COMBUSTION PROCESSES IN WILDLAND FUELS
(A Research Progress Report 1980-1985)

Charles K. McMahon[1]

Abstract.--A 5-year summary of accomplishments, current activities, and planned actions for fire research project SE-2110 are presented. Areas of discussion center on: (1) characterization of wildland smoke, and (2) fuel, fire, and emission relationships. Characterization summaries include physical and chemical properties of smoke, smoke from burning pesticide-treated forest fuels, and smoke tracers.

Reducing smoke from smoldering combustion, understanding moisture relationships in forest fuels, and developing remote sensing methods for fire behavior and effects offer opportunities for the wildland fire manager to expand prescribed burning programs while minimizing detrimental environmental effects.

Additional keywords: Air quality; visibility; photo and video documentation; organic soil; image analysis.

INTRODUCTION

The Combustion Processes in Wildland Fuels Research Project (SE-2110) was established in 1980 following the phaseout of the Smoke Management Research and Development Program. The original title of the Project was changed from "Smoke Chemistry and Physics" to the current title to reflect expansion of our research from smoke characterization into several related areas of fire research. The words "combustion processes" were chosen to help convey the notion that our research would examine all phases of the wildland fire process, including smoldering combustion, a phase of the fire process often ignored in previous fire research efforts.

The Project's mission was described:

"To determine the chemical and physical characteristics of emissions from wildland fires, and to describe the mechanisms of formation permitting the use of source-related predictive equations for smoke management."

The work to be accomplished was initially divided into three broad problem statements:

Problem No. 1: Resource managers need information on the chemical and physical properties of forest fire smoke in order to be responsive to existing and emerging air quality legislation. (What is smoke?)

---

[1] Supervisory Research Chemist and Project Leader, Southern Forest Fire Laboratory, Southeastern Forest Experiment Station, USDA Forest Service, Dry Branch, Georgia.

Problem No. 2: Resource managers need information on atmospheric reactions of smoke in order to predict visibility impact at sites downwind from the fire source. (What is the fate of smoke in the environment?)

Problem No. 3: Functional relationships between flaming and smoldering processes, fire intensity, fuel characteristics, and emissions are needed in order to develop smoke management systems. (How can the process be modeled?)

Shortly after the Project was organized, we consolidated Problems 1 and 2 into a single problem entitled, "Characterization of Wildland Smoke is Needed." Consolidation was in response to the loss of several scientists and a sharply reduced operating budget.

This paper is intended as a summary of the Project's significant accomplishments, current activities, and planned actions. The literature cited are limited to recent related publications by Project personnel.

CHARACTERIZATION OF WILDLAND SMOKE IS NEEDED (Problems 1 and 2)

Many forest-land managers recognize that wildland productivity can be increased by the expanded use of prescribed burning. At the same time, they realize they must be able to develop methods to reduce or minimize the impact of smoke on air quality. As a first step, basic information is needed on smoke properties to defend the beneficial use of fire where burning regulations are being considered. This information will also provide the building block for developing predictive models for use in smoke reduction strategies and smoke management systems. Work on this combined problem was outlined in a problem analysis (McMahon and Tangren 1981) with the research divided into three components:

1. Chemical characteristics of smoke.

2. Physical characteristics of smoke.

3. Characterization methodology and instrumentation.

Chemical Characteristics of Smoke

Smoke from forest fires contains thousands of major, minor, and trace constituents. Our characterization research has been limited to constituents of national or regional significance. These include particulate matter, polycyclic organic matter, organic soil smoke, smoke from pesticide-treated forest fuels, and smoke tracers.

Smoke particulate matter.--Particulate matter is the most important single category of emissions from forest fires. It is the major cause of visibility impairment and contains compounds known to affect human health. Total suspended particulate matter, or TSP, is that portion which is transported long distances in the atmosphere and has the greatest potential for environmental impact. Particles below 2 to 3 microns (fine particulates) have an especially long residence time in the atmosphere, contribute to smog formation, and penetrate deeply into the lungs. Effects of particulate matter are determined by three properties: size, sorption characteristics, and chemical composition. Interest in the properties of forest fire particulate matter was renewed in 1984 because of new efforts by the Environmental Protection Agency (EPA) to identify sources of visibility impact. In addition, EPA is in the process of proposing a new national standard for particulate matter for particles under 10μ in diameter (PM_{10}).

For years, particulate matter has been measured in units of mass determined by gravimetric analysis of the material collected on a glass fiber filter in a "hi-vol" sampler. In recent years, the chemical analysis of particulate matter, especially the organic fraction, has become a high-priority need for environmental and air pollution scientists because of possible effects on human health.

The organic fraction of TSP has traditionally been estimated by solvent extraction with benzene and reported as the "benzene soluble organics," or BSO. This fraction of ambient air TSP has been monitored for over 20 years. Many of the first characterization studies centered on the biologically active organic substances known collectively as Polycyclic Organic Matter (POM).

Polycyclic organic matter (POM).--Following publication of the Southern Forestry Smoke Management Guidebook in the late 1970's, one of the key characterization questions that remained concerned the magnitude of polycyclic organic matter (POM) emissions in wildland smoke. POM is a large class of chemicals released into the air as a result of incomplete combustion of carbonaceous fuels. Concerned about the cancer-causing potential of POM, EPA was collecting data on POM emissions and was considering ways to regulate sources that produced POM compounds. POM's from burning forest fuels were first reported by McMahon and Tsoukalas in 1978. Because of the regulatory potential surrounding this issue, high priority was given to continued study of these pollutants. Benzo(a)pyrene (BaP), one of the most studied POM compounds, was chosen for further study. Recently, White and others (1985) reported that the ratio of benzo(a)pyrene to particulate matter averaged 24 μg/g in four forest fuels common to the Southeastern States. Significant differences were not found between heading and backing fire types, but were among fuel types. Based on these data, a new national estimate for BaP production from prescribed burning was reported to be 11 metric tons annually. Earlier estimates were as high as 140 metric tons annually. POM studies continue in slash fuel types in cooperation with the Pacific Northwest Experiment Station. In addition, a comprehensive profile of organic chemicals in forestry smoke particulate matter is now being developed in cooperation with the USDA Tobacco Smoke Research Laboratory in Athens, Georgia. That work should be available for publication in late 1985.

At this time, it does not appear that wildland smoke management strategies will need to incorporate the complexities related to the POM compounds. Our current efforts, which focus on reducing smoldering combustion, should suffice to minimize total POM production.

It is worth noting here that in August 1984 EPA decided not to regulate POM as a class of compounds under the Clean Air Act "....until the agency had enough information to determine if regulation is appropriate...." According to current EPA figures, the major sources of POM are wood- and coal-burning stoves (44 percent); mobile sources such as automobiles, trucks, and aircraft (40 percent); forest fires (3 percent); fireplaces (3 percent); incinerators (3 percent); coke oven emissions (2 percent), and other sources (5 percent). It is clear, however, that small national percentages do not guarantee freedom from regulation. Coke oven emissions will soon be regulated under Section 112 of the Clean Air Act, and a standard for diesel emissions is in place. EPA is also considering other regulatory options for reducing POM emissions from wood stoves.

EPA is now in the process of reexamining the potential risk of POM emissions, source by source. Control technologies will be evaluated for their effectiveness in reducing emissions and health risks, and for their economic and social effects. Then, the agency may act to regulate additional specified sources of POM under the Clean Air Act.

Smoke from burning organic soil.--Organic soils cover many millions of hectares in the United States, including 2.8 million hectares in the Southern United States with about 1.0 million in south Florida. If these soils are sufficiently dry, they will support combustion when ignited by surface fires. Organic soils are generally consumed by smoldering fires that can last for months, burning down to the water table before going out. These slow-burning fires (horizontal rates of spread in the range of several meters per day) produce visible smoke when burning near the surface but can become remarkably smoke free as they burn through deeper layers. Combustion is evident from a general haze over the area combined with a disagreeable and pungent odor from partially oxidized organic material. These soils can, however, burn more rapidly and produce copious amounts of smoke around deep fissures in the soil or where the soil is overturned.

We began a study in the late seventies to learn more about the soil burning process. Field studies of soil burning would be very costly because the soil combustion rate is uncertain and it is difficult to collect representative emission samples. We decided to measure emissions from small blocks of burning soil in the laboratory. As reported by McMahon and others (1980, 1984) small blocks of organic soil collected in south-central Florida were burned and monitored at the Southern Forest Fire Laboratory. The soils sustained combustion for up to 4 days, even through layers containing 135 percent moisture. Peak temperatures were in the 400-600 ^{o}C range. Particulate matter emission factors ranged from 1 to 63 g kg^{-1}. The particulate matter was soot free and virtually all organic in nature (95 percent soluble in methylene chloride). The particulate matter was separated into neutral, strong acid, weak acid (phenolic) and basic fractions. The neutral fraction, which predominated (63 percent), was further separated into four subfractions. The subfractions containing polynuclear aromatic hydrocarbons (PAH) were purified by gel permeation chromatography and analyzed by gas chromatography. Percent distributions of various PAH ring systems were determined. Organic soil particulate matter was found to contain high percentages of methyl and polymethyl PAH's in the three- and four-ring PAH systems. For 13 samples, the benzo(a)pyrene emission factor averaged 213 µg kg^{-1} with a range between 9 and 785 µg kg^{-1}. Emission factors for carbon monoxide (269 ± 135 g kg^{-1}), nitrogen oxides (1.7 ± 1.8 g kg^{-1}), and total hydrocarbons (23 ± 15 g kg^{-1}) as methane were also reported.

Smoke from burning pesticide-treated forest fuels.--Since 1982, we have carried out three smoke-related research studies as part of the National Agricultural Pesticide Impact Assessment Program (NAPIAP): (1) pesticides released from burning treated wood, (2) release of copper, chromium, and arsenic (CCA) from the burning of wood treated with preservative, and (3) release of herbicides from the burning of treated understory forest fuels.

(1) Pesticides released from burning treated wood.--Rapidly rising energy costs have created a large demand for alternative energy sources in home heating. Many households have turned to wood as a primary or supplemental energy source because of the abundance of this fuel in many parts of the country. A common source of this firewood is hardwood stems killed by herbicides or wood that has been sprayed following a beetle attack. Recently, there have been numerous inquiries from the public regarding the safety of burning pesticide-treated wood in home fireplaces or stoves.

A novel combustion tube furnace technique (Fig. 1) was developed to simulate the wide range of thermal conditions possible in wood stoves and fireplaces. A range of conditions from slow smoldering combustion to rapid flaming oxidation was applied to wood samples treated with seven pesticides. The implications of the study as reported by Clements and others (1984) are:

"...Pesticide treated wood will release substantial amounts of pesticides when the sample is heated slowly. This can occur in damped wood stoves as well as stove and fireplace fires that are not fully developed."

"...The amount of pesticide released will depend on the physical and thermal properties of the compound. Relatively stable compounds such as Lindane and Dicamba as well as compounds with significant vapor pressures can be expected to be released (distilled) in significant amounts when the wood is heated slowly."

"...Under conditions of rapid flaming combustion, most pesticides decompose readily, with higher temperatures causing complete decomposition. With a well-ventilated fully developed fire in a wood stove or fireplace (where temperature can reach 800-1000^{o}C), one can expect complete decomposition of most common pesticides."

"...Because of the uncertainty of ventilation and temperature in many domestic wood-burning devices, a safe-side approach to the use of pesticide treated wood is well advised. Thus, the indoor storage and burning of pesticide treated wood is not recommended unless it has been predetermined to have decomposed or removed from the wood by aging and weathering processes."

(2) Release of copper, chromium, and arsenic (CCA) from the burning of wood treated with preservative.--Chemicals have been used to protect wood from insect and water damage for many years. One of the

more common formulations contains copper, chromium, and arsenic salts and is referred to as chromated copper arsenate or CCA. Public concern has been raised over the possible release of highly toxic smoke when CCA wood scraps are burned. The levels of CCA released when wood is burned under different combustion conditions is not known. This study has two primary objectives:

a. To determine the percent of total copper, chromium, and arsenic released to the atmosphere when CCA-treated wood is burned under various combustion conditions.

b. To determine on selected samples the nature of the arsenical chemicals released to the atmosphere.

In this laboratory study, CCA-treated wood is being burned under controlled conditions (time/temperature) in a combustion tube furnace. To date, experiments have been run at 400°C and 800°C. An average of 17 percent of the arsenic is released at 400°C, while a range of 19 to 31 percent is released at 800°C (depending on exposure time). Arsenic speciation and additional experiments at 1000°C are planned. Results will be reported at the National Air Pollution Control Association Conference in June 1985.

(3) <u>Release of herbicides from the burning of treated understory forest fuels.</u>--Concern has been raised about the possible impact on air quality from the popular "brown and burn" method of controlling unwanted vegetation in forests. In this method, herbicides are applied to the vegetation, and a few weeks later--after the leaves are brown--the area is burned by prescription. The concern centers on the possible harmful amounts of parent herbicides and their thermal decomposition products that may be released to the atmosphere during burning.

A study is underway to quantify emissions of parent herbicides as a function of fire type and to identify the major herbicide thermal decomposition products produced under these conditions. A worst case application of a Tordon mixture (2,4-D and Picloram) was applied to pine needle litter and burned under controlled conditions in the combustion laboratory at the Southern Forest Fire Laboratory (Fig. 2).

Results to date (Clements and others 1984b) indicate that a very high percentage of Tordon components will thermally decompose when sprayed on a fine forest fuel and then burned. Picloram decomposed (>99 percent) in all fires. 2,4-D decomposed (>99 percent) in the simulated backing fires, but was released in small amounts (4.8 percent) in the simulated heading fires.

The amounts of herbicides released or decomposed in this experiment cannot be extrapolated to other herbicides that have different chemical and physical properties. Also, some decomposition products are known to be hazardous. However, it is clear that burning techniques that cause flaming to dominate not only favor pesticide thermal decomposition but will also enhance the convective lift and rapid dilution of the smoke away from the burn site.

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

Several receptor techniques are being developed to assess the environmental impact of wood stove and fireplace emissions; they could also prove useful as forestry smoke tracers (McMahon 1983). Atmospheric scientists are also mapping the tropospheric distribution of trace gases from biomass burning; their results should prove helpful in finding a forestry smoke tracer. Ward and others (1982) reported emission factors for trace sulfur species released from five forest fuels burned in the laboratory.

Receptor models are very new and still an emerging technology. At present, methods often only provide qualitative information. However, with expected advances in sampling and analysis methods, these techniques could become the primary diagnostic and predictive tool used in air resource management. Perhaps the greatest opportunity for improving receptor models lies in the area of detailed analysis of organic emissions. Most of the models up to now have concentrated on elemental fingerprints. At present, there are no reliable elemental signatures for many combustion sources. Elemental analysis is relatively simple and inexpensive when compared to the techniques needed for organic analysis. However, advances in organic sampling and analysis, which can be expected, may provide the opportunity for finding compounds or ratios of compounds that will distinguish between two closely related sources. Approaches should consider the type of organic matrix present in the fuels and then focus on expected pyrolysis and combustion products. For forest fuels, specific aldehydes, furans, phenols, or terpenes would be a place to start. Organic group, class, or functional group analysis may also be appropriate, as well as individual constituent analysis, or a combination of both.

Physical Characteristics of Smoke

The physical characteristics of smoke are important because of their effects on smoke dispersion patterns, human health, and visibility (McMahon 1981). Particle size, particle shape, absorptive properties, density and refractive index all contribute to the reduction of visibility by smoke. Many of these characteristics are also important in describing human health effects. Inhalation and lung retention are directly dependent on particle size. Particles below 2.0 microns penetrate deepest into lungs and cause the greatest concern. In addition, particle surface properties may cause additional chemical species to be absorbed and carried to the lungs. Particle size and aerodynamic characteristics determine the drift pattern of particles and their residence time in the atmosphere. Fine particles (below 2.0 micron diameter) generally behave as a gas and can remain dispersed in the air for weeks and months.

Smoke particle size.--Some early reports on the size of forestry smoke particulate matter erroneously indicated a particle size range from 50 to 100 μm in diameter based on examination of microscopic slides placed downwind from the fire. The particles examined were primarily partially consumed fuel fragments and ash particles. These large particles are produced primarily by high-intensity fires when the turbulent convective activity in the fire zone is sufficient to mechanically generate and entrain large particles in the smoke column. In most cases, they drop out near the fire and are not found in forestry smoke plumes at great distances from fires. A number of studies reviewed by McMahon (1983) have now shown that most of the particles formed in forest fires are of submicron size, typical of a combustion aerosol. These studies generally agree on an average particle diameter between 0.1 and 0.5 μm, for mass, number, or volume distributions.

Visibility relationships.--The effect of smoke on visibility depends not only on the concentration of particles emitted, but on the optical properties of the particles as they affect the scattering, absorption, and total extinction of light. A number of studies have reported the relationship between the mass of forest fire particulate matter and light scattering properties. Comparison of data is hampered by the use of instruments with different spectral reponses and/or by different methods of analysis. Tangren (1982) has recently reviewed this topic and recommends a backscatter ratio of 2.8×10^5 for smoke plumes on the ground near the fire and 2.0×10^5 for airborne measurements of aged smoke downwind from the fire. From a smoke management perspective, these new values reduce some of the error in making visibility predictions down range from a burn.

The color of forest fire smoke can vary from dark black, through various shades of grey, to pure white. Black smoke will predominate during vigorous flaming combustion, especially when burning foliage fuels containing a high percentage of extractable hydrocarbons. As flaming combustion diminishes, tarry droplets from smoldering combustion begin to predominate and the smoke color changes from black to white. On a volume, number, and mass basis, the tarry droplets usually predominate over the solid black soot particles. Soot particles scatter as well as absorb light. This double effect gives soot particles an influence on visibility greater than their atmospheric concentration alone would suggest. Also, the soot particles, although chemically inert, carry on their surface reactive groups that take part in important atmospheric reactions. Recently, the absorption properties of smokes from laboratory fires that represent prescription burns in the Southern States were quantified by Patterson and McMahon (1984). Measured optical properties and previously measured size data were used to determine the overall radiative properties for the smokes from these fires. As expected, results showed significant differences in absorption of the smoke emissions between flaming and smoldering combustion, with specific absorption coefficient B_a values from 0.04 to 1.0 m^2g^{-1} at 632.8 nm. These data indicate that under conditions of flaming combustion approximately 50 percent of light extinction will be due to particulate matter absorption, while under purely smoldering conditions, only 5 percent of light extinction will be due to absorption. This information is providing a means of discriminating forest fire visibility effects based on type of burning and fuel characteristics. It is also serving the needs of researchers attempting to model the effects of forest fires on global climatology, carbon cycling, and mass fire behavior (Patterson and McMahon 1985).

Characterization Methodology And Instrumentation

Many of the procedures and much of the equipment associated with the study of air pollution and atmospheric chemistry are relatively new. As a result, most studies undertaken by the project required the development and/or validation of instruments and procedures unique to smoke monitoring and evaluation. Some recent examples are:

A micromethod for benzo(a)pyrene.--A simple and rapid method employing a high-pressure liquid chromatographic technique has been developed and validated for determining benzo(a)pyrene concentrations in particulate matter from prescribed burning (White 1985). The procedure is being used in studies in the Southeast as well as in cooperative work with the Pacific Northwest Experiment Station.

A microcombustion method applied to forest fuels.--This method requires thermogravimetric (TG) instrumentation and small (10 mg) samples of ground-up forest fuels (Fig. 3). An average of 95 percent of the combustion products released as particulate matter, volatile organic carbon, total hydrocarbons, carbon monoxide, and carbon dioxide are accounted for. The method best simulates slow smoldering combustion and oxygen-starved pyrolytic conditions of fuel decomposition (Clements and McMahon 1984). The TG system was used to determine the amount of nitrogen oxides produced from burning 12 forest fuels that varied widely in nitrogen content (Clements and McMahon 1980). Results indicate that approximately 25 percent of the fuel nitrogen is converted to nitrogen oxides when the fuels burned below 1000^{o}C.

Smoke monitoring systems.--A sampling concept originally developed for use with a balloon system for monitoring forestry smoke plumes (Ryan and others 1979) has been modified and used in many new applications. The original system was portable (2.3 kg) and consisted of: a temperature and windspeed monitor, a particulate matter sampler, and a gas grab-sampler. The system was designed to make use of the "carbon-balance" procedure for obtaining fuel consumption data. In the past, fuel consumption was often determined by tedious before-and-after "lift & weigh" techniques. The carbon balance method chemically balances the fuel's known carbon content with the carbon content of the measured combustion products. This technique was summarized and evaluated by Nelson (1981) and has proven to be crucial to the monitoring of forest fires where traditional lift-and-weigh techniques are not possible. The system was applied by Ward and others (1980) using a tower-based vertical array in burning studies of southeastern understory fuels. Upon transfer to the Pacific Northwest Station, Ward further modified the system to operate on a real-time basis in a horizontal configuration over broadcast fuels. Portable versions of the system are evolving (Fig. 4) and have been used by White (1984) for monitoring benzo(a)pyrene/particulate matter ratios and by McMahon (1982) for monitoring emission from piled forest residues mixed with organic soil. This latter experiment also demonstrated the feasibility of using a platform monitoring system and a modified tepee burner to monitor emissions and combustion rate from large-scale (>500 kg) burning experiments (Fig. 5 and 6).

FUEL, FIRE, AND EMISSIONS RELATIONSHIPS ARE NEEDED (Problem # 3)

Smoke reduction and management cannot be achieved simply by a chemical and physical characterization of emissions. There is also a need to understand how fuel characteristics and fire behavior are related to the amount and type of combustion products. This information can then be used to develop burning prescriptions that will assist in predicting and minimizing smoke production.

Initially, the activities for this problem (under the leadership of Darold Ward) focused on studies which would lead to particulate matter emission models that extended the utility of the Southern Forestry Smoke Management Guidebook. As a first step, Nelson and Ward (1980) described a relationship between particulate matter emission factors[2] (EF_p) and Byram's fireline intensity[3] (I) for backfires in southern fuels (Fig. 7). Emission factors were predicted by the expression

$$EF_p = 60.8I^{-0.313} \quad (1)$$

for fires with I between 20 and 300 kw m^{-1}.

An extension of that work was published by Ward and others (1980) to include a relationship between EF_p and I for head fires in the palmetto-gallberry fuel type with fireline intensities up to 1750 kw m^{-1} (Fig. 8). A parabolic model fit the data below 500 kw m^{-1} with

$$EF_p = 19.5 - 0.0737I + 0.000145I^2. \quad (2)$$

For a fireline intensity range from 500 to 1750 kw m^{-1}, the equation that best fits the data is

$$EF_p = 16.7 + 0.000243I. \quad (3)$$

It follows from the above equations that particulate matter production can be minimized for prescribed fires in the palmetto-gallberry fuel type by fire management techniques which keep fireline intensity between 200 and 300 kw^{-1}.

A further extension of this work was reported by Ward (1983), who

---

2 Emission factor (EF) defined as mass of particulate matter produced per unit mass of fuel consumed, expressed as grams per kilogram g kg^{-1} or the English equivalent lb ton^{-1}.

3 Fireline intensity (I) is expressed as kilowatts per meter (kw m^{-1}) or the English equivalent BTU sec^{-1} ft^{-1}.

proposed a method for estimating particulate matter emission rates[4] using flame length as the independent variable. Flame length tends to integrate those factors affecting smoke production for fire conditions where flaming combustion dominates and smoldering does not persist for longer than 30 minutes.

Given an emission rate model, a forest manager can apply a number of fire management techniques to burn under conditions that accomplish burning objectives while minimizing the adverse environmental effects caused by smoke production. The model can also be used in conjunction with the Southern Forestry Smoke Management Guidebook to predict smoke concentrations downwind from the source.

The draft problem analysis prepared in 1980 to guide the work in Problem 3 gave emphasis and priority to modeling emissions from burning forest residues. Shortly afterwards, D. Ward was transferred to the Pacific Northwest Station to address the urgent needs in that region for smoke management. Emphasis and priority were given to reducing emissions from the broadcast burning of forest residues in the Pacific Northwest.

With the loss of a key scientist and the need to minimize any duplication of effort, we revised our Problem 3 problem analysis. The new analysis was approved in June 1983 and given the title, "Fuel, Fire, and Emissions Relationships in Wildland Combustion Processes are Inadequately Described" (McMahon and others 1983). We focused on three broad problem areas:

1. Reducing smoldering combustion in southeastern fuel types.

2. Moisture relationships in dead forest fuels.

3. Developing remote-sensing methods for fire behavior and fire effects applications.

Smoldering Combustion

The progress made in recent years in describing smoke from various types of forest fuels has provided much needed information on smoke properties, fuel, and emissions. The early research efforts were geared at filling major voids needed to rapidly produce a state of knowledge guidebook (Southern Forestry Smoke Management Guidebook 1976) and a national EPA source assessment document (Chi and others 1979). Very little research was aimed at providing cause and effect relationships among fuel, fire, and emission characteristics. Earlier fire research dating back to the 1940's did develop some fuel and fire relationships; but the emissions component of the process was largely ignored because air quality was not a major issue and air resource management was not a well-established concept. In those days, fire research was aimed at

---

[4] Emission rate (ER) is defined as the rate of production of emissions per unit length of fireline expressed as micrograms per meter per second or the English equivalent pounds per foot per second.

providing a better understanding of fire danger, fire occurrence, fire suppression, and fire behavior. Research objectives and methodology dealt primarily with the flaming or active phase of the combustion process. The smoldering phase did not receive much attention because it was not perceived to be related to operational needs. In effect, when smoldering combustion commenced, most fire problems ceased. Ironically, it has become increasingly evident that one of the most serious smoke problems in the South is associated with the smoldering stage of the combustion process. During this stage of combustion, the fire is often judged to be out, but smoke continues to be produced by smoldering snags, logs, stumps, or organic soil. Local visibility can be seriously impaired; property is damaged or lives lost because of smoke transport into sensitive areas (especially toward the end of the day). This smoke effect is similar to the one described in the Southern Forestry Smoke Management Guidebook during the no-convective-lift phase[5] of combustion. The smoke is produced during the smoldering combustion of ground fuels which actually carry the fire. Due to the low rate of heat release in this phase, the smoke tends to stay near the ground, creating smoke problems in the local area.

The research question posed by this problem component is: How are fuel characteristics and fire behavior related to smoldering combustion? The operational question is: How can the smoke impact from smoldering combustion be predicted and minimized? These considerations raise more specific questions on how live fuels, duff moisture, and moisture gradients in the fuel layer affect the smoldering component in spreading fires. For fires in piled or windrowed fuels, the relationship of fuel particle size, fuel bed porosity, and fuel bed arrangement to duration of smoldering combustion remains unknown.

There is little doubt that smoke production and smoldering potential are strongly affected by fire behavior and firing techniques; however, quantitative relationships are lacking for most fuel and fire types. From an operational perspective, a land manager may have a choice of a heading, backing, or strip-head fire in a given situation. It would help if he knew in advance which technique would minimize smoldering combustion and to what degree. Knowing in advance when smoldering combustion might be a problem introduces new options in scheduling and planning prescribed burning.

Information from studies dealing with effects of fuel characteristics and fire behavior can be applied directly to update prescribed burning guidelines, and to improve techniques of writing smoke management plans. In addition, data originating from these studies can be used to strengthen models of fuel complexes, fuel moisture, and fire behavior now used to make management decisions.

---

[5] The convective-lift phase of combustion occurs when most of the emissions are entrained into a definite convection column caused by rapid release and ascent of heat during combustion. The no-convective-lift phase of combustion occurs when no well-defined convection column is present and entrainment of emissions is small.

In order to broaden the range of studies in support of this research, the Southern Forest Fire Laboratory combustion room and wind tunnel facility was renovated in 1983. In addition, some field studies will be conducted using the large outdoor platform described earlier (Fig. 6).

Moisture Relationships in Dead Forest Fuels

Moisture content of dead forest fuels is obviously an important factor determining forest fire burning rates and products of combustion. It is also one of the few combustion-related parameters that land managers can control or factor into their prescribed burning decisions. Although the effect of fuel moisture on rates of fuel consumption and energy release is generally understood, the corresponding effect on composition of the smoke is not well known. It is believed that increasing amounts of live fuel in the burning material are associated with increases in particulate matter (or smoke) production per unit mass of consumed fuel since reduced energy release is expected to lead to less efficient combustion. A similar effect is expected when dead fuels at high moisture contents are added. However, these effects have not been demonstrated with carefully controlled experiments.

This discussion is limited to information gaps and needed studies of fuel moisture in dead fuels. Fire behavior models and the National Fire Danger Rating System (NFDRS) attempt to predict effects of dead fuel moisture content. Both user and research personnel have suggested that the NFDRS generally overestimates the drying rates of southern fuels, thus causing an overestimation of fire danger.

Further work on forest fuel moisture relationships is needed. One problem in the NFDRS is that its derivation is based primarily on moisture relationships and drying rates of wood. In many areas, especially in the South, a fire's growth is determined by its spread through a layer of pine needles, grasses, and other plants on the forest floor. Information on these fuels, as well as wood, should form the basis for modeling fire behavior and moisture changes in southern fuels.

Understanding moisture relationships in forest fuels and describing them quantitatively can be divided into three researchable areas:

1. Equilibrium relationships.

2. Rates of moisture loss.

3. Effects of cycling and infiltration.

Equilibrium relationships.--Equilibrium moisture contents are determined by relative humidity, ambient temperature, and sorption history. The research needs can be subdivided into four categories: isotherm characterization, weathering effects, hysteresis effects, and fuel classification.

(1) Isotherm characterization.--The graph of moisture content of wood or forest fuel in equilibrium with various relative humidities at constant temperature is referred to as a sorption isotherm. Most of the practical work on sorption isotherm characterization has been done for wood and textiles. The model

currently used by most researchers to describe equilibrium forest fuel moisture requires evaluation of five parameters. A model proposed recently by Nelson (1983) uses only two parameters and is mathematically simple. It applies over a relative humidity range from about 5 to 90 percent, and has accurately correlated sorption data for wood and cotton. Its applicability to forest fuel sorption was recently described by Nelson (1984), who applied the model to five sets of sorption data in the literature to illustrate goodness of fit (Fig. 9).

The effect of temperature on equilibrium moisture content has not been extensively studied. A sorption model should be selected and temperature dependence of the parameters studied to resolve questions concerning the temperature effect. This effect is important in equilibrium relationships and in description of the drying process.

(2) Weathering effects.--The effect of weathering of fuels on moisture equilibrium is unclear. Generally, weathering increases the moisture content unless the material lost in weathering is more hygroscopic than the remaining material. There is a need to determine the extent to which sorption isotherms for southern fuels are affected by weathering and to what extent this process determines moisture exchange and retention characteristics.

(3) Hysteresis effects.--Sorption measurements in cellulosic materials are complicated because the amount of water held at equilibrium is determined by the direction from which equilibrium is approached. This hysteresis effect has been studied carefully by wood and textile researchers. The significance of hysteresis in forest fuel moisture relationships is not clear because the magnitude of the effect is not known. Studies of the magnitude and variation in the hysteresis ratio will provide useful information about equilibrium moisture values.

(4) Fuel classification.--Though many fuel types exist on the forest floor, it may be possible to subdivide them into three or four classes in terms of their sorption properties at a constant relative humidity to account for small differences due to species. There is a need to examine the possibilities for combining species, or mixtures of species, into classes according to the values of their sorption isotherm parameters.

In 1983, we began a small-scale laboratory experiment to study the sorption of water in wood and fine forest fuels under controlled conditions of humidity and temperature. Equilibrium moisture contents have been completed for four southern fuels exposed to varying relative humidities at 80°F. Measurements at 95°F are underway, with additional runs at 65°F and 50°F to follow during the winter of 1985.

Rates of moisture loss.--Classical diffusion theory forms the basis for predicting drying rates in processed wood and textiles, as well as forest fuels. The theory, in its most common form, utilizes a constant drying rate coefficient, whereas numerous experiments on wood, textiles, and forest fuels have shown that these coefficients are dependent on the state of the fuel and environmental variables.

Experimental observations of forest fuel drying have been more extensive than theoretical work, but both approaches are needed for studies in this problem component. A significant gap in current understanding of moisture exchange in forest fuels is the form of the gradient that drives moisture diffusion in fuels both above or below the fiber saturation point. Our research plans in this area can be subdivided into three categories--basic mechanisms, surface effects, and model development.

Theoretical work on mechanisms of moisture movement in wood begun in 1982 is rapidly nearing completion, and three manuscripts are in press (Nelson 1985, 1985b, 1985c). The first two papers identify the driving force for bound water diffusion and describe a model of diffusion under isothermal conditions. The third paper confirms the ability of thermodynamic equations to describe moisture changes in wood under nonisothermal conditions and discusses a model for calculating rates of change. The results of this work will apply to similar processes in forest fuel particles. A summary of this work was presented by Nelson (1984b) at a recent North American Wood Drying Symposium.

Effects of cycling and infiltration.--Studies of sorption and drying under constant environmental conditions are only preliminary work upon which to build more realistic moisture predictions under field conditions. Our theoretical and laboratory studies just described apply primarily to a "drying phase," but here our interest is centered on a "wetting phase" due to precipitation and to diurnal fluctuations of temperature, solar radiation, relative humidity, and windspeed. Our research plans for this area have been subdivided as follows: diurnal cycling, interception of rainfall by litter, and development of a final model to predict rates of moisture gain and loss. We will begin studies in this area in 1985.

Developing Remote-Sensing Methods for Fire Behavior and Fire Effects Applications

Over the years, research has provided several operational guidelines on how to quantify fire behavior and fire effects. Unfortunately, the research database is often narrow while the operational applications are broad; as a result, models don't seem to fit in specific cases. In prescribed burning and in control of wildfires, personnel are often required to make subjective estimates of phenomena that are difficult to define and measure (e.g. flame length and tree scorch).

This component of the problem analysis is aimed at developing objective and quantitative methods for measuring fire behavior and effects through the use of low-cost photo and video techniques. In the process, we hope to broaden and strengthen the research database for some of the models that apply to fire behavior and fire effects.

Fire behavior applications.--Estimated flame length is one of the most widely used descriptors of fire behavior. Recent experiences at our laboratory indicate that 50 percent error can occur between an observer estimate and an accurate photographic measurement. Furthermore, in operational fires, flame length as currently defined (distance from flame tip through the center of the flame to the fuel surface) is often obscured by a curtain of flame surrounding the elliptical-shaped fire fronts. Better methods for measuring fire behavior are needed using flame geometry techniques as suggested by Nelson (1980). Photographic measurements of flame length offer the opportunity to replace subjective estimates with objective quantitative appraisals that can be documented and retrieved for later reexamination (Adkins and others 1976; Clements and others 1983).

Portable video cameras and recorders show potential as an improvement over photographic methods for fire behavior research both in technical features and for a fraction of the cost. Advances in image tube technology produce well-defined images of flame, and camera-recorder systems have integral calendar-clock annotation. An approximate cost comparison based on running time for continuous operation between video and 16-mm film is--film $6.90/min. versus $.12/min. for video tape. Once the photo or video image is acquired, computer-based image analysis systems can be employed for rapid data reduction and analysis (Fig. 10).

In 1983, a study was initiated in the recently renovated Fire Lab wind tunnel (Fig. 11) to examine video images of flame geometry as useful descriptors of fire intensity. Results should provide fire researchers with a low-cost, objective method for quantifying fire behavior. Further development should yield a system with low-cost operational utility.

<u>Fire effects applications</u>.--The inability to easily and accurately measure flame length and/or fire intensity has hampered fire researchers from fully describing the effects of fire on forest and range ecosystems. Although numerous studies have been conducted to determine the relationship of fire intensity to fire effects, many investigators are forced to use subjective estimates of fire behavior and tedious, labor-intensive methods for describing fire effects. In some cases, the ecosystem reponses to fire are reported without any descriptive, quantitative statement of fire treatment level or fire intensity. Promoting the use of prescribed fire will be difficult without developing more economical and accurate methods for measuring fire effects. Aerial photography, combined with computer-based image analysis, should help to solve this problem.

Determining the effects of prescribed fire treatment on living trees is one of the more important objectives of fire research and forest management. Present methods such as line transect sampling of crown scorch height for fire intensity are highly subjective. Prescribed fire effects can range from enhanced growth and yield to various degrees of scorch, leading to reduced growth rate or, in severe scorching, total tree kill. Quantifying tree scorch and other fire effects in forest stands is complex because of the number of variables that need to be considered. Site factors such as soil type, drainage, accumulation of understory fuels, fire history, and age of stand all enter into the ability of trees to withstand fire. Determining how these factors affect a site before and after a treatment with prescribed fire is necessary if the net effects from that fire on the forest are to be isolated and evaluated. In the past, age of stand and age of rough were usually provided as descriptors of site conditions prior to a prescribed fire. This information may not be adequate in describing site conditions prior to burning and, consequently, the effect of various fire intensities. Questions concerning the preburn and afterburn conditions of forest stands continue to shadow results from prescribed fire treatment because no practical quantitative method exists for determining forest stand conditions that integrate all site factors and fire effects.

Measurements of increases in tree diameter and height to determine effects of fire on growth are expensive and highly variable, considering the manpower and time required to sample even a small portion of one experimental field fire. Aerial color infrared (CIR) photography combined with computer-based image analysis offers a possible solution to problems with characterizing forest sites and determining the fire effects. The ability of aerial CIR photography to contrast diseased, stressed farm crops and trees that otherwise are invisible to humans is well documented. Physical changes to plants and foliage that are caused by disease affect their reflectivity of the electromagnetic spectrum. Differences in color are easily distinguished visually in the advanced stages of infection, but the reflectivity in the near infrared of material from a stressed plant or tree is altered dramatically and can be detected before the stress becomes visually apparent using a film that is sensitive to that band of electromagnetic radiation. Other conditions of the forest, such as time of year, age of stand, differences between sites, and moisture content of leaves and needles, also affect infrared reflectivity. Since CIR film can detect these differences, it may be possible to better define conditions of sites prior to experimental burns so that the effects of the fire can be isolated from other site stresses. Heat effects from prescribed fires and wildfires may affect the near infrared reflectivity of foliage and plants. The variation in reflectivity of a subject can be measured from photographic film both for color and density. If varying intensities of heat applied to tree crowns affect the infrared reflectivity proportionally to the amount of heat received, then by measuring this difference on the film, the heat effect can be quantified. Comparing film density readings with ground measurements of crown scorch would be required to calibrate this method as a remote sensing technique.

Before any field efforts to test this concept are initiated, we plan to conduct a laboratory experiment with a controlled heat laboratory furnace to test changes in infrared reflectivity of live fuel samples as affected by known quantities of heat. This preliminary work should begin in 1985.

TECHNOLOGY TRANSFER

Our Project's accomplishments are being applied at the regional and national level. Research users include fire scientists conducting prescribed burning research and earth scientists studying the effects of fire and smoke on atmospheric chemistry and climate. Operational users include: federal land managers responsible for air resources and federal and state personnel involved in smoke management, prescribed fire, and fire management planning. Some recent technology transfer activities include:

1. May 1982 and March 1983. Forestry smoke characteristics and their impact on air quality were presented at a prescribed fire management course to Forest Service and other land management personnel at the National Advanced Resource Technology Center at Marana, Arizona.

2. June 1983. A session on forest fire emissions was presented to a national air-quality audience at the Air Pollution Control Association Annual Conference.

3. January 1984. Smoke characteristics and management lectures were presented at the USFS Region 8 Prescribed Fire and Smoke Management Workshop.

4. 1984. Provided chapter material for the National Smoke Management Guidebook under the sponsorship of the National Wildfire Coordinating Group.

5. 1985. A video tape program about smoke characteristics and smoke monitoring were presented to an interagency audience at the Smoke Management Workshop, Marana, Arizona, and nine regional locations.

CONCLUSIONS

If wildland fire managers are to expand prescribed burning programs while minimizing detrimental environmental effects, they will need improved understanding that only research can provide. Research can help to reduce smoke from smoldering combustion, it can determine moisture relationships in forest fuels, and it can develop remote sensing methods for fire behavior and effects.

The art of smoke management, begun in the Southeast in the 1970's, has evolved into the science of smoke management. At local, regional and national levels, wildland managers have developed partnerships with air-quality specialists resulting in reasonable guidelines instead of harsh regulations. We must sustain our progress by continuing to accept our new role as air resource managers and by incorporating smoke management guidelines into our prescribed burning programs. In addition, we must be prepared to address new national regulations dealing with small particles and visibility standards. Even more compelling is the need to find ways to reduce smoke-caused accidents on highways which crisscross the prescribed burning network in the South.

The tools for smoke management are building blocks of knowledge which deal with fuel, fire, emission, and weather variables. Although some information is already available, much remains to be accomplished if we are to greatly expand the use of prescribed burning in the South. In the years ahead, the Southern Forest Fire Laboratory will continue to provide the leadership in developing new tools for prescribed burning and smoke management.

LITERATURE CITED

Adkins, C. W., and H. B. Clements
1976. Photographic measurements of flame size over flat terrain. Functional Photography 11(6): 32-34.

Chi, C. T., D. A. Horn, R. B. Reznik, and others
1979. Source assessment: prescribed burning, state of the art. EPA-600/2-79-019h, U. S. Environmental Protection Agency, Research Triangle Park, NC, 107 pp.

Clements, H. B., and C. K. McMahon
1980. Nitrogen oxides from burning forest fuels examined by thermogravimetry and evolved gas analysis. Thermochimica Acta 35: 133-139.

Clements, H. B., and C. K. McMahon
1984. A microcombustion method to measure forest fuel emissions. J. Fire Sci. 2: 260-275.

Clements, H. B., C. K. McMahon, and P. B. Bush
1984. Pesticides released from burning treated wood. NAPIAP Progress Report 7/31/84. [Data on file: USDA Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, GA].

Clements, H. B., C. K. McMahon, and P. B. Bush
1984b. Release of herbicides from the burning of treated understory forest fuels. NAPIAP Progress Report 5/11/84. [Data on file: USDA Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, GA].

Clements, H. B., D. E. Ward, and C. W. Adkins
1983. Measuring fire behavior with photography. Photog. Eng. and Remote Sensing 49(2): 213-217.

McMahon, C. K.
1981. Effects of The Clean Air Act on prescribed burning. In: Proceedings, Symposium on Prescribed Fire and Wildlife in Southern Forests; 1981 April 6-8; Myrtle Beach, SC; 16 p.

McMahon, C. K.
1982. Slash burning studied. In: Lyon, C. B., ed. Forest Fire News. Washington, DC: U.S. Department of Agriculture, Forest Service, January 1982; 16 p.

McMahon, C. K.
1983. Characteristics of forest fuels, fires and emissions. Pap. No. 83-45.1. In: 76th Annual Meeting of Air Pollution Control Association; 1983 June 19-24; Atlanta, GA; 24 p.

McMahon, C. K., R. M. Nelson, Jr., and C. W. Adkins
1983. Fuel, fire, and emissions relationships in wildland combustion processes are inadequately described. RWU FS-SE-2110 Problem Analysis #3; [Data on file: USDA Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, GA].

McMahon, C. K., and C. D. Tangren.
1981. Characterization of wildland smoke. RWU FS-SE-2110 Combined Problem Analysis #1 and #2; [Data on file: USDA Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory, Macon, GA].

McMahon, C. K., and S. N. Tsoukalas
1978. Polynuclear aromatic hydrocarbons in forestry smoke. In: Carcinogenesis, Vol. 3: Polynuclear Aromatic Hydrocarbons, P. W. Jones and R. E. Freudenthal, eds.; New York: Raven Press; pp. 61-73.

McMahon, C. K., D. D. Wade, and S. N. Tsoukalas.
1980. Combustion characteristics and emissions from burning organic soils. Pap. No. 80-15.5 presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec (June 1980).

McMahon, C. K., J. D. White, and S. N. Tsoukalas.
1984. Organic compounds in the particulate matter from burning organic soils. In: Proceedings, Environmental Impact of Natural Emissions Speciality Conference. Publ. TR-2. Pittsburgh, PA: Air Pollution Control Association: 169-180.

Nelson, R. M., Jr.
1980. Flame characteristics for fires in southern fuels. Res. Pap. SE-205. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Nelson, R. M., Jr.
1981. An evaluation of the carbon balance technique for estimating emission factors and fuel consumption in forest fires. Res. Pap. SE-231. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Nelson, R. M., Jr.
1983. A model for sorption of water vapor by cellulosic materials. Wood and Fiber Sci. 15(1): 8-22.

Nelson, R. M., Jr.
1984. A method for describing equilibrium moisture content of forest fuels. Can. J. For. Res. 14(4): 601-604.

Nelson, R. M., Jr.
1984b. A model for bound water diffusion in wood. In: Proceedings, North American Wood Drying Symposium, Mississippi State, MS: Forest Products Laboratory; 1984 November 27-28.

Nelson, R. M., Jr.
1985. Diffusion of bound water in wood. Part I. The driving force. [In press]. Wood Sci. Technol.

Nelson, R. M., Jr.
1985b. Diffusion of bound water in wood. Part II. A model for isothermal diffusion. [In press]. Wood Sci. Technol.

Nelson, R. M., Jr.
1985c. Diffusion of bound water in wood. Part III. A model for nonisothermal diffusion. [In press]. Wood Sci. Technol.

Nelson, R. M., Jr.
1980. Backfire particulate emissions and Byram's fire intensity. Res. Note SE-290. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 6 p.

Patterson, E. M., and C. K. McMahon
1984. Absorption characteristics of forest fire particulate matter. Atmos. Environ. 18(11): 2541-2551.

Patterson, E. M., and C. K. McMahon
1985. Studies of physical and optical properties of forest fire aerosols. In: Proceedings, Conference on Large Scale Fire Phenomenology; 1984 September 10-13; Gaithersburg, MD. [In press].

Ryan, P. W., C. D. Tangren, and C. K. McMahon
1979. A balloon system for profiling smoke plumes from forest fires. Pap. No. 79-6.1. In: 72nd Annual Meeting of the Air Pollution Control Association; 1979 June 24-29; Cincinnati, OH; 24 p.

Tangren, C. D.
1982. Scattering coefficient and particulate matter concentration in forest fire smoke. J. Air Pollut. Control Assoc. 32(7): 729-732.

Ward, D.E.
1983. Particulate matter emissions for fires in the palmetto-gallberry fuel type. For. Sci. 29(4): 761-770.

Ward, D. E., H. B. CLements, and R. N. Nelson, Jr.
1980. Particulate matter emission factor modeling for fires in southeastern fuels. In: Proceedings, Sixth Conference on Fire and Forest Meteorology of the American Meteorological Society and Society of American Foresters; 1980 April 22-24; Seattle, WA; 9 p.

Ward, D. E., C. K. McMahon, and D. F. Adams
1982. Laboratory measurements of carbonyl sulfide and total sulfur emissions from open burning of forest biomass. Pap. No. 82-51.9. In: 75th Annual Meeting of the Air Pollution Control Association; 1982 June 20-25; New Orleans, LA; 16 p.

White, J. D.
1985. Validating a simplified determination of benzo(a)pyrene in particulate matter from prescribed forestry burning. [Submitted for publication to Am. Ind. Hygiene Assoc. J.; Data on file Southern Forest Fire Laboratory, Macon, GA.]

White, J. D., C. K. McMahon, and H. L. Gibbs
1985. The ratio of benzo(a)pyrene to particulate matter in smokes from prescribed burning in the Southeast. In: Proceedings, 4th Annual National Symposium on Recent Advances in Pollutant Monitoring of Ambient Air and Stationary Sources; 1984 May 8-10; Raleigh, NC. [In press].

U.S. Department of Agriculture, Southern Forest Fire Laboratory Staff
1976. Southern Forestry Smoke Management Guidebook. Forest Service Gen. Tech. Rep. SE-10, U.S. Department of Agriculture, Southeastern Forest Experiment Station, Asheville, NC; 140 p.

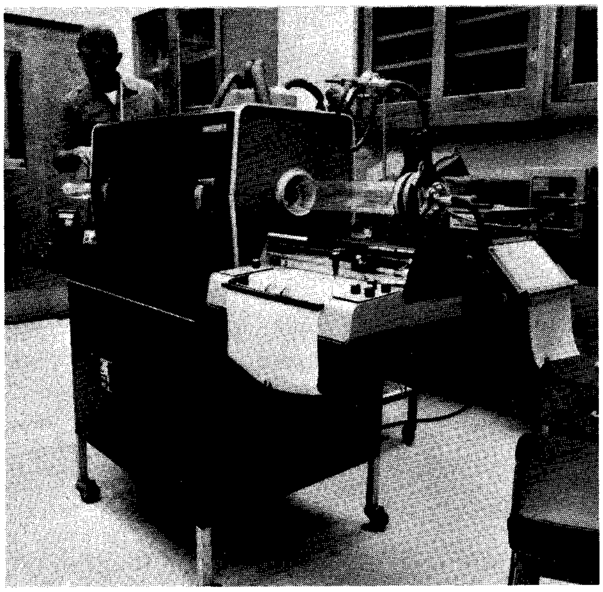

Figure 1.--A combustion tube furnance. Temperature, flow rate, and composition of combustion gases can be controlled by the operator.

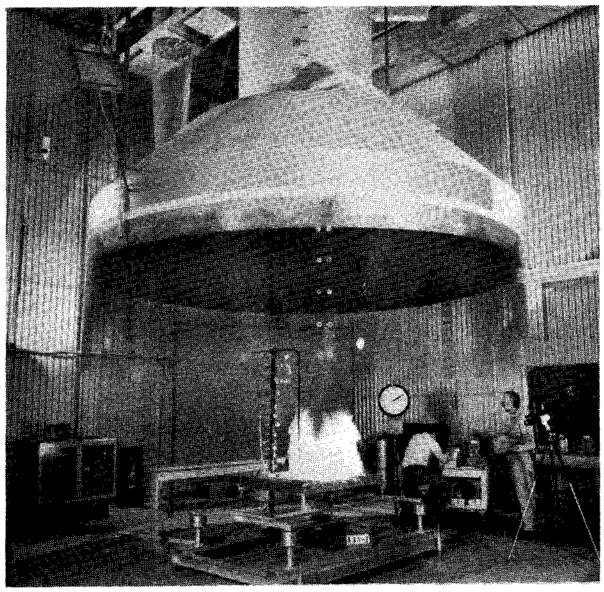

Figure 2.--Southern Forest Fire Laboratory Combustion Room. Slope of burn table can be adjusted to alter burning conditions.

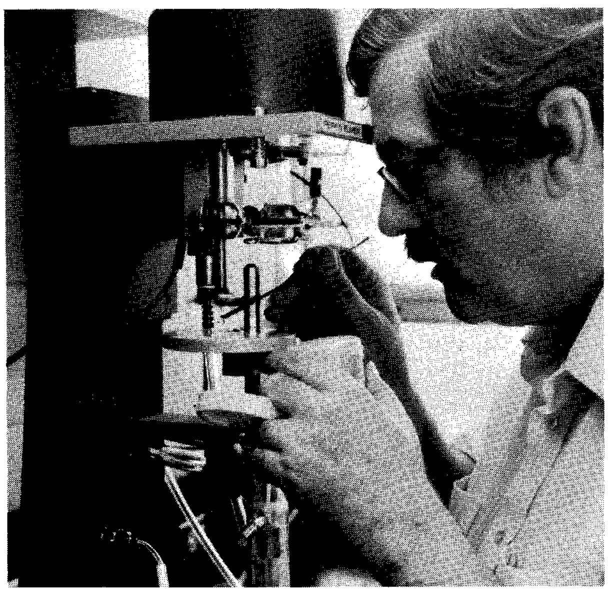

Figure 3.--A Thermogravimetric System is a useful microcombustion apparatus. The balance pan is being loaded with a fuel sample.

Figure 4.--Portable sampler for monitoring emissions from burning forest fuels.

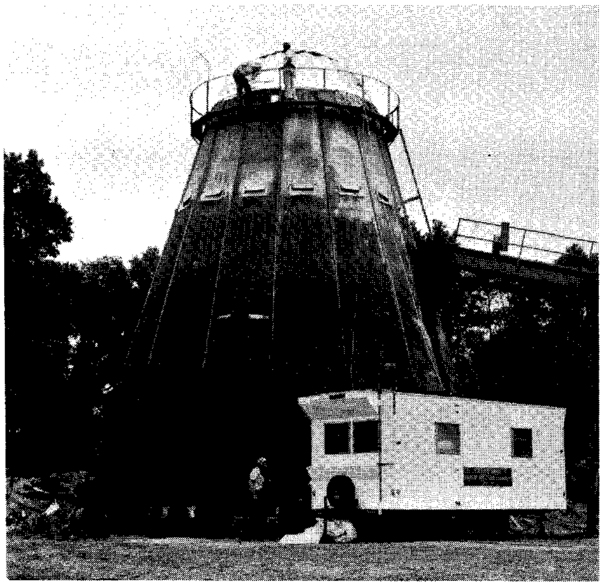

Figure 5.--A tepee burner was converted into an experimental combustion chamber. Emission monitors were installed at the tepee outlet.

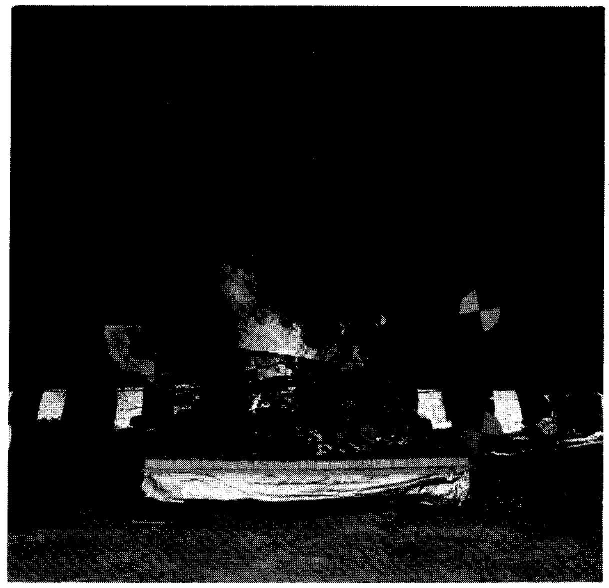

Figure 6.--A transducer-based weighing platform was used to continuously monitor combustion rate during flaming and smoldering periods.

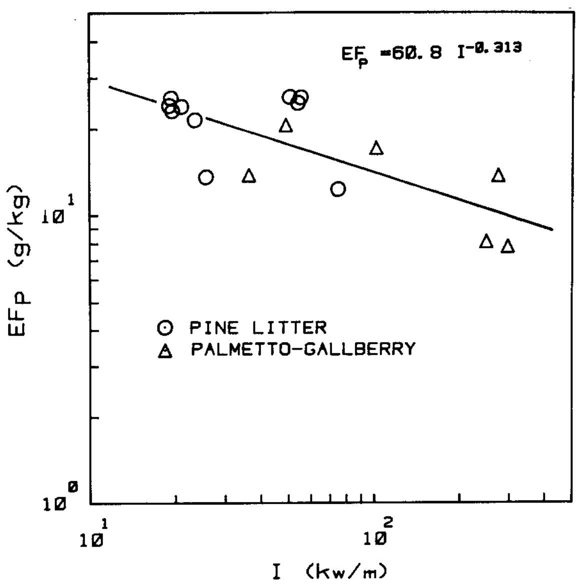

Figure 7.--Particulate matter emission factors for backfires in southern fuels as a function of Byram's fire intensity (Nelson and Ward 1980).

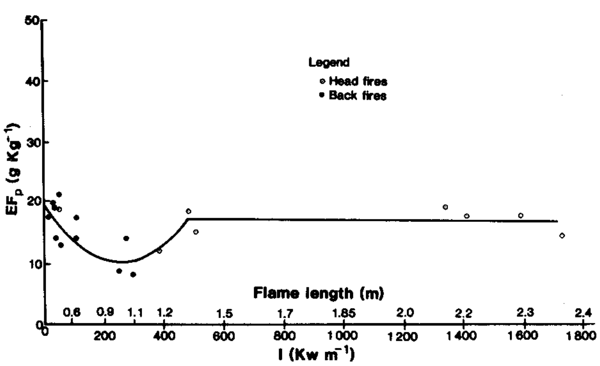

Figure 8.--Relationship between particulate matter emission factors (EF_p) and fireline intensity (I) for the palmetto-gallberry fuel type (Ward 1983).

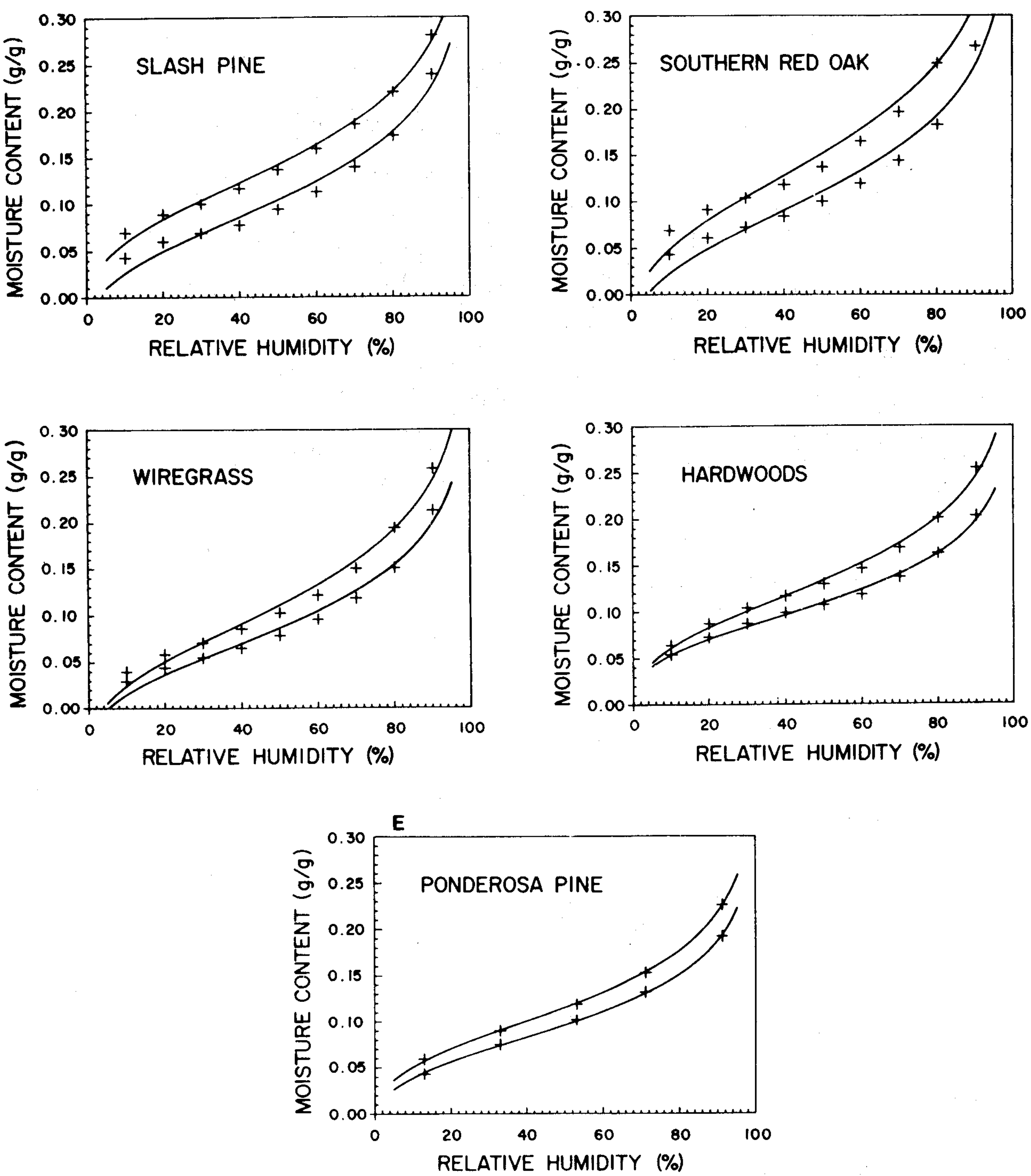

Figure 9.--Model representation of adsorption and desorption data for five forest fuels and temperatures. Upper curves are for desorption and lower curves for adsorption. The line represents model calculations; + represents experimental data (Nelson 1984).

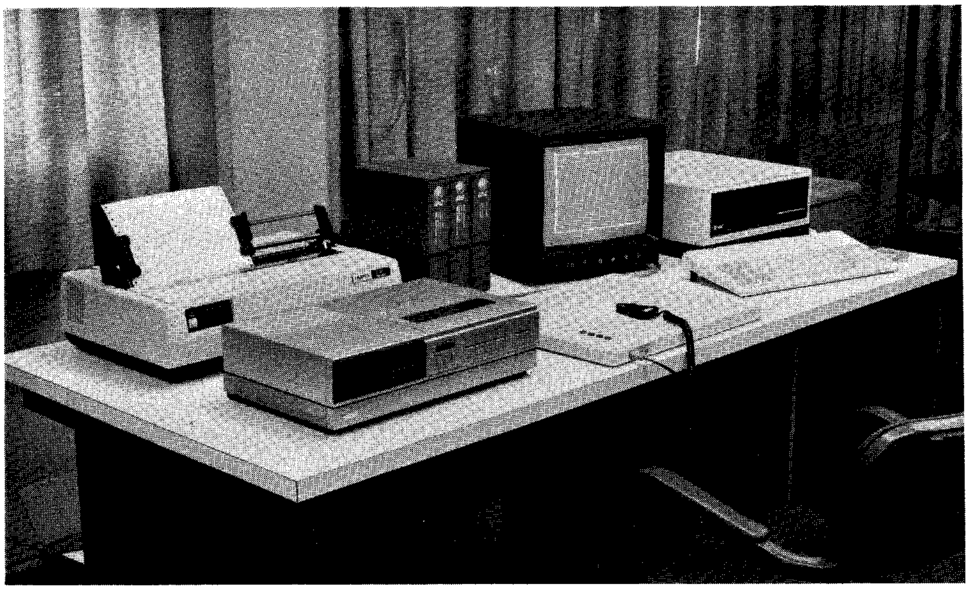

Figure 10.--A computer-based image analysis system permits rapid data reduction and analysis of fire parameters acquired by photo and video cameras.

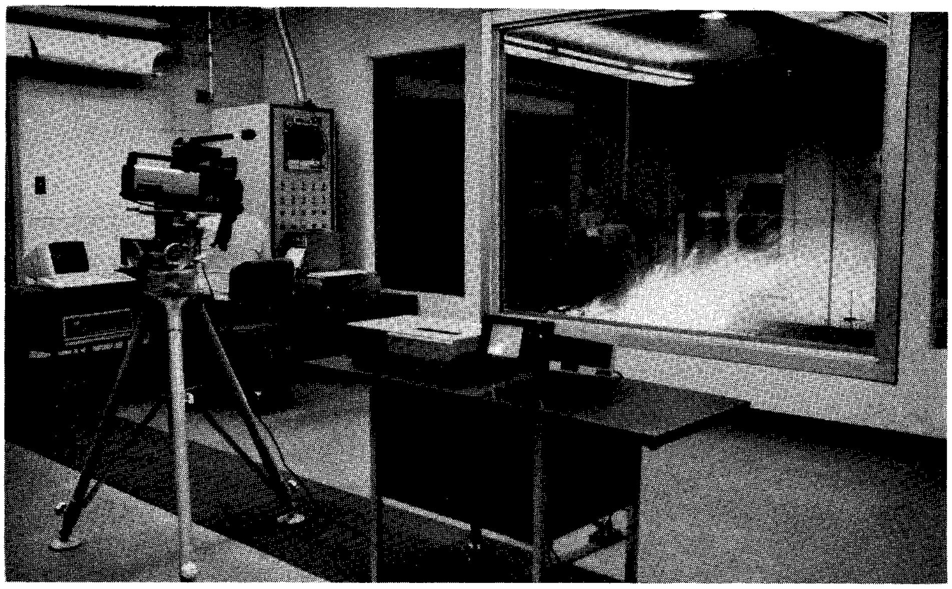

Figure 11.--Southern Forest Fire Laboratory Wind Tunnel. Small-scale fires can be burned under controlled conditions of windspeed, fuel moisture, and fuel loading.