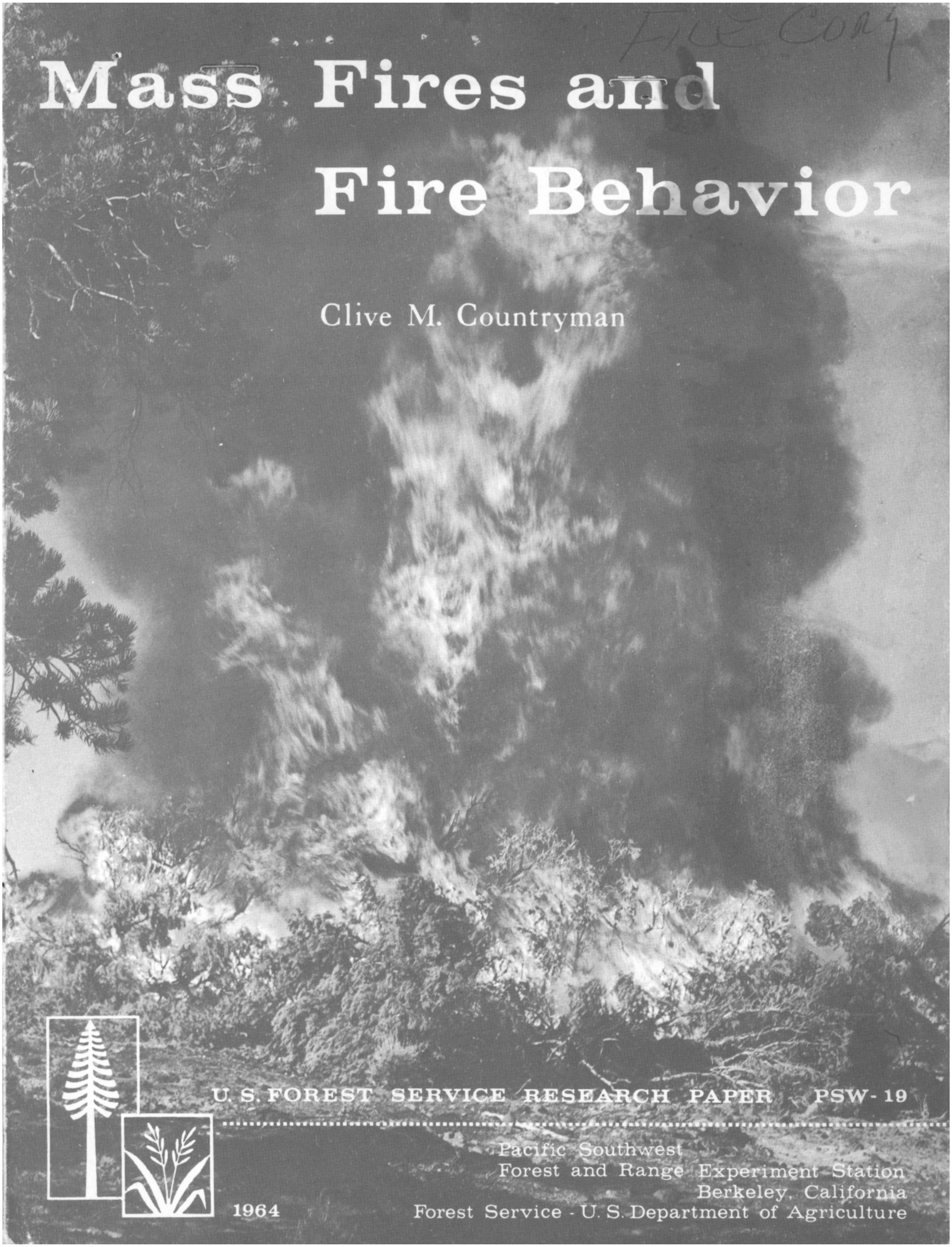
Mass Fires and Fire Behavior

Clive M. Countryman



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Foreword

Subtask 2521E, "Interaction of Mass Fire and Its Environment, " sponsored by the Office of Civil Defense, Office of the Secretary of the Army, has been designed to help alleviate the lack of quantitative information on the characteristics and behavior of mass fire. The broad objectives of the project, as stated in the contract (OCD-OS-62-173, OCD-PS-64-3), are to:

1. Investigate and seek to establish the relationship of fire spread, fire intensity, and other fire behavior characteristics of mass fire in relation to air mass, fuel, and topography and to determine the effect of the fire system itself on the environment surrounding it under various synoptic conditions.
2. Investigate the rate of energy output of fires under various environmental conditions and also the output of noxious gases that might have a bearing on military and civilian action and safety.

Both field and laboratory work are needed to meet these objectives. Because of the need for quantitative information characterizing large and intense fires, present work has been largely confined to the development of instrumentation and the preparation and burning of field test fires. Size of test fires are being scaled upwards as instrumentation and ability to measure such fires are perfected.

This first interim report reviews knowledge of fire behavior and factors affecting it, describes the test fires that are being conducted, and presents results and observations from the initial phase, April 1962 through June 1964.

This report has been reviewed in the Office of Civil Defense and approved for publication. It should be noted that because of the exploratory nature of the fire tests reported herein, this report does not purport to describe a mass fire resulting from a nuclear weapon attack. The results are suggestive of possible future outputs of this work which could be applicable for operational planning purposes. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

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Contents

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The Author

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The control of large fires is a problem of continuing concern to the Forest Service, other public agencies, and private owners of forest and rangeland. A few large fires each year account for all but a small share of the Nation's forest fire losses. In time of war, this problem can be of vital concern to civil defense. Modern weapons make it possible to ignite mass fires in both rural and urban areas. To improve their ability to combat such catastrophes, the fire services need much more quantitative knowledge of the characteristics and behavior of large fires.

Developing this knowledge is the aim of the studies reported here. They were designed primarily to gather information useful in civil defense problems, but much of the data will be applicable in predicting the behavior of wildfires that take a heavy toll in peace time.

Losses Due to Fire

In World War II, fires resulting from high explosive and incendiary raids often produced physical damages and casualties greater than those caused by the explosions themselves. Bond (1)[1] states that "the destruction was seldom less than two-thirds fire damage and in many cities, notably those of Japan, the damage was practically one hundred percent fire damage. " The loss of life from such fires was enormous. Three raids on Dresden, Germany, on February 13, 1945 resulted in fires that caused an estimated 130, 000 deaths. The much publicized fire storm raid on Hamburg, Germany, caused an estimated 40, 000 deaths. Loss of life was also heavy in the 65 cities in Japan that were wholly or partially destroyed by fire.

Disastrous city fires are by no means confined to military action. The National Fire Protection Association (33) lists 133 major conflagrations in American cities during the period between 1900 and 1950. They include such well-known fires as the San Francisco fire in 1906 which destroyed 28, 000 buildings and caused $350, 000, 000 damage, and the Texas City fire in 1947 which caused $67, 000,000 in damage. Other countries also have suffered disastrous peacetime fire losses. In 1923 an earthquake in Japan started fires in Tokyo that covered nearly 7 square miles (3).

The development of nuclear weapons has greatly increased the potential for destruction by fire. Atomic bombs dropped on Hiroshima and Nagasaki caused fires that burned out more than 6 square miles in the two cities (1). The area subject to immediate ignition and subsequent burn-out from multimegation nuclear weapons has been estimated to be between 450 and 1, 200 square miles, depending on weapon yield and height of burst (32). Under certain conditions ultimate spread from one nuclear explosion has been estimated to be as great as 10, 000 square miles (29).

Not so well known, but rivaling many city fires in damage and casualties, are wildland fires. Many of these are described by Holbrook (27). For example, at about the same time of the great Chicago fire in 1871, a wildland fire in Wisconsin burned 2, 000 square miles and killed 1, 152 persons, more than four times as many as were killed in the Chicago fire.

The huge areas over which ignitions and burn-out can occur with multimegaton weapons makes it virtually certain that wildland areas as well as cities would be involved in fire in many regions. The hazard to life and property in these regions has been greatly increased by recent population changes. In many places suburban developments are encroaching into formerly uninhabited wildlands. These developments do not replace the wildland fuel complex, but merely supplement it

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[1] Numbers in parentheses refer to Literature Cited, p. 51.

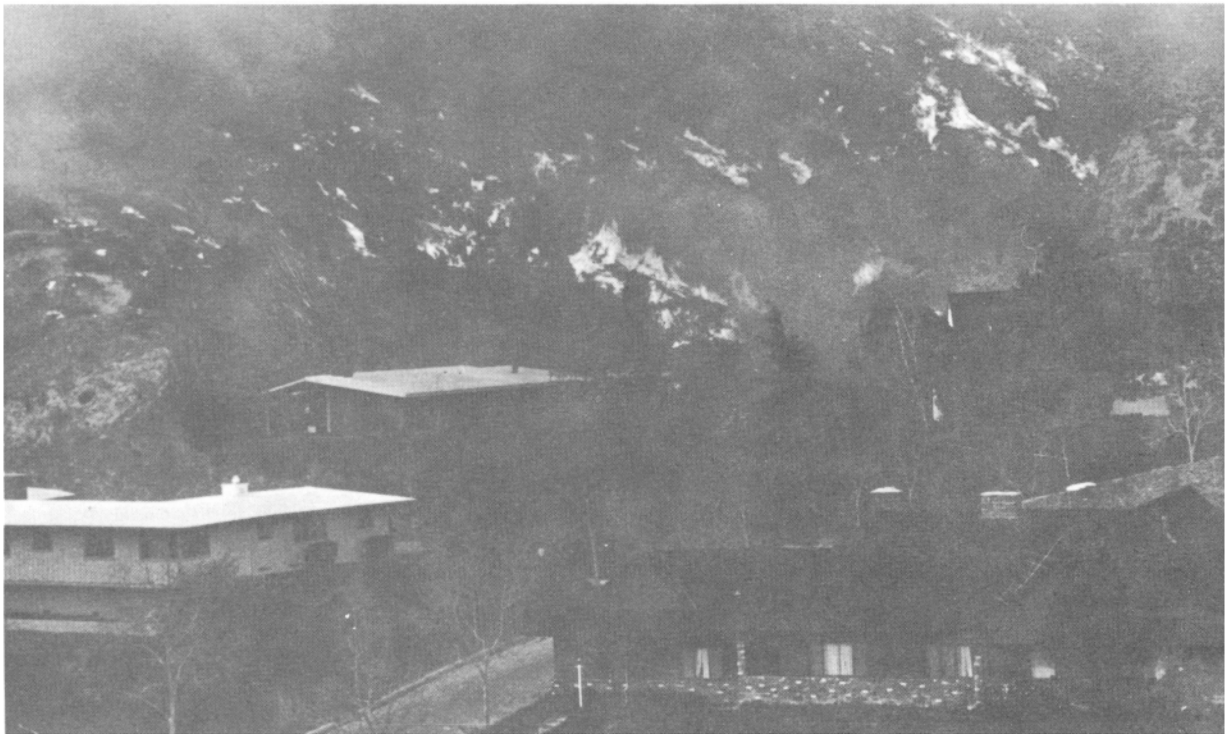


Figure 1.--Dwellings and other structures in urban areas supplement wildland fuels.

Figure 2.--Part of destruction by the Bel Air fire, Los Angeles County, November 6, 1961.

(fig. 1). Fires starting in either structures or wildland fuels can spread from one to the other. The Bel Air fire in Los Angeles on November 6, 1961, which burned 6,090 acres and destroyed 505 buildings, started in wildlands and spread to residential areas where further fire spread was in both structures and wildland fuels (fig. 2). On July 10, 1961, the Harlow fire in the foothills of the Sierra Nevada in California burned 19, 000 acres in 2 hours, and destroyed the towns of Awahnee and Nippinawasee. On March 16, 1964, three fires within the city limits of Los Angeles, Pasadena, Burbank, and Glendale burned 11, 000 acres, destroyed 20 houses, severely damaged 10 more and seriously threatened hundreds of others. One of these fires started from a burning house and spread to wildland fuels; the other two started in wildland fuels from high tension lines arcing in the wind. Although the problems of a wildland residential fuel complex are perhaps most acute in California, similar problems exist in many other areas.

In the spring of 1962, fires in New Jersey burned 186, 000 acres, caused the death of seven persons, and destroyed 500 homes and other buildings. A single fire burned 60, 000 acres in one day.

Increasing recreational use has created additional hazards. During a 46, 000-acre fire in an intensively used recreation area on the Tahoe National Forest, recreationists were--as one of the firefighters put it--"running out of the brush like rabbits." For a time people evacuating the area clogged the roads and hampered movement of fire-control equipment and crews. No loss of life occurred; the fire started as a single spot and spread as a moving front, giving time (sometimes barely sufficient) for people to escape. But escape for many would not have been possible if the fire had started by multiple ignition over the area.

Mass fire from whatever cause, in cities, wildlands, or in combinations of both poses a major threat to civilian populations, property, and natural resources.

Fire and Civil Defense

In event of nuclear or incendiary attack, fire poses three broad problems in the protection and welfare of civilian population:

<u>Protection of personnel</u>. --Provision of shelters or other measures and devices to protect people from fire raises these questions: How will fire affect air supply and quality? How much heat will be produced and for how long? How much area will the fire burn? How quickly will mass fire develop? And how quickly will fire spread to other areas?

<u>Fire control</u>. --To limit fire damage and danger to the population, effective countermeasures are needed to suppress the fire, or at least limit its spread. To take any kind of effective counteraction on a going fire, it is essential to know what the probable behavior will be as the fuels, weather, and topography change during the control effort.

<u>Pre-fire planning</u>. --Pre-fire planning, or pre-attack planning, is concerned with measures taken to minimize possible ignitions and to limit spread of those ignitions that do occur. Here again we need to know what the fire characteristics are likely to be if practical and effective countermeasures are to be devised.

Knowledge of fire behavior is of paramount importance in all three types of problems. We must be able to predict in quantitative terms fire characteristics and fire behavior for the wide variety of environmental conditions and situations that may be encountered.

Status of Fire Behavior Knowledge

What is known about the behavior of free-burning fires? Although we are a long way from a complete understanding of fire behavior and still farther away from being able to write precise mathematical equations of it, there does exist a large store of practical and scientific information concerning fire behavior and fire characteristics. This knowledge has been derived from years of research and operational practice in controlling and using fire.

Research by the National Fire Protection Association and experience of city fire departments have developed considerable knowledge concerning structural and urban fires. Similarly, wildland management agencies have acquired a large store of knowledge concerning fire behavior through research, years of fire suppression activities, and use of fire in wildland management. Fire is now a commonplace tool in wildland management. It is frequently and effectively used in silvicultural practice, in rangeland improvement, and in fuel hazard reduction. Such use of fire is not haphazard--the kind of fire needed to do a given job is obtained through manipulation of fuel and carefully prescribing the firing pattern and conditions of weather and fuel moisture required for each fire. Thus in approaching the solution of fire problems in civilian defense, we approach a field that is not completely new and unknown.

Much of the practical knowledge of fire and fire behavior is concerned with relatively small fires and those of low intensity. Most wildfires are suppressed when small. Control forces are efficient, and the combination of fuel, weather, and topography needed to produce large and intensive fires occur infrequently. Similarly, urban fires involving more than one structure are relatively rare. In applied use of fire, too, burning conditions are selected so as not to produce a fire that cannot be readily controlled.

Research on mass fire has been hampered by the necessity of confining studies to small-scale fires in the open or in the laboratory (fig. 3). Such studies are essential for understanding of fire phenomena. They permit careful control and measurement of experimental conditions, and allow accurate analysis of some basic fire relationships. There is considerable question, however, as to the validity of extrapolating from small fires to the large, intense fires which are of particular concern in civilian defense.

Some characteristics of large fires have not been observed on small fires, either because they do not occur in small fires or because they are too minute to be detected. It seems likely that a different set of controls of fire behavior may take over after a fire reaches a certain size or intensity. Scaling laws that will permit extrapolation of results of small fire studies to large fires have not been developed. In fact, it is not known if such laws can be developed for some aspects of fire behavior. It is an imposing problem to scale to laboratory size only the aerodynamic factors of the range and variety found in the environment affecting a large fire.

The difficulty of extrapolating from small to large fires is further complicated by the fact that behavior of fire is a pattern phenomenon--the behavior at one point is often dependent on the behavior at another point. The behavior of one part of a fire may change even if burning conditions at that point do not vary when the characteristics of the fire at some other point changes. Since fire behavior and characteristics are controlled by the environment in which it is burning, it is necessary to measure both the fire pattern and the environmental pattern controlling it.

Even though large urban fires occur occasionally and large wildfires more frequently, there is little quantitative information concerning them. This is understandable since the time and place that fires will occur is unknown, and the capability of making valid measurements on such fires has been virtually non-existent. Consequently, descriptions of fire behavior on large fires have been largely qualitative. Some attempts have been made to make post-fire analyses and to set up hypotheses for the observed fire behavior. Such analyses have usually been severely handicapped by fragmentary data on environmental conditions and by the uncertainty of eye-witness accounts. In recent years attempts have been made to obtain better information on both large fire behavior and the environmental conditions under which it burned (8, 10).

In general then, one must conclude that although there exists a considerable body of knowledge about the characteristics of small fires and of fires burning under "normal" conditions, there is a dearth of quantitative information concerning large and intensive fires.

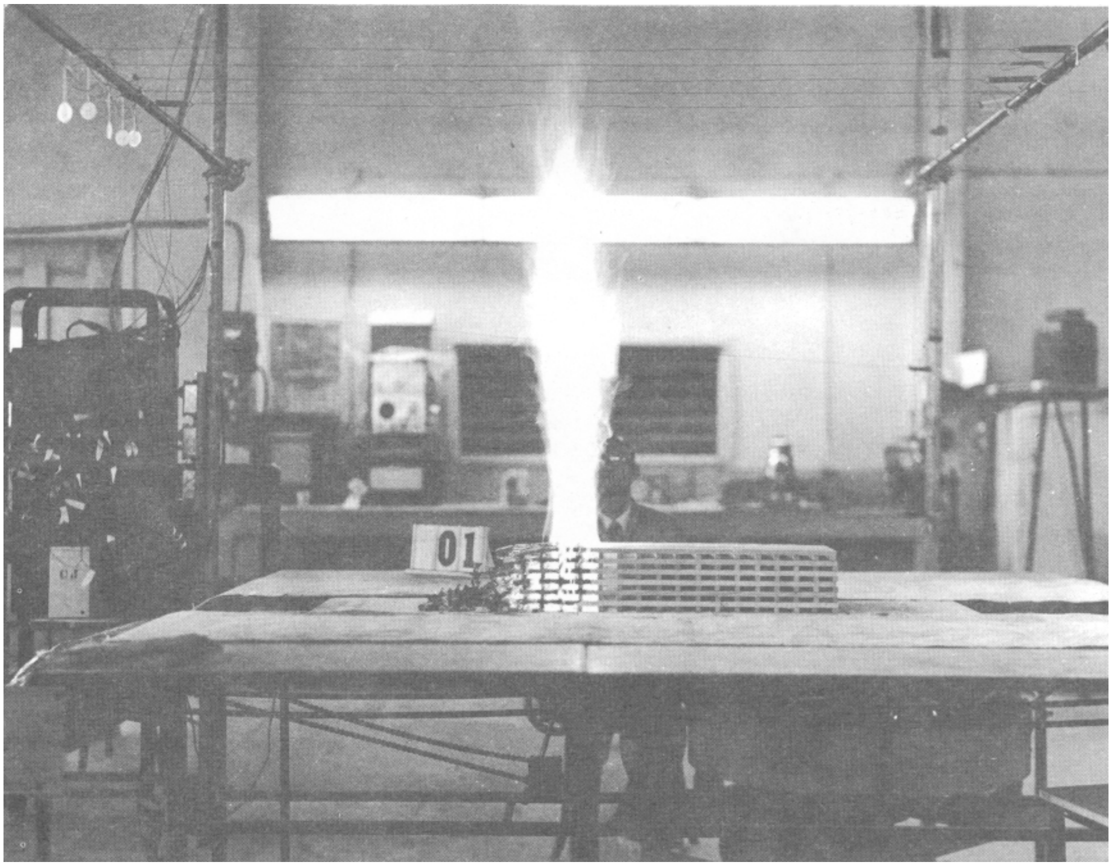


Figure 3.--A laboratory crib fire.

Classification of Mass Fires

Just where on the scale of fire behavior a fire becomes a "mass" fire has never been specifically defined. The term, however, has generally been applied to those fires exhibiting the more violent fire behavior. Fires large in area are not necessarily mass fires. When rates of energy released per unit of area or fire front are low, violent fire characteristics are usually absent, and the behavior of a small sector of the fire is little different than if that sector was burning alone. On the other hand, very small fires burning with a high rate of enemy release also may not exhibit violent fire characteristics. The term "mass fire," then, carries the connotation of both large size and high rates of energy release.

Two broad classes of mass fire are generally recognized. These are:

Fire storms. --Fire storms represent the most violent type of mass fire. They occur when there are many ignitions over a wide area that 'quickly coalesce into a single fire, burning intensely over a large area. Convective activity in these fires is very great, and tall convective columns develop (fig. 4). Fire-induced winds become very strong, and large whirlwinds, or fire whirls, are common. There is usually little outward spread of fire in a fire storm. The lack of spread is probable due to the strong indrafts and also because fire storms appear to develop most readily under light wind conditions.

Conflagrations. --These are hot burning fires with definite and moving "heads" or "fronts" (fig. 5). The depth of the intensely burning area is usually relatively

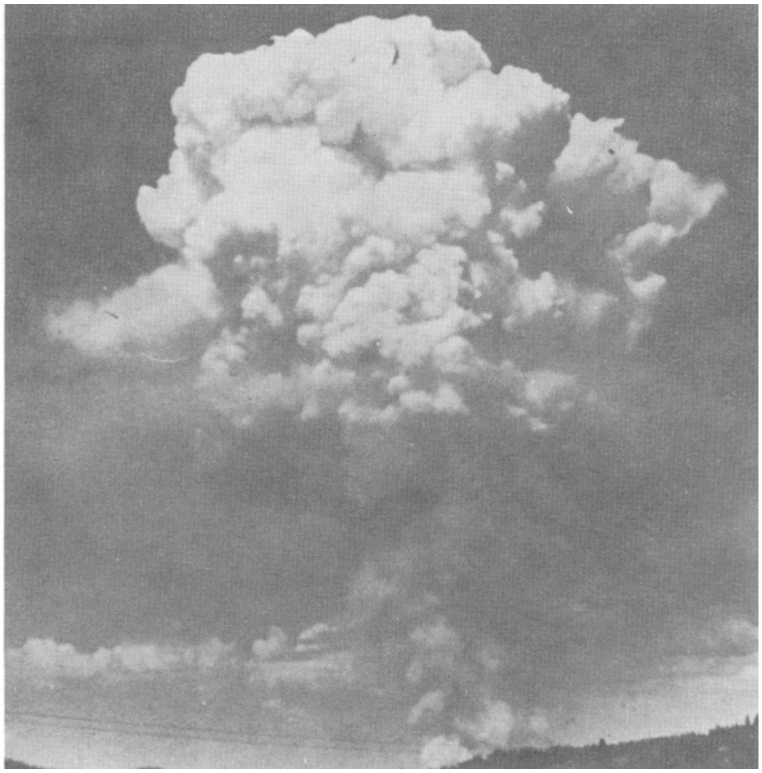


Figure 4.--Tall convection columns are a characteristic of fire storms. This column was estimated to extend to 35,000 feet.

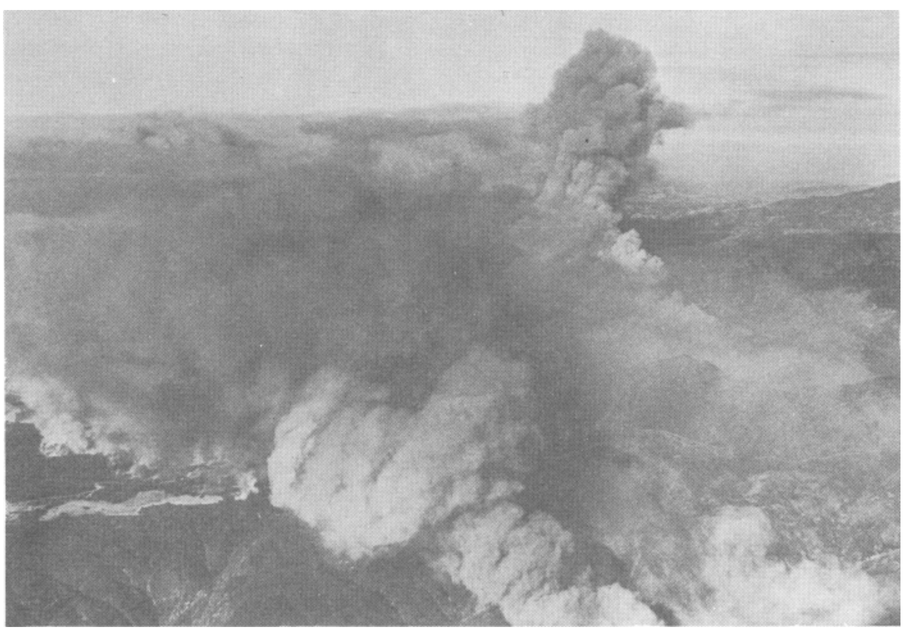


Figure 5.--Conflagrations develop numerous moving fronts or heads.

narrow. Tall convection columns may or may not develop. Whirlwinds and fire whirls often appear in conflagration type fires, but their size, violence, and duration is much less than those associated with fire storms. Conflagrations are strongly affected by wind and topography and, because they can move rapidly, they can burn out vast areas.

As with the separation of "ordinary" fire from mass fire, there is no clear cut line of demarcation between fire storms and conflagrations. Under certain conditions, particularly with the widespread ignition to be expected from nuclear explosions, both types of mass fire can develop at the same time. An ordinary fire may also develop in intensity and activity to a conflagration or fire storm and back again as conditions vary. Such fire behavior is common in wildland fires where spatial variations in fuels and topography are great and the life of the fire if often long enough to burn through major changes in weather conditions.

Fire Environment

"Fire environment" is the complex of air mass, fuel, and topographic factors that affects the inception, growth, and behavior of fire. Fire environment is not fixed, but varies in both space and time. The extent of the environment affecting a fire also changes with the size and characteristics of the fire itself. For a very small fire the environment of concern is limited to a few feet both horizontally and vertically. In a large fire the environmental envelope may cover many miles horizontally and extend thousands of feet vertically.

The factors of fire environment are closely interrelated--that is, changes in one group of factors can cause changes in others. Thus topography can affect local weather through differential heating and cooling of slopes of different aspects. Fuel (vegetative cover) can modify these changes. Weather in turn may modify such factors as fuel moisture and amount or kind of fuel.

Open and Closed Environments

Two broad classes of fire environment can be delineated: closed environment and open environment. In urban conditions the fire environment inside a building is nearly independent of the outside conditions. Fuel arrangement and fuel characteristics are dictated by the construction of the building and its furnishings or equipment. Climate and the moisture content of hygroscopic fuels is controlled by the heating and cooling systems. Wind movement as experienced in the open air is non-existent. There are no topographic effects. This is "closed" or confined environment.

In the city as a whole the environment is not confined. Current weather can vary with the synoptic weather patterns. Fuel temperatures can vary with the aspect and from day to night. Wind movement is almost always present. Topographic effects are prevalent. This is "open" environment.

Fire burning inside a building is controlled by the ,environment within the building. It is little affected by the outside environment. As long as the fire is within the building (fig. 6), there can be no spread to adjacent fuel elements--the fire is confined. Once the fire breaks out of the interior of the building, it is no longer burning in a closed environment. Outside conditions can affect the behavior, and the fire can spread to other fuel and grow in size and intensity (fig. 7).

Although not as clearly defined as with urban conditions, closed and open environments also exist in wildland fuels. A fire burning under a dense timber stand (fig. 8) is burning in an environment quite different than that above or outside the stand. Fuel moisture is frequently much higher and wind movement is greatly slowed within the stand (12). If the fire builds in intensity and breaks out through the crowns of the trees and becomes a crown fire (fig. 9), it then is burning in an

Figure 6.--Fire burning in a closed environment.

Figure 7.--Fire burning in an open environment.

Figure 8.--Fire burning in a wildland closed environment.

Figure 9.--Fire burning in wildland open environment.

open environment and comes under a different set of controls. Fire behavior and characteristics can change radically.

In wildland fuels fires may burn from a closed environment to an open environment and back again a number of times during its life. Such a series of changes is unlikely in urban fires.

Wildland fires that can be classified in the mass fire category are affected strongly by the open environment in which they burn. Knowledge of the fire environment pattern in the area involved often permits the behavior of the fire and the extent of spread to be predetermined (13, 14). In the Forest Service the position of "fire behavior officer" has been established in the fire-control organization to advise on relations between fire behavior and fire environment (9) .

Because much of the fuel in urban areas is in a closed environment, the relation between open environment and mass fire behavior is not as strong as with wildland fires. Open fire environment does have considerable effect on mass fire in urban areas, however, and may be the deciding factor in whether a fire storm or conflagration may develop.

Components of Fire Environment

The major components of fire environment are fuels, topography, and air mass. The study of mass fire in relation to its environment, then, is concerned with fire characteristics and behavior as affected by these three variables.

Fuels

The characteristics of burnable fuels are of major importance in the inception, spread, and behavior of mass fires. Fuel characteristics may be grouped into either fuel particle characteristics of fuel bed characteristics.

FUEL PARTICLE CHARACTERISTICS

Fuel particles are the individual units that make up the fuel bed. They may vary greatly in size. In wildland fuels, the particles may be leaves, twigs, or stems of plants--or even stumps and logs. Fuel particle characteristics known or suspected of being important in ignition and fire behavior are:

Particle geometry. --Particle geometry refers to the shape (flat, irregular, round, angular) and size (thickness, diameter, length) of the fuel particles. Fons (21) found distinctive differences in ignition time and burning rates with variations in fuel particle geometry and used surface-to-volume ratio to quantify the variation in fuel particles.

Surface. --Other factors being equal, fuel particles with rough or fissured surfaces ignite more easily than those with smooth, even surfaces.

Moisture content. --The moisture content of fuel has long been recognized as having major influence on ignition and behavior of fires (25). All wildland fire danger rating systems use moisture content of fuel as one of the major variables (17). Numerous studies have been made of moisture content variations in dead wildland fuels. The moisture content of living wildland fuels has also been the subject of extensive research.

Chemical composition. --Little is. known concerning the effect of chemical composition on combustion and fire behavior., Although chemical differences are known to exist (35), there is surprisingly little difference in the total heat value of common forest fuels. Chemical differences may be reflected in burning rate, however. Observation of wildland fires has indicated that some fuel species burn more readily than others. Kilzer and Broido (30) have found that burning rate may be related to ash content of the fuel.

Specific gravity. - -Fons, et al. (22) found a significant relationship between specific gravity of wood and rate of spread in crib fires.

Thermal absorbtivity. --The thermal absorbtivity of wildland fuels has been found to vary widely (6). , In situations where radiation is important in the inception and spread of fire, this characteristics will be significant.

FUEL BED CHARACTERISTICS

Fuel beds are seldom homogeneous, but consist of a variety of fuel particles. It is the association of these fuel particles, each with individual characteristics, that determines to a major extent the fire behavior. Attributes of fuel beds considered of importance are:

Continuity. --"Continuity" is used to describe the gross distribution of fuel in the horizontal. Fuels may be spread more or less continuously over an area, may occur only in patches with bare areas in between, or may surround bare or nonflammable areas.

Arrangement. --Fuel arrangement refers to the vertical and horizontal distribution of fuel particles of various characteristics. For example, small or "fine" fuel particles may be uniformly distributed vertically throughout the fuel bed or may occur only at the ground level. Similarly, all fuel particles may be close together (compact) or may be widely spaced. Fuels may be concentrated in certain areas with relatively little between these spots.

Amount. --Amount of fuel is the total (dry) weight of fuel per unit of area. This characteristic of fuel beds is probably most easily measured. It must be considered in conjunction with fuel particle and other fuel bed characteristics, however, to be useful in prognosis of fire behavior. For example, an area covered with a few widely-spaced large logs may have the same total fuel weight as an area covered more uniformly with small fuel particles loosely arranged. Behavior of fire in these two areas would be vastly different.

FUELS AND FIRE BEHAVIOR

Observations of wildfires, prescribed burns, and test fires have indicated marked differences in fire behavior apparently associated with variations in fuel bed characteristics. There have been some attempts to quantify these variations in terms of rate of spread or combustion rate in laboratory scale fires and small field tests. Such investigations have not provided enough information, however, to have much practical application.

Studies have also been conducted on wildland fuels to obtain quantitative data on fuel bed characteristics. Most extensive of these was a study conducted on certain chaparral fuels in southern California during Operations Firestop (20). In that study, mil-acre plots of fuel were dissected to obtain amounts and distribution of fuel particles within the fuel bed. Results from typical plots in three different fuel "types" are shown in tables 1 to 3. This illustrates the great variation in characteristics of wildland fuels that are grossly similar in appearance.

In very small fires it is probable that the burning characteristics of individual fuel particles, their arrangement, and continuity are of paramount importance in the growth and spread of fire. Thus with a fire burning in a ground layer of pine needles, the rate of burning of each needle and its distance from the next unburned needle will determine whether the fire will continue to spread. As a fire becomes larger, both horizontally and vertically, the burning characteristics of the more gross elements of the fuel bed will control fire behavior and spread. In a crown fire in a timber stand, for example, it is the burning characteristics of the individual tree and the spacing of trees that determine whether the fire will continue to crown, the fire's intensity, and its rate of spread. The scale of the fire thus is a major factor in determining the fuel bed characteristics of importance in fire behavior.

A close parallel may be drawn between urban and wildland fuels. In urban fires, the characteristics of the individual fuel particles, their arrangement, continuity, and amount in an individual structure will determine the characteristics of a fire in the structure. In a mass urban f ire, however, the individual buildings in effect become the fuel particles and the complex of structures the fuel bed, just as in a. crown fire in timber, the individual tree becomes the fuel particle and the timber stand the fuel bed. In the urban fire, the arrangement and height of buildings of different types (fuel arrangement), their size and number (fuel amount), and the presence or absence of fuel-less spaces (fuel continuity) will determine fire behavior.

Table 1.--Composition of light chaparral fuel type

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	2.19	17.6
Dead	4.10	33.0
Duff and litter	6.13	49.4
Total	12.42	--
Predominant species:		
California sage (*Artemisia californica*)	0.59	9.4
White sage (*Salvia apiana*)	4.45	70.7
Deerweed (*Lotus scoparius*)	1.25	19.9
Height feet):		
Over 6	.00	.0
4-6	.02	.3
2 -4	4.47	7.5
0 - 2	5.80	92.2
Size class:		
Flowers	.00	.0
Leaves	.76	12.1
Twigs to 1/4 in.	2.43	38.5
Stems 1/4 - 1/2 in.	1.45	23.1
Stems 1/2 - 1 in.	.98	15.6
Stems 1 - 2 in.	.76	10.7
Stems 2 in. or over	.00	.0

Table 2.--Composition of medium chaparral fuel type

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	9.76	46.1
Dead	5.32	25.2
Duff	6.06	28.7
Total	21.14	--
Predominant species:		
Chamise (*Adenostoma fasciculatum*)	11.02	73.0
Buckbrush (*Ceanothus cuneatus*)	3.02	20.0
Sumac (*Rhus laurina*)	1.05	7.0
Height (feet):		
Over 6	.92	6.1
4 - 6	2.90	19.2
2 - 4	5.09	33.7
o - 2	6.19	41.o
Size class:		
Leaves	1.20	8.0
Twigs to 1/4 in.	3.80	25.2
Stems 1/4 - 1/2 in.	2.78	18.4
Stems 1/2 - 1 in.	5.51	36.4
Stems 1 - 2 in.	1.81	12.0
Stems over 2 in.	.00	.0

A

B

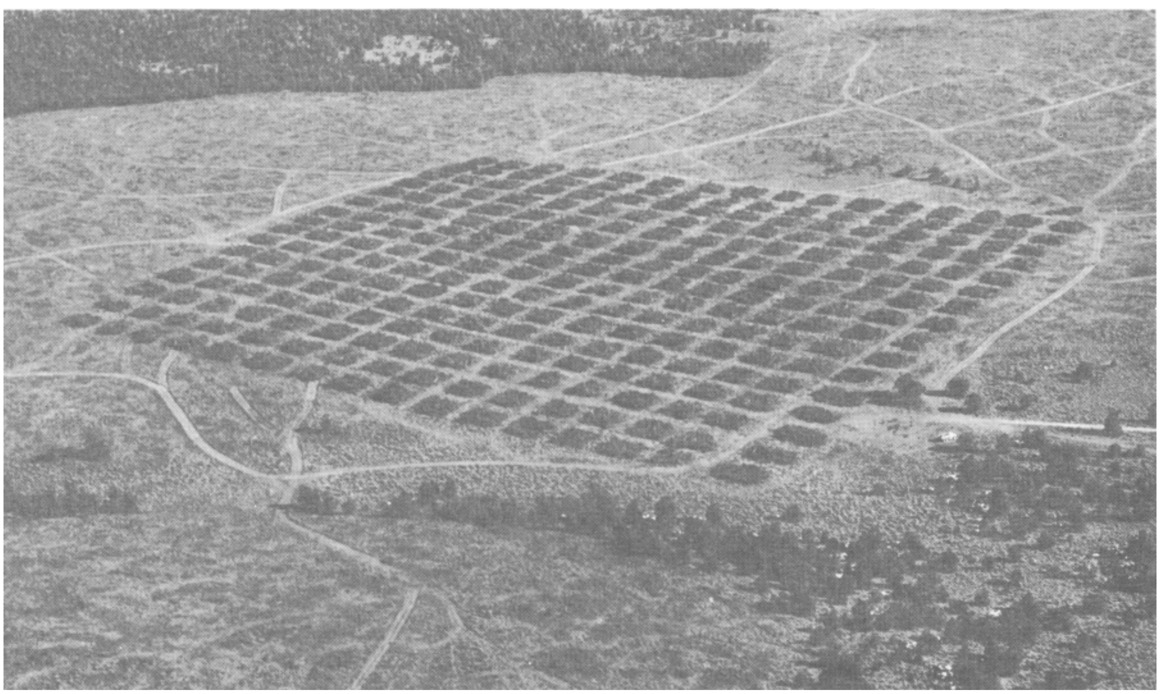


Figure 10.--Residential fuel type; A, new subdivision, B, simulated with wildland fuels in piles 50 feet on a side and spaced 25 feet apart.

Table 3.--Composition of heavy chaparral fuel

Item	Dry weight (tons per acre)	Percent of class weight
Total fuel:		
Living	28.62	72.6
Dead	2.56	6.5
Duff	8.25	20.9
Total	39.43	--
Predominant species:		
Scrub oak (Quercus dumosa)	22.80	73.1
Buckbrush (Ceanothus cuneatus)	8.38	26.9
Height (feet):		
Over 6	7.96	25.5
4 - 6	8.46	27.1
2 - 4	11.42	36.7
0 - 2	3.35	10.7
Size class:		
Leaves	2.64	8.5
Twigs to 1/4 in.	4.04	13.0
Stems 1/4 - 1/2 in.	4.08	13.1
Stems 1/2 - 1 in.	4.45	14.3
Stems 1 - 2 in.	11.36	36.3
Stems over 2 in.	4.61	14.8

The major differences between mass fire in urban and wildland fuels results from the differences in fuel bed characteristics. By arranging wildland fuel in a pile with the same general burning characteristics as a building, a burning building can be simulated. A number of such piles of fuel arranged as buildings in a city can be expected to produce the same kind of fire as would occur in a city (fig. 10). Since it is impossible to burn more than one or two buildings at a time for tests in urban areas, simulation with wildland fuels was the approach used in this investigation.

Topography

Topography has both a direct and an indirect effect on fire behavior. Fires spread more rapidly upslope than on level ground because fuels upslope from the fire are exposed to greater heating from radiation and convection and because of upslope winds are generated by the fire of natural heating. Rate of spread of wildland fires has been estimated to approximately double for each 15 degree increase in slope (38). It is not known if this relationship holds for urban fire, but acceleration of fires uphill in urban fires has also been noted (34, 39).

Fire spread downslope is generally slower than on level terrain because of lessened radiative and convective heating of fuels on the downslope side and opposing convective winds. An exception occurs when fire is spread downslope by rolling debris.

In broken topography with short slopes, fire spread is slower and behavior more erratic than with long, unbroken slopes. Orientation of the topography with respect to windflow is also important in fire spread and behavior.

In general, for short time periods fire spread in hilly or mountainous areas can be much greater than on level or rolling terrain; over longer time periods, spread on the less steep terrain may be greater (11). This difference is attributed to a greater number of breaks and barriers to fire spread in mountainous country. Slow spread downslope is probably also a contributing factor.

Topography affects fire behavior indirectly through its effects on local weather and microclimate (19, 26). The aspect of a slope affects the amount of local heating (23) and thus affects fuel moisture of dead and living fuels. The variation of heating on slopes of different aspects may also be reflected in the kind and amount of vegetation. Differential heating in mountainous areas has a major effect on local wind patterns and hence on fire behavior (13, 14, 16). Channeling of wind flow by topography is also an important indirect effect of topography on fire behavior.

Air Mass

The air mass overlying fuels and topography is perhaps the most variable of the components of fire environment. Near the surface the air mass is affected by the topography and interacts with the fuel. The air mass affects, and may be affected by any fire system that exists. Air mass characteristics now recognized as important in fire behavior are: wind, humidity, precipitation, temperature, and air stability.

WIND

Wind has long been recognized as a major element in fire behavior. Reports of city conflagrations frequently mention strong winds as a major problem (33). Wind also plays a major role in spreading wildland fires. Besides supplying oxygen to the fire and driving the flames forward into unburned fuels, wind can transport burning firebrands far ahead of the main fire. The structure of the wind field above a fire may also have a marked effect on fire characteristics. Byram (5) has associated wind speed profiles with fire behavior and has developed an equation relating strength of the wind field and energy release of a fire to the development of convection columns.

Wind can also have an indirect effect on fire behavior through its effect on fuel moisture (28). When exposed fuels are wet, wind will often promote drying, when more nearly dry, further drying can be slowed by the cooling effect of wind.

HUMIDITY

The effect of humidity on fire appears to be largely an indirect one. The moisture content of hygroscopic fuels is very closely associated with relative humidity. In finely divided fuels, the moisture content follows the relative humidity very closely. Relative humidity alone has sometimes been used as a parameter of fire hazard and a guide for stopping or curtailing operations in timberlands.

Test Procedures

One of the chief aims of the first tests in the study was to identify and describe, both quantitatively and qualitatively, various fire behavior and fire characteristics and the conditions under which they occurred. This store of information will provide the necessary data to (a) develop cause and effect relationships where data are sufficient, (b) check the validity of hypotheses postulated by theoretical or mathematical development, (c) develop hypothesis of fire behavior based on full scale data, and (d) design more sophisticated field or laboratory tests where needed to provide additional information.

Ideally, with this experimental approach it would be desirable to be able to vary fuel and fuel arrangement and the instrumentation to take full advantage of knowledge gained in one test in the next. Practically, however, this is not possible. Much time is required to prepare test plots and to allow the fuels to dry before burning. Weather conditions are variable; to burn under the desired conditions, the test plot must be ready beforehand. Consequently, it was decided to prepare several tests in each of four general fuel types and to vary the instrumentation and conditions under which each test was burned as seemed desirable or was possible.

Plots

One set of tests, called series 428, was in plots up to 92, 000 square feet in area and loaded with fuels almost entirely less than 2 inches in diameter (fig. 11). Fuel consisted of typical central Sierra shrubs, chiefly ceanothus, scrub oak, and manzanita species crushed in place by a bulldozer. Additional fuel was brought into the plots to fill in light spots and provide uniform fuel loading. Fuel depth averaged about 24 inches. The test area (Sugarloaf, Sierra National Forest) had steep terrain. The plots were rectangular, the length being two to three times the width. They were laid out with the long axis generally at right angles to the slope.

Heavy-Fuel Plots

Timber killed by wildfire was used to build plots in the 380 and 330 series (Donner Ridge and Forest Hill test areas). The wildfire had burned most of the fine material in the timber stand, leaving only the tree trunks and the large limbs.

On six plots, the timber was bunched in tree lengths by a bulldozer. The piles varied in size from 7, 200 to 49, 750 square feet (fig. 12). Depth of fuel averaged about 60 inches on all plots except the largest (380-6-63), in which the fuel depth averaged about 96 inches. Fuel loading varied- from 19 to 25 pounds per square foot in the smaller piles. The large plot contained 40 pounds of fuel per square foot.

On one additional plot in this area, 102, 000 pounds of brush were brought into the plot and spread among the standing trees to provide fine fuels. The trees were then felled in place (fig. 13). This plot was about 170, 000 square feet in area with a fuel loading of 3. 5 pounds per square foot.

All plots in the 380 series have been burned.

The 330 series was planned as two multiple-fire plots--one of 218, 000 square feet, the other of 653, 000 square feet. Each plot was to have piles of fuel covering 2, 500 square feet and spaced 25 feet apart. Construction of these plots proved to be excessively expensive because of the large stumps in the area, and work was discontinued after one plot of 96, 250 square feet including 20 piles was completed. This plot has not yet been burned.

Mixed-Fuel Plots

Living pinyon pine and juniper trees provided the fuel for tests in the 760 and 460 series. Entire trees were uprooted by a bulldozer and grouped into piles by a log loader to minimize loss of fine material. Each pile covers about 2, 500 square feet and contains about 40, 000 pounds (dry weight) of fuel. This is about the same amount of combustible fuel as in a single-story residence and garage, and covers about the same area. In all, 15 single-pile plots and 15 multiple-pile plots were constructed in these two series.

The multiple-pile plots were designed to simulate urban conditions. They range in size from 218, 000 to 2, 200, 000 square feet, (1 to 10 city blocks). Within the plots the piles of fuel were spaced 25 feet apart in one series and 115 feet apart in another (fig. 14). This spacing gave 9 simulated houses in the smallest wide-spaced plots and 36 houses in the close-spaced plots of the same size. In the largest plots the relative numbers were 81 and 420.

In all the multiple-pile plots but one, the fuel piles were arranged so that the "streets" were straight in both directions. In one plot alternate rows were offset so as to simulate blocked streets. This plot covers 653, 000 square feet and contains 104 simulated houses.

Figure 11.--Fuel was spread uniformly over the area in the fine-fuel plots. Largest fuel in the foreground is about 2 1/2 inches in diameter.

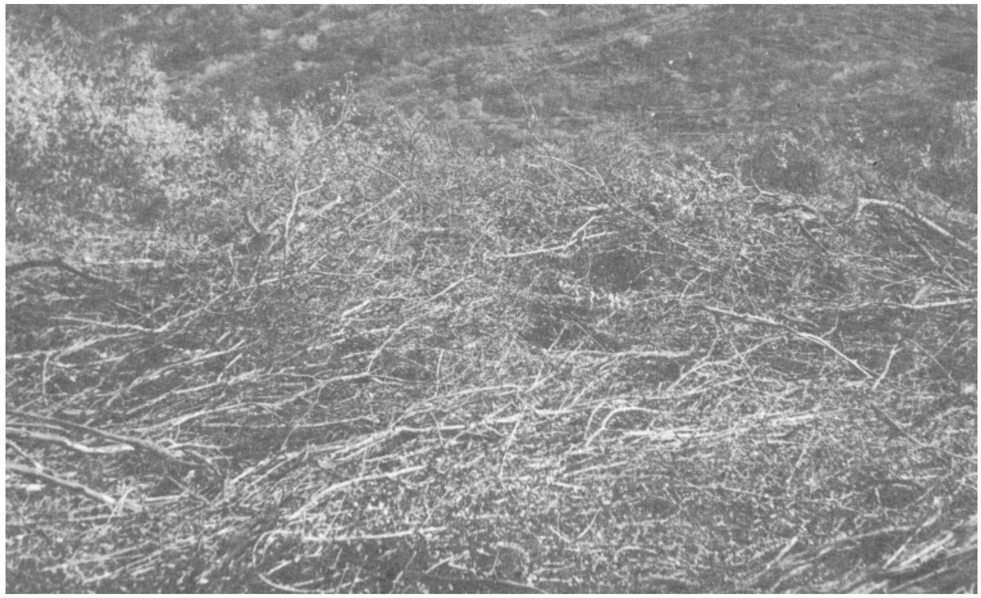


Figure 12.--Heavy fuel plots (380 series); largest pile about 370 feet long and 150 feet wide.

Figure 13.--Test plot 380-1-62. Felled fir and pine trees averaged about 8 inches in diameter.

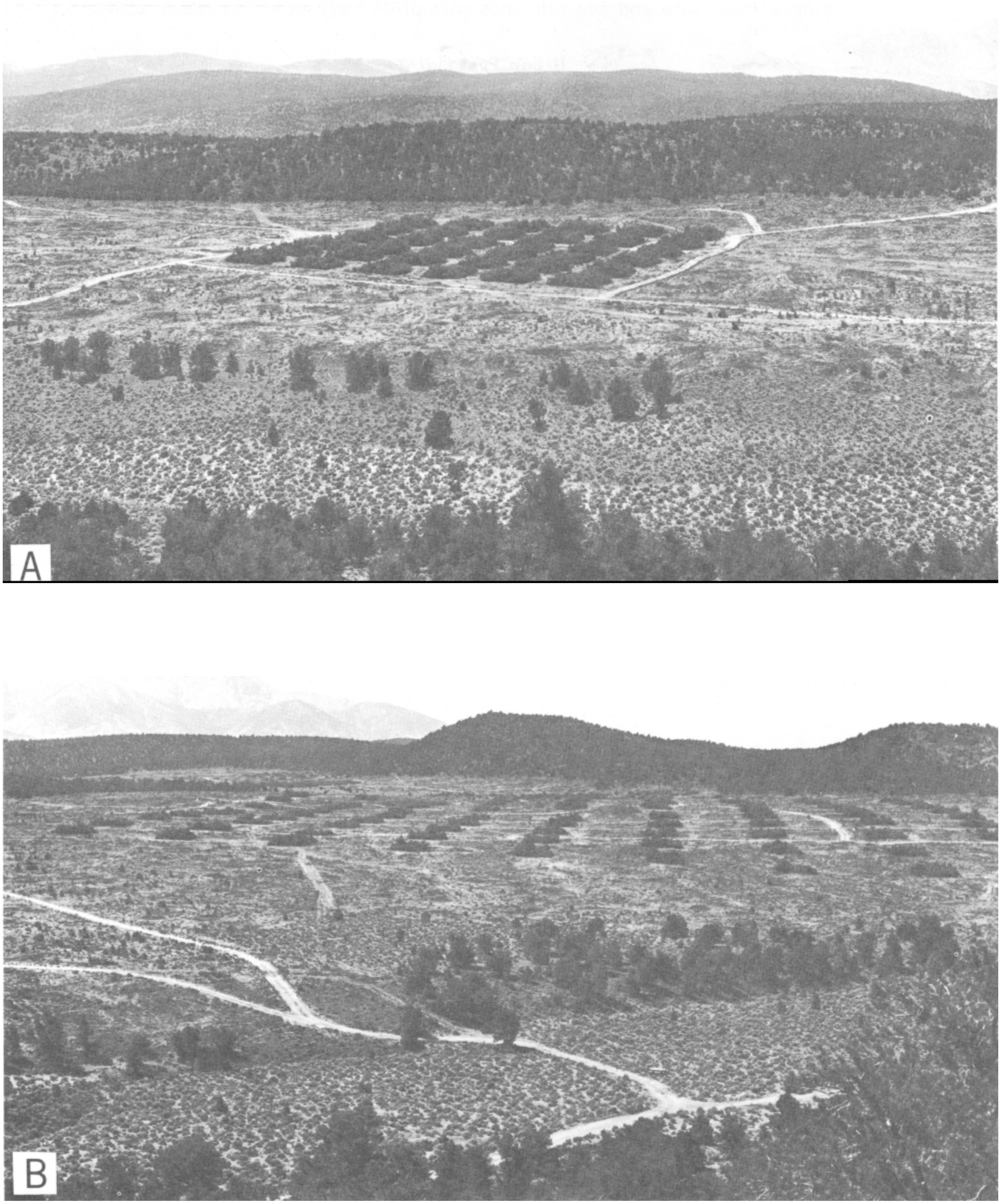


Figure 14.--Multiple-pile plot of mixed fuels; A, close-spaced plot (piles 25 ft. apart) covering 218,000 square feet; B, wide-spaced plot (piles 115 ft. apart) covering 2,200,000 square feet.

Six single-pile plots and two multiple-pile plots have been burned in the mixed-fuel series.

Urban Fuel Plot

Only one test was prepared in this series (642). It consisted of a two-story wooden frame house covering 1, 300 square feet (fig. 6). The exterior of the house was painted redwood siding; the inside, lath and plaster. Floors were wood, and the roofing consisted of wooden shingles covered with asphalt roofing paper.

Table 4.--Fuel size distribution, fine-fuel plot 428-1-63[1]

Fuel	Percent
Litter	2.0
Leaves	7.9
Twigs:	
Less than ½ in. in dia.	32.4
½ - 1 in. dia.	22.5
More than 1 in. in dia.	35.2
Total	100.0

[1]/Pounds per square foot: 1.45 preburn; 0.01 postburn.

Table 5.--Fuel [1] size distribution in heavy-fuel test fires

Diameter (inches)	Percent
Less than 4	1.78
4 - 6	3.21
6 - 8	6.96
8 - 10	12.10
10 - 12	10.50
12 - 14	15.66
14 - 16	15.23
16 - 18	11.31
18 - 20	10.22
20 - 22	6.76
22 - 24	1.70
More than 24	4.57
Total	100.00

[1]/Trunks only.

Fuels

The differences in the fuels used to build the test plots required a different analysis for each fuel type to determine fuel amounts and fuel particle size distribution. In the fine fuels, several mil-acre plots were established in the test areas. The fuel on half of these plots was collected before the areas were burned, separated into size classes, weighed, and the dry weights determined. The fuel remaining on the other half of the mil-acre plots was collected after the area had been burned, results of this analysis for one plot are given in table 4.

Obtaining fuel weights and size distribution for the heavy-fuel plots had to be done indirectly since the fuel piles had already been built in land-clearing operations before the project was started. Fortunately about 1 acre of the fire-killed timber adjacent to the test area had not yet been cleared. The diameter (table 5) and length of the trees in this area were measured. These trees were then piled in the same manner as the test piles and the dimensions of the pile determined. Knowing the dimensions of the test piles, we could then estimate the amount of fuel in each pile. (The amount of small limbs was not determined since these made up a very small proportion of the total weight, and much of this material was lost in building the test piles.)

More elaborate sampling procedures were used in the mixed-fuel plots--partly because little was known about the type of fuel used and partly because these plots were to make up the more important tests. The dimensions of a number of randomly sampled pinyon pines were measured, and then these trees were cut and weighed. The moisture content of different parts of the tree was determined, and the dry weight of the entire tree calculated. This weight was then correlated with different tree dimensions. Good correlations were obtained between dry weight of the tree and stem diameter, average tree crown diameter, and maximum crown diameter. Because of the ease of measurement, the correlation with maximum crown diameter (fig. 15) was used to estimate amounts of fuel. Analysis of juniper trees showed that the same curve could also be used to determine the total weight of trees of this species. The wide-spreading growth habit of juniper compensated for its larger trunks and limbs.

Total heat value of the wildland fuels, obtained by calorimetric analysis varied little by species (table 6), and the values were in the same order of magnitude as those found by other workers for various kinds of wood. The possibility that partially burned material may have lost some of its heat value was also investigated. Sound wood samples taken from just beneath the charcoal layer on partly burned pine, and fir logs did not have significantly less heat value than samples taken from unburned material. Distribution of fuel particle sizes was obtained for pinyon pine (table 7).

Ignitions

All test fires conducted in the project thus far were stationary fires. That is, all of the area to be burned was ignited and there was no fire spread as a moving front. This type of fire was used to give the maximum area possible burning at high intensity for each plot so as to set up a fire storm potential.

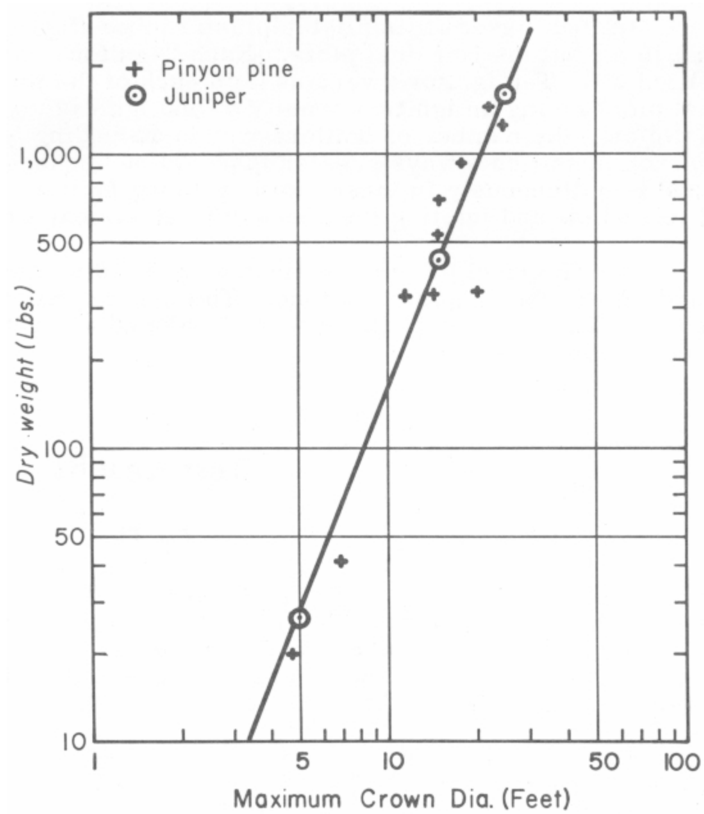
Table 6.--Heat value of fuels used in fire tests

Material	Heat Value
	BTU/lb. (dry wt.)
Tanoak wood	9,750
Tanoak bark	12,432
Douglas-fir	8,848
Madrone wood	8,419
Manzanita wood	8,676
Manzanita leaves	9,208
Ponderosa pine wood	9,386
Ponderosa pine needles	9,776
Ponderosa pine bark	9,603
Pinyon pine wood	8,762
Pinyon pine needles	9,48o
Pinyon pine roots	8,300

Table 7.--Fuel particle size distribution, Pinyon pine trees, 6 inches diameter breast high, 9 ft. 5 in. tall

Size class (inches)	Weight (pounds)	Percent of total
Upper tree:		
Needles	32.50	33.0
Less than ¼	13.00	13.2
¼ - ½	5.00	5.1
½ - 1	7.00	7.1
1 - 2	5.50	5.6
2 - 4	11.00	11.2
4 - 6	16.00	16.3
Total	90.00	91.6
Roots:		
Less than ¼	0.25	0.3
¼ - ½	1.00	1.0
½ - 1	2.00	2.0
1 - 2	1.00	1.0
2 - 6	4.00	4.1
Total	8.25	8.4
Entire tree	98.25	100.0

Figure 15.--Weight of pinyon pine and juniper in relation to maximum crown diameter.



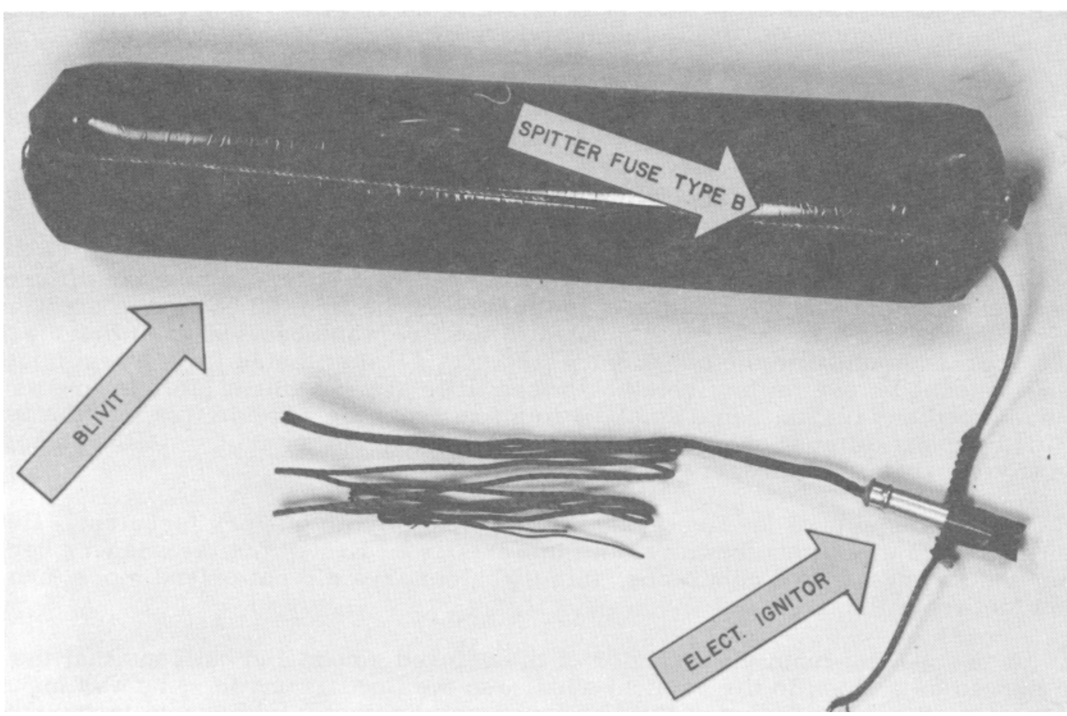


Figure 16.--Jellied diesel oil ignitor.

Jellied diesel oil in pliable plastic tubes (fig. 16) was used as ignition material in all but the fine-fuel plots. Each " ignitor" contained a half-pound of the jellied oil. Ten ignitors were used in each of the simulated houses in the mixed fuel plots giving an ignition density of one ignition to 250 square feet. In the heavy fuel plots, the number of ignitors varied according to the size of the pile with ignition densities always greater than 1 to 500 square feet. All of the ignitors were fired simultaneously in these plots by using spitter fuse wrapped around the tubes of jellied oil and igniting the fuses with electrical squibs.

The fine-fuel plots were fired with fused sections of fusees wrapped in one-third of a rubber automobile tube. The ignitors were also fired with electrical squibs. This method of firing was abandoned when the jellied diesel oil ignitors became available.

Test Results

Air Flow

Often mentioned in reports of urban conflagrations are the high wind speeds that occur in the vicinity of the fire. In wildland fires too, such winds have been mentioned frequently in narrative fire reports. Often these winds have been assumed to be indrafts flowing into the base of the fire replacing air and gases heated and rising in the fire convection column.

That such air flow is always into the fire base or fire area is by no means certain. Instances of wind blowing out of the fire at speeds considerably higher than the ambient wind have been documented (11, 15, 37). This phenomenon has been observed by the author on several large wildfires and it has been reported by others. There is also some evidence (36) that major air entrainment into the convection column may take place at considerable distance above the ground level. Qualitative observations on prescribed burns and some wildfires have indicated only light indrafts into the base of the fire.

As part of the instrumentation on the test fires, wind vanes and sensitive anemometers were installed at two levels (7 ft. and 20 ft.) on all sides of the fire. These installations were made about 100 feet from the fire edge so as to provide a reasonable chance that the equipment would survive the fire. Wind speed and directions were recorded at 1-minute intervals. Closer to the fire air movement was traced with colored smoke and no-lift balloons.

In the heavy-fuel plots (380 series), ambient wind speeds during the different burns ranged from 5 to 12 m.p.h. At 100 feet from the fire, no change in the wind speed or direction that could be attributed to the fire was observed at either the 7- or 20-foot level, despite the hot burning fire (fig. 17) that lasted for several hours. Smoke released close to the fire also showed little air movement into the fire on the windward and flanks; some smoke 3 to 5 feet from the edge drifted into the fire. No-lift balloons followed the same path as the smoke, not entering into the fire unless very close to the edge.

On the lee side of the fires, the air was observed to be very turbulent. Here, colored smoke was often drawn rapidly into the fire. Except for the one fire burned under the strongest wind conditions, this turbulent area did not extend more than 25 or 30 feet from the fire.

It is apparent from the behavior of the colored smoke and balloons that the fire served as a block to the ambient wind, and the flow around the fire was much the same as the flow of moving fluid around a solid object. Eddies and turbulence formed in the lee or "wake" of the fire (fig. 17, inset).

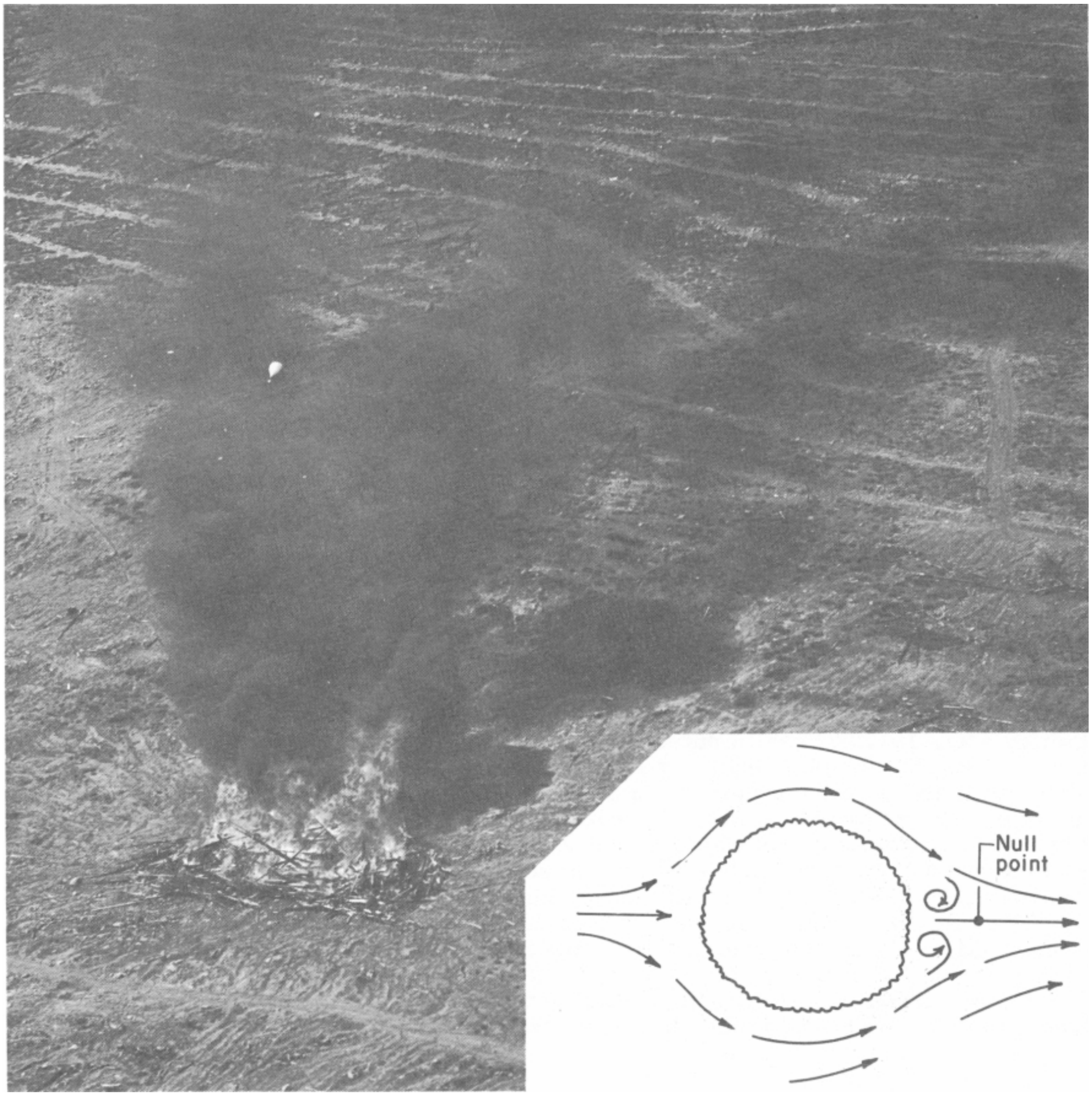


Figure 17.--Test fire 380-2-64 in heavy fuel plot near peak intensity. Flames are 50 feet high. No significant inflow of air was evident at ground level. (Inset: schematic of airflow around a stationary fire.)

During one of the heavy-fuel fires, an opportunity arose to observe the air flow in the turbulent area in considerable detail. A small spot fire started in a decayed log apparently just about at the point of no air flow (null point) on the lee side of the fire. This spot fire produced a steady stream .of smoke that revealed the air flow pattern diagramed in figure 17 very clearly. At times the smoke moved directly into the fire and at other times directly away from the fire area. Whenever one of the wake eddies broke loose and moved downstream, the smoke from the spot followed the eddy and showed its circular motion.

The convection column of test fire 380-3-63, which was burned under strong wind conditions, stayed close to the ground for a considerable distance downstream from the fire. Lateral movement of air into the fire could not be detected on the windward and flank sides. As might be expected, however, turbulence and eddy formation was much more pronounced in the wake of this fire. No-lift balloons moving past the fire appeared to accelerate in speed on the downstream side. This apparent increase in wind speed on the lee side could not be confirmed, however, since the anemometer station was not in line with the convection column.

Dust devils and whirlwinds frequently appear beneath a strongly tilted convection column on wildfires. This phenomenon was also observed on test 380-3-63. Dust devils formed frequently under the convection column at distances up to 400 feet from the fire. One no-lift balloon floated a few feet above ground downstream for nearly 600 feet before suddenly rising vertically into the convection column. Since outdrafts from fires have usually been observed under conditions where the convection column was strongly tilted, it appears likely the increase in wind speed is caused by transfer of momentum downward to the ground by turbulence between the convection column and the ground. Transfer of momentum in this manner may also account in part for the violent fire behavior Byram (4) has associated with wind profiles having a "jet point" near the ground surface.

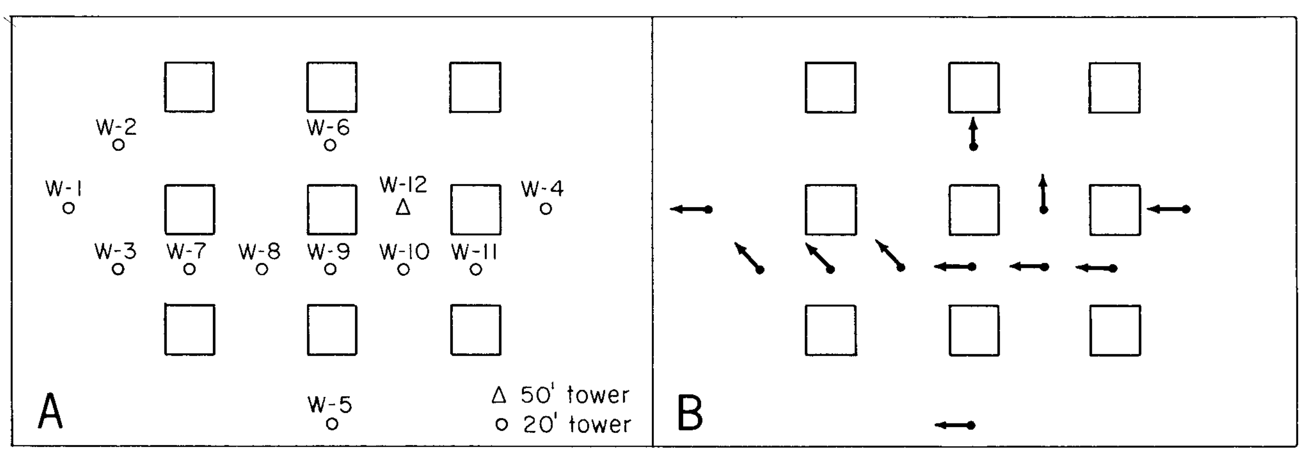
In test fire 760-1-64, anemometer stations were placed between the separate piles (fig. 18) as well as outside the fire area. Station W-12 was a 50-foot tower with anemometers and wind vanes at 2-1/2, 5, 10, 22-1/2, and 50 feet. The other stations had vanes and anemometers at 7 and 20 feet.

Wind flow patterns have been plotted at the 20-foot level for the most intense portion of the fire. Before ignition, wind direction near the round was across the plot from right to left, approximately parallel to the "streets ' as indicated by the outside stations W-1, W-4, and W-5 (fig. 18, B).- Within the plot, the fuel piles apparently affected the wind direction to some extent.

The fire began to have a noticeable effect on the flow pattern very soon after ignition (fig. 19) . Three minutes after ignition a definite indraft had developed into the fire from all sides. Opposing air currents were well developed around the center pile and on the downstream side of the fire within 6 minutes after the fire, and fire whirl activity was also observed about this time. Nine minutes after ignition air movement was still generally into the fire from all sides, but turbulence on the downstream side made the wind direction very erratic in this area. By 12 minutes after ignition, air flow on the windward side more closely approached the pre-fire condition, but the turbulence and whirl action was still present on the downstream side; 23 minutes after ignition, the indraft was no longer apparent.

Wind direction at the 50-foot tower (station W-12) did not fluctuate greatly during the fire. The direction, however, was not the same at all levels (fig. 20).

Figure 18.--Location of air flow measuring stations, A, and pre-ignition air flow pattern, B, in test fire 760-1-63.



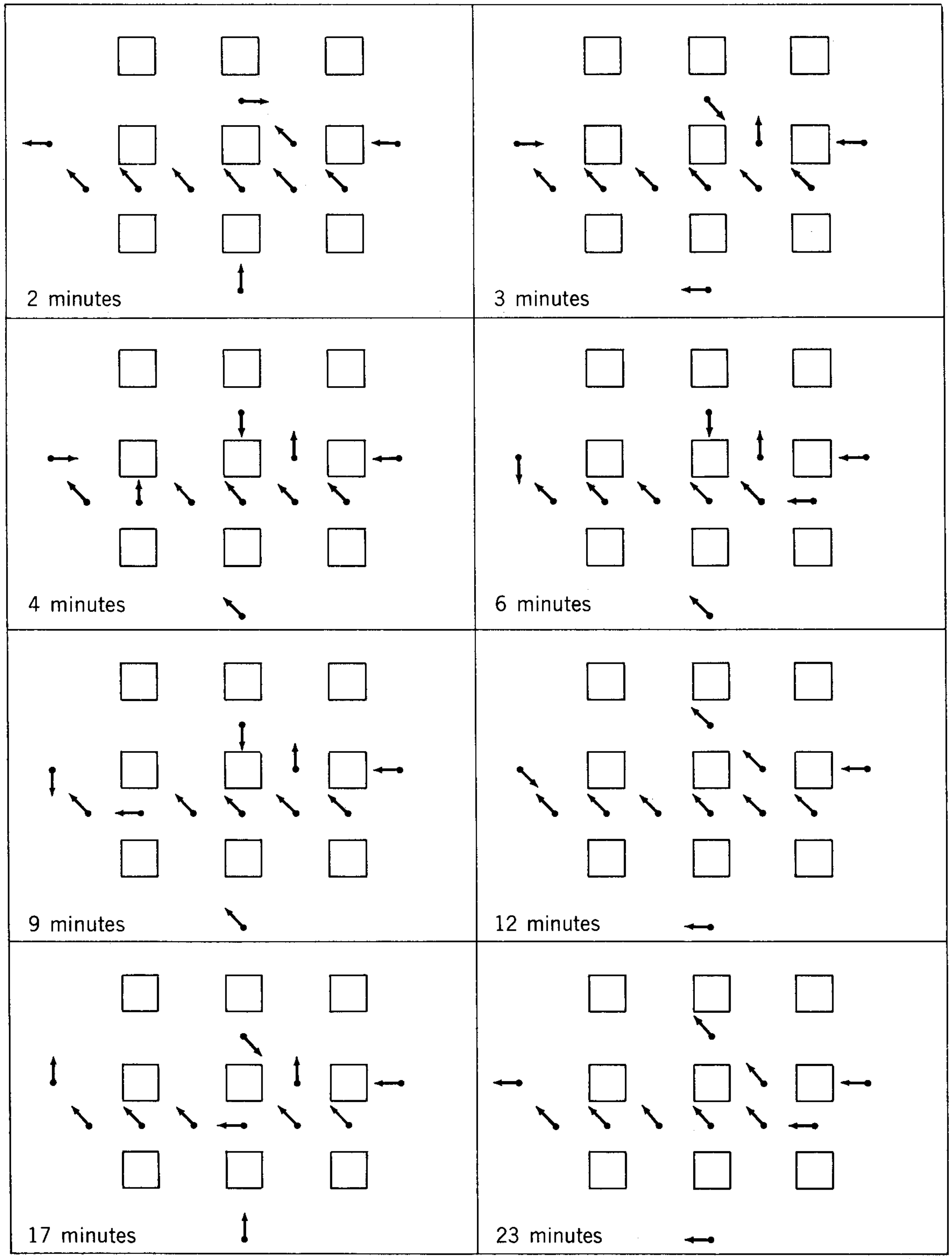


Figure 19.--Air flow pattern, test fire 760-1-63, at specified intervals, after ignition.

Wind speeds at all levels within the fire area showed a marked increase, but the pattern was not the same at different stations (fig. 21). Greatest increase in speed was at the 50-foot level, where a peak speed of 42 miles per hour was reached--more than 5 times the pre-ignition speed. Wind speed increased markedly at other levels, but the lower the level , the less the increase (fig. 22). The exact position of the tower with respect to the convection column at different times has not yet been determined, so that it is not certain whether this change in wind speed is an effect of the vertical currents on the horizontal-type anemometers or an effect of inflow into the convection column. In either case, it represents greatly increased air movement at higher levels as compared with the surface flow.

Fire Whirlwinds

Firefighters frequently report that whirlwinds develop in and adjacent to the intensely burning fires. Apparently originating at the ground surface, these "fire whirls"--as they are often called--are similar in appearance and behavior to the dust devils common to strongly heated bare land surfaces. Fire whirls vary greatly in size, strength, and duration. Whirls one-quarter mile in diameter and extending several thousand feet into the air have been reported from wildland fires. Speeds attained by the gases in these whirls have not been accurately determined but must be great: limbs may be twisted from trees and shrubs uprooted, even in moderate sized whirls. A large whirlwind that developed in the Polo fire near Santa Barbara, California, in 1964 moved out of the fire area and demolished a house and severely damaged several others (fig. 23). This whirl uprooted large trees and stripped limbs from others. A piece of quarter-inch plywood was driven 3 inches into an oak tree in the path of the whirl.

Fire whirls have also been reported in urban conflagrations. In the Tokyo fire after the 1923 earthquake, fire whirls were reported in several eyewitness accounts (3). One very large whirl in this disaster was apparently the cause of many casualties and of extensive fire spread.

Tornado-like winds have also been reported in both wildland and urban fires. These winds seem to differ from the fire-whirls in origin; that is, they appear to originate well above the ground surface and then extend to the ground where their behavior is the same as for fire whirls.

Besides the destruction caused by wind, fire whirls and tornadoes contribute greatly to fire spread because they pick up large firebrands and scatter them over a wide area. Many wildfires seemingly controlled have been lost when a fire whirl scattered burning debris across the cleared fire lines. Accounts of some urban fires indicate that fire whirls may transport noxious gases and deplete oxygen supplies.

Although the causes of fire whirls and tornadoes and the mechanism of their development is far from being completely known, research and observation have provided some clues. Byram (7) and Broido (2) have used a special device to create a fire whirl on a miniature scale. The device imparts a circular motion to the air flowing into a fire burning a small quantity of hydrocarbons. Greatly increased rates of burning and flame heights were observed in these experiments. Observers on wildland fires and prescribed burns report that whirls develop most frequently on the lee side of a ridge. It has been postulated that the whirls may result from lower pressure caused by the air flow across the ridge (24). Fire whirls have been observed to develop when fire burned over an area where an air flow eddy created by topography was known to exist (13). Fire whirls have also been observed to occur more frequently on wildfires when the air mass was unstable to a considerable depth. The Hamburg fire storm during World War II occurred during light wind and unstable air conditions (18).

Conditions conducive to fire whirl development, then, appear to be unstable air, a large heat source, circular motion in the ambient air, and fire on the lee side of a ridge. Test fire 428-1-63 was set up to meet as many of these conditions

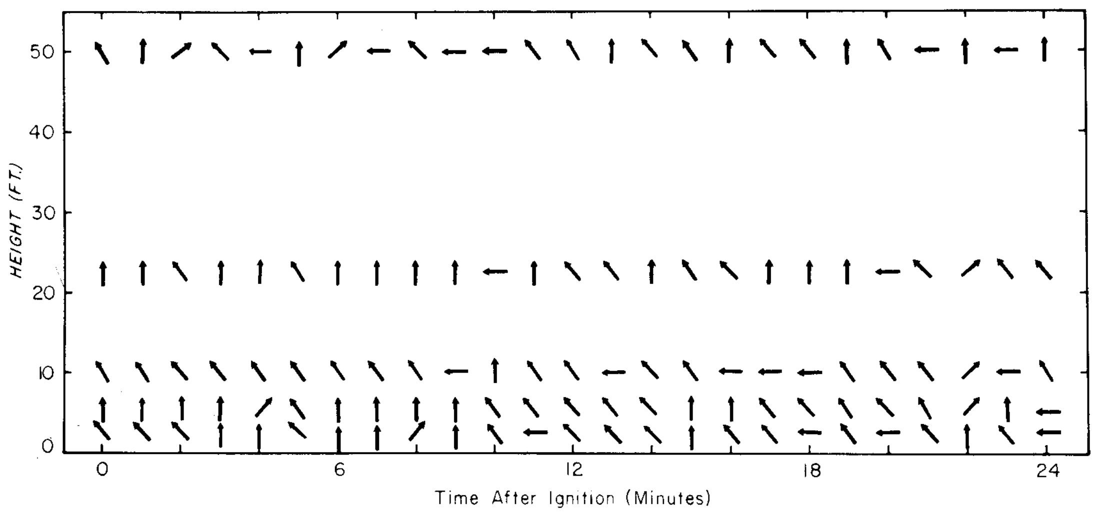


Figure 20.--Air flow direction at 50 ft. tower (station W-12, fig. 20 A), test fire 760-1-63.

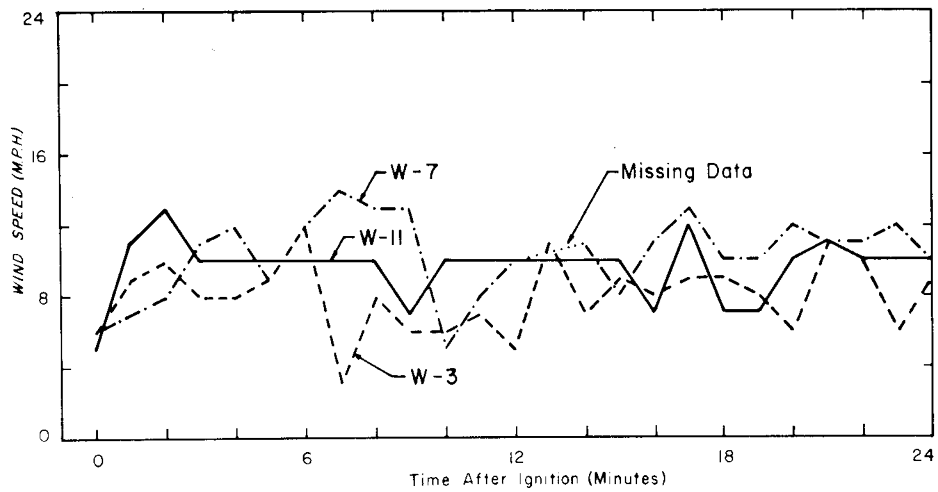


Figure 21.--Wind speed in "streets" (stations W-3, W-7, W-11, fig. 20 A), test fire 760-1-63.

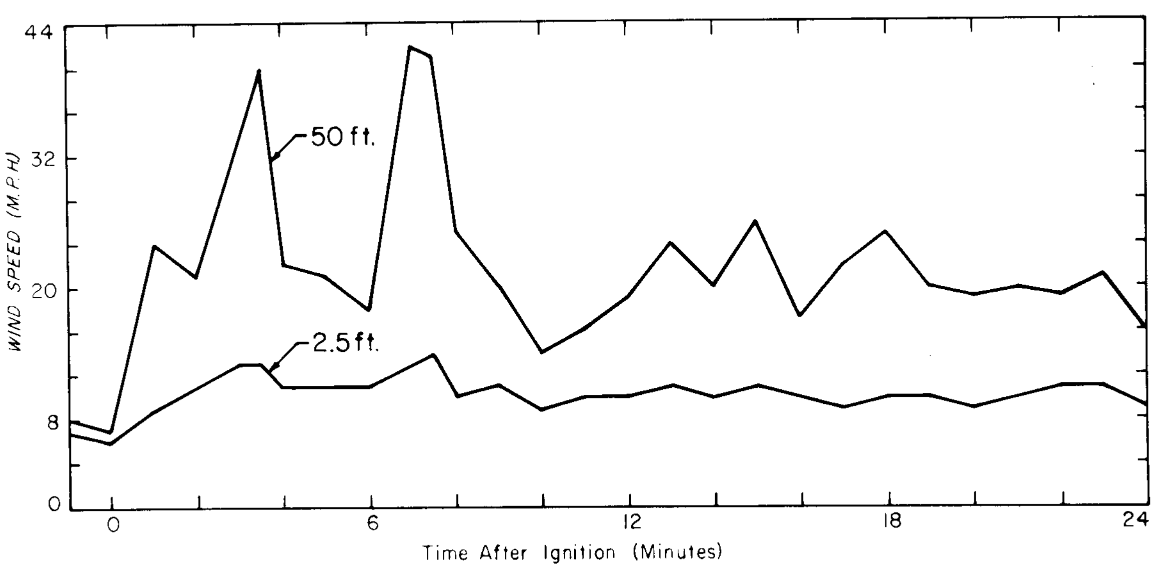


Figure 22.--Wind speed at two levels, station W-12 (fig. 20 A), test fire 760-1-63.

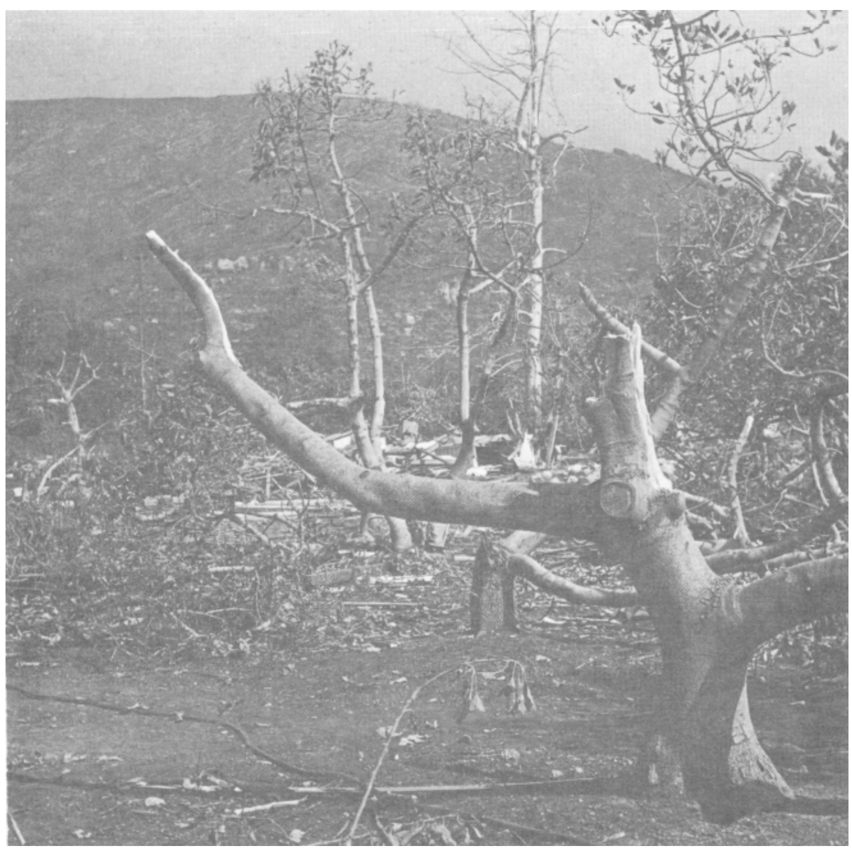


Figure 23.--House destroyed, and trees stripped and broken, by fire.

as possible. The plot of 72, 000 square feet was located on the lee slope of a canyon. The plot was loaded uniformly with fine fuel at the rate of 1.45 pounds per square foot. The plot was fired in the late afternoon during unstable air conditions and with a wind of 8 to 10 m.p.h. across the ridge top.

Multiple ignitions were used to fire the plot, with a delay in firing the lower half to create upslope thermal winds (fig. 24). As expected, the fire built up in intensity very rapidly, and fire whirl activity commenced as soon as the ignition fires began to merge (fig. 24, B). The whirls increased in frequency and size as the fire developed (fig. 24 , C). The largest whirls, however, developed after the fuel was practically all consumed (fig. 24, D). The height of these whirls could not be determined precisely since their tops were in the smoke layer above the fire. As happens so frequently in wild fires, the whirls scattered so many firebrands in the adjacent plot that the suppression crew could not control them all and this plot burned also. Fire whirls were somewhat less numerous in the adjacent plot although strong and active whirls did develop. The difference in activity appeared likely to be due to the irregular ignition pattern caused by the spotting and a slower fire build up. Parts of the plot had burned out before the entire plot was ignited.

The strong whirl activity in test 428-1-63 destroyed much of the instrumentation--particularly temperature sensors --so that quantitative information in some areas was rather sketchy. A good photographic record of the fire is available, however, to confirm notes of observers on the scene.

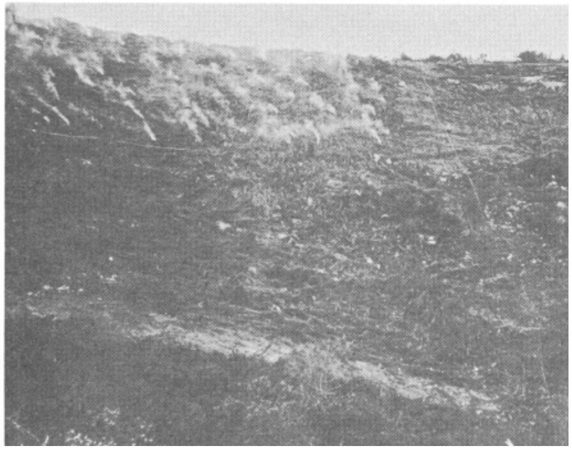
In the early and peak flaming periods of the fire the whirls consisted mostly of flame. Whirling activity was generally less than 30 feet in height with the flame usually less than half this height. Close-hand observation of development of these whirls showed that flames in a hot burning area would suddenly start moving in opposite directions. Flames that had been leaning up the slope would lean downslope while adjacent flames would continue to hold their upslope direction. A whirling motion would then begin, first over a relatively wide area. Once the whirling action started, the whirl was quickly compressed into a small area, and the speed of the circular motion increased greatly. Inflow into the whirl appeared to be solely from a layer close to the ground. A whirl 3 to 4 feet in diameter could be seen to affect flame direction at the ground level for at least 50 feet (fig. 24, C). The whirls tended to stop as suddenly as they formed. The speed of the whirl would decrease and the circular flow spread over a wide area and then stop entirely. Except near the ground surface, air flow into the whirl was not apparent; that is, no air entrainment into the whirl appeared to occur except at the bottom. In the later stages of the fire whirls heavily loaded with dust, ashes, and smoke extended more than 200 feet into the air.

The development and behavior of the fire whirls in this test closely parallels that postulated for vorticity. It is likely that theoretical and mathematical treatment of vortices can be applied successfully to fire whirls. This treatment will be attempted as quantitative data are collected.

Fire whirls were observed to develop in all test fires burned thus far, although not as numerously as in test 428-1-63 described above. Test 380-1-62 was also burned on a lee side of a ridge. This fire of about 170, 000 square feet did not burn very intensely, and active whirl action was not observed until some time after peak intensity. In this fire, the height of each successive whirl tended to increase until the fire activity had decreased greatly (table 8).

Test fire 380-6-63 was burned on nearly level terrain and under relatively stable conditions. Although a very intense fire developed because of the size (49, 750 sq. ft.) and heavy fuel loading (40 lbs. /sq. ft.), comparatively little whirl activity developed. In one area outside the plot, long twisted whirls were observed to develop repeatedly and move into the fire (fig. 25) instead of out of the fire as in the case of other fire tests. It was observed that air flow in this area tended

A



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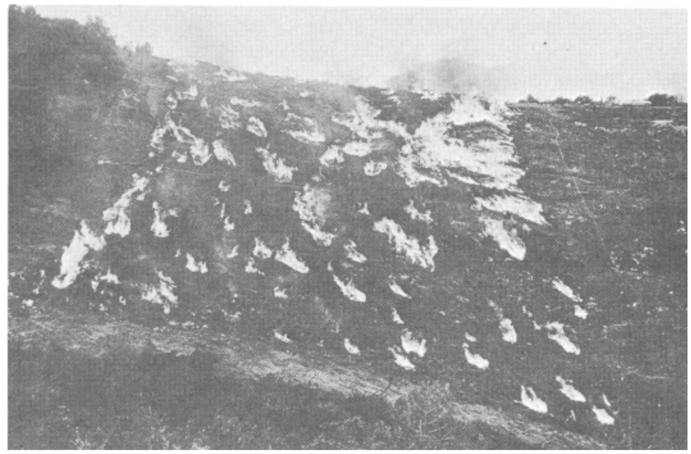

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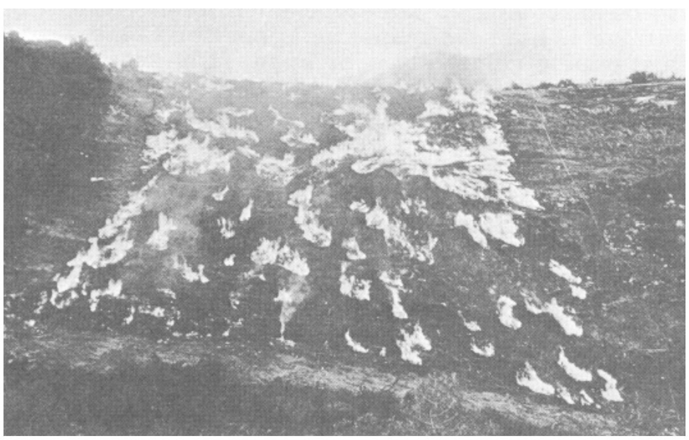

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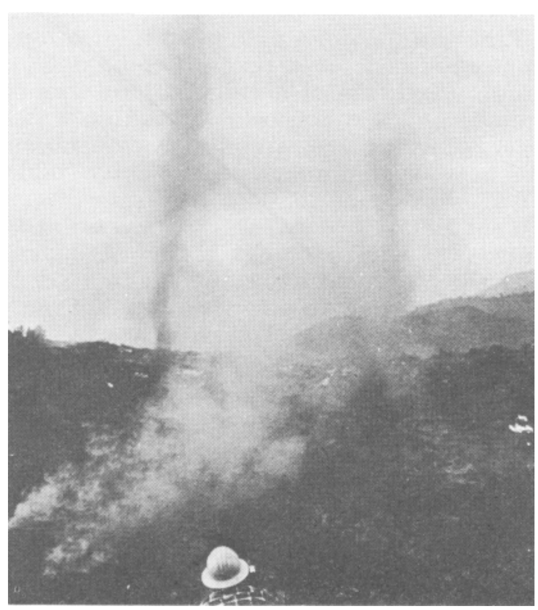


Figure 24.--Test fire 428-1-63. A, Top half of plot was fired first to create upslope winds; B, fire whirl activity began as ignition fires began to merge; C, fire whirls increased in intensity and size as the fire developed; D, largest fire whirls developed after fuel was nearly all consumed.

Figure 25.--Whirling dust cloud just outside of fire at right marks place where fire whirls developed repeatedly in test 380-6-63. Picture taken after major flaming had subsided.

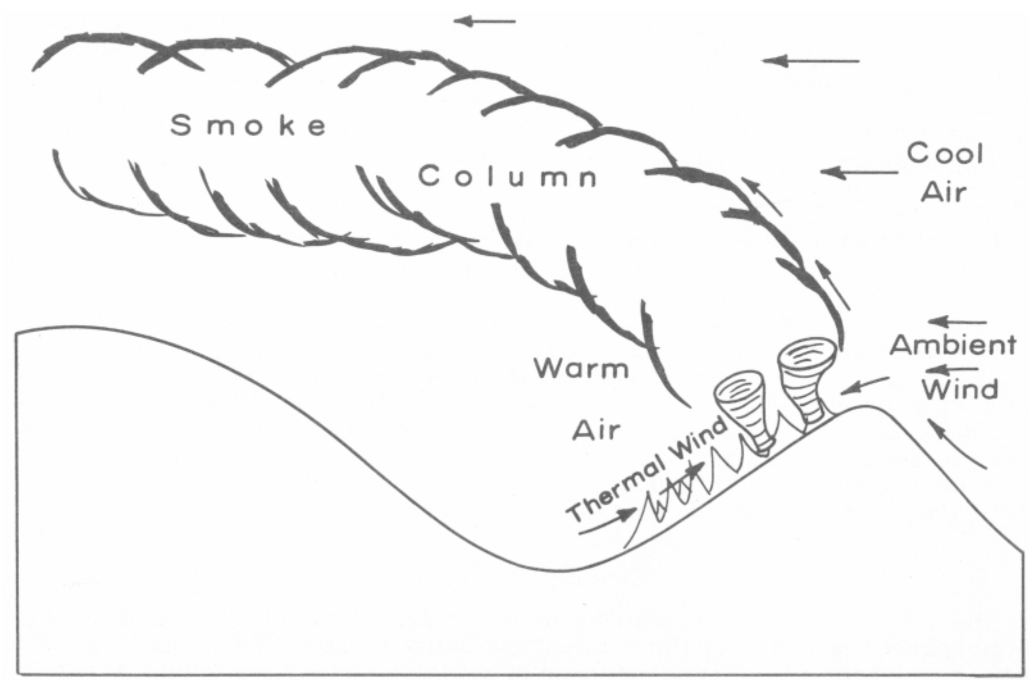


Figure 26.--Development of fire whirls on lee slopes.

Table 8. --Fire whirl heights, test fire 380-1-62

Time after ignition	Height (feet)	Description
9 min. 30 sec.	27	Flame
24 min. 15 sec.	134	Dust and smoke
28 min. 10 sec.	238	Flame, dust, and smoke
33 min. 30 sec.	310	Flame and smoke
35 min. 0 sec.	663	Flame, dust, and smoke
- - -	- -	(Moved out of fire)
46 min. 0 sec.	621	Flame and smoke
55 min. 30 sec.	477	Dust and ashes
79 min. 0 sec.	528	Dust and ashes

to move in opposite directions owing to the ambient wind, the configuration of the test plot, and indraft into the fire. In tests 760-1-63 and 760-2-64, major whirl activity tended to occur where air currents were opposed.

The frequency with which opposing air currents appear as a factor in the development of fire whirls indicates that this type of air flow is one of the requirements for fire whirl development and possibly for the development of fire storms. Such air flow may occur under natural conditions in situations where eddies tend to develop. Or the effect of the fire on air flow may induce such a flow pattern. When this pattern is present, heat from a fire apparently triggers the development of vortices. Air stability also appears to be of major importance in whirl development. When the air is unstable, upward movement of air is enhanced; consequently, fire whirls require a less intense heat source to start, or to become stronger with a given heat source than in stable air.

The prevalence of fire whirls on lee slopes is likely due to both fire-induced air flow patterns and air instability. When fire is burning over a sizeable area on the lee slope of a canyon somewhat sheltered from the ambient wind, the fire creates upslope thermal winds. These winds can be expected to meet the downslope ambient wind on the upper part of the slope. This is the area in which whirls have been observed to develop most frequently and was the case in test fire 428-1-63. The air within the canyon is heated by the fire; cool air flows over the ridge, an unstable condition is created which also favors the development of fire whirls (fig. 26).

Opposing air currents and air instability probably are not the only controlling factors of development of fire whirls. It is also not known with any degree of certainty how much fire area and rate of heat production are needed to produce such whirls with a given lapse rate in the atmosphere. Nevertheless, the knowledge that fire whirls are likely to occur where there are opposing air currents or eddies, and that they are more likely as instability increases, can help predict fire behavior in both wildland and urban fires. Knowledge of local air flow patterns should permit the fire control officer or fire behavior specialist to pinpoint areas where fire whirls are most likely to occur for a given fuel type and loading. Delineation of these danger spots could be done before any fire occurred and steps taken to limit the danger or to plan for control action and personnel safety.

Convection Columns

The convection column, which may tower 25, 000 or 30, 000 feet or more into the atmosphere, is probably the outstanding characteristic of a large fire. Perhaps because of the frequent occurrence of massive convection columns over large fires and their striking appearance, fire convection columns have received considerable attention and have been the subject of a number of theoretical analyses.

Usually such analyses have been based on the resemblance of a convection column to thermal plumes and jets. Actually there is little quantitative information available about the characteristics of a large convection column over a free-burning fire. Problems in obtaining measurements are extremely difficult and have not been adequately solved.

Although towering convection columns have sometimes been postulated as essential to the development of large and intense fires, there is little evidence that this is true. Under strong wind conditions, intense rapidly spreading fires often occur without a strong convection column. Rates of spread and areas burned in such fires often exceed those in similar fuels when active convection columns do develop. In fact, observation of wildland fires indicates that the development of a strong convection column may reduce rate of spread where long-distance spotting is not a factor. In some types of prescribed burning, such as logging debris disposal, ignition of the area in such a way as to produce a strong central column is often attempted. The indrafts produced when convective activity is strong help prevent fire spread beyond the desired boundaries.

A tall convection column may be a symptom of high rate of combustion and not necessarily the cause. The intensity with which a fire burns is often greater when convective activity is strong, and it is under these conditions that most erratic and unusual fire behavior occurs. It is likely that the strong fire convective activity results from favorable environmental conditions--low surface wind speed, unstable air mass, and plentiful dry fuels. Once an active convective column does develop, it may contribute greatly to fire spread under certain conditions by carrying firebrands far ahead of the main fire. It is also possible that through turbulence the momentum of the higher levels of air is transferred to the ground under certain circumstances.

From a distance, a convection column looks like a single rising stream of gases and smoke. On an active large fire the column appears to rise from the entire burning area as a continuous mass. Viewed close to the fire, however, it loses its continuity and is seen to be made up of a number of smaller convection columns developing over relatively small "hot spots" of active fire (fig. 27). These individual columns merge some distance above the fire area to form the single column appearance characteristic of the distant view.

Even on small test fires, the tendency for the fire to break up into small convection columns was evident. After the initial "flash over, " which lasts for only a few minutes, fires as small as 2, 500 square feet developed hot spots and separate convection columns with relatively clear air between (fig. 28). In some cases the separate columns developed immediately.

In the larger fires the hot spots were more numerous (fig. 29). The hot spots did not remain in one place but would form, burn actively a short time, die down, and then reappear later. Occasionally two or more of these active areas would merge for a short time. Over the burning mass of fuel, then, the more intensely flaming areas were continually shifting from place to place.

On test fire 380-6-63, low-lift balloons were released so that they would drift into the convection column. Usually these balloons reached the edge of the fire area and rose along the edge of the column to the rolling turbulence about 250 feet above the ground. Here they were drawn into the column, made an outward and downward loop, and be drawn back into the column again, occasionally appearing again in another roll higher above the ground.

On two occasions the balloons drifted directly over the center of the fire at a height of about 75 feet instead of rising along the edge of the column. These balloons did not rise immediately, but moved up and down several times before reaching the level of the rolling turbulence. Here they suddenly shot upward at high speed and disappeared in the smoke.

Figure 27.--Three separate convection columns are apparent in this wildland fire. Tallest trees on horizon are about 20 feet high.

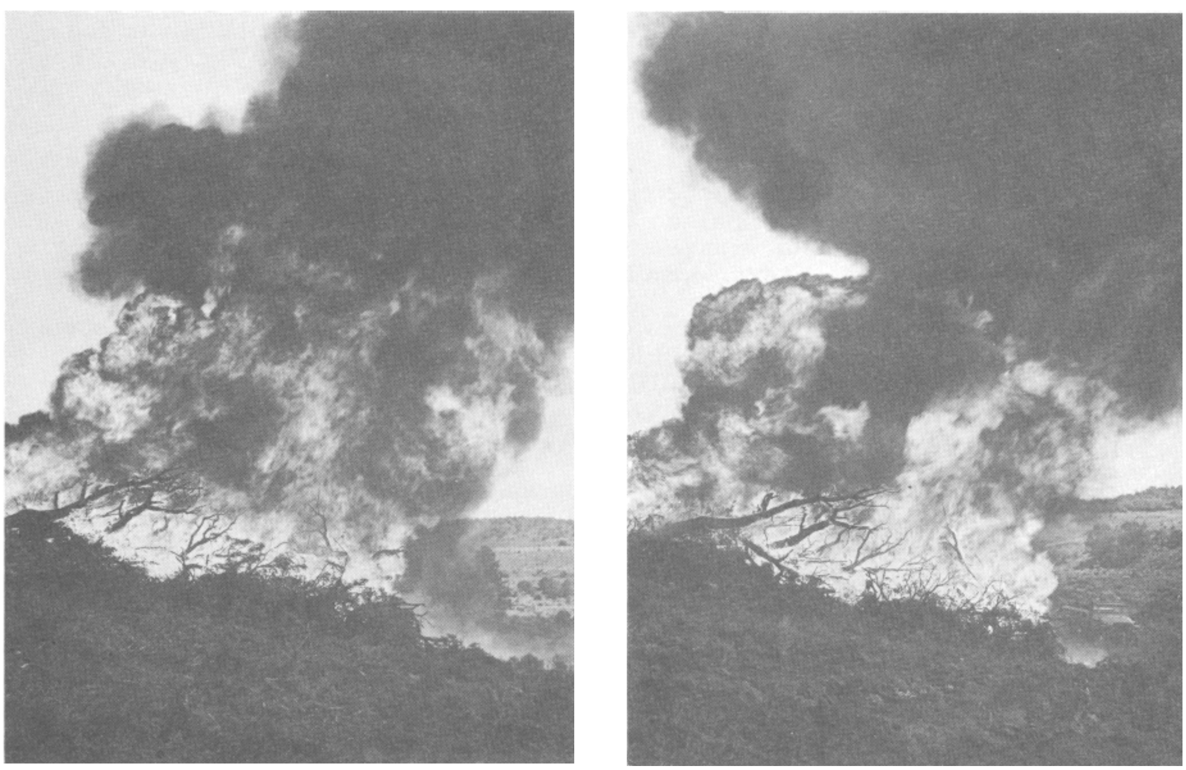


Figure 28.--Flame column beginning to break up into two separate columns, left; and separate columns fully developed, right. (Fire 760-1-63.)

Figure 29.--Hot spots and separate convection columns were numerous on larger fire areas. Flame heights in right foreground are about 55 feet. (Fire 380-6-63.)

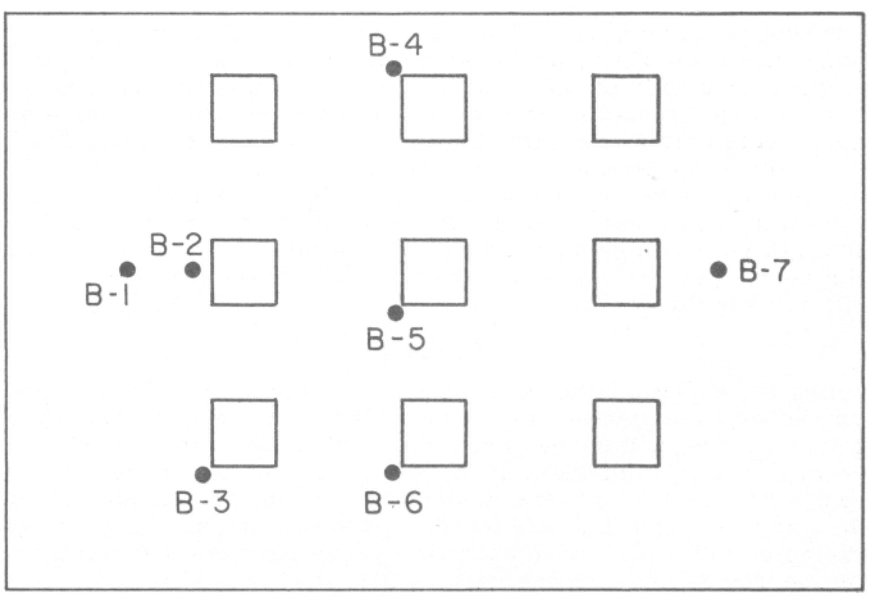


Figure 30.--Location of pressure sensors, test fire 760-1-63.

The behavior of these balloons and the tendency for hot spots to develop in the fire area strongly suggest that within a layer over the fire area both updrafts and downdrafts exist, and that the fire may obtain air for combustion from above as well as from the periphery of the fire area. Updrafts probably develop around the hot spots with downdrafts between. Thus the air for combustion does not necessarily enter the combustion zone at the level of the fuel bed, but may well be entering from a relatively deep area surrounding the fire. This mechanism of air supply would permit fire to burn simultaneously over a very large area--with combustion not limited by oxygen deficiency, and strong indrafts not necessary to supply air.

Pressures

The rapid vertical motion of heated gases and smoke in the convection column of a fire, and the movement of air into the combustion zone, has frequently led to the assumption that the pressure inside a fire is lower than the ambient pressure outside. To determine the magnitude of this pressure differential, a sensitive pressure device was buried underground in the fuel bed with the inlet tube about 18 inches above the ground surface. Surprisingly, a positive instead of a negative pressure was found in this area of the fire for the three fires in which such a measurement was made. This positive pressure persisted through a large part of the duration of the fire. Instrumentation difficulties make the magnitude of the pressure differences somewhat uncertain, but it appeared likely that the increase in pressure might be greater than 0. 5 inches of mercury.

The air flow pattern around the heavy-fuel fires suggested that a low pressure area might exist in the wake of the fire. A pressure sensor was buried about 20 feet outside the fire in test 360-6-63 in the area just upstream from where it was estimated that wake eddies would form. A negative pressure developed in this area as the fire approached its peak flaming period and apparently persisted for a considerable time. Again difficulties with the instrumentation made the exact magnitude and duration of the pressure difference uncertain. It appeared possible, however, that the negative pressure may have exceeded 1 inch of mercury for a time.

Pressure sensors were placed adjacent to and between piles of fuel in test 760-1-64 (fig. 30). All but one of these sensors (B-7, on the upwind side) showed substantial pressure drops. The sensors in the interior of the plot showed rapid fluctuations during the peak flaming period, varying quickly from negative to positive pressure and back again. These fluctuations may have been caused by fire whirls.

This pressure distribution, if substantiated, would be of major importance in the design and operation of ventilation systems in shelters which might be beneath burning buildings or debris or adjacent to fires. The positive pressure occurs within the fire where the maximum concentrations of carbon monoxide are found. This pressure could thus force lethal gases into a shelter located below. In a moving fire where a low pressure area may exist ahead of the fire, it is possible that an open ventilation system would permit air in the shelter to be partially evacuated, thus creating a greater pressure differential when the fire reached the shelter. These tentative findings suggest that during the time a fire is in the area of a shelter the ventilation system should be closed to prevent intrusion of combustion products into the shelter area.

Radiation

Obtaining the experimental data needed to establish an energy-rate balance on the test fire systems has been a basic goal. These data are necessary inputs toward quantifying fire ignition and spread problems. Radiation measurements, using flat plate or directional radiometers or both, were made on all of the test fires. One of the major purposes of making these measurements was to provide part of the necessary data to compute a heat balance for the individual fires. This analysis has not yet been attempted. The radiation data also served to show the relative rate of fire build-up for fuels of different types.

In the heavy-fuel plots, peak radiation occurred 10 to 18 minutes after ignition (fig. 31). The drop in radiation intensity in test 380-4-63 at 10 minutes after

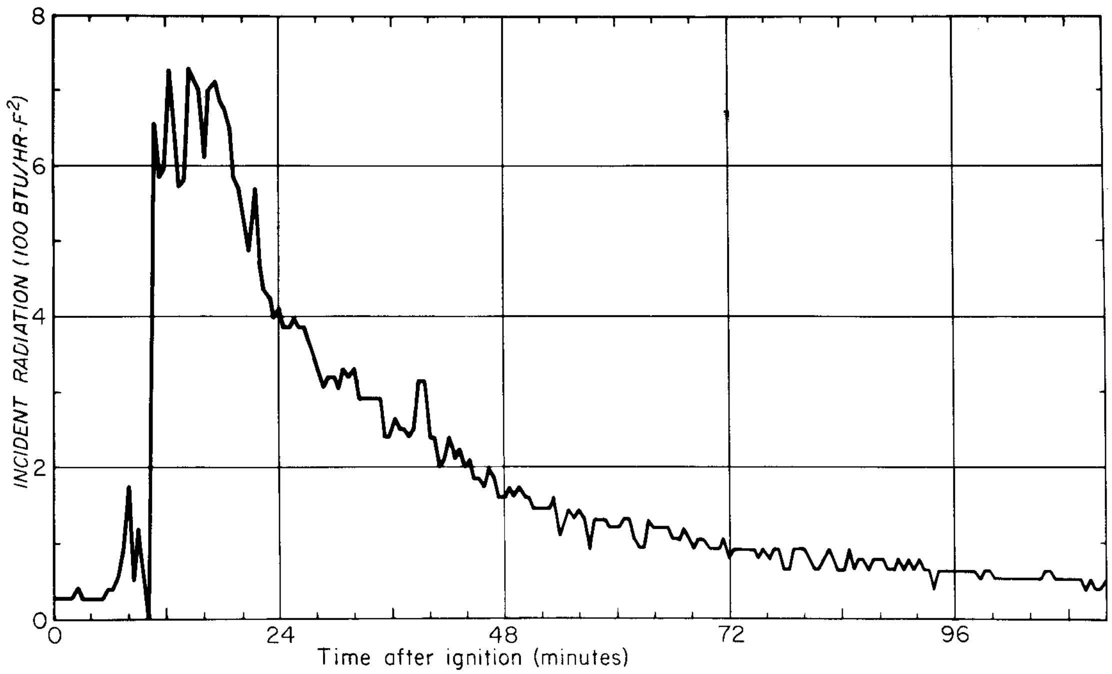


Figure 31.--Incident radiation on flat plate radiometer 100 feet from fire edge. (Test fire 380-4-63.).

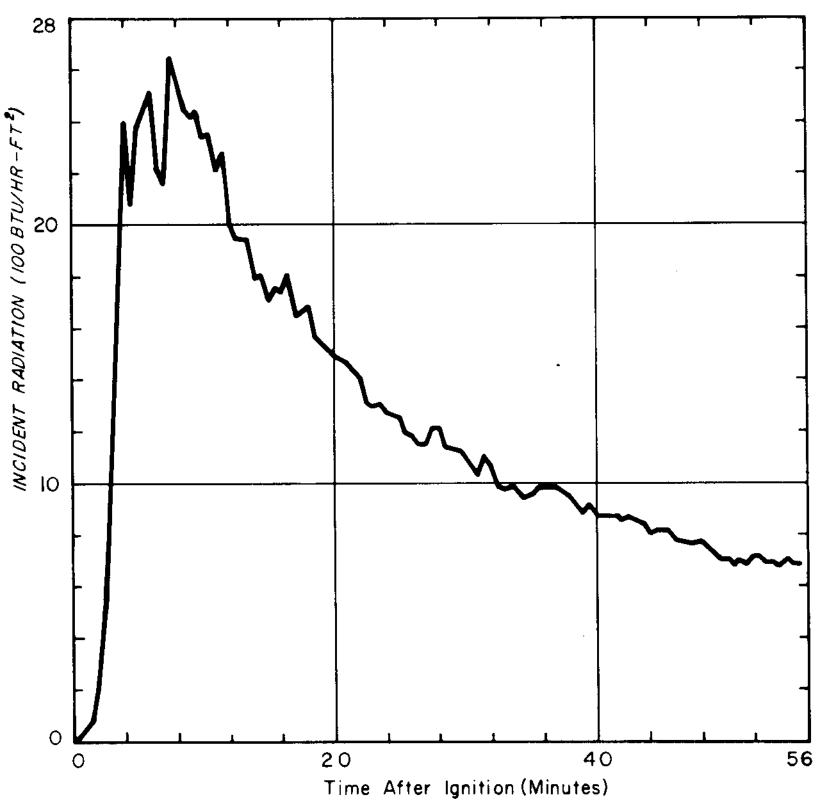


Figure 32.--Incident radiation on flat plate radiometer 90 feet from center of observed pile. (Test fire 760-1-64.)

ignition was probably caused by smoke momentarily obscuring the radiometer. In the mixed-fuel plots peak radiation was usually reached 4 to 8 minutes after ignition (fig. 32), but in one case occurred 2 minutes after ignition. Peak radiation on the flat plate radiometers occurred during the peak flaming period.

On all of the fire tests, it was observed that ignition by radiation of fuels on the ground outside the fire area was limited to a very short distance from the fire edge (fig. 33). On the windward side and flanks, this distance was limited to, 3 to 5 feet; on the downwind side, to less than 15 feet. Even in the narrow zone around the fire, it was not certain how much ignition was caused by radiation alone and how much by small firebrands falling on heated fuels.

Radiation heating of small fuel particles was measured with dowels containing thermocouples. Hardwood dowels 4 inches long and 1/4 inch in diameter were drilled longitudinally to within 1-1/2 inches of the end; a thermocouple inserted in the hole was held in tight contact with the dowel by means of a wooden plug. These dowels were then exposed in an upright position about 24 inches above the ground at various distances from the fire edge.

On test fire 380-6-63, the maximum temperature of the dowel exposed 6 feet from the fire edge was only 295° F, despite flames that reached 50 to 60 feet in height and a hot fire that persisted for several hours. The temperature-time curve (fig. 34) of these dowels was similar to the radiation intensity curve measured with a flat plate. radiometer. In the initial stages of the fire, the dowels close to the fuel pile were shielded from radiation and temperature of dowels farther away rose more rapidly (fig. 35). When the fire had enveloped the entire pile and the peak flaming period had passed, the logarithm of the dowel temperature varied linearly with the logarithm of the distance from the fire (fig. 36).

It is possible that fuels of a different size or configuration could be more strongly heated by radiation. In a fire moving through continuous fuels, however, it appears unlikely that radiation from flames above the fuel bed is a very important factor in fire spread because of the slow rate of heating. McCarter and Broido (31) found this to be true in crib fires. When fuel ahead of the fire was shielded from flame radiation, the rate of fire spread in the crib remained virtually unchanged. Observations of wildfires also have indicated that radiation becomes important in fire spread only under special situations, such as in very narrow, steep-sided canyons. Flame contact with unburned fuels and firebrands falling ahead of the fire appear likely to be the main mechanism by which fire spread, particularly where wind is a factor.

Temperature

To provide information on the magnitude and pattern of temperature in the fires, thermocouples were placed at various points in and above the fuel bed. Shifting fuels, fire whirls, and high fire intensity frequently destroyed or damaged the thermocouple supports or lead wires before the fires burned out. Methods of supporting and exposing the thermocouples were modified continuously to improve the durability of the temperature sensing system. Thermocouples sheathed in inconel or stainless steel and supported on insulated steel pipes were found to work most satisfactorily, and this system was used in the later tests.

Heavy Fuels

In the heavy-fuel tests, it was necessary to clear an area 5 or 6 feet in diameter around the pipe supports. Thermocouples on these supports were thus not in direct contact with the burning fuel, although they were frequently engulfed in flame. Thermocouples were also strung between pipe supports directly over the fuel bed.

Flame temperatures in these fires appeared to be considerably higher than the 1, 400° to 1, 600° F. reported for laboratory fires. Valid temperatures of 2,300° F. or greater were recorded on nearly all fires. Temperatures in fire whirls were probably considerably greater as indicated by the bright orange flame in the whirls as compared with the darker red of the surrounding flames.

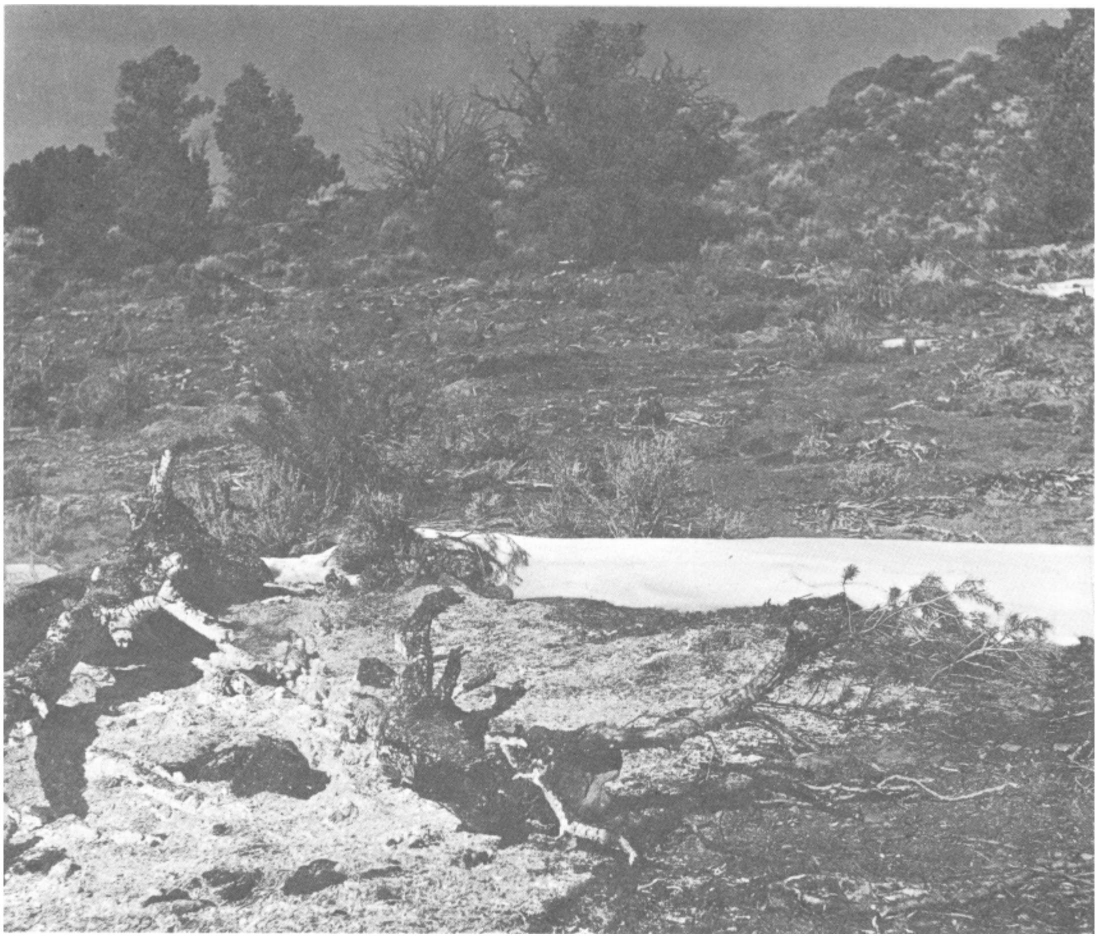


Figure 33.--Snow drift on edge of mixed-fuel plot was not melted appreciably by radiation. Note unburned vegetation close to fire edge.

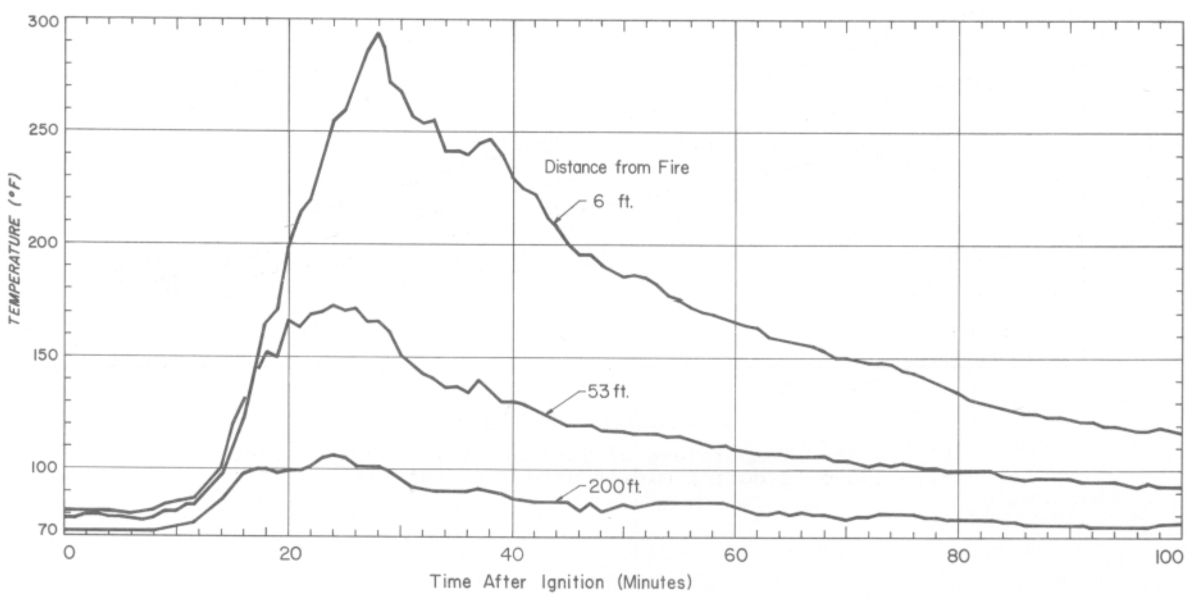


Figure 34.--Time-temperature history of fuel particles outside test fire 380-6-63.

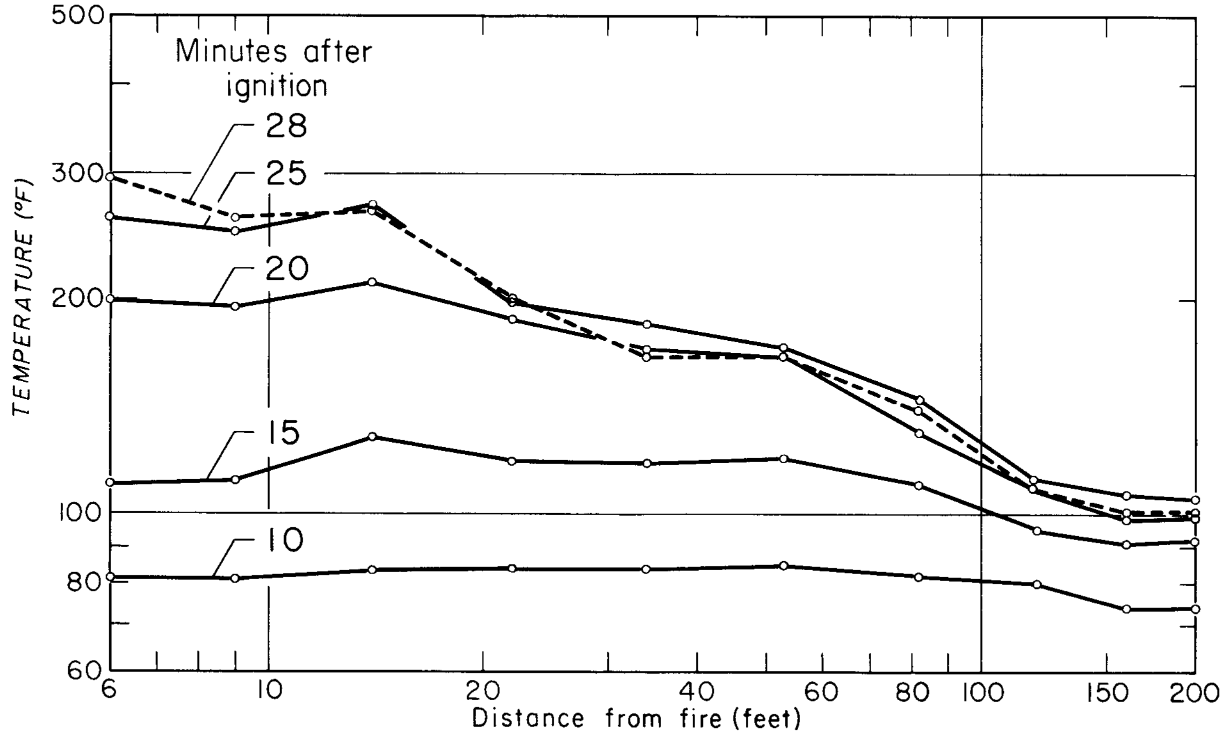


Figure 35.--Temperature of fuel particles outside test fire 380-6-63 during early stages of the fire.

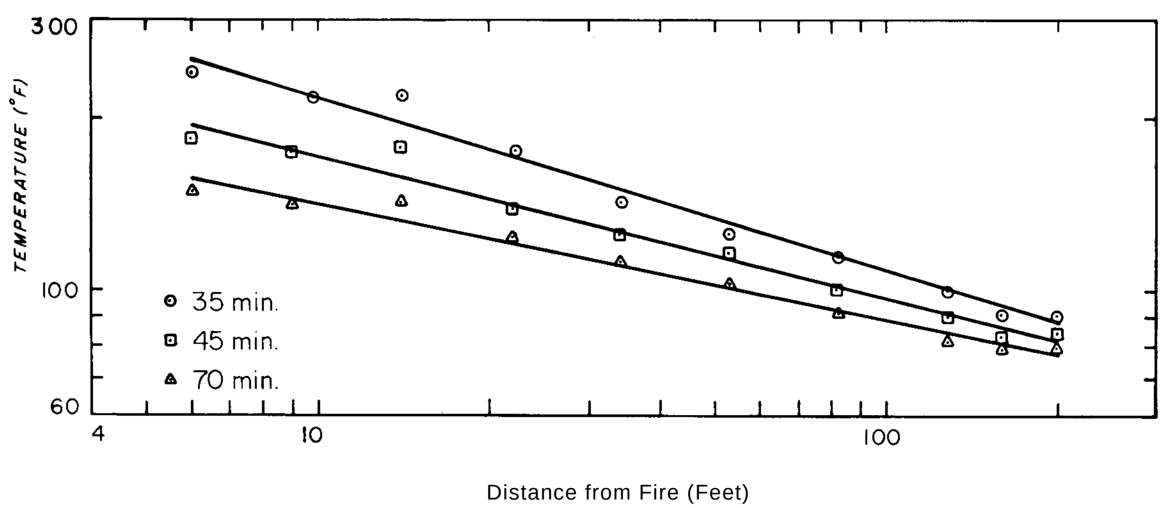


Figure 36.--Temperature of fuel particles outside test fire 380-6-63 during middle stages of the fire.

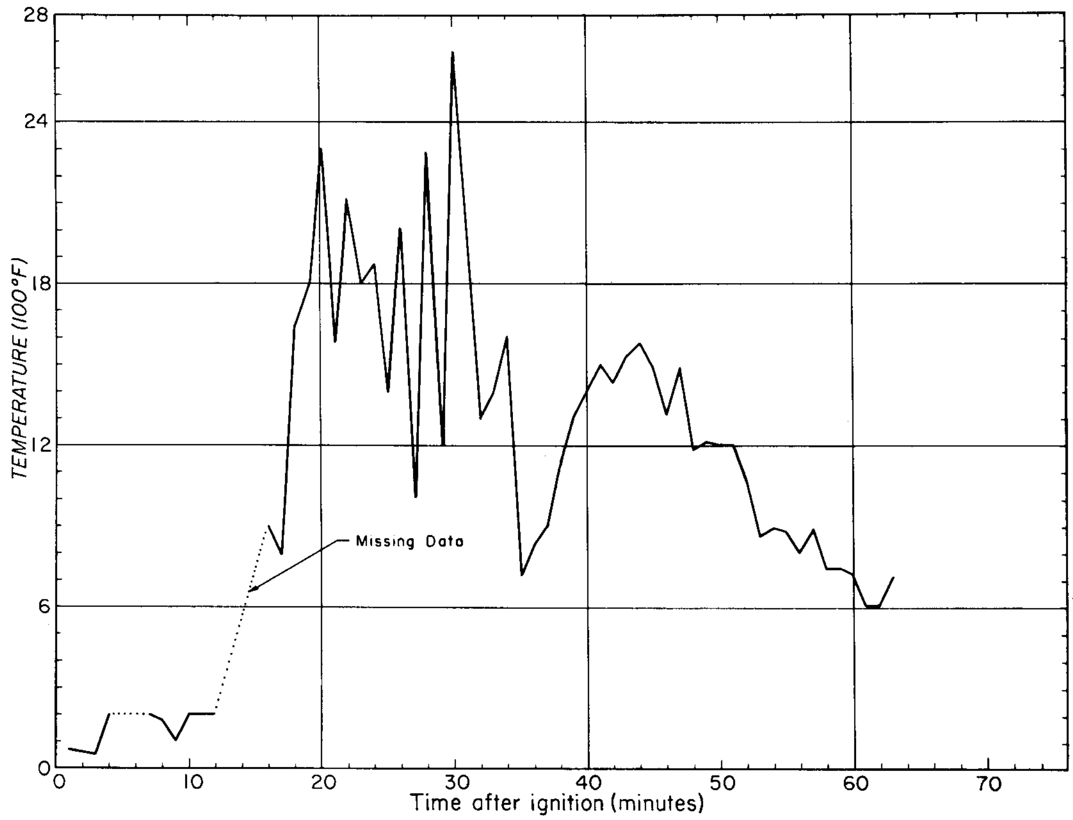


Figure 37.--Temperature at 15 feet above the fuel bed, test fire 380-4-63.

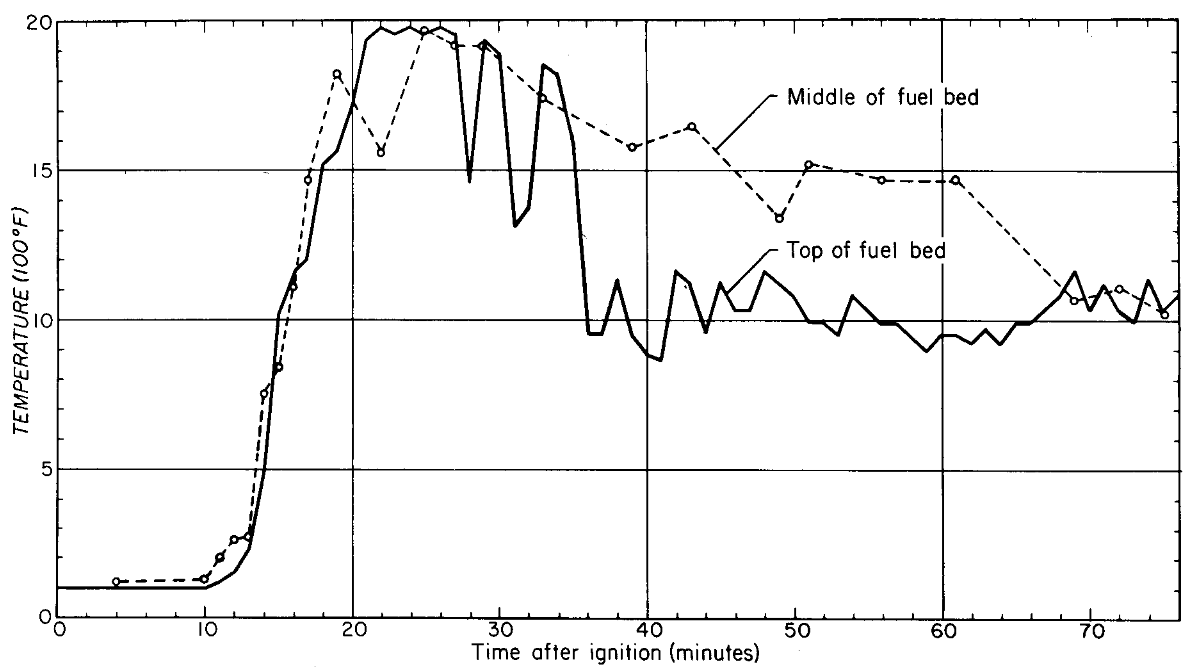


Figure 38.--Temperature at top and middle of fuel bed, test fire 380-4-63.

The temperature pattern of the thermocouples above the fuel bed was marked by very rapid fluctuations of considerable magnitude (fig. 37). This was caused by flame 'flicker. " Burning gases would shoot up rapidly and die away or shift position so that the temperature sensor was seldom more than momentarily in the flame. Only for a brief time during the maximum flaming period early in the fire history did a solid mass of flame appear above the fuel. For most of the active fire the combustion zone was a mass of constantly moving, shifting flames. "Hot spots" would develop, burn briefly, and die away only to reappear somewhere else.

Close to the top of the fuel bed and within the fuel bed, temperature fluctuations were not as rapid as above the fuel bed (fig. 38). The lower peak temperature measured in this area in test 380-4-63 is probably due to the cleared area around the sensor support. The indicated temperatures thus more nearly represent gas temperatures than flame temperature.

Mixed Fuels

The effect of wind on the temperature pattern was apparent in some of the individual fires in multiple-fire test 760-1-64. Thermocouples were strung in a line approximately 3 feet above the fuel bed and spaced so that one thermocouple was over the center of the pile, another about 9 feet in from the edge of the pile on the windward side, and a third the same distance from the edge of the pile on the downstream side.

In all three positions the temperature rose very rapidly soon after ignition (fig. 39). For the first 8 to 10 minutes, or during the violent flaming period, the temperature remained high at all three points. After this initial period the wind began to tilt the convection column. The temperature on the windward side then

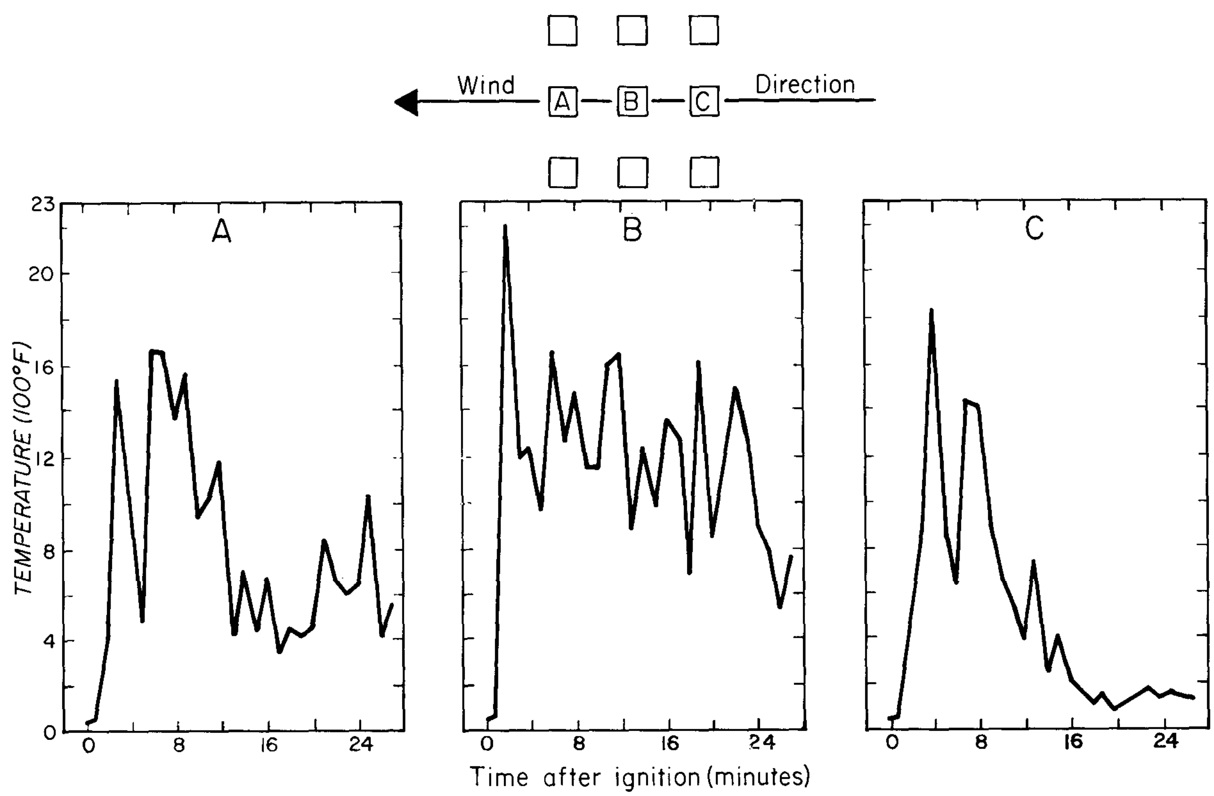


Figure 39.--Temperature 3 feet above test fire 760-1-64, at windward, middle, and lee locations.

dropped rapidly and after 16 minutes never rose more than 120° F. above the ambient air temperature. Above the center of the pile the temperature remained high; the temperature on the lee side, although lower than the center, was considerably higher than at the windward position.

Urban Fuels

In the house fire (test 642-1H-64) thermocouples were placed in a number of locations in all of the rooms. Ignitors were placed on the roof and outside walls, and in the rooms on the north side of the house. The ignitors on the roof and walls failed to start fires, but the house was ignited by the inside ignitors and by a fire that started in trash at the rear or east side. The fire at the rear built up most rapidly so in general the fire spread from the rear toward the front of the house. Thermocouples in the center of the first and second-story rooms in the southwest corner of the house showed similar and typical patterns (figs. 40, 41). Temperatures rose slowly as the fire moved toward the rooms. When the rooms "flashed over" and became filled with flames, the temperature rose abruptly to more than 2,300° F. The walls of the rooms burned through quickly and, as the house began to collapse and outside air was able to enter, the temperature dropped quickly. The temperature rose again after the house had collapsed completely and the remaining fuel began to burn more intensely. The position of the thermocouple with respect to the fuel bed was not known during this latter period.

Convection Column

Temperature measurements in the convection column at greater heights than was possible with the steel pile towers were sought by suspending modified radiosondes from tethered weather balloons. Because of the extreme turbulence in the convection column, the balloons survived only a short time. The turbulence also made it difficult to keep the sensor in the convection column. Fragmentary temperature records, however, indicated that temperatures in the convection column 100 to 125 feet above the fire were surprisingly low. In test 760-1-64 at 16 minutes after ignition, the temperature at 125 feet was 98° F., indicating a great deal of air entrainment and heat loss in a very short distance.

"Street" Temperatures

In test 760-1-64, an aspirated temperature sensor was placed between two of the piles at a height of 4. 5 feet. Air temperature increased at this point soon after ignition, reaching a peak of 65° F. (24° F. above ambient) in 60 to 90 seconds (fig. 42). The temperature then dropped slowly and by 6 minutes after ignition was only 4 or 5 degrees above the ambient air. Although the air temperature was not high, the heat radiated from the burning piles made it impossible for unprotected personnel to walk in the streets between the piles during the first 12 to 15 minutes after ignition while flaming was at a maximum. After this initial period, it was possible to walk between the piles without undue discomfort, although the piles of fuel were still burning actively.

Noxious Gases

Reports of some fire raids in World War II noted that many people that died in shelters were apparently untouched by fire. In areas subject to high temperatures, the position of the bodies and mien of some victims indicated that death was probably not caused by fire. It has been postulated that deaths under these circumstances may have been caused by carbon monoxide poisoning or lack of oxygen or both. Medical examination of the bodies lent some evidence to this theory. Therefore, we decided to check this theory in some fires. In many of the completed test fires, continuous samples of gases were taken near the center of the fire, either within the fuel pile or 20 feet above the ground level. Intermittent samples were also drawn from other areas within or adjacent to the fire. These samples were analyzed for carbon monoxide, carbon dioxide, and oxygen.

Peak concentrations of carbon monoxide and carbon dioxide were found to occur during the intense flaming period when samples were taken near the ground

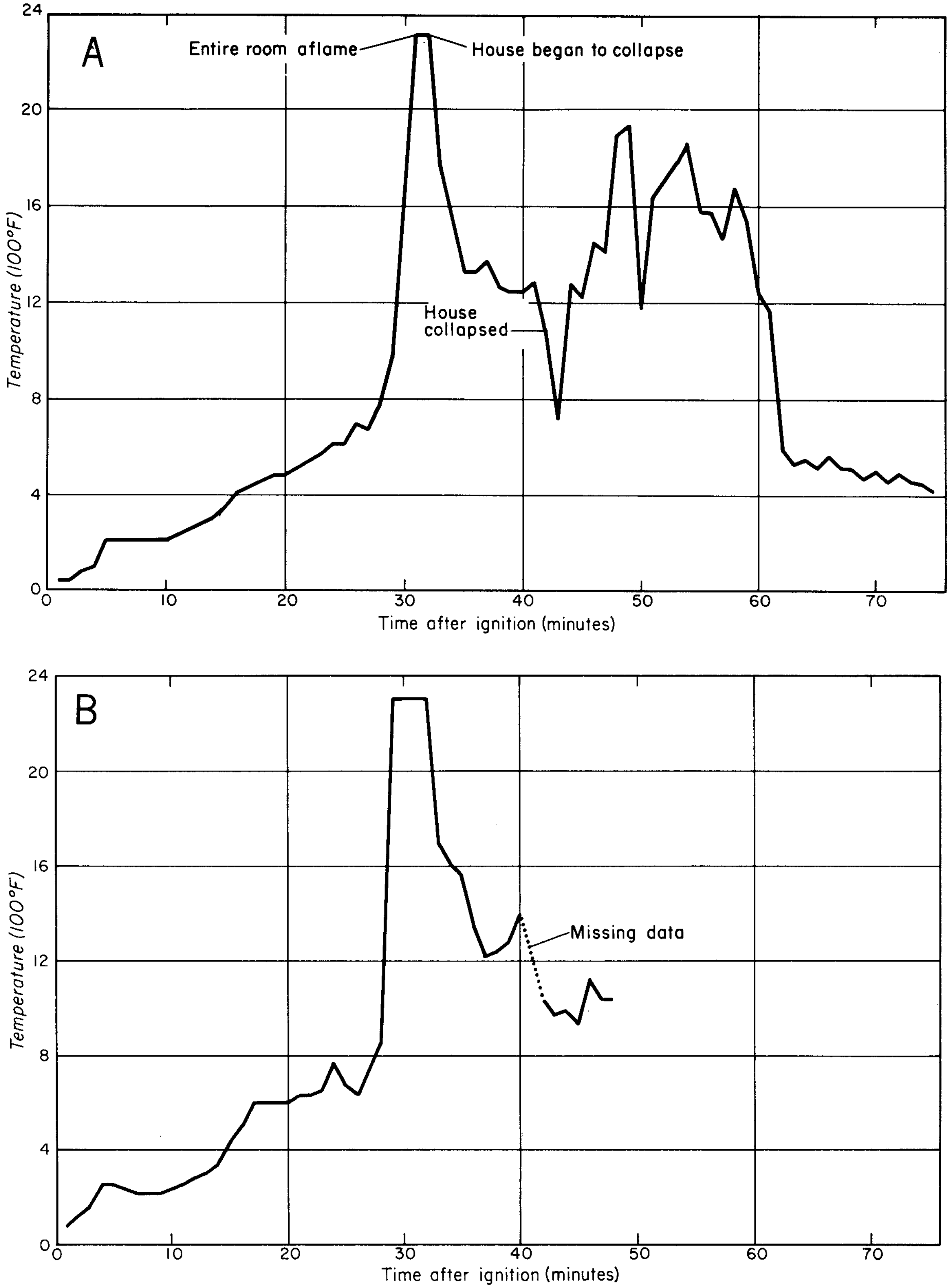
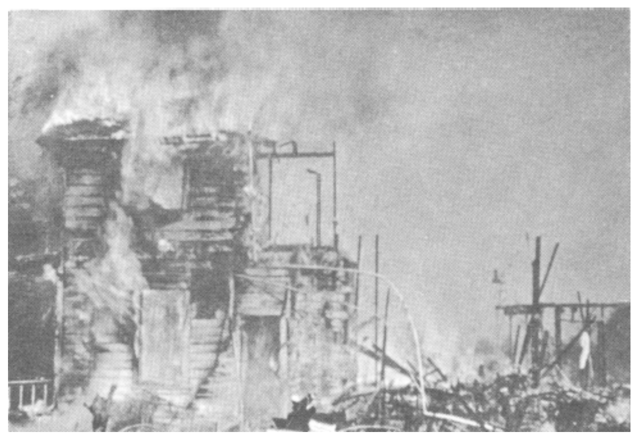


Figure 40.--Temperature pattern, test fire 642-1H-64; A, in center of first story sw. corner room; B, in center of second story sw. corner room.

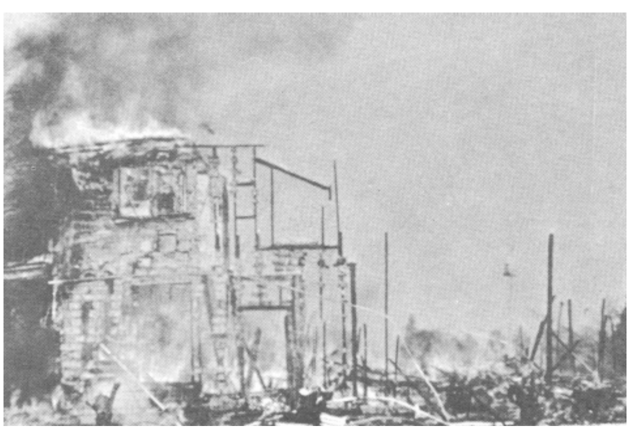
Figure 41.--House fire (test 642-1H-64). A, North side showing ignitors (dark spots) on walls and roof. B, E, South side, at specified intervals after ignition.

A

B - 28 minutes



C - 36 minutes



D - 42 minutes

E - 65 minutes

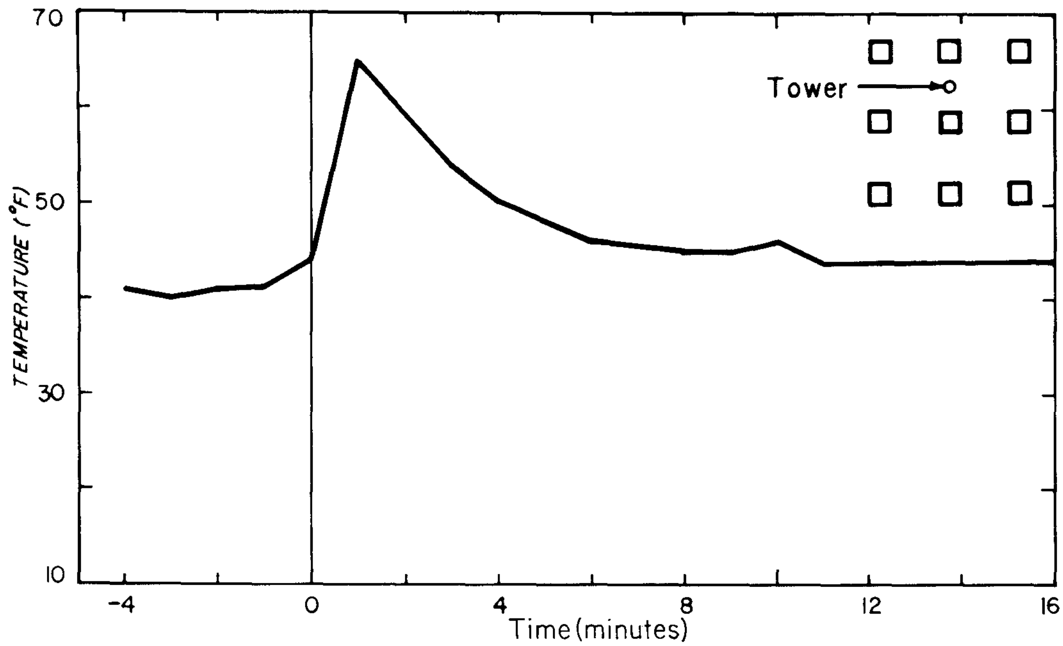


Figure 42.--Temperature at 4.5 feet in "street," test fire 760-1-64.

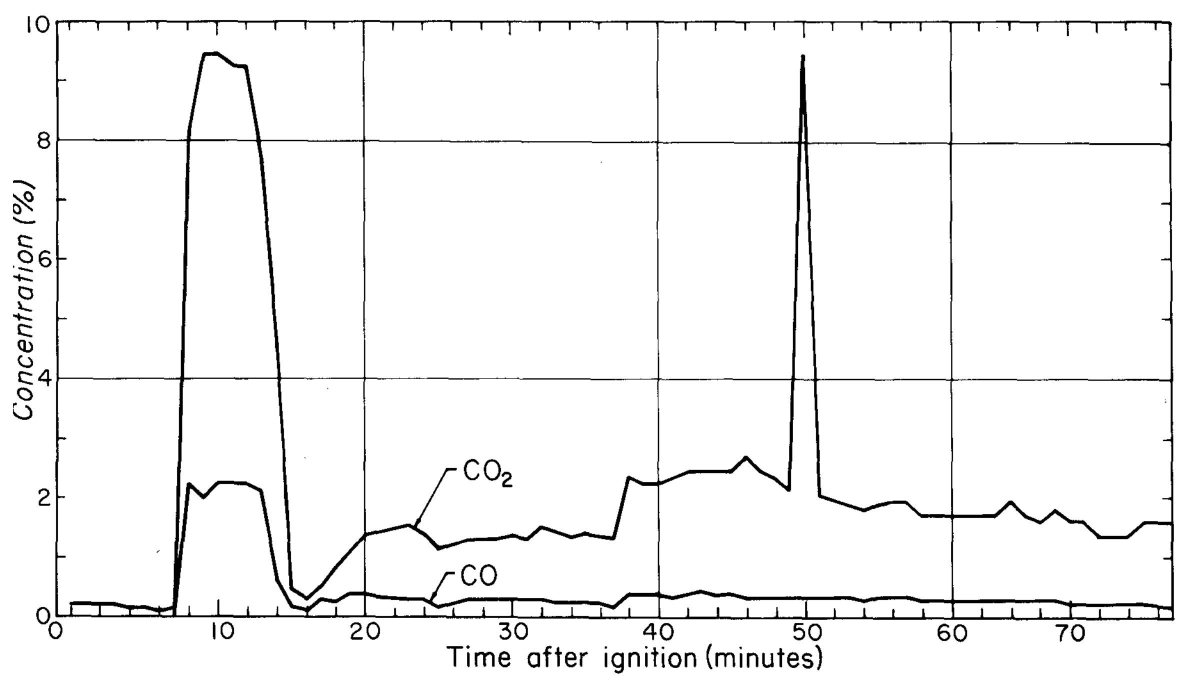


Figure 43.--Concentration of carbon monoxide and carbon dioxide 12 inches above ground, test fire 380-2-63.

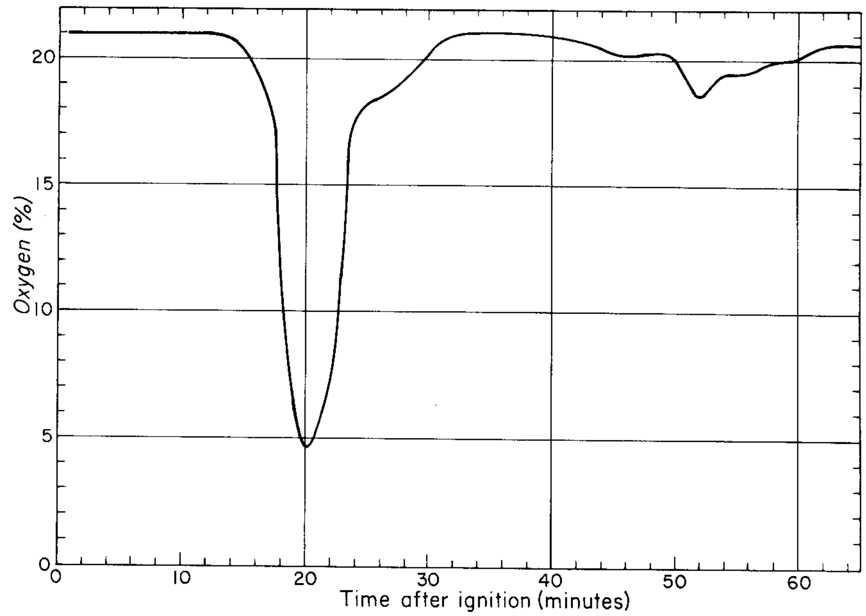


Figure 44.--Concentration of oxygen 12 inches above ground, test fire 380-3-63.

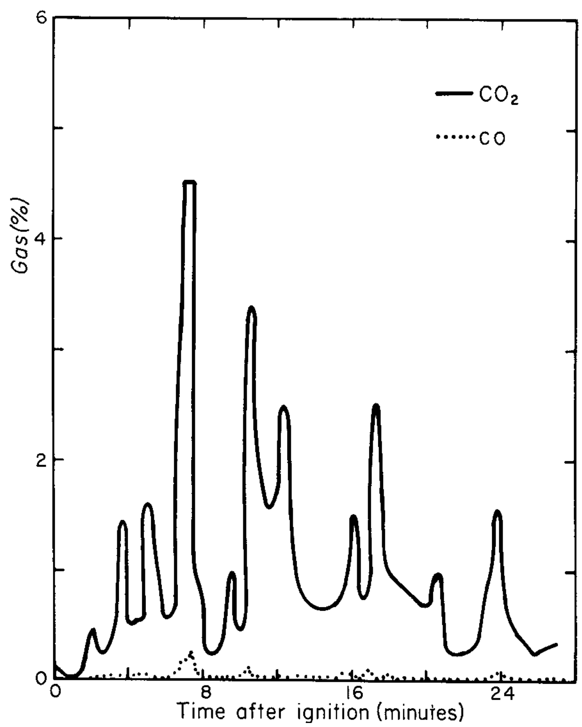


Figure 45.--Concentration of carbon monoxide and carbon dioxide 20 feet above ground, test fire 760-1-64.

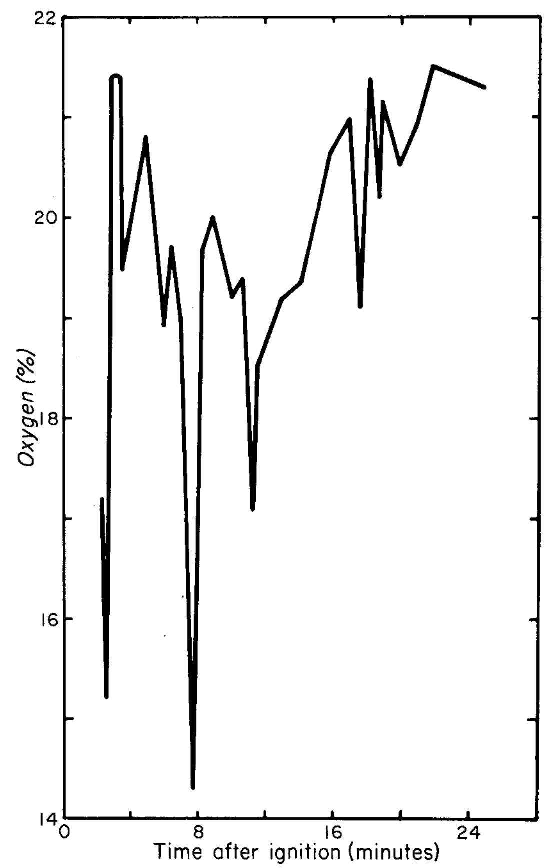


Figure 46.--Concentration of oxygen 20 feet above ground, test fire 760-1-64.

within the fuel pile (fig. 43). The high concentrations lasted for a relatively short time, but moderate concentration of carbon monoxide varied from fire to fire--in some cases exceeding 5 percent. Oxygen depletion was also very evident in the test fires (fig. 44). The greatest depletion also occurred during the maximum flaming period of the fire.

In test 760-1-63, the sampling tube was placed in the center fuel pile 20 feet above the ground. At this level carbon monoxide concentrations were relatively low, and carbon dioxide concentrations were also considerably less than at the 12-inch level of previous fires (fig. 45). Some oxygen depletion was still evident at this level (fig. 46).

The high concentrations of carbon monoxide in all probability is the result of incomplete combustion in the active part of the fire. Preliminary tests have indicated much lower •concentration near the edge of the fire, and no significant concentrations of this gas were found in the "streets" of test fire 760-1-64. Whether lethal concentrations of gas or oxygen deficiency can be transported into nonburning areas in larger fires with closer spacing is yet to be determined.

Summary and Conclusions

The relatively small-scale field tests conducted on Project 2521E were largely exploratory in nature, and preliminary to larger multiple-fire tests planned in the later series. Fifteen multiple-fire plots have been prepared, the largest covering about 10 city blocks and containing 420 simulated houses. A gradual stepping up of the size of test fires was decided on. This approach was used because of the dearth of quantitative information about large fire behavior; even those factors to be measured, and the phenomena that might be significant were not known with any degree of certainty. No precedent existed for determining the kinds and amount of instrumentation needed and measuring systems that would succeed in large-scale tests. Large test fires are expensive to prepare and conduct. Essentially they are "one shot" affairs. Once ignited there is little opportunity for changing their course or modifying instrumentation to record any unforeseen event. The smaller fires burned so far were essential to provide at least a general knowledge of what to expect in larger tests and to develop instrumentation and techniques to gain maximum information from the larger tests.

The completed tests cannot be considered mass fires in the strict context of the term because of their relatively small size. Yet they have provided invaluable information about fire and provided good indications of what may occur in larger scale fires. Some of the data obtained also strongly suggests that conditions may exist in field-scale fires that are not evident in small-scale or laboratory fires. The results also indicate some areas where theoretical analysis can aid greatly in the prediction of probably fire behavior.

Some of the more important results and conclusions from the completed tests are:

1. Wildland fuels can be used to simulate many urban conditions. --Individual fires in the piled wildland fuels behaved in much the same manner as building fires conducted in this study and in other studies by the Pacific Southwest Station. The use of wildland fuels to simulate urban fires permits experimental fires of a size and intensity not practical under urban conditions.

2. Field scale fires can be replicated. --Tests conducted thus far have indicated that under like air mass conditions and with similar fuel types and arrangements the fire characteristics will also be reasonably similar. Fire behavior phenomena observed on one fire can thus be verified in replicate tests.

3. Eddy circulations are important in the development of fire whirlwinds and possibly of fire storms. --Observations of the fire tests showed that fire whirlwinds tended to develop in areas where opposing air currents or eddies occur. Such air flow may result from natural causes or from air currents induced by the

fire. Fire-induced whirlwinds appear more likely to develop under unstable rather than stable air mass conditions. Since it is possible, that fire storms are large-scale vortices or groups of vortices, these factors are also likely to be important in the development of firestorms.

Locating areas where natural or fire-induced eddy circulations are probable should be feasible with present knowledge. Such information would be valuable for prefire planning of control and safety action. Modification of conditions so as to lessen the hazard would also be possible. Accuracy of such predictions can be greatly improved with more information on the interrelationships of rate of heat production, air stability, direction and strength of opposing air currents, and the development of vortices in fires.

4. Maximum air entrainment into the fire area may occur well above the base of the fire. --Air flow into the base of the single-fire test was negligible. On the one multiple-fire test (760-1-64), indrafts were more noticeable but still of low speed. In this test wind speed was considerably increased in the streets between the fires and this increase was greater with increasing height above the ground surface.

5. Fires may block ambient air flow. - -Ambient air flow around a hot fire is similar to the flow of a moving fluid around a solid object with turbulence and eddies developing in the wake. There are some indications that with a tilted convection column there is transfer of momentum toward the ground from the convection column.

6. Radiation may be of minor importance in fire spread for many fires. --Very little effect of radiation on spread of fire was found in any of the test fires completed. This verifies observations on wildland fires and some laboratory tests. Where wind is a factor, fire spread is more likely because of flame contact with unburned fuel and firebrands falling ahead of the fire.

7. Behavior differences between small and large fires may be due in part to temperature. -- Flame temperatures and consequently combustion zone temperatures were found to be considerably higher in the test fires than those found in small experimental fires. Flame temperatures in the test fires exceeded 2, 500° F. and may be greater than 3, 000° F. In a small fire, the air for combustion is drawn from the relatively cool ambient air which acts to cool the flame. In a large fire much of the air for combustion is drawn from above the fire and from air passing through the combustion zone from the sides. Air reaching the interior flames is superheated, often reaching 1, 000° F. or more, and hence provides relatively little cooling. These higher temperatures can be expected to create more violent fire activity.

8. Fires burned as multiple jets after the initial "flash-over. "--After the initial flaming period, fires tended to break up into a number of "hot spots" each with a separate convection column. Gas movement in a zone of considerable depth above a fire was highly turbulent, with both upward and downward currents. Above this turbulent zone the convection columns merged and the more organized flow of thermal convection was apparent.

During the initial flaming period, the fires had some aspects of a single-orifice diffusion flame. This quickly changed into a multiple-orifice "burner" with numerous and shifting areas of active flaming. Height of flames in a fire is therefore controlled principally by laws governing multiple jet orifices.

9. Temperatures within the convection column were relatively low. --The temperature within the "organized" flow of the convection column of a fire is apparently very much lower than in the turbulent combustion zone. This change in temperature may be rather abrupt. The ambient lapse rate (air stability) may thus have a much greater effect on the convection activity than supposed and may account in part for the observed strong effect of air mass instability on large fire behavior.

10. Positive pressures may occur in the combustion zone and negative pressures may occur outside. --Observations in the test fires have indicated that an increase in pressure may occur within the combustion zone and negative pressures may develop in the lee or wake of the fire.

11. Lethal concentrations of noxious gases occurred within and adjacent to fire. --High concentrations of carbon monoxide and deficiency of oxygen were

detected in the combustion zone of fires, with lower concentrations at, the edge, The peak concentration of lethal gases and minimum oxygen concentration occur at about the same time, hence may have a more serious effect than their individual effects in a normal atmosphere. The presence of the lethal gases combined with the possible pressure pattern suggests that shelters beneath a fire or adjacent to it should be sealed during peak fire intensity at least. Significant concentrations were not found in the "streets" of the test fire area.

12. Heat intolerable to unprotected persons can be reached very quickly in a fire area. --The rate of build-up of a fire in a fuel bed ignited simultaneously on the exterior and interior is extremely rapid. Heat conditions intolerable for human survival can be reached within 2 to 3 minutes inside a building or in streets as wide as 115 feet between burning buildings.

13. Instrumentation is a major problem in large-scale fire tests. --The size of the tests, the nature of the phenomena involved, and the large number and variety of measurements needed make the instrumentation of larger-scale test fires a major problem. Conventional laboratory techniques are generally not practical. The problem is not insoluble, however, and solutions are being obtained in this and other projects.

14. Larger fires are needed. --Tests thus far completed have been indicative of the kind and magnitude of fire behavior phenomena observed in large and intense fires. Some leads have been obtained as to why extrapolation of data from small fires does not adequately predict observed behavior of large fires. Larger fires are needed to further explore and substantiate these indications and to determine the effect of fire size on the observed phenomena. Fires larger than those already prepared will probably be required.

15. Effects of fire pattern and ignition pattern need study. --Prescribed burning and observations of wildfire have indicated that both ignition pattern and fire pattern have a marked effect on fire behavior. These effects need to be quantified in controlled tests. Fine fuels, such as crushed brush, should provide media excellent-for such tests. Preparation of tests in this fuel type is relatively low in cost, and the fuel is in plentiful supply.

16. Behavior of long-burning fires needs exploration. --There are some indications that long-burning fires, such as might occur in large buildings of heavy or relatively slow burning construction, may develop different fire behavior characteristics than more rapidly burning fuels. Tests are needed to explore this possibility. Because of the high cost of preparing such tests, they should not be attempted until more quantitative information on large fire behavior is available.

17. Intensive investigation of fire vortices would be invaluable. --Fire test 482-1-63 showed that strong vortices can be intentionally developed in experimental fires with the right combinations of weather, fire intensity, and topography. The role that each of these factors play in the development of vortices is not known except in a very general way. Additional information on fire vortices is expected from the currently planned tests. Because of the importance of this phenomenon in fire damage and control, a series of tests designed specifically to investigate large-scale vortices would be desirable to speed acquisition of data that would lead to the understanding and prediction of fire storms. It would also be desirable to attempt to map situations with a high potential for fire vortices in wildland and urban fires.

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