smoke components as they are transported downwind and react with other elements in the air?

For several decades we have used prescribed fire in the National Forests of the South and since the early 1900's in residue reduction following timber sales throughout the National Forests. Is smoke from wildfire a greater threat to air quality than smoke from a prescribed fire? The contents of the smoke may be about the same but the amounts differ greatly. Prescribed fire consumes less fuel and is used under conditions more effective for combustion. Since prescribed fire is under our control, it is used when atmospheric conditions are more conducive to dispersion into the atmosphere and away from smoke sensitive areas. As professionals, we must work to keep options open for continued use of prescribed fire in land management alternatives.

On the other hand, wildfire takes the planned options out of man's hands and dictates the rules. This past August, in Washington and Oregon, the "Freezeout" fire on the Wallowa-Whitman National Forest and the "Rocky" fire on the Mt. Hood National Forest, discharged an estimated 175,000 tons of particulate into the atmosphere. There was no way for this to be dispersed in either time or space. During the disastrous 1970 season in the Pacific Northwest, it is estimated 700,000 tons of smoke emissions poured into the atmosphere.

In contrast, a prescribed fire can be located in space and time for best dispersion of smoke into the atmosphere and to take advantage of weather conditions for the most desired results. Prescribed fire usually involves smaller volumes of combustible material, thus less potential source of smoke. Prescribed fire offers benefits in wildlife habitat, silviculture, disease control, ecological balance, range management and fire protection.

Since becoming Director of Fire Management, I have been closely associated with an effort we refer to as Close Timber Utilization. A study on the subject made 11 recommendations which, when fully implemented, will reduce wood residue and subsequently smoke.

In another effort, a group has been asked to try to develop a pilot log chip sale in the Pacific Northwest aimed at utilizing all forest products with little left to be disposed of in the form of forest residue. These, plus other efforts, will supply more fibre to the economy, lower the cost and time of beginning new crops, enhance future fire protection capabilities by lowering the flammability of these lands, and result in reduced smoke emission into the atmosphere.

Regional Forester Schlapfer referred in his keynote address on Wednesday to Oregon's memorandum of agreement concerning slash burning. This agreement outlines the basic system by which burning and smoke dispersal conditions are determined from weather forecasts. All slash burning is conducted in such a way as to produce minimum visible smoke. The point is that workable solutions can be achieved when options remain open.

I have tried in this brief time to express our concern for smoke and its management, to point out that prescribed fire provides a better option for smoke management than wildfire, and that through better timber utilization smoke emissions are reduced.

As scientists, professionals, and concerned environmentalists, we must work to assure that workable, economic smoke management measures will progress and the use of fire under scientific management will be an option available to land managers now and in the future.

FIGURE 1. This scene is from the Tri-Creek Fire in Montana, where women served as members of fire crews this past summer.

FIGURE 2. The Battle Fire, Prescott National Forest, Arizona. In the past, during periods of severe wildfire occurrence, little attention was paid to smoke in the air except to perhaps compare the smoke cloud to a nuclear bomb cloud.

FIGURE 3. Wellman Fire, Los Padres National Forest, California. Smoke was used as an indicator of hot spots and major wind shifts.

FIGURE 4. Round Fire, California. Little attention was paid to smoke except that it restricted air operations.

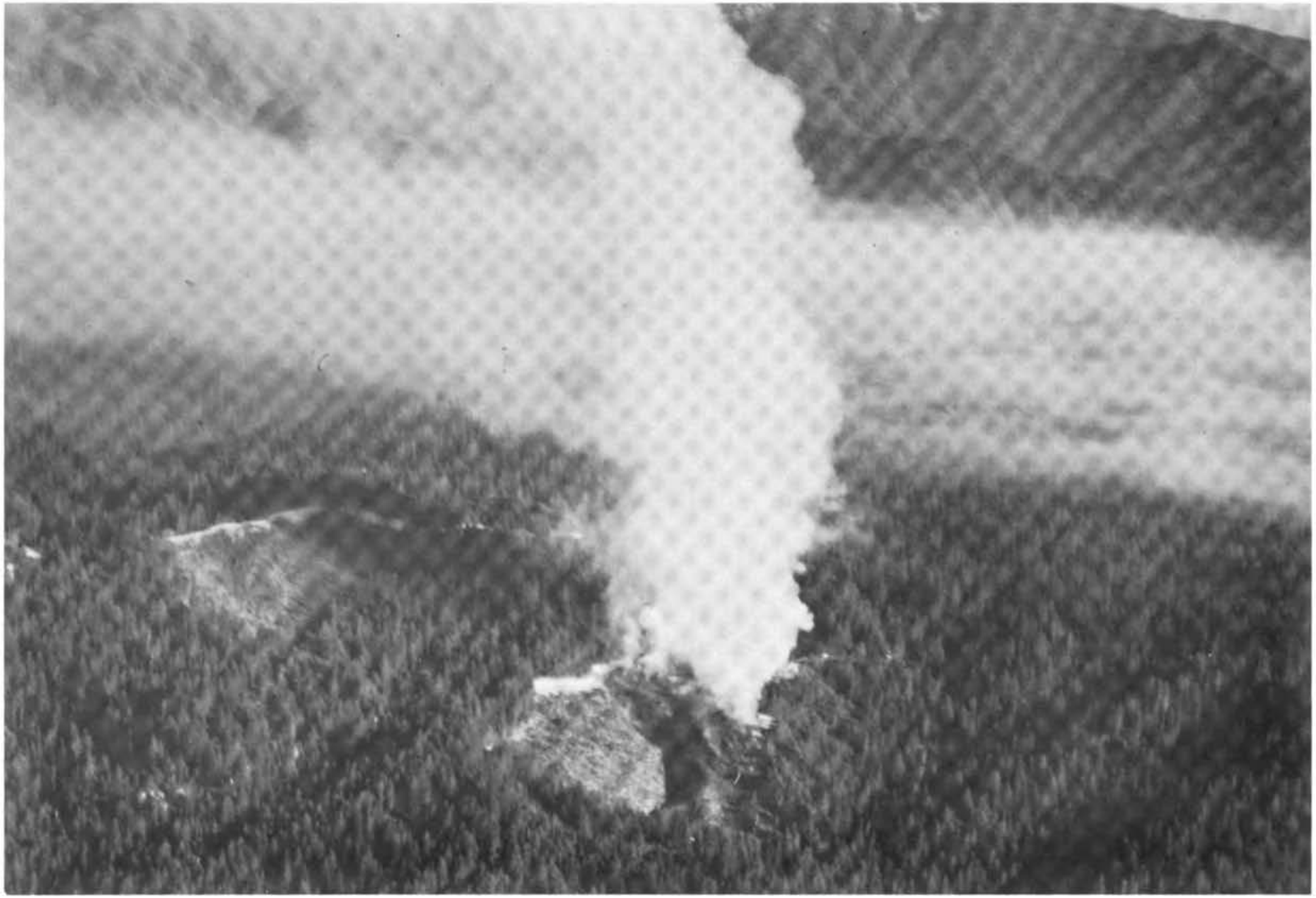

FIGURE 5. Prescribed slash burning fire, Klamath National Forest, California. In the past, limited attention was paid to smoke; its management was not important in the use of prescribed fire.

FIGURE 6. Good utilization of timber products, Siskiyou National Forest, Oregon.

STATE FORESTRY PROGRAMS FOR SMOKE CONTROL

Ralph C. Winkworth
State Forester, North Carolina

I should begin by pointing out that I have taken the liberty of changing my assigned subject area to state forestry programs instead of state forest programs, as listed in the Symposium program. This will allow me to report to you on the entire role of the State Forester, and his state forestry agency, in the control of smoke and the protection of air quality.

The most important aspect of this role is his long established responsibility and jurisdiction in the control of forest fires on both state and private forest lands. These forest fire control programs, the most basic activity of every state forestry agency, involve state forestry personnel in every form of open burning which takes place in or near any of the forest, brush, or range lands of the fifty states.

Since the beginning of organized forest fire control our program objectives have included the protection of the environment from the ravages of wildfire. A generation ago this protection was extended to the intentional use of fire as a hazard reduction measure. During the past three decades we have developed the practice of using fire by scientific prescription to accomplish silvicultural, wildlife, and range management objectives, thus improving the environment by the judicious use of fire.

This complete program of forest fire control has become a highly organized effort of tremendous proportion. Our tools of the trade include sophisticated networks of detection and communications facilities, burning permit systems, specialized weather forecasting services, well developed public information programs, adequate enabling legislation, trained field organizations, and specialized research support. In most cases our entire state forestry programs have been developed around fire control as a nucleus. In every state government, we have long been looked to for protection of the resource from fire.

Now, with the environmental concern of the seventies, the new dimension of smoke as a factor in air quality has emerged. With strong pressure from the federal government, almost every state has developed a program of air quality protection with provisions relating to open burning. In most cases these programs deal specifically with the uses of fire directly associated with forestry. It would seem logical that these programs would be developed and later administered through the joint efforts of each state's resource managers in the fields of air quality control and forest fire control. This has happened in a few states. Unfortunately, this has not been the general rule. Instead, it has come about by corrective action in more cases, and in some states these "twain have yet to meet."

But our concern during this Symposium is not with what has happened in the past. We are all aware of the growing pains associated with new programs, particularly when they are developed in a climate of urgency. We should now address ourselves to where we are today and which way we should go tomorrow.

On the positive side, a close working relationship has now developed in most states between the agencies responsible for air quality protection and those responsible for forestry. The State Forester has had an active part in drafting the air quality control regulations relating to open burning in several states. In those regions of the country where prescribed burning is prevalent, several of the State Foresters are participating to some degree in the administration of air quality programs relating to this practice. The extent of this participation ranges from the role of advisor to that of complete administration of regulatory programs. In a growing number of states, including my own, air quality control and forestry agencies are being placed in the same department through reorganization of state government. This makes communications much easier and greatly facilitates better working relationships. The ultimate goal, at least to us state foresters who have major prescribed burning programs, has been reached in such states as Oregon and Washington where the State Foresters administer cooperative programs of smoke management, hand in hand with their programs of forest fire control and forest management.

Also on the positive side is the recognition most air quality agencies have given to the practice of prescribed burning. Research has shown and it is generally accepted that prescribed burning for hazard reduction is preferable to wildfire in terms of both forest resource and air quality protection.

Prescribed burning for silvicultural purposes such as site preparation prior to regeneration and the control of species composition has gained at least temporary acceptance by air quality administrators. Satisfactory exemptions are now included in most state regulations. However, there is some evidence of erosion of these exemptions--exemptions that are based primarily on the economic need for the practice. State Foresters are worried about the continued recognition of the importance of prescribed burning as a forest management tool. I would like to justify our concern by simply stating that we have no practical alternate methods; none are on the research horizon, and forestry in my part of the country would be set back thirty years by the loss of prescribed burning as a forest production practice. Before such action is taken the environmental and economic trade-offs should be examined carefully. With the expertise at our disposal the practice can be conducted with minimal degradation of air quality. Its loss would have an economic impact which would be reflected in such basic elements of our standard of living as homes, furniture, and paper products.

To this point I have emphasized areas in which good progress has been made by cooperative effort in some states, and consequently improvement should be expected in others. But unlike most controversies involving resource managers of different disciplines, there are some very valid conflicts to be resolved in achieving the objectives of air quality protection and forest fire protection.

The most basic conflict is in the weather requirements for successful burning to meet the objectives of the two programs. They are diametrically opposite, the most favorable weather for air quality protection being the most dangerous weather for forest fire protection. Dual burning permit systems exist in some states and the citizen is damned if he does and damned if he does not. Only genuine recognition of our mutual interest in environmental protection--recognition that no single resource has a monopoly on environmental quality--and responsible compromises for the best overall solutions will resolve these problems. Foresters must learn to live with controlled burning on days when control is marginal. And air quality administrators must designate no-burning days when conditions are best for pollution abatement but most hazardous for forest fires.

I believe it is appropriate to close with some grounds for optimism. The Florida Division of Forestry has assumed administration of all open burning provisions of their air quality regulations. Some 57,000 permits were issued the first year. In contrast to the mountain of paper work reported by some states, most of these permits were issued by phone through local fire control dispatchers. They report very positive results in forest fire prevention as one direct benefit. After five years of administering a comprehensive smoke management plan, Oregon's State Forester reports that 97% of their prescribed burns caused no problems in designated smoke sensitive areas and the problems from the remaining 3% of the burns were minor. California reports better air quality on burn days than on no-burn days. Most of the State Foresters from across the Nation who contributed to this paper look forward to increased participation by state forestry agencies in future air pollution control programs. Precedents are being established and it is becoming obvious that the gains are mutual. State Foresters have been in the fire business for a long time and smoke is just one more dimension which we should be able to take in stride.

U.S. DEPARTMENT OF THE INTERIOR PROGRAMS FOR SMOKE CONTROL

James H. Richardson
Bureau of Land Management

The Department of Interior is actively engaged in the smoke management business from two apparently opposite viewpoints. In one case we are trying to prevent or extinguish wildfires and minimize adverse effects on air quality as well as other resources. On the other hand we are setting prescribed fires to improve the site or habitat, reduce the potential of disastrous fires, and also minimize adverse effects on air quality as well as other resources. This seeming paradox in which we appear to be stomping out fires one day and touching them off the next has been hard to explain in a simplistic manner to certain segments of the public. The key, of course, is management, the judicious application of knowledge and skill to use the right practice at the right time and place.

The magnitude of our business is portrayed in the following table.

Estimated Average Number of Acres Burned on Lands of Interior Agencies

	BLM	BIA	NPS	BSF&W
Wildfire	1,300,000	36,000	26,000	3,000
Prescribed Fire	14,000	30,000	3,000	4,500
Total.	1,314,000	66,000	29,000	7,500

This table indicates 1,365,000 acres burned in an average year due to wildfire. In addition, we burn approximately 51,500 acres per year in prescribed burns, primarily in forested areas following logging, and in other areas to improve wildlife habitat.

We are trying to reduce the average annual acreage loss due to wildfires because the fires occur at times and places not of our choosing, burn too hot, burn resources and structures we do not want destroyed, and create too much smoke in a given period of time. At the same time we are tending to increase the acreage of prescribed burns as we gain more knowledge about the beneficial effects of fire under certain conditions, as we gain knowledge in how to burn safely in western terrain, and as funds are made available to resource managers for this activity.

Since the time when I was invited to participate in this Symposium, I have been conscious of recent articles relating to smoke pollution that happened to cross my desk. Selected quotations from several of these publications include:

1. "Wildfire Versus Prescribed Fire in the Southern Environment" by Hugh E. Mobley and Ed Kerr. July 1973.

   "The most important emission into the air from wildfires is the visible smoke or particulates...When particulates are present in large quantities, they can cause a drastic reduction in visibility and create locally hazardous conditions for movement of surface and air transportation. A good example of this occurred during the severe fire season of 1971 in south Florida when smoke blanketed highways and airports, causing numerous car wrecks and disrupting air traffic."

2. "Wildfire Smoke Conditions in Alaska" Review draft by Richard J. Barney and Erwin R. Berglund. July 1973.

   "Based on available data, smoke does not appear to be the general problem previously assumed. However, under specific situations at several locations smoke has been a detrimental force and will continue to present reoccurring problems. Smoke has inhibited fire control operations, especially in close proximity to a fire, on numerous occasions."

3. "Environmental Quality, The Fourth Report of the Council on Environmental Quality, September 1973."

   "Of the five pollutants measured, between 1970 and 1971 there was an increase in one (particulates)...The rise in particulates is due entirely to an increase in the size and number of forest fires...

   "There is good evidence to indicate that damage caused by certain combinations of pollutants is greater than the sum of the damage caused by equal amounts of the same pollutants acting independently. For example, one part per million of SO_2 probably is more damaging to health when there is a high level of particulate matter than when there is a low particulate level."

4. "The Ecology of Smoke Particulates and Charcoal Residues from Forest and Grassland Fires: A Preliminary Atlas" by E. U. Komarek, Betty B. Komarek, and Thelma C. Carlysle, Sept. 1973.

   "Low intensity forest and grassland fires create airborne particulates and charcoal which act as environmental

> cleansing agents. The morphological integrity of plant materials which remains after burning creates a natural filter with varied porosity."

5. *Washington Post*, September 11, 1973.

> "Smoke Halts Firefighters in California. A pall of smoke hanging over a 7,000-acre timber fire in a rugged mountainous area of northern California yesterday nearly hid the blaze from 500 firefighters. 'Visibility is almost impossible, and even lookouts 20 miles away find it impossible to see the perimeters of the fire,' said a California Division of Forestry spokesman."

You will notice two themes in these quotations that I have selected concerning the adverse effects of smoke from wildfires.

First, one of the principal adverse effects of smoke from wildfires is its limiting effect on the detection of fires and the use of aerial firefighting methods to combat a large fire or new starts in high priority areas.

Second, the measured particulate load due to wildfires is increasing. Its most serious effect on people is felt when smoke from large fires drifts into population centers. You will also note the contrasting quoted viewpoints on the effect of particulate matter in the air on people's health. Other speakers have already discussed this theme, the health aspects of smoke in air. The point I want to emphasize is the effect of smoke on fire operations as illustrated by the following figures.

Figures 1 and 2 show that wildfires burn hot and produce a good deal of smoke. Figure 3 shows the Y-33 fire near Northway, Alaska. Figure 4 shows the Junction fire near Big Delta, Alaska. Figure 5 shows this year's fire at Horse Butte, south of Boise, Idaho. Figure 6 shows the Ft. Hall, Idaho fire. Figure 7 shows the Everglades National Park wildfire which, along with all of the others, contributed its share of smoke to the atmosphere.

Smoke does not necessarily localize, but drifts. Thus there can be a downstream effect in which smoke from a fire in a relatively low-value area drafts over an area of high resource value (see Fig. 8, 9, and 10).

In addition to the other effects, I want to illustrate some examples of the effect of excessive smoke on wildfire control operations. In 1966 in the Chicken Fire in Alaska (Fig. 11), helicopters were grounded by smoke at critical times when they were needed to move crews and equipment to remote locations miles from the highway. Only ground equipment could operate and reconnaissance was inadequate due to poor visibility (Fig. 12). This burnout operation along the Taylor Highway could not be supported by aerial retardant aircraft, and the main fire jumped the highway in several locations. In Alaska in 1969, pilot reports indicated dense smoke from wildfires covered the area on the map (Fig. 13) for a depth of three miles. As lightning bolts flashed down through the smoke, the new starts were detected only when they were large enough to send a convection column boring up through the smoke layer (Fig. 14). Only fires in critical areas were fought. There were too many large fires, and aerial fire forces, including helicopters, smoke-jumpers, and retardant aircraft were grounded (Fig. 15, 16, and 17). The Bureau of Land Management organized a military riverboat flotilla to take action on a fire threatening the village hospital at Tanana because infra-red imagery showed a flame front approaching within a mile of the town and aircraft could not land at the Tanana airstrip (Fig. 13). We could not respond to a request for firefighting assistance from a remote military base because there was no means to get through the smoke to the base.

Smoke from prescribed fire operations, however, such as the Everglades National Park burn, can be controlled and dispersed (Fig. 18 and 19). The Oregon Smoke Management Plan has demonstrated that resource management objectives can be met by the use of fire without the dense smoke haze in the fall at slash-burning time.

The objective of smoke control programs is to minimize the adverse effects on air quality of fires on wildlands, either from unplanned starts or from prescribed burns.

In conclusion, I want to emphasize that from an air quality standpoint there is no conflict of objectives between the control of wildfires and the use of prescribed fire. Kenneth P. Davis made this point in 1959 when he titled his book "Forest Fire: Control and Use."

Smoke from both wildfires and prescribed burns can seriously interfere with man's activities, but often with a different chain of consequences. Smoke from uncontrolled wildfires may drift from an area of relatively low resource values to a high value, densely populated area and prevent detection and aerial suppression of new fire starts. Smoke from prescribed fires is more controllable since the land manager can select the time, atmospheric condition, place, and amount of acreage to ignite. However, managers are subject to public criticism in either case if smoke becomes a nuisance that interferes with clear mountain vistas, aircraft transportation, vacation plans, or firefighting efforts in towns, villages, and the urban fringe.

FIGURE 1. Smoke from wildfires.

FIGURE 2. Smoke from wildfires.

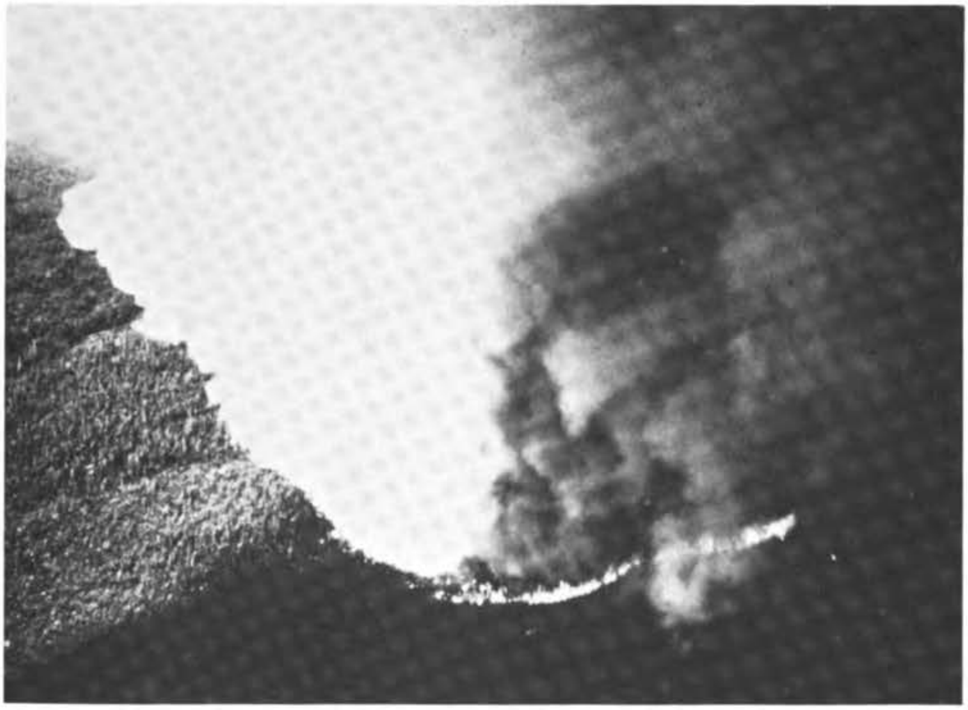

FIGURE 3. Y-33 Fire, Northway, Alaska.

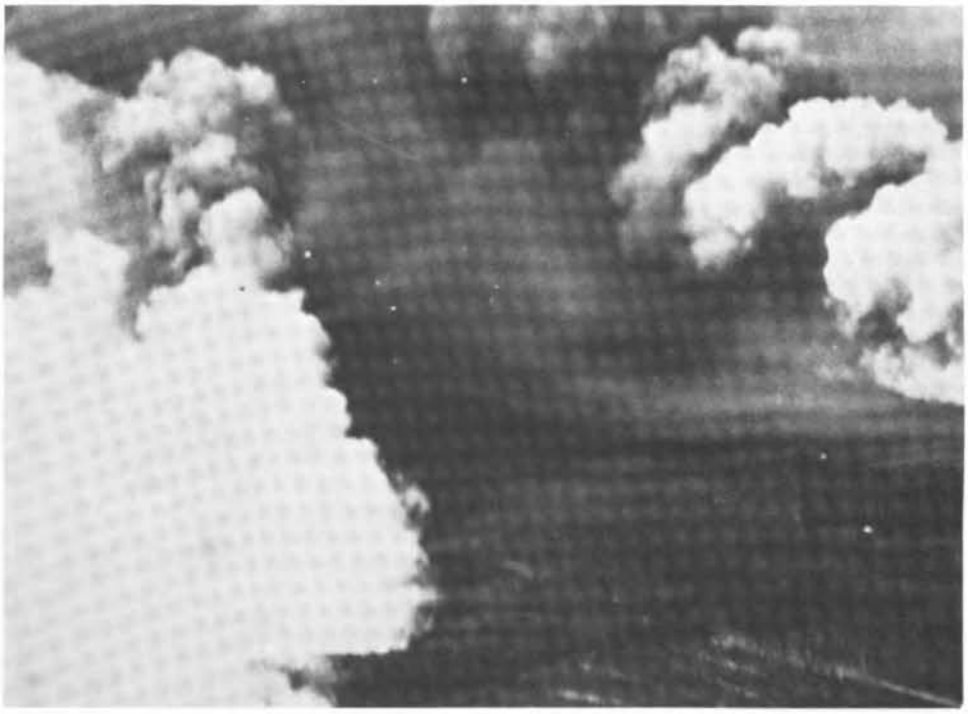

FIGURE 4. Junction Fire, Big Delta, Alaska.

FIGURE 5. Smoke from Horse Butte Fire, Boise, Idaho.

FIGURE 6. Fire at Fort Hall, Idaho.

FIGURE 7. Wildfire in Everglades National Park.

FIGURE 8. Smoke drifting over high resource value area.

FIGURE 9. Smoke drifting over high resource value area.

FIGURE 10. Smoke drifting over high resource value area.

FIGURE 11. Helicopters grounded due to smoke in Chicken Fire in Alaska.

FIGURE 12. Poor visibility during Chicken Fire.

FIGURE 13. Range of dense smoke from wildfires in Alaska in 1969 as reported by aircraft pilots.

FIGURE 14. Convection column boring up through smoke layer.

FIGURE 15. Grounded helicopter.

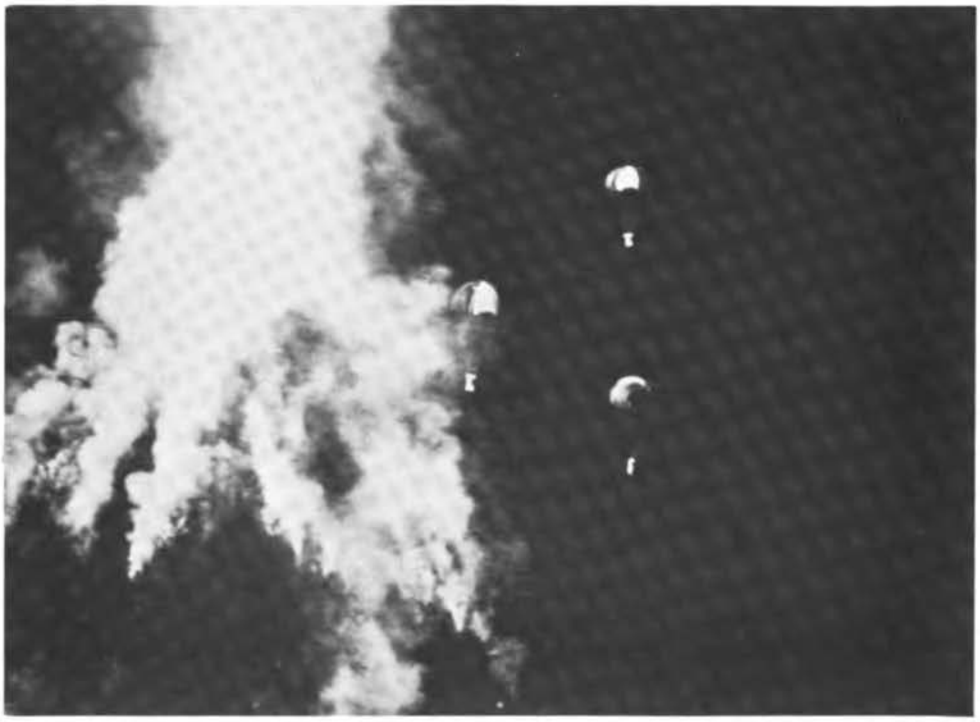

FIGURE 16. Smoke-jumpers.

FIGURE 17. Retardant aircraft.

FIGURE 18. Prescribed burn in Everglades National Park.

FIGURE 19. Prescribed burn in Everglades National Park.

INDUSTRY PROGRAMS FOR SMOKE CONTROL IN FOREST MANAGEMENT BURNING

Sharon R. Miller
The Chesapeake Corporation of Virginia

It would be presumptuous of me to charge forward here on the basis of presenting a case or status report for the entire forest industry. Most of my experience in forest management has been in the South, and *all* of my direct contact with prescribed burning as a forest management practice has been in the South. Consequently, I will speak from that background, recognizing that many of the basic principles are similar country wide.

Also, I wonder what more I can say at this meeting that has not already been said, perhaps several times, by the 33 or 34 very capable speakers who have appeared before me. Being next to last on a program of this size is rather overpowering, but I can imagine and appreciate how the speaker who follows me must feel. I hope that we can add something of value that will help round out this very informative and timely symposium.

Ten years or so ago, the industrial forester in the South thought he had come a long way in reducing and controlling the drastic effects of fire on forest resources. The U.S. Forest Service had given us "Smokey Bear" and his subsequent impact on public awareness for protecting our forests; the same agency had given us results of years of research into fire suppression methods and fire danger ratings; industry and state forest agencies had developed strong public relations and fire prevention programs of their own; states and industries had geared up with fire fighting men and equipment; and last but not least, we had learned how to turn the force of fire against itself, using fire under prescribed, selected conditions to prevent or reduce the catastrophic effects of fire under uncontrolled conditions.

Some four or five years ago, however, we began to feel that others did not view our progress with the same pride that we did. Prescribed burning in the forest was criticized more and more regardless of its purpose and regardless of its relative consequences. State Air Pollution Boards started preparing regulations that could ban open burning of any kind; Federal agencies began investigations; and environmental groups let their concerns be known.

This all came as quite a shock to those of us who had been close to the situation for years and who felt strongly that prescribed burning as a forest management tool had proven itself. It seemed a much better way to go than any known alternative, especially that of going back to the times when wildfires were a common and tremendously destructive happening in our southern forests. Evidence is "crystal clear" and readily available showing that prescribed burning in the South for hazard reduction purposes has had a major impact on the intensity, acreage, and number of annual wildfires. Losses have been greatly reduced. In a less dramatic but still important way, uses of fire for other forest management purposes have proven superior in many ways to known alternatives.

Our first major concern with smoke from prescribed burning probably came about as a result of visibility problems, primarily on highways, near airports, and around populated areas. It was soon discovered that predictability of smoke behavior left much to be desired. Lack of relevant weather information, rapidly changing weather conditions, and a lack of understanding contributed to the situation. A number of bad experiences taught some unforgettable lessons within a relatively short period of time.

As a result, the cry went out for fire weather forecasting both from the standpoint of wildfires and prescribed burning. How can we predict when smoke might settle to the ground after dark to mix with other fog ingredients to form a blanket across major highways? How can we predict when winds might shift drastically and blow smoke in directions that we did not want it to go? How can we tell when fuel and weather conditions are at the optimum to produce the least amount of smoke for the intended objectives?

After years of operational experience and research results, we feel that we have a working knowledge of smoke behavior, and we have been given fire weather forecasting services that help us avoid many of the problem conditions encountered in the past. Still there is a feeling of uncertainty at times, and occasionally plans go astray. The number of obvious, ideal burning days in a season are often not enough to accommodate the size of the job to be done. As a result, guesswork is still a part of the game which means that prescribed burning is done occasionally under less than ideal conditions with less than ideal results.

Even with these limitations, however, I think it is safe to say that forest industries throughout much of the country feel that the use of fire is a vital and indispensable tool in our forest protection and management programs. At the same time, we feel that further refinements are necessary in light of increasing concerns about environmental quality and in light of increased pressure on our forest lands to provide the goods and services that the public wants.

The question now is what are forest industries doing to help improve the situation and at the same time preserve the use of fire under reasonable conditions and restraints. First of all, a lot more thought and care are used in planning and implementing prescribed fires than was the case 10 or 15 years ago. Wind, atmosphere, and fuel conditions in relation to nearby property, homes, highways, airports, etc., are taken into account and may cause the postponement or abandonment of burning plans in specific cases.

Secondly, forest industries are cooperating with state forest agencies and air pollution control boards in setting up guidelines and regulations and in limiting burning programs where smoke conditions are questionable or obviously not good for smoke dispersion.

For example, the Virginia Division of Forestry notified forest industries in the State on five different occasions during this past summer that, due to unfavorable weather conditions, an air pollution alert had been called and asked that all prescribed burning be stopped. Over 20 days of "no burning" were involved during the summer, many of which were satisfactory for burning from just the fire standpoint. And yet, I know of no instance where any prescribed burning was done by forest industries in the State or by Virginia Division of Forestry personnel during these air pollution alerts.

A third thing that is being done by industry is to prepare a state-of-the-art overview report on the use of fire in forest management throughout the United States, which will also cover the history of fire in the development of our forests in the past. Several experts in the field have been retained to do this through the sponsorship of the National Forest Products Association. This is now in progress.

Finally, forest industries are interested in seeing the following things take place:

1. Smoke management guidelines should be prepared for each active region of the country utilizing the best information available, and these should be revised periodically as new information becomes available.

2. Research efforts should be intensified to answer remaining significant questions connected with smoke management for prescribed burning.

3. Major research efforts should be undertaken to determine smoke composition from wildfires and from prescribed fires under a range of forest fuel and weather conditions.

4. Forest industries should continue to assist and provide input to agencies charged with the job of preparing guidelines and regulations to control air pollution; the situation regarding forest management burning should be clearly explained.

5. Prescribed burning should be retained as a viable, effective, and usable forest management tool with whatever restrictions are realistic and are based on sound information.

FIGURE 1. Fuel conditions that build up under southern pine stands and increase the threat of a damaging wildfire.

FIGURE 2. Hardwood brush, and other undergrowth, that develops under southern pine stands and causes competition to the existing stand as well as to establishment of future stands.

FIGURE 3. Hardwood brush, and other undergrowth, that develops under southern pine stands and causes competition to the existing stand as well as to establishment of future stands.

FIGURE 4. Hardwood brush, and other undergrowth, that develops under southern pine stands and causes competition to the existing stand as well as to establishment of future stands.

FIGURE 5. Wildfire in a southern pine stand.

FIGURE 6. Results of a wildfire in southern pine.

FIGURE 7. Results of a wildfire in southern pine.

FIGURE 8. Preparation for prescribed burning to reduce fuel (hazard reduction) and to reduce undergrowth in an existing southern pine stand.

FIGURE 9. Prescribed fires in progress under existing southern pine stands.

FIGURE 10. Prescribed fires in progress under existing southern pine stands.

FIGURE 11. Mechanical site treatment with crawler tractors and rolling drum choppers in preparation for prescribed burning to provide site conditions suitable for establishing new stands of southern pine.

FIGURE 12. Mechanical site treatment with crawler tractors and rolling drum choppers in preparation for prescribed burning to provide site conditions suitable for establishing new stands of southern pine.

FIGURE 13. An area, following harvesting operations, that will be treated with fire in preparation for establishing new stand of southern pine.

FIGURE 14. An area immediately following chopping and burning for site preparation.

THE CALIFORNIA AIR RESOURCES BOARD PROGRAM TO REGULATE AGRICULTURAL BURNING

James J. Morgester
California Air Resources Board

Introduction

The California Air Resources Board program to regulate agricultural, range and forest burning is designed to minimize the adverse effects on air quality of smoke from urban and rural fires. In 1970, agricultural, range and forest burning as a source of emissions, ranked second in carbon monoxide, third in particulate matter, and fifth in organic gases when compared to total emissions from stationary sources in California. Of the estimated five million tons of debris disposed of by controlled burning in 1972, agricultural operations contributed 60% of the total debris; range improvement, 18%, and forest management 22%. In the Sacramento Valley alone, an estimated one million tons of rice and straw stubble are burned annually, during October and November. Agricultural, range and forest burning is banned by the Air Resources Board on days of poor smoke dispersal, and regulated on the remaining days.

History

During the last 26 years, air pollution control in California has evolved from a matter of local concern in areas of the State where problems were already apparent, to the present concept of air quality management on a statewide basis.

In 1947, the California Legislature passed a law that enabled each county to activate an air pollution control district. The Los Angeles County Air Pollution Control District, established in 1947, was the first such district formed.

In 1955, the San Francisco Bay Area Air Pollution Control District was created by the Legislature for the purpose of controlling air pollution in the nine counties of the San Francisco Bay Area on a regional basis. A State air pollution program was also established that year within the Department of Public Health.

In 1967, the Mulford-Carrell Air Resources Act was enacted which created the Air Resources Board (ARB). The act assigned local and regional authorities primary responsibility for control of air pollution from nonvehicular sources. In addition, it empowered these authorities to establish standards more stringent than State law or the ARB regulations.

As required by the act, the ARB divided the State into air basins after examination of the physical and meteorological factors that influence the climatic conditions within the State. Air basin boundaries are shown in Figure 1.

Early efforts to regulate open burning included the programs of the Rice Growers Association, the Tri County Group, the Los Angeles District and the Bay Area District.

Rule 57 of the Los Angeles District, adopted June 6, 1955, regulated agricultural burning to days designated by the air pollution control officer based on meteorological criteria.

On October 1, 1957, the Bay Area District adopted Regulation 1 to regulate burning. Agricultural burning is limited to certain periods during the year. During these periods, burning is permitted only on days designated by the air pollution control officer in accordance with certain meteorological criteria.

The Rice Growers Association Program, started in 1968, controlled air pollution from rice stubble burning by requiring the burning to be done on days of good ventilation. In the Tri County Group, comprised of farmers in San Joaquin, Stanislaus, and Merced Counties and formed in October, 1970, burning was allowed on days with good ventilation. These days were determined by temperature soundings funded by the Farm Bureau.

The Air Resources Board Program

Two incidents added to the generally recognized need to control agricultural burning. The first occurred during the dedication ceremonies at the Sacramento Metropolitan Airport, when smoke from a nearby agricultural burn reduced the visibility below the landing minimum and delayed the first scheduled landing until the smoke cleared. The second, a fatal freeway accident in Northern California, was a result of reduced visibility from agricultural burning.

In 1970, Chapter 10 of Part 1, of the Mulford-Carrell Act was enacted to provide a uniform statewide policy regarding the control of open burning for the disposal of combustible wastes, including agricultural wastes. Agricultural burning was defined to include burning of agricultural waste, range improvement burning, forest management burning, and burning for improvement of wildlife and game habitat. All non-agricultural open burning, with certain limited exceptions, was prohibited as of January 1, 1972. The exceptions, in addition to agricultural burning, are fires used for:

1. Prevention of a fire hazard which cannot be abated by any other means;

2. Instruction of public and industrial employees in the methods of fighting fires;

3. Backfires necessary to save life or valuable property;
4. Abatement of a fire hazard by a public fire protection agency;
5. Disposal of combustible or flammable solid waste of a single or two-family dwelling on its premises;
6. Right-of-way clearing by a public entity or utility or for levee, ditch and reservoir maintenance on a day specified by the ARB (permissive-burn day);
7. Disposal of solid waste at city and county dumps if approval is obtained from ARB; and
8. Disposal of wood waste from property being developed for commercial or residential purposes. This type of burning can take place on burn days only after the local district has developed criteria to reduce smoke and improve combustion and the ARB has approved the criteria.

In order to protect the agricultural industry, the complete banning of agricultural burning by the local district is prohibited by law. Agricultural burning, however, is regulated to days where dispersion and diffusion of smoke will be adequate - "permissive burn" days: The ARB is responsible for the development of guidelines and for determining permissive burn days.

The basis of the ARB Program to regulate agricultural burning is the Agricultural Burning Guidelines. These Guidelines provide the basis for the districts to regulate agricultural burning. The districts were required to adopt implementation plans based upon permits. The Guidelines require each district to develop enforcement procedures, a system for regulating the amount of waste burned, and specific provisions regarding waste preparation.

The Guidelines subdivide agricultural burning into three classifications: burning of waste from the growing of crops or raising of fowls or animals, range improvement burning, and forest management burning.

In controlling open burning in an agricultural operation in the growing of crops or raising of fowls or animals, districts were required to adopt rules which:

1. Require the material to be burned to be free of material that is not produced wholly in an agricultural operation;
2. Require the material to be arranged and reasonably free of dirt, soil and visible surface moisture so that it will burn with a minimum of smoke;

3. Require the material to be dried for minimum periods specified in the implementation plan.

In addition, the districts were required to consider provisions with respect to:

1. Hours of burnings;

2. No-burn season or seasons;

3. Regulating burning when wind is toward a populated area;

4. Limiting ignition to approved ignition devices.

In controlling range improvement burning, each district was required to include rules which:

1. Require the burn to be ignited as rapidly as practicable with approved ignition devices;

2. Regulate burning when the wind is toward a nearby populated area;

3. Require brush to be treated (felled, crushed or uprooted by mechanical means or desiccated with herbicides) at least six months prior to burn if technically and economically feasible;

4. Require unwanted trees over six inches in diameter to be felled and dried as specified prior to the burn;

5. If wanted, specify a period between January 1 and May 31, during which time range improvement burning may be conducted by permit on a no-burn day, provided that more than 50% of the land has been brush treated; and

6. If the burn is to be done primarily for improvement of land for wildlife and game habitat, require the permit applicant to file with the district a statement from the Department of Fish and Game certifying that the burn is desirable and proper.

In controlling forest management burning, each district was required to adopt rules and regulations which:

1. Require the waste to be ignited as rapidly as practicable with approved ignition devices;

2. Regulate burning when the wind direction is toward a nearby populated area;

3. Require the waste to be dried for a minimum period (to be specified by the fire control agency);

4. Require the waste to be burned, to be windrowed or piled where possible;

5. Require piled waste to be prepared so that it will burn with a minimum of smoke and be free of tires, rubbish, tar paper or construction debris; and

6. Require piled wastes to be reasonably free of dirt and soil.

The Guidelines also allow the districts to exempt:

1. The burning of agricultural (farm) waste at elevations greater than 3,000 feet;

2. Agricultural burning above 6,000 feet except the Tahoe Basin; and

3. The burning of pesticide sacks or containers.

The Guidelines also provide for issuance of 48-hour advance burning notice for specific range improvement burns at any elevation below 6,000 feet or specific forest management burns at elevations between 3,000 feet and 6,000 feet upon request, seven days in advance of the proposed burn date. Between January 1 and October 10, 1973, 96 such notices were issued to burn 40,000 acres. The Guidelines also provide for the districts to allow range improvement burning on any day during the period January 1 to May 31 if more than 50% of the land has been treated.

The Guidelines allow burning of agricultural waste on days designated by the ARB as "permissive burn" days. The districts are permitted, however, to authorize burning on days designated as "no-burn" days if the denial of such permit would threaten imminent and substantial economic loss. A report of permits issued to allow burning on "no-burn" days is required quarterly from the districts.

The 50 districts in California have adopted open burning control programs consistent with the ARB Agricultural Burning Guidelines. The program usually operates in the following manner: a permit to burn is obtained from a local fire control agency, which is valid for a certain period of time. On the day of the burn, the permittee is told by the agency he must either phone the district or fire control agency office or listen to the radio for the announcement of a permissive-burn or no-burn day. In many districts, he is required to notify the district after the burn and report how much of what crop was burned.

The district programs must include those items required by the Guidelines but may be more specific in many cases to satisfy local conditions and make the regulation workable. Listed below are variations which may exist and are encountered in California:

Designated Agency - These are agencies responsible for issuing burning permits. The districts generally ask that the U.S. Forest Service or California Division of Forestry issue permits. In some cases they also asked that local fire protection agencies issue permits. In two areas, the district is the only agency which issues burning permits; in many areas the district is included with the other agencies which issue permits.

Drying Times - The districts were required to specify drying times for the following agricultural waste materials: trees and large branches, prunings and small branches and wastes from field crops cut in a green condition. Drying time was also required for trees felled in range improvement burning operations. Material burned as part of a forest management operation is required to be dried for a period specified by the permit issuing agency. The drying times generally prevalent in each air basin are listed in Table 1.

Regulate the Amount of Waste Burned - Three general types of rules were adopted by the districts to regulate the amount of waste burned.

1. The air pollution control officer may limit the amount of waste burned as necessary to preserve ambient air quality.

2. Only one large burn is allowed within a specified number of days. Three days are frequently specified for range improvement burns and five days for forest management burns.

3. If the number of acres of a specified crop expected to be burned on a given day exceeds a given percentage (usually 5% or 10% of the acreage of that crop in the district), burning allotments are issued by the air pollution control district. Burning is allowed within each fire district based on the portion of the total crop acreage within that fire district.

Many districts use two of these types of rules (either Numbers 1 and 2 or 2 and 3).

Free Period - The Guidelines allow the districts to specify a period between January 1 and May 31 during which range improvement burning is allowed on any day if more than 50% of the brush has been treated. Twenty-four of the districts specified the period January 1 to May 31; one specified January 1 to March 31; one specified January 1 to April 1; and 24 did not include this provision in their regulation. Thus, in these 24 districts, range improvement burning can be conducted only on permissive burn day regardless of prior treatment.

Enforcement

The primary responsibility for the enforcement of agricultural burning regulations rests with the local district. This includes enforcement of the burning ban on "no-burn" days and requiring that all burning be done in accordance with conditions specified in the permit. The district has the additional responsibility to insure that authority to burn on a "no-burn" day is given only if there is a threat of imminent and substantial economic loss.

The legal avenues available to the districts for enforcement include warnings, citations, and court prosecution. A violation of the Agricultural Burning Regulations is a misdemeanor punishable by imprisonment in the county jail not exceeding six months, or by fine not exceeding five hundred dollars ($500), or both, and the cost of putting out the fire.

Table 2 is a listing of estimated enforcement actions taken during 1972 in five California air basins.

Operation of the Program

The program to regulate agricultural burning is based on the district enforcing the provisions of the law to allow burning only on the days designated by the ARB. The basis of the designation of permissive burn and no-burn days is the meteorological criteria adopted by the ARB in conjunction with the Agricultural Burning Guidelines.

The meteorological criteria utilize three general considerations:

1. The depth of the lower atmosphere through which smoke may be expected to be diluted;
2. Horizontal dilution to be expected from horizontal air transport (wind speed); and
3. Direction of transport of the smoke (wind direction).

The depth of mixing is dependent on the stability of the lower atmosphere. Thus, criteria are stated in terms of the intensity of the nighttime temperature inversion, or the expected daytime lapse rate, or both.

Direction of transport of the smoke is important since transport from a region of poor ventilation to a region of good ventilation may make burning acceptable when it might not be otherwise.

In mountainous areas where few meteorological observations are available, the meteorological criteria are stated in terms of atmospheric pressures aloft since these provide a more representative regional circulation pattern than surface weather observations, which frequently reflect the effects of terrain rather than the pressure field itself. In general high pressures aloft are associated with poor dispersion of atmospheric pollutants.

Three of the air basins utilize split criteria. In the North Coast, Sacramento Valley and San Joaquin Valley Air Basins criteria are specified for those areas above 3,000 feet elevation and those below 3,000 feet.

In addition to the criteria for above and below 3,000 feet, the Sacramento Valley Air Basin has been divided into northern and southern sections with somewhat different criteria for each section. This was done to allow for closer control of the rice residue burning during the fall. Special criteria were also established for the Lake Tahoe portion of the Sacramento Valley because of its unique beauty and vulnerability.

The program to regulate agricultural burning was initiated in the six air basins having the majority of the agriculture production in September, 1971, and extended to the entire State in December, 1972. The first six air basins were the North Central Coast, Sacramento Valley, San Francisco Bay Area, San Joaquin Valley, South Central Coast and South Coast. Table 3 shows the percentage of permissive burn days allowed in each air basin and is based on the total time of operation of the ARB program in each air basin.

The length of time the waste has been dried is important because it affects the amount of particulates, carbon monoxide, and hydrocarbons that are emitted. Studies done at the University of California on burning orange tree debris show that emissions are reduced by two-thirds for a six week drying period (see Table 4)*. Most of the emissions from burning relatively green materials are due to the leaves and twigs. The rate of emission yield is quite high during the initial part of the fire when the leaves and twigs are being consumed and falls to a low, relatively steady-state value during the burning of the heavier pieces of wood.

An important provision of the Agricultural Burning Guidelines is the requirement for the districts to report the daily amount and type of waste burned. This information is being used to evaluate the impact of agricultural burning on ambient air quality. This reporting requirement was only recently established and data has been processed for the period January 1, 1973 to March 31, 1973. The total waste reported burned during this period was generally less than that reported in previous years because of an unseasonably wet winter (see Table 5).

The impact of agricultural burning on ambient air quality is reflected in two types of air quality measurements: visibility and suspended particulate matter (coefficient of haze). Correlations with visibility and coefficient of haze have been developed for the first six air basins in which burning was regulated (see Figs. 2, 3 and 4).

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* Progress Report, "Air Pollution From Forest and Agricultural Burning," University of California, July, 1973.

Figure 2 shows the median visibility at midafternoon on days on which burning was permitted, compared to days on which it was prohibited. Figure 3 shows the average coefficient of haze on days when burning was permitted compared to days when it was prohibited. Figure 4 compares visibility and the amount of waste reported burned in the San Joaquin Valley Air Basin for the period February 17-26, 1973.

Figures 2 and 4 show overall visibility was better on days when burning was allowed than on days when it was prohibited. This indicates that the forecasts were accurate and that the ban on burning prevented further deterioration of air quality on days of poor dispersal. Figure 3 indicates the average coefficient of haze was lower in every air basin on days when burning was permitted than on days when it was prohibited.

The staff of the Air Resources Board will continue to work closely with the agricultural, range and forest managers and air pollution control district personnel in an effort to implement the program and make it as responsive as possible to the needs of all the people.

TABLE 1

DRYING TIMES GENERALLY USED BY AIR BASIN (DAYS)

AIR BASIN	TREES	PRUNINGS	FIELD CROP	RANGE IMPROVEMENT (LARGE TREES)
Great Basin Valleys	40	20	0	180
North Central Coast	60	30	10	180
North Coast	60	15	10	60
Northeast Plateau	60	20	0	90
Sacramento Valley	30	15	3	180
San Diego	60	30	15	60
San Francisco Bay Area	60	60	60	180
San Joaquin Valley	40	20	3	*
South Central Coast	40	20	10	40
South Coast	60	30	10	60
Southeast Desert	30	15	30	180

*As specified by the designated agency.

TABLE 2

DISTRICT AGRICULTURAL BURNING ENFORCEMENT ACTIONS

1972

AIR BASIN	WARNINGS	CITATIONS	COURT CASES	FINES	JAIL SENTENCES
Sacramento Valley	75	25	7	6	0
San Joaquin Valley	613	48	23	16	1
South Central Coast	1	0	0	0	0
North Central Coast	1	1	1	1	0
San Francisco Bay Area	NA	106	NA	NA	NA

NA: Not Available

The jail sentence listed for the San Joaquin Valley Air Basin was of five days duration.

TABLE 3

PERCENTAGE OF PERMISSIVE - BURN DAYS

NOTICES ISSUED STARTING
September 27, 1971

AIR BASIN	PERCENT
North Central Coast	71
Sacramento Valley (South Section)	72
Sacramento Valley (North Section)	80
San Francisco Bay Area	64
San Joaquin	74
South Central Coast	68
South Coast	50

NOTICES ISSUED STARTING
December 20, 1972

AIR BASIN	PERCENT
Great Basin Valley	93
North Coast (above 3,000 feet)	90
North Coast (below 3,000 feet)	76
Northeast Plateau	93
Sacramento Valley (above 3,000 feet)	93
Sacramento Valley (Lake Tahoe)	92
San Diego	75
San Joaquin (above 3,000 feet)	91
Southeast Desert	96

TABLE 4

VARIATION OF EMISSIONS WITH DRYING TIME, ORANGE TREES

(APRIL-MAY, 1973)

Drying time weeks	Emissions, lbs. per ton of weight loss		
	Part.	CO	HC
0	10.1	123	16.1
1	4.8	120	7.6
2	4.0	85	6.9
3	3.4	71	4.5
4	2.9	77	4.5
6	3.3	46	4.2

TABLE 5

AMOUNT OF WASTE REPORTED BURNED
(January-March, 1973)
TONS

AIR BASIN	WASTE BURNED
Great Basin Valley	50
North Coast	5,600
North Central Coast	4,200
Northeast Plateau	30
Sacramento Valley	136,000
San Diego	NA
San Francisco Bay Area	20,000
San Joaquin	941,000
South Coast	6,800
South Central Coast	2,800
Southeast Desert	4,700
Total:	1,121,180

NA - Not Available

FIGURE 1. California Air Basins (State of California, The Resources Agency, Air Resources Board).

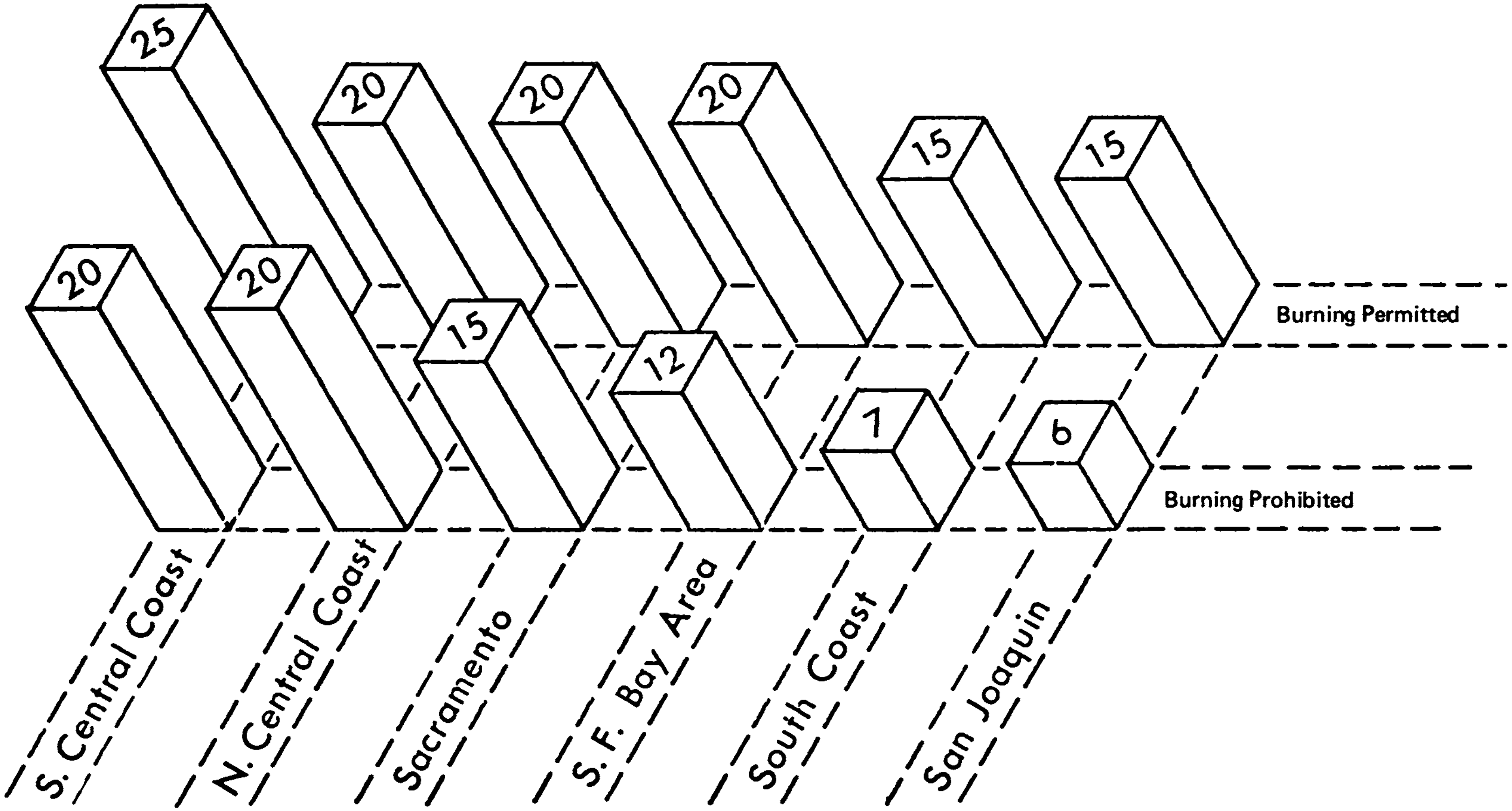

FIGURE 2. Comparison of median visibility in miles at 3 p.m. in air basins subject to control of agricultural burning (October 1971-August 1972).

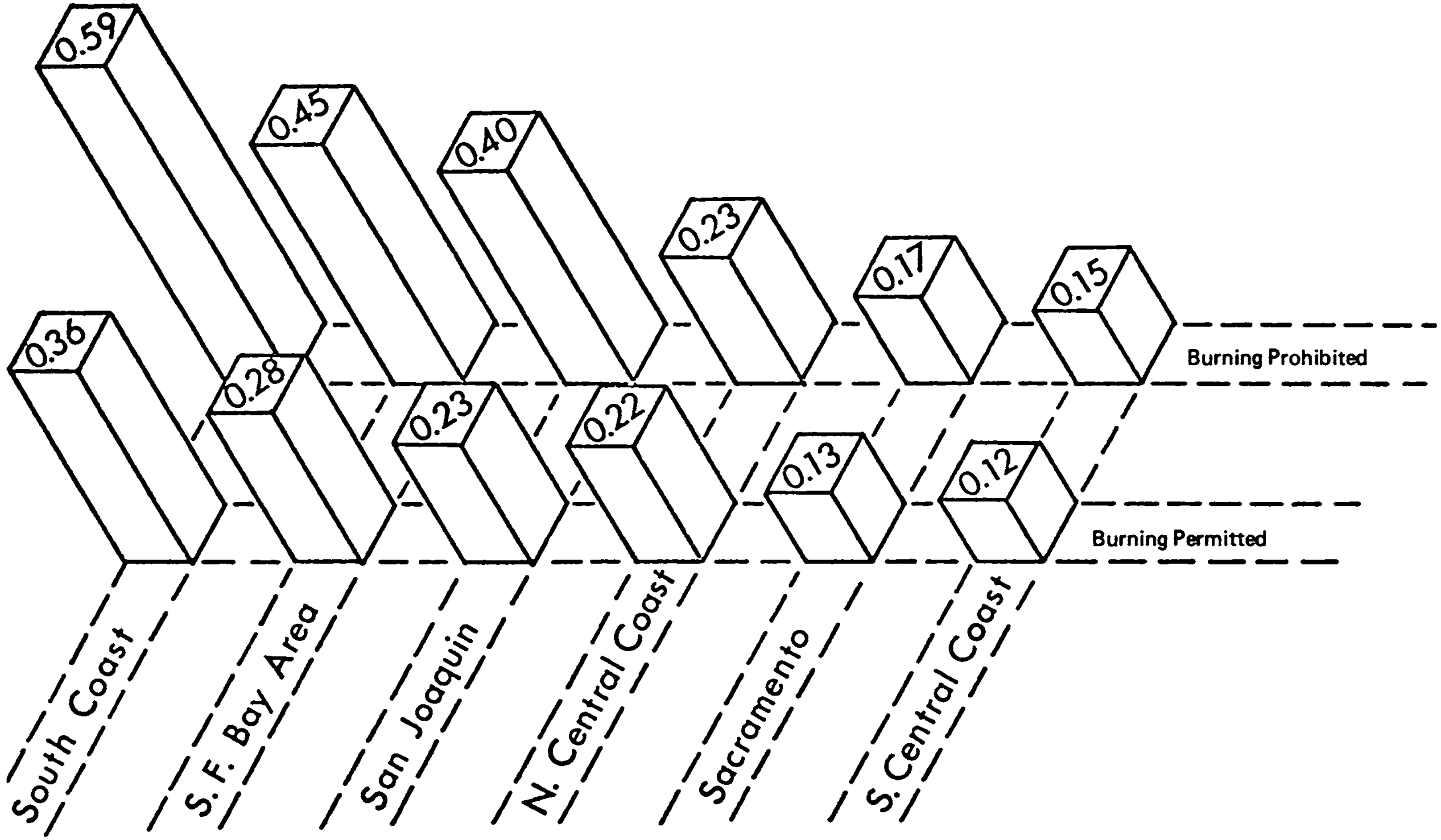

FIGURE 3. Comparison of average coefficient-of-haze values at 3 p.m. in air basins subject to control of agricultural burning [values are in coh units] (October 1971-July 1972).

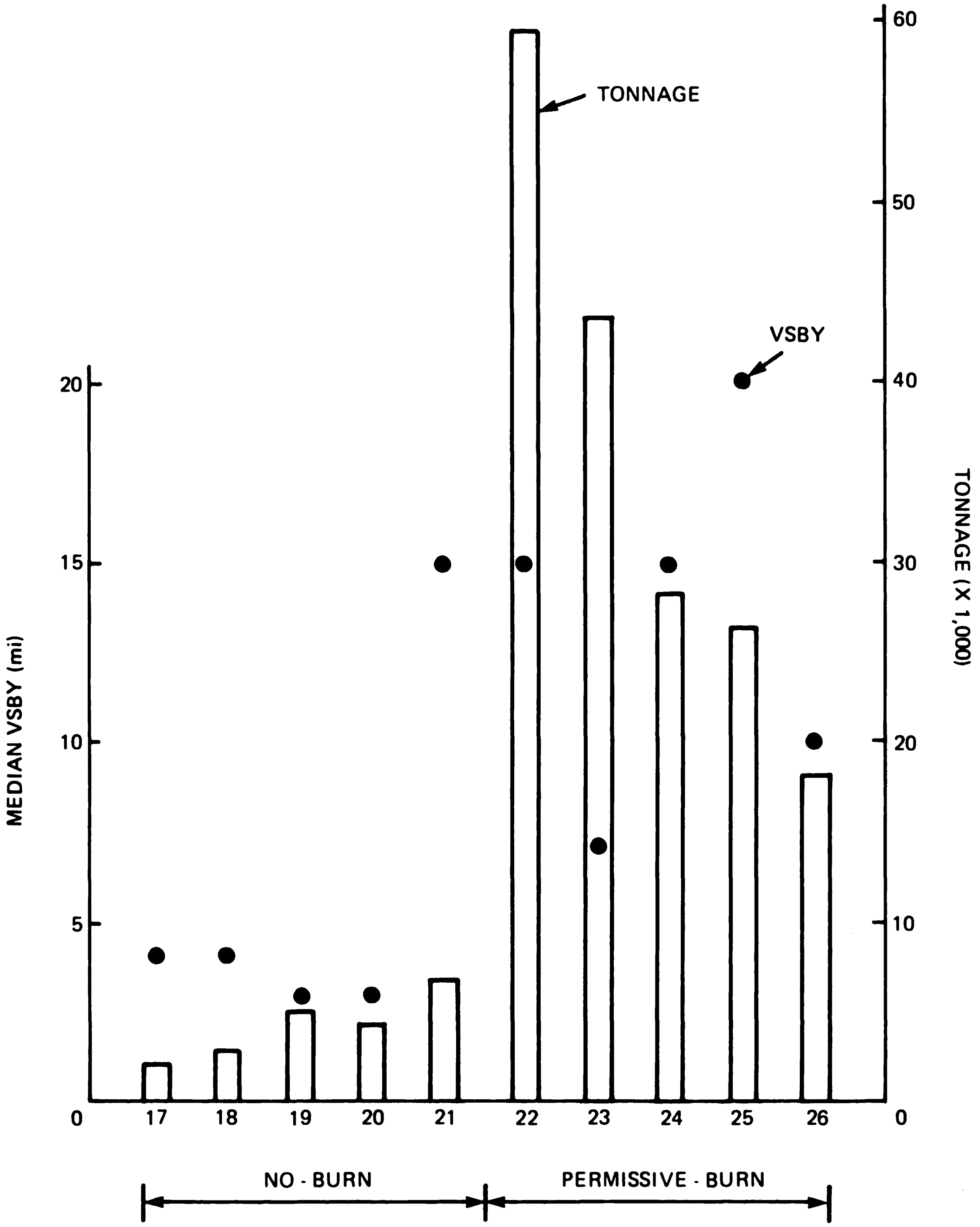

FIGURE 4. Median visibility at 1 p.m. and tonnages of agricultural wastes burned in the San Joaquin Valley Air Basin, February 17-26, 1973.