

# Forest Fire

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## CONTROL AND USE

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## CHAPTER THREE

# *Combustion of Forest Fuels*

by George M. Byram

In all forest fires, materials such as leaves, grass, and wood combine with oxygen to form carbon dioxide, water vapor, and smaller amounts of other substances. This process, known as combustion, is accompanied by the release of large amounts of heat. Combustion is a chain reaction chemically similar to photosynthesis in reverse (Chap. 1). The energy of forest fires thus comes indirectly from the energy of sunlight; in a very short time combustion in the forest can release energy that was stored over a period of many years.

Combustion is a part of the field of fire behavior; hence any discussion of the combustion of forest fuels must necessarily include forest fire behavior. Fire behavior is a general descriptive term used to designate what a fire does. Crowning, fire whirlwinds, rate of fire spread, and spotting are examples of fire behavior phenomena, all of which receive their driving energy from the basic combustion process. Their nature being inseparable, combustion and basic forest fire behavior will be considered together in this chapter. Because of their storm characteristics, the behavior of high-intensity fires can be studied best from a meteorological point of view, and this part of the field of fire behavior is given in Chap. 4.

### THE COMBUSTION PROCESS

#### *Oxidation, Combustion, and Heat of Decomposition*

Combustion is one of many types of oxidation processes. Some of these, including combustion, are chain reactions which take place rapidly at

high temperatures. Other oxidation processes, such as the hardening of a coat of linseed oil in a paint film, take place very slowly at ordinary temperatures. Over a period of time the oil film combines with oxygen in the air and hardens as it oxidizes. The process is very slow, and the rate of heat release is so gradual that the temperature rise is negligible. However, there are conditions under which initially slow oxidation can terminate in a high-temperature chain-reaction combustion process. For example, a loose pile of rags or cotton waste saturated with linseed oil will undergo a temperature rise when the oil starts to oxidize because the cotton waste is a good insulator and retains much of the heat generated. The temperature rise increases the oxidation rate, and vice versa, until a point is reached when the pile of cotton waste begins to smoke and ultimately bursts into flame.

The hardening of a film of linseed oil bears little resemblance to combustion, although the two phenomena are chemically similar. On the other hand, there are processes which closely resemble combustion but are not even oxidation reactions. An example is the thermal decomposition of wood—an exothermic reaction which occurs when wood substance is heated. In this reaction, wood substance breaks down into secondary products and releases heat. If the wood specimen is well insulated, the resulting temperature rise will in turn increase the reaction rate, and hence the rate of heat release. The accelerating rise of temperature continues until the volatile material is distilled off and charcoal remains. It is difficult to state at what temperature the exothermic reaction begins. In attempts to measure the initiating temperature, the results will depend on the method of measurement. For rapid heating in an oven in which the temperature of the wood samples lags considerably behind the oven temperature, Stamm and Harris (1953) give the exothermic-reaction temperature as 523°F. However, for heating in an oven in which the temperature difference between the oven and sample is kept small by raising the temperature of the oven very slowly, the exothermic-reaction temperature may be much lower, possibly 300°F or even less.

The heat of decomposition can, and sometimes does, result in combustion and is the cause of an occasional fire in industrial processes in which well-insulated wood-composition products are stored without sufficient cooling after receiving a final heat-treatment. It is possible that the exothermic reaction may be important in the persistence of ground fires in organic soil, although this possibility has not been demonstrated. The exothermic reaction does not require oxygen, so an insulated underground fuel would be in a favorable environment.

Fires resulting from either the linseed-oil type of oxidation reaction or from the exothermic reaction are usually referred to as *spontaneous-combustion* fires.

*Chemistry of Combustion*

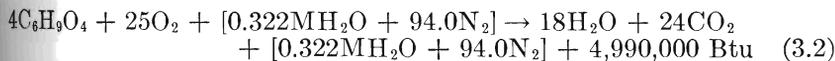
In its simplest form, the chemical equation for combustion can be illustrated by the equation for the complete combustion of a simple substance such as D-glucose sugar:



This equation states that one molecule of the sugar,  $\text{C}_6\text{H}_{12}\text{O}_6$ , combines with six molecules of oxygen to give six molecules of carbon dioxide and six molecules of water plus 1,211,000 Btu of heat per pound mole of sugar burned. A pound mole is the weight of a substance in pounds equal to its molecular weight. The molecular weight of D-glucose is 180, so the heat of combustion is  $1,211,000/180$ , or 6730 Btu per pound of sugar. A British thermal unit, or Btu, is  $1/180$  the quantity of heat required to raise the temperature of one pound of water from 32 to 212°F. The heat of combustion of a fuel may be defined as the quantity of heat released when a fuel has undergone complete oxidation or burning. In fire behavior work a suitable unit of measure is Btu per pound of fuel.

Chemically, wood is a very complex substance, with cellulose and lignin the main constituents. Even the molecular weight of these basic substances is not known. However, the proportion of carbon, hydrogen, and oxygen atoms in wood can be expressed to a close approximation by the formula  $\text{C}_6\text{H}_5\text{O}_4$ . This formula does not represent the wood molecule, but in combustion calculations it can be treated as such. Its weight will therefore be referred to as the equivalent molecular weight.

All forest fuels contain moisture the presence of which should be indicated in the combustion equation even though the moisture is chemically inert. The same is true of the nitrogen in the atmosphere. The equation for the complete combustion of wood with a moisture content  $M$  per cent of its oven-dry weight is



Moisture in the fuel and nitrogen in the air are shown as bracketed quantities because they do not take part in the combustion reaction. In this chapter and in Chap. 4 the fuel moisture content will always be expressed as a per cent of the oven-dry weight of the fuel. If  $M$  is expressed in per cent, it must be multiplied by a constant which is equal to 0.01 times the ratio of 4 pound moles of fuel to 1 pound mole of water. The equivalent molecular weight of wood is 145, and the molecular weight of water is 18, so the desired constant is  $0.01 \times 4 \times 145/18$ , or 0.322. The nitrogen symbol in Eq. (3.2) must be multiplied by a constant which is equal to 25 times the volume ratio of the quantities of nitrogen and

oxygen in the atmosphere (other gases in the atmosphere being neglected). Because there is about 3.76 times as much nitrogen as oxygen by volume in the atmosphere, the desired constant is  $25 \times 3.76$ , or 94.0.

The heat of the combustion reaction in Eq. (3.2) is shown as 4,990,000 Btu for the 4 pound moles of fuel. This would be equivalent to  $4,990,000 / 4 \times 145$ , or 8600 Btu per pound of fuel. Part of this heat will be in the form of latent heat of vaporization of water because after combustion both the initial fuel moisture and the water formed by the reaction will be in the form of vapor. For the lower moisture contents, most of this water vapor comes from the combustion reaction, but for moisture contents greater than 56 per cent the initial fuel moisture contributes the larger amount of water vapor.

The over-all density of the combustion gases on the right side of Eq. (3.2) at a given temperature and pressure is affected by the initial fuel moisture. For low moisture contents, the gases are slightly heavier than air. If the fuel moisture content is greater than 23 per cent, then the combustion gases are slightly lighter than air. Complete combustion is assumed in both instances.

#### *Phases of Combustion*

In woody fuels there are three phases of combustion, although they overlap somewhat and all exist simultaneously in a moving forest fire. First comes the preheating phase in which fuels ahead of the flame front are heated, dried, and partially distilled. In the second phase, the distillation of gaseous substances continues but is now accompanied by their burning. Ignition might be regarded as the link between the first, or preheating, phase and the second, or gaseous, combustion phase. Ignition may also be regarded as the beginning of that part of the combustion process in which oxidation occurs. The flames seen over a forest fire or in a fireplace are the burning of distilled gases which give invisible water vapor and carbon dioxide as the main combustion products. If combustion is not complete, some of the distilled substances will condense without being burned and remain suspended as very small droplets of liquid or solid over the fire. These condensed substances are the familiar smoke that accompanies most fires. Some of the water vapor may also condense and give the smoke a whitish appearance.

In the third and final combustion phase the charcoal left from the second phase is burned and leaves a small amount of residual ash. In this phase the fuel is burned as a solid, with oxidation taking place on the surface of the charcoal. If combustion is complete, the primary combustion product in this phase will be carbon dioxide. The initial water, or fuel moisture, is driven off in the first two phases. Some carbon monoxide is formed as an intermediate product, which in turn burns as a gas to

form carbon dioxide. The small blue flames appearing over the coals in a fireplace are carbon monoxide burning.

The composition of charcoal varies, depending on the conditions under which it is formed. If the distillation temperature is low, 400 to 500°F, the charcoal will contain considerable tar coke and the carbon content will be about 60 per cent. Some water vapor will be a combustion product in the burning of this type of charcoal. However, in the rapid heating and resultant high temperatures existing in a forest fire, the deposits of tar coke are probably low. If the distillation temperature is 1500°F or greater, the carbon content of the charcoal is about 96 per cent (Stamm and Harris, 1953, p. 442).

Even though there is some overlap, the three phases of combustion can be plainly seen in a moving fire. First is the zone in which the leaves and grass curl and scorch as they are preheated by the oncoming flames. Next is the flame zone of burning gases. Following the flames is the third but less conspicuous zone of burning charcoal.

### *Combustion and the Energy Yield*

The energy which maintains the chain reaction of combustion is the heat of combustion—a quantity which can be measured for any particular fuel. Heat transferred to unburned fuel raises its temperature to the

Table 3.1. The Heat of Combustion of Some Woods, Woody Materials, and Pitch as Given by Carmen (1950)

<i>Substance</i>	<i>Heat of combustion for oven-dry material, Btu/pound</i>
Wood (oak).....	8,316
Wood (beech).....	8,591
Wood (pine).....	9,153
Wood (poplar).....	7,834
Pine sawdust.....	9,347
Spruce sawdust.....	8,449
Wood (shavings).....	8,248
Pecan shells.....	8,893
Hemlock bark.....	8,753
Pitch.....	15,120
Average (excluding pitch).....	8,620

point where the fuel, or the gases distilled from the fuel, can react with the oxygen in the atmosphere, and in so doing give off more heat. This in turn raises the temperature of additional fuel, and thus the chainlike nature of combustion becomes established.

The heat energy released by burning forest fuels is high and does not vary widely between different types of fuels. The heat of combustion is given in Table 3.1 for a number of substances which approximate forest

fuels. A little arithmetic shows that the burning of 1 pound of an average woody fuel gives off enough heat to raise the temperature of 100 pounds of water about 86°F. To raise the temperature of 100 pounds of water (about 12 gallons) from a temperature of 62°F to the boiling temperature (212°F at sea-level pressures) would require about 1.74 pounds of an average woody fuel if it burned with maximum efficiency. The combustion of about 1 pound of pitch would accomplish the same result.

The heat of combustion varies slightly for the wood of different species. It is a little higher for a coniferous species such as pine than for the hardwood species. This is a result of both the higher resinous content and higher lignin content of the conifers.

### *Heat Losses*

The heats of combustion shown in Table 3.1 are the maximum values obtainable because they represent complete combustion conditions obtained in a bomb calorimeter. The heat evolved under forest fire conditions is not precisely known, but is less because combustion is not complete under natural conditions. In addition, certain heat losses must be taken into account in estimating the energy budget of forest fires. For this reason it is necessary to use a smaller heat value in fire behavior work, which may be defined as the heat yield. Physically it is, to a very close approximation, the quantity of heat, per pound of fuel burned, which passes through a cross section of the convection column, or smoke plume, above a fire which is burning in a neutrally stable atmosphere.<sup>1</sup> The only restriction on the height of the cross section above the surface of the earth is that it be in that part of the convection column which radiates a negligible amount of energy and receives a negligible amount of radiation from the fire. Probably any height greater than five times the flame height would be adequate because most of the radiant energy from a fire originates in the combustion zone. Like the heat of combustion, the heat yield is measured in Btu per pound. Numerically, it is equal to the heat of combustion minus the heat losses resulting from radiation, vaporization of moisture, and incomplete combustion.

Total radiation measurements on a fire are difficult to make, and in addition the fraction of the energy given off as radiation may be affected by the intensity of the fire as well as by the size and shape of the burning area. Measurements indicate that the heat radiated from a fire is from 10 to 20 per cent of the heat of combustion. Some of the latest measurements described by Vehrencamp (1955) were made on different types of test fires and gave values which ranged from 3 to 30 per cent of the heat of combustion. A tentative working value might be taken as 15 per cent.

<sup>1</sup> The reasons for basing the standard on a neutrally stable atmosphere are given in Chap. 4.

Since Vehrencamp used a heat of combustion of 8000 Btu per pound, this would place the radiant energy at about 1200 Btu per pound. However, in estimating the heat yield not all radiant energy can be considered lost. Some is absorbed by the smoke in the convection column directly above the fire. Also, that part of the radiation responsible for the temperature rise of preheated but unburned fuel cannot be considered lost. The actual loss would be somewhat less than 1200 Btu per pound of fuel, possibly in the neighborhood of 800 Btu per pound.

Table 3.2. Water Heat Requirements for the Combustion of 1 Pound of Wood Fuel

Nature of heat requirement	Heat requirement in Btu with oven-dry per cent moisture content of:				
	0	10	25	50	100
For initial moisture:					
1. Raising the temperature of water from 62 to 212°F.....	0	15	37	75	150
2. Separation of bound water from wood (heat of desorption).....	0	31*	48*	50*	50*
3. Vaporization of water.....	0	97*	243*	486*	972*
4. Heating of superheated vapor from 212°F to a flame temperature of 1600°F.....	0	70	175	350	700
For water of reaction (based on 0.559 pound of water):					
5. Vaporization of water.....	543*	543*	543*	543*	543*
Total water heat loss (sum of requirements 2, 3, and 5).....	543*	671*	834*	1,079*	1,565*

(Heat requirements are expressed in Btu for moisture contents of 0, 10, 25, 50, and 100 per cent. Asterisks indicate actual heat losses.)

Because of the presence of moisture, heat is required (1) to raise the temperature of water in fuel, (2) to separate the bound water from the fuel, (3) to vaporize the water in the fuel, and (4) to heat the water vapor up to the flame temperature. However, only requirements 2 and 3 can be treated as heat losses. Also, for high-intensity fires requirement 3 may be only a partial loss<sup>2</sup> but will be considered a complete loss. These heat requirements are summarized in Table 3.2, which also includes the vaporization heat requirement for the water of reaction. Complete combustion is assumed for the Table 3.2 values. Requirements 1

<sup>2</sup>For small fires, the heat required to vaporize the fuel moisture should be considered a heat loss. For large fires, it may be only a partial loss because part of this moisture sometimes condenses high in the convection column in the form of a white cloud cap. The significance to fire behavior of this returned energy at high levels is not yet known.

and 4 are not heat losses because the heat is stored in the combustion products ( $\text{CO}_2$  and  $\text{H}_2\text{O}$  vapor), in the residual inert nitrogen, and in the excess entrained air.

The weight of the water of reaction as computed from Eq. (3.2) is 0.559 pound per pound of wood fuel burned. The heat required to vaporize 0.559 pound of water is 543 Btu and is independent of the initial fuel moisture. Because of the constancy (for any given fuel) of the heat stored in the vapor of the water of reaction, engineers sometimes subtract this heat from the heat of combustion to obtain what is known as the "low" heat of combustion.

The heat yield for complete combustion for any given moisture content can be computed by the following procedure. Add the radiation loss, 800 Btu per pound of fuel, to the total water heat loss (the last row of values in Table 3.2). Subtract the result from the estimated heat of combustion, 8600 Btu per pound (Table 3.1). Repeat the computation for different moisture contents, and plot the results as a function of fuel moisture. This procedure is illustrated in Fig. 3.1A, which shows the heat yield as a function of fuel moisture.

Because curve A is computed for complete combustion, it represents the maximum, or limiting, value of the heat yield for forest fires. However, one of the largest heat losses may be a result of incomplete combustion. Actually, this is heat not produced rather than heat lost, but it amounts to the same thing. Most of the loss takes place in the second

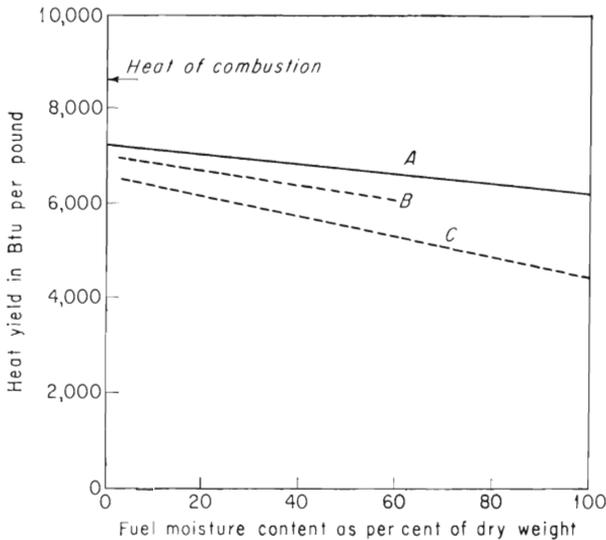


Fig. 3.1. Heat yield of combustion as a function of fuel moisture content. A. Complete combustion. B. Estimate for small fires. C. Estimate for large fires.

phase of combustion, in which the distilled gases are burned. Combustion appears to be more complete on small fires than on large fires; hence the heat yield should be greater for the small fires. Incomplete combustion on major fires is indicated by the occasional flashes which can extend upward several hundred feet in the convection column. In the intervals between flashes part of the distilled-fuel fractions are escaping unburned.

Although the efficiency, or completeness, of combustion for forest fires is not known, the heat loss must be estimated in making energy calculations. There are several rough guidelines for doing this from the appearance of the smoke and flame, intensity of fire, and average moisture content of the fuel which burns. The combustion efficiency should be greatest for a low-intensity fire in a dry fuel, such as cured grass, which burns with bright-yellow flames and very little smoke. For a major high-intensity fire burning with dull-red flames, and giving off large quantities of dark smoke, the combustion efficiency should be considerably lower. The increase in quantity of smoke with increasing fuel moisture for a fire of any size indicates decreasing combustion efficiency with increasing moisture content.

Curve *B* in Fig. 3.1 represents a tentative heat-yield estimate for small fires (flame height 1 to 4 feet) as a function of fuel moisture content. The curve is terminated at about 60 per cent because small fires will not burn at higher moisture contents in most fuels. Curve *C* is a similar estimate for high-intensity fires (flame height 50 to 200 feet). High-intensity fires can burn in fuels with much higher moisture contents than can low-intensity fires. Also, the average moisture content of the fuel which burns in a large fire is higher than for a small fire because of the larger proportion of green material, such as needles and green brush, which is consumed.

### FACTORS AFFECTING THE RATE OF ENERGY RELEASE

Figure 3.1 can be used to estimate the energy released in a forest fire if the quantity of fuel per unit area and its average moisture content are known. This energy is an important quantity, but of even more immediate significance to fire behavior is the rate of energy release. This rate is closely related to fuel energy but depends also on the fuel combustion rate.

#### *Fuel Moisture*

The effect of fuel moisture on the burning rate of wood fuel is so pronounced and so obvious that no measurements are needed to illustrate its over-all effect. However, the mechanisms by which water affects the

burning rate are not so simple. Curve A in Fig. 3.1 shows that the presence of a relatively large amount of water in wood produces a relatively small decrease in the heat yield for optimum or complete combustion conditions.

The most important effect of fuel moisture on combustion may be described as a smothering process in which water vapor coming out of the fuels dilutes the oxygen in the air surrounding the fuel. For the higher moisture contents the pressure of the heated water vapor coming out of the fuel may nearly equal the atmospheric pressure. The sum of the pressures of all the gases (oxygen, nitrogen, carbon dioxide, and water vapor) surrounding the fuel must equal the atmospheric pressure. Hence if the pressure of the water vapor itself is nearly equal to the atmospheric pressure, then most of the oxygen as well as other gases will be excluded from the space immediately adjacent to the fuel. Combustion of flammable gases could not occur in this space until enough water had boiled out of the fuels to lower the pressure of its vapor to the point where the pressure of the oxygen was high enough to support combustion. The smothering effect of water vapor or any other inert gas is closely related to the phenomenon of flammability limits.

The flammability limits for the gases distilled from wood substance are not known but may roughly approximate those for vapors of liquid hydrocarbon fuels. The upper flammability limit determines how "rich" a gas-air mixture can be and still burn. The corresponding lower limit determines how "lean" the mixture can be and still burn. These limits as given by Newman (1950) do not vary greatly for the vapors of several liquid hydrocarbon fuels. Benzene vapor for which the upper and lower limits are, respectively, 6.75 and 1.35 per cent by volume is a representative example. This means that if there is more than 6.75 per cent or less than 1.35 per cent of benzene vapor by volume in an air-benzene-vapor mixture, combustion cannot take place. Newman (1950) also gives data for computing the flammability limits when the air contains an inert gas such as water vapor. If the air is replaced by a mixture of air and water vapor to form an air-water-vapor-benzene-vapor mixture, the benzene-vapor content (in per cent of the total volume of the mixture) is decreased for the upper flammability limit and simultaneously raised for the lower limit. For example, if the air-water-vapor component is by volume 22 per cent water vapor and 78 per cent air, the upper and lower limits for benzene vapor by volume become about 1.6 per cent and 5 per cent of the total volume of the air-water-vapor-benzene-vapor mixture. As the water-vapor content of the air-water-vapor component of the mixture is still further increased, the two flammability limits come closer together and meet at a critical value of about 2.4 per cent (that is, benzene vapor will be 2.4 per cent of the total gaseous mixture by

volume). The air-water-vapor component now contains about 36 per cent water vapor and 64 per cent air by volume. If the water-vapor content is higher than 36 per cent, the benzene vapor will not burn. The flammability-limit values would probably be somewhat different for the burning of gases distilled from wood, but the basic principles would be the same.

Because the products of the combustion reaction must share a part of their heat with the inert moisture evaporated from the fuels, there is a resulting reduction in flame temperature. This could possibly have a significant effect in reducing the rate of fire spread. Flame temperature measurements show considerable variation. The thermocouple measurements of Fons (1946) for several different kinds of fuel gives a mean value of 1500°F. Vehrencamp (1955) gives 2000°F for the flame temperature but states that his value may be rather high. A compromise choice might be 1800°F for fuels with a low moisture content and 1600 or 1700°F for fuels with a high moisture content of 40 per cent or more.

### *Wind*

Air movement is one of the major fire behavior factors. Wind directly affects the burning rate of forest fuel by influencing the rate of oxygen supply to burning fuel. Also, strong winds increase the rate of fire spread by tilting the flames forward so that unburned fuel receives energy by radiation and convection at an increased rate. These two mechanisms are especially important in causing smaller fires to build up their intensity.

The speed of the wind, both at the earth's surface and aloft, appears to have a dominant role in controlling the convection process over large fires, and hence in determining the intensity that such fires will reach. The relationship of air movement to fire behavior is discussed in Chap. 4.

### *Heat Transfer*

Heat is transferred in three primary ways, by conduction, convection, and radiation. The carrying of embers and firebrands ahead of the fire (the familiar phenomenon of spotting), although dependent on convection, is a type of ignition-point transfer and is equivalent to a fourth means of heat transfer.

As a heat-transfer mechanism, conduction is of much greater importance in solids than in liquids and gases. It is the only way heat can be transferred within opaque solids. By means of conduction, heat passes through the bottom of a teakettle or up the handle of a spoon in a cup of hot coffee.

Convection is the transfer of heat by the movement of a gas or liquid. For example, heat is transferred from a hot-air furnace into the interior

of a house by convection, although the air picks up heat from the furnace by conduction.

Radiation is the type of energy one feels when sitting across the room from a stove or fireplace. It travels in straight lines with the speed of light.

Most of the preheating of fuels ahead of a flame front is done by radiation. For a fire that occupies a small area and can be thought of as a "point" (such as a small bonfire or a spot fire), the intensity of radiation varies inversely as the square of the distance from the fire. For example, only one-fourth as much radiation would be received at 10 feet as at 5 feet from the fire. If the fire is stretched out in one dimension, such as a long line of low-intensity backfire, the intensity of radiation does not decrease so rapidly with increasing distance from the fire. In this case the intensity varies inversely as the distance from the fire; the intensity at 10 feet would be about one-half as great as at 5 feet. For a fire front of two dimensions, as is approximated by the wall of flame at the front of a large fire, the intensity of radiation drops off even more slowly. This tendency for radiation to maintain its intensity in front of a large fire is an important factor in the rapid increase of the fire's energy output.

Convection, with some help from radiation, is the principal agent of heat transfer from a ground fire to the crowns of a conifer stand. Hot gases rising upward dry out the crown canopy above and raise its temperature to the kindling point. Although convection initiates crowning, both convection and radiation preheat the crown canopy ahead of the flames. The effects of both radiation and convection in preheating are considerably increased when a fire spreads upslope, because the flames and hot gases are nearer the fuels. The opposite is true for downslope spread.

Convection and radiation can transfer heat only to the surface of unburned (or burning) fuel. Radiant heat may penetrate a few thousandths of an inch into woody substances, and this penetration may be of some significance in the burning of thin fuels, such as grass blades and leaves. However, radiation, like convection, for the most part transfers heat only to the surface of fuel material, and conduction may be considered the only means of heat transfer inside individual pieces of fuel. For this reason conduction is one of the main factors limiting the rate of burning in heavy fuels, such as slash and limbs and logs in blowdown areas. Materials that are poor conductors of heat, such as most forest fuels, ignite more readily than do good conductors, but they burn more slowly.

#### *Fuel Size and Arrangement*

For a given amount of fuel per unit area, the rate of burning increases with increasing surface area of the fuel provided there is an adequate

oxygen supply. This is why a pile of finely split kindling burns faster than does a pile of larger pieces of wood containing the same volume of fuel.

The effect of size and arrangement of fuel on combustion can be illustrated by the following example. Consider a large pile of dry logs all about 8 inches in diameter. Although somewhat difficult to ignite, the log pile will burn with a hot fire that may last for 2 or 3 hours. The three primary heat-transfer mechanisms are all at work. Radiation and convection heat the surfaces of the logs, but only conduction can transfer heat inside the individual logs. Since conduction is the slowest of the three heat-transfer mechanisms, it limits the rate of burning in this case. Consider now a similar pile of logs that have been split across their diameters twice, or quartered. Assume that the logs are piled in an over-all volume somewhat greater than the first pile, so there will be ample ventilation. This log pile will burn considerably faster than the first one because the burning rate is less dependent on conduction. The surface area was more than doubled by the splitting, so that convection and radiation are correspondingly increased in the preheating effects. The burning surface is also increased by the same amount.

Assume that the splitting action is continued until the logs are in an excelsior state and occupy a volume thirty or forty times as great as in their original form. Convective and radiative heat transfer will be increased tremendously in the spaces throughout the whole fuel volume, and the rate of burning might be increased to a point where the fuel could be consumed in a few minutes instead of hours.

The effect of fuel arrangement can be visualized if a volume of excelsior-like fuel, such as that just described, is compressed until it occupies a volume only four or five times that of the original volume of logs. The total surface and radiative conditions are the same as before compression, but both convective heat exchange and oxygen supply are greatly reduced. There will be a corresponding decrease in the rate of combustion.

Fuel size and fuel arrangement have their greatest effect on the lower-intensity fires and in the initial stages of the buildup of a major fire. When a fire reaches conflagration proportions, the effect on fire behavior of factors such as ignition probability and quantity of firebrand material available for spotting may be greater than the effect of fuel size and arrangement.

### *Retardants and Inhibitors*

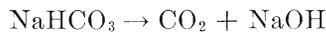
How to stop or slow down the combustion reaction by introducing extraneous substances at some point in the combustion process is of great practical significance in fire control operations. A good discussion of the field of fire extinguishing agents and the manner in which they work is

given by Friedman and Levy (1957). Although much of their discussion concerns the combustion of gaseous fuels and the vapors of liquid fuels, it can also be applied to combustion of solid fuels. They list two general mechanisms of flame extinguishment—physical and chemical.

Two of the physical mechanisms given appear to have considerable significance in the burning rate of forest fires. One is a blanketing mechanism aimed to separate the combustible material from its air supply. The “blanket” might be a layer of carbon dioxide gas or water vapor. Another physical mechanism is the cooling of the flame zone, which may be accomplished in several different ways, as by use of dirt and water on forest fires.

The most commonly used and one of the most effective combustion inhibitors is water (Chap. 13). The inhibiting mechanisms of water applied to burning forest fuels appear to be the same as for moisture already in the fuel and are primarily physical in nature. However, the cooling action of applied water is probably more effective than moisture already in the fuel because it takes place on the surface of the burning fuel. The same should be true of its smothering and oxygen-diluting effect. A part of the initial fuel moisture evaporates in advance of the flame front and thus loses some of its effectiveness.

Friedman and Levy (1957) give considerable attention to chemical mechanisms which are not well understood but seem to be promising in the development of new effective agents. Some chemicals such as the halogenated hydrocarbons appear to break the combustion chain reactions. Salts of the alkali metals are inhibitors of the combustion reaction. One of the most familiar is sodium bicarbonate. When heated it undergoes the reaction



It might thus appear that the inhibiting action of this salt would be through physical mechanisms; the salt particles would tend to cool the flames, and the released  $\text{CO}_2$  would have a blanketing as well as a cooling effect. However, Friedman and Levy (1957) believe that there is sufficient evidence to indicate that the principal inhibiting action of this salt is of a chemical nature.

### THE FIRE TRIANGLE

The fire triangle is a simplified device for illustrating the principles of combustion and their application. The three sides of the triangle are FUEL, OXYGEN, and TEMPERATURE. Heat is the significant combustion product. In the absence of any one of these three sides, combustion cannot take place. The fire triangle can be visualized as the basic link in the

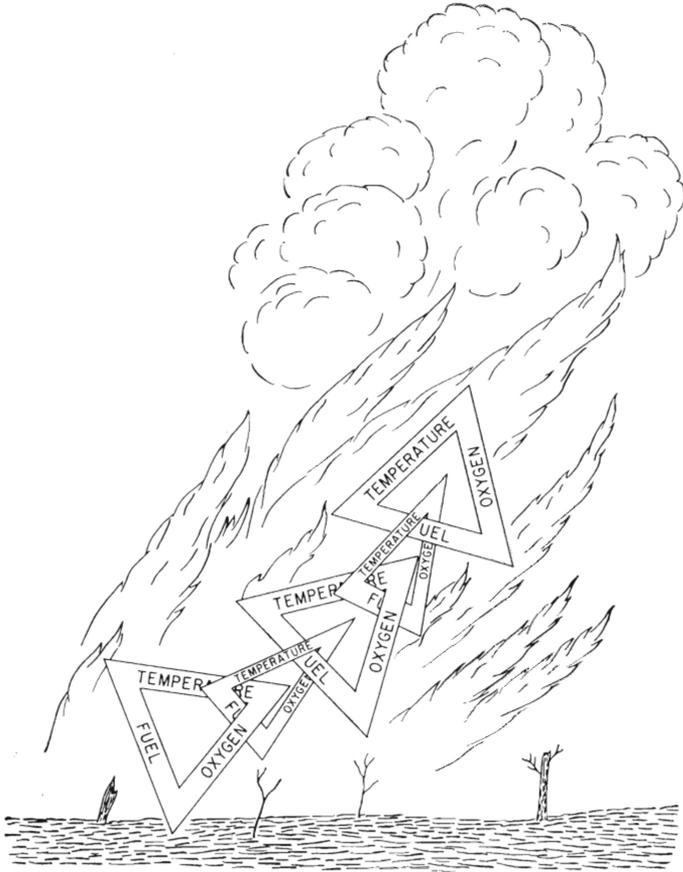


Fig. 3.2. The fire triangle is the basic connecting link in the chain reaction of combustion.

chain reaction of combustion as illustrated in Fig. 3.2. Removing any one or more sides of the triangle breaks or destroys the chain. Weakening any one or more sides weakens the chain and diminishes the combustion rate and fire intensity correspondingly.

The purpose of all fire suppression efforts is to break or weaken, directly or indirectly, one or more sides of the fire triangle. Conversely, all conditions that increase fire intensity operate in such a way as to greatly increase or strengthen the sides of the triangle and, hence, the chain reaction of combustion. In a major conflagration, the chain becomes so strong that it cannot be readily broken by any of the fire control methods now in use.

The significance of specific fire suppression measures can be illustrated by means of the fire triangle (Chap. 11). Obviously, clearing a fireline

removes the fuel side of the triangle and breaks the combustion chain for low-intensity fires. Throwing dirt on a fire weakens the oxygen side of the triangle by reducing the amount of fuel surface exposed to the air. It also weakens the temperature side by cooling the fuels and reducing the distillation rate of the volatiles. The application of water also works on both the temperature and oxygen side of the triangle, but more effectively.

### FUEL-WATER RELATIONSHIPS

Moisture in fuels has such a significant effect on combustion and fire behavior that it is a key variable in fire danger rating. The moisture part of a fire danger rating system is equivalent to a method for keeping books on the forest fuel moisture budget. An understanding of the variations in the flammability of forest fuels requires a knowledge of the factors which control the moisture of the fuels.

The moisture content of the nonliving fuels has a very large range. It seldom goes below 2 per cent but can exceed 200 per cent for fuels such as punky wood and duff after a prolonged rain. The moisture content of living vegetation is less variable. For the living material which burns in a high-intensity fire, such as green leaves and needles, twig endings, and brush up to 3 and 4 inches in diameter, the moisture content usually ranges from 75 to 150 per cent of its dry weight.

The main weather variables which control the moisture of nonliving fuel are rainfall, relative humidity, and temperature. Wind and sunshine are important factors in fuel drying, but they exert their influence by modifying the temperature of the fuels and the temperature and relative humidity in the thin air film adjacent to the fuels.

The only way in which fuels with a moisture content of 25 or 30 per cent can gain a further appreciable increase in moisture is by rainfall. However, fuels exposed to the open sky on a clear cloudless night gain considerable moisture in lowland locations by collecting dew. The mechanism involved is radiation cooling and is described by Byram (1948).

Woody materials can literally take moisture out of the air, although the presence of air as such has nothing to do with the hygroscopic process. The water which wood takes from the air is called bound water. Its properties are different from those of free or ordinary water; the boiling point is higher, the freezing point lower, its density greater, and its vapor pressure lower. Energy is required to separate the bound water from wood, as indicated in Table 3.2. When wood substance is taking moisture from the air, the process is called adsorption. When wood is giving up bound water, the process is known as desorption. The amount of bound water in fuels is determined to some extent by temperature, but relative

humidity is the main controlling factor. Wood that is neither gaining nor losing moisture in an environment of constant relative humidity and temperature is said to be in equilibrium with that particular humidity-temperature combination.

Temperature and relative humidity also have a pronounced effect on the rate at which bound water is lost or gained by forest fuels when equilibrium conditions do not exist. Actually, equilibrium conditions are a rare exception rather than the rule. Forest fuels are usually gaining or losing moisture as the temperature and relative humidity go through their daily cycle. Superimposed on the daily cycle are smaller random fluctuations in the two variables which cause them to change from minute to minute. Variations in temperature and relative humidity, in combination with fuel size, produce complex lag effects. In the case of the thinnest grass blades, the lag may be of an order of magnitude that can be measured in minutes. The lag time increases with size of fuel and for large logs may be of such a length that it would have to be measured in terms of months or even years.

The complex field of wood-water relationships is discussed in greater detail in publications by Stamm and Harris (1953), Stamm (1946), Stamm and Loughborough (1935), Byram and Jemison (1943), and Byram, Fons, Sauer, and Arnold (1952).

## COMBUSTION OF FOREST FUELS

Before considering combustion as it actually occurs in the fuels of the forest, it is desirable to define specific combustion and fire behavior terms and establish units of measurement, which thus far have been used in a general sense only.

### *Definition of Basic Combustion and Fire Behavior Terms*

*Available fuel* is the quantity of fuel that actually burns in a forest fire. It is subject to wide variation. Even in a homogeneous forest type the available fuel will vary widely with the fuel moisture conditions. It will also vary with the intensity of fire; for example, more fuel usually burns in a fire spreading with the wind than in a fire spreading against the wind.

The primary unit for the measurement of available fuel in energy calculations is pounds per square foot. A secondary unit useful in field measurements is tons per acre. Conversion factors for different units are given in Table 3.3 for several basic quantities used in combustion and fire behavior.

*Total fuel* is the quantity of fuel which would burn under the driest conditions with the highest-intensity fire. The virtue of introducing the

concept of total fuel is that it sets a maximum value for the available fuel. Total fuel is measured in the same units as available fuel.

*Available fuel energy* is the amount of energy released when the available fuel burns. It is measured in Btu per square foot and is numerically equal to the product of the available fuel and the heat yield.

When dealing with convective phenomena over large fires, the available fuel energy must be replaced by what may be defined as the fuel energy available for convection (Chap. 4). With the exception of fuels which have components which require a long time to burn out, such as logs and heavy limbs, these two energies are ordinarily equal.

**Table 3.3. Units and Conversion Factors for Some of the Basic Variables Employed in Combustion and Fire Behavior Calculations**

Variable	Unit of measurement	Conversion factor and alternate unit
Quantity of fuel (available and total)	Pounds per square foot Tons per acre	21.8 (tons per acre) 0.0459 (pounds per square foot)
Fuel energy (available and total)	Btu per square foot	
Rate of spread:		
Forward rate of spread	Feet per second Feet per second Miles per hour Feet per minute	0.682 (miles per hour) 60.0 (feet per minute) 1.47 (feet per second) 0.0167 (feet per second)
Rate of area spread	Acres per hour Square feet per second	12.1 (square feet per second) 0.0826 (acres per hour)
Rate of perimeter increase	Chains per hour Feet per minute	1.1 (feet per minute) 0.909 (chains per hour)
Fire intensity	Btu per second per foot	
Total fire intensity	Btu per second	
Combustion rate	Btu per second per square foot	
Heat yield	Btu per pound	
Heat of combustion	Btu per pound	

*Total fuel energy* bears the same relationship to the available fuel energy as does total fuel to available fuel.

*Rate of spread* is a general term used to describe the rate at which a fire increases either its area or linear dimensions. In fire behavior, one of the most useful measures is the forward rate of spread for which the

primary unit is feet per second. A related unit is miles per hour. Other units are given in Table 3.3, including units for area rate of spread.

*Fire intensity* is the rate of energy release, or rate of heat release, per unit time per unit length of fire front. Numerically, it is equal to the product of the available fuel energy and the forward rate of spread. It is also equal to the product of the available fuel, the heat yield, and the forward rate of spread. The primary unit is Btu per second per foot of fire front. Because fuel requires time to burn, the heat release will not be confined to the leading edge of the fire but will extend back through the width of the strip in which combustion is taking place. For a fire backing slowly into the wind, the burning strip may be only a few inches wide and the fire intensity as low as 5 Btu per second per foot of fire front. In a major fast-spreading fire, the width of the burning strip might be 1/4 mile or more and the fire intensity in the neighborhood of 30,000 Btu per second per foot of fire front.

*Total fire intensity* is the rate of heat release for a fire as a whole. The primary unit is Btu per second. Total fire intensity is not as useful a concept as fire intensity but affords an effective means of comparing the total rate of energy output of a fire with that of other sources such as a thunderstorm or a house furnace.

The *combustion rate* is the rate of heat release per unit burning area per unit of time. The primary unit is Btu per second per square foot of ground area. This is an important basic variable related primarily to fuel size, fuel arrangement, and fuel moisture. Factors such as size of burning area and wind speed may have a relatively small influence on the combustion rate, but this has not yet been determined. The combustion rate should not be confused with fire intensity, which is a different type of variable.

#### *Fire Intensity and Associated Fire Characteristics*

Fire intensity expressed in Btu per second per foot of fire front has more meaning if it can be associated with specific characteristics, such as what the fire looks like, what it sounds like, and how fast it travels. This can be accomplished by starting at the bottom of the fire-intensity scale and working up to the higher-intensity fires.

Fire intensity can be written as the simple equation

$$I = Hwr \quad (3.3)$$

where  $I$  = fire intensity in Btu per second per foot of fire front

$H$  = heat yield in Btu per pound of fuel

$w$  = weight of available fuel in pounds per square foot

$r$  = rate of spread in feet per second

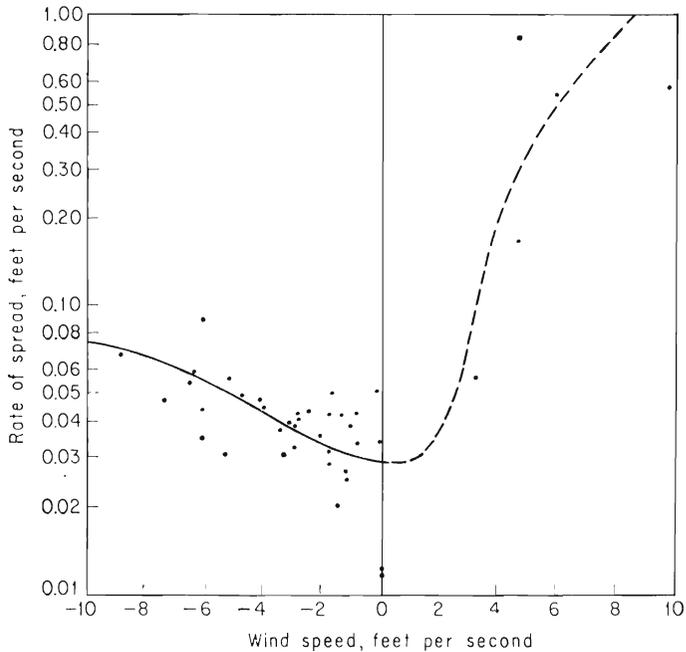


Fig. 3.3. Rate of spread (mostly for backing fires) in light grass-needle fuels for different wind speeds measured at approximately 3 feet above the ground.

Equation (3.3) can also be written as  $I = Er$ , where  $E$  is the available fuel energy which is equal to the product  $Hw$ .

For a homogeneous idealized fuel which has a constant combustion rate  $R$ , the fire intensity may also be written as

$$I = Rd$$

where  $d$  = width of burning strip of fuel.

Figure 3.3 shows the rate of spread in feet per second plotted as a function of wind speed in miles per hour. The data<sup>3</sup> in this figure were obtained on small test fires on the Francis Marion National Forest in South Carolina. The light fuels were fairly uniform mixtures of grass and pine needles in rather open longleaf and loblolly stands and weighed approximately 0.1 pound per square foot, or about 2 tons per acre. Wind speeds are shown as negative for fires burning against the wind. This method of representation results in a complete wind-speed scale ranging

<sup>3</sup> Rate of spread as such was not the main purpose of the experimental fires on which the data for Fig. 3.3 were obtained, and no attempt was made to isolate the effects of fuel moisture. Some of the scatter for individual observations is a result of fuel moisture variation. Most of the observed points are for fires backing into the wind rather than burning with the wind because the test fires were part of a prescribed burning study.

from negative wind speeds through zero (calm conditions) up into the positive, or headfire, winds. The rate-of-spread curve is shown as a broken line in the headfire region of the diagram because the scarcity of points makes its position somewhat uncertain there. It will be noticed that backing fires spread faster into the stronger winds than they do into the lighter winds. This phenomenon shows that an increased rate of oxygen supply increases the rate of spread, and in this particular instance may also indicate an increase in combustion rate.

Estimates of fire intensity can be readily made from the rates of spread shown in Fig. 3.3. For example, consider a fire spreading 0.04 foot per second. Combustion efficiency on these low-intensity fires at the lower fuel moisture contents should be high, so the heat yield might be as much as 6500 Btu per pound of fuel (dry-weight basis). If the available fuel is 0.1 pound of fuel per square foot, Eq. (3.3) shows that the intensity of this fire would be  $0.04 \times 6500 \times 0.1$ , or 26 Btu per second per foot of fire front. Very few fires burning in forest fuels would have an intensity as low as 2 or 3 Btu per second per foot of fire front. Most prescribed fires burning against the wind travel at a rate of 0.03 to 0.06 foot per second. If the available fuel is 0.10 to 0.15 pound of fuel per square foot (roughly 2 to 3 tons per acre) their intensities in this case would range from about 19 to 58 Btu per second per foot. The burning strip would be less than a foot wide, and the flames about 12 to 20 inches high. The flame length would be somewhat longer, possibly 2 1/2 feet, because the flames would be tilted over by the wind. By moving briskly one could step over the fire without getting burned.

Going up the scale of fire intensity into the headfire region of Fig. 3.3, a fire spreading 0.25 foot per second would have an intensity of about 160 Btu per second per foot of fire front if the available fuel is 0.1 pound per square foot and the heat yield is 6500 Btu per pound. This intensity is probably near the maximum for headfires or flanking fires that could be used in prescribed burning work. Ordinarily, backing fires are used in prescribed burning, but in the older stands flanking fires are used as well as headfires, which are not permitted to run for long distances. A fire with an intensity of 160 Btu per second per foot would have flames 4 or 5 feet in length.

On that sector of their perimeter which burns with the wind, a majority of wildfires probably have intensities in the range from 100 to 1000 Btu per second per foot of fire front. For an available fuel of 0.1 pound per square foot and a heat yield of 6500 Btu per pound, a fire would have to spread at a rate of 1.54 feet per second to develop an intensity of 1000 Btu per second per foot. This is nearly twice the intensity of the fastest-spreading experimental fire represented in Fig. 3.3. Ordinarily, a fire with this intensity would be burning in heavier fuel but not spread-

ing so fast. For example, if the available fuel was 0.3 pound of fuel per square foot (a little over 6 tons per acre), the corresponding rate of spread to give an intensity of 1000 Btu per second per foot would be about 0.51 foot per second. This would be considered a fairly hot fire. The flames would average about 9 feet in length, and considerable radiant heat could be felt 30 or 40 feet from the blaze. The roar of the flames would be accompanied by occasional explosive and whistling sounds. Foliage and small twigs on much of the green understory brush would be consumed and thus become a part of the fuel. There would be occasional flashes into the crowns in conifer stands, especially where there was draping of dead fuels over brush and the lower part of the crown canopy was within 20 feet of the ground.

An approximate relation between the flame length  $h$  in feet and the fire intensity  $I$  is given by the equation

$$h = 0.45I^{0.46} \quad (3.4)$$

which on comparison with Eq. (3.3) can be written as

$$h = 0.45(Hwr)^{0.46} \quad (3.5)$$

Equation (3.5) is represented by the diagram in Fig. 3.4 in which the flame length  $h$  is plotted as a function of the rate of spread  $r$  for different values of the available fuel  $w$ . The heat yield  $H$  was given a constant value of 6000 Btu per pound of fuel. A diagram of this sort could serve

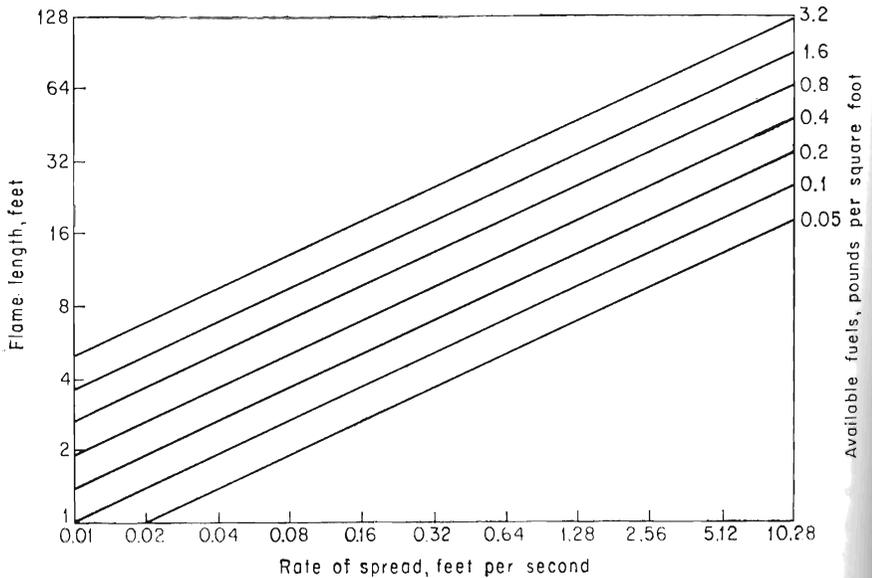


Fig. 3.4. Approximate relationship between flame length, available fuel, and rate of spread.

as a rough guide for estimating the width of firebreak needed to stop a fire of any expected intensity provided that severe spotting has not started. For example, assume that the width of a firebreak needs to be 1.5 times the flame length. Then this width can be estimated from estimates of the available fuel and the expected rate of spread.

Equations (3.4) and (3.5) will give too low a flame for high-intensity crown fires because much of the fuel is a considerable distance above the ground. However, this can be corrected for by adding one-half of the mean canopy height to  $h$ . For example, if Eq. (3.5) gave an estimated value of  $h$  of 40 feet and the mean canopy height is 60 feet, then the corrected estimate is 70 feet.

Equations (3.4) and (3.5) are better approximations for low-intensity than for high-intensity fires. They are based on the assumption that the leading edge of the fire is a long straight line and that the fire intensity is constant. However, the leading edge of a high-intensity fire tends to curve and form a prong-shaped head (or heads if the fire is large enough). Also, a high-intensity fire has a tendency to pulsate or burn in surges which can produce a rather wide fluctuation in flame length. In addition, the sudden ignition of unburned gases in the convection column can result in flame flashes which can momentarily extend several hundred feet into the convection column aloft.

### *Levels of Fire Intensity*

The preceding discussion might indicate that the nature of the fire intensity scale is such that as wind speed increases, as fuel moisture decreases, and as the general fuel flammability increases, the expected fire intensity would increase in a uniform way from the lower to the higher intensities. It is more realistic to visualize fire intensity in terms of a discontinuous-type scale because of the tendency for intensity to increase rather abruptly from one level to another level of considerably higher intensity because of fuel arrangement. Although the highest and most important level of intensity, which is reached in major fires, discussed in Chap. 4, is not necessarily a result of vertical fuel distribution or stratification, discontinuity throughout the range of intensities considered thus far is primarily due to fuel stratification. For example, consider a low-intensity fire burning in a rather dense pine stand 50 feet in height which also has an understory of dense brush. Below the dense brush is a surface layer of heterogeneous dead fuel consisting of pine needles and cones, leaves, some grass, and limbs and twigs of various sizes. A low-intensity fire can burn in this surface fuel and not consume the brush. As the intensity increases in the lowest level, a point is reached when the leaves and smaller twigs on the brush start to burn. The intensity and rate of spread may now increase rapidly until a considerable part of the brush

foliage is burning. The next abrupt increase comes when the pine crowns start to burn, in which case the fire is said to be "crowning." Actually, these changes do not necessarily come all at once, but are accompanied or preceded by sporadic bursts of intensity and flashes of burning into the fuel of the next higher level. There are times when lulls and gusts in the wind as well as variations in fuel and density of stand can cause a fire to alternate from one level to another. This is greatly facilitated by the presence of "ladders" of draped needles and moss which may be present below the crown canopy and are discussed more fully in Chap. 6. Also, height of canopy base and canopy compactness have a pronounced effect. The rather open short crowns in stands of southern pine require a considerably higher fire intensity to start a crown fire than do the compact deeper crowns in spruce and fir stands in the northern and western states.

Fire intensity levels should not be thought of as plateaus of constant fire intensity, because there can be a considerable range of intensity within a given level, but more as regions in which the available fuel is approximately constant. Although the concept of available fuel is essential in energy calculations, its wide fluctuations make it an elusive and difficult quantity to measure or even estimate. More fuel becomes available as the fire passes from one intensity level to the next. The magnitude of the increase in available fuel differs considerably between different fuel and stand types. Possibly from 1 to 2 tons per acre are added when the foliage and smaller twigs in the understory brush burn. Depending on the conifer species and density of stocking, an additional 3 to 6 tons per acre might be added when the crown canopy burns.

### THE MECHANISMS OF FIRE PROPAGATION

The sight of a fire eating its way through the dry weeds of a vacant city lot or through the fuels of the forest is so familiar that the process seems very simple. Actually, the phenomenon of fire spread is baffling and difficult to understand. Some of the dominant mechanisms for major fires are of a meteorological nature and will be considered in Chap. 4. For low-intensity slow-spreading fires, the simpler combustion mechanisms dominate. Even the combustion processes in fire spread are not the same for fires of all intensities. This can be illustrated by starting with some of the simpler examples and progressing to higher-intensity fires.

#### *Flow of Fuel and Heat and Transport of Ignition Points*

Probably the simplest type of fire spread for solid fuels is the flame traveling slowly, but at a fairly constant speed, down the stem of a vertically held kitchen match. If the match is moved upward at a speed

equal to the rate of downward motion of the flame, the latter will appear to remain stationary. Fuel is moving upward through the stationary base of the combustion zone. Simultaneously heat is flowing into the fuel in the opposite direction at the base of the combustion zone. The heat flow distills volatile fractions from the match which combine with oxygen in the combustion zone to maintain the rate of heat output. That the whole process is in a rather delicate equilibrium can be illustrated in several different ways. Any agent which results in cooling in the combustion zone, especially near its base, will cause the match flame to go out. Anything which tends to separate the flame from its fuel supply, such as a sudden puff of air, will have the same result.

Although radiation may make a minor contribution, conduction is the main heat-transfer mechanism controlling the rate of heat flow in the match stem. The situation is somewhat different for a low-intensity fire spreading in a layer of dry pine needles in calm air. Again the flame can be visualized as stationary if the fuel is assumed to be on a horizontal tray moving toward the flame at the same rate that the flame moves relative to the pine needles. Fuel is thus flowing through the front of the combustion zone, and heat is flowing in the opposite direction to the unburned fuel. In this case, the dominating heat-transfer mechanism appears to be radiation.

A still different situation exists when a fire is spreading under the influence of a light wind in a fuel of some depth, such as an area of dry grass. The basic process of the flow of fuel into the fire and flow of heat from fire to fuel is the same as in the previous two examples, but convection is now an important heat-transfer factor. Some of the hot gases are carried into direct contact with unburned fuel when the flames are tilted over by the wind. Also, radiative heat transfer is increased accordingly.

Qualitatively, the flame propagation in the three preceding examples can be described by a combustion model which is the same in each case even though there is considerable difference in the relative significance of the three heat-transfer mechanisms. The basic process is a flow of fuel into the combustion zone and a flow of heat in the reverse direction into the unburned fuel. For this type of combustion model, Fons (1946) has made a theoretical analysis to obtain equations for the rate of fire spread in specially prepared fuel beds.

Proceeding to fires of higher intensity, it is found that the heat-transfer mechanisms are accompanied by an entirely different process which begins to dominate the fire propagation as the intensity increases. This mechanism is not a true heat-flow process. It can best be described as a transport of discrete ignition points ahead of the main flame front, although all three heat-transfer mechanisms are still involved. In fire

spread by the extension or transport of ignition points, the combustion state is established in cold, unburned fuel with an extremely small transfer of heat; thus the simple combustion model based on a continuous flow of heat and fuel is no longer valid.

The transport of ignition points can be brought about in three ways. First, radiation from an extensive flame front may be intense enough to ignite isolated patches of light or flashy fuels. Second, turbulent motions on the leeward side of a flame front may bring hot gases momentarily into contact with flashy fuels and establish new ignition points. An example is that type of flame front which tends to break or roll like waves on a beach. The third source of ignition points is the transport of burning embers, or spotting, which appears to be the dominating fire-propagating mechanism for the highest-intensity fires.

### *Ignition Probability*

One of the most important combustion factors involved in fire propagation by transport of ignition points is ignition probability. Since falling embers are the most important source of ignition points on the worst fires, ignition probability will be discussed from the standpoint of spotting, but most of the discussion applies also to the other sources of ignition points.

Like available fuel, the ignition probability is a widely variable quantity and as yet has not been determined experimentally. It increases rapidly with decreasing fuel moisture, hence with decreasing relative humidity. It is known that the ignition probability for most firebrands is essentially zero when fuel moisture is 25 to 30 per cent. It is also known that ignition probability, like the combustion rate, is greatest for oven-dry material. In addition, both appear to be considerably affected in the lower fuel moisture content range by a change of only a few per cent in fuel moisture.

The importance of the relation between fuel moisture and ignition probability in the behavior of large fires can be illustrated by a hypothetical example. Suppose that from the convection column over a large fire, 10,000 embers per square mile per minute are dropping in front of the fire. Assume that the surface fuel moisture content is such that only 0.1 per cent of these firebrands catch and produce spot fires, thus giving only 10 spot fires per square mile. If, however, the surface fuel moisture is low enough for 5 per cent of the embers to catch, then there would be 500 spot fires per square mile. As they burn together, these spot fires would greatly increase the rate of spread and intensity of the main fire; this in turn would increase the rate of production of new firebrands. Thus, relative humidity (working through fuel moisture) has a twofold effect on rate of spread in certain types of extreme fire behavior. First is

the effect on fuel combustion rate and rate of spread of the ordinary flame front. This effect would be present on small and large fires alike. Second is the effect in accelerating rate of spread and fire intensity by increasing the probability of ignition from falling embers. This latter effect would be present only on fires where spotting was abundant. Ignition probability will also depend on other factors, such as the nature of the surface fuel in which firebrands fall and the fraction of the ground area covered by the fuels.

Fuel characteristics that make plentiful and efficient firebrands are not definitely known. The material would have to be light enough to be carried aloft in updrafts, yet capable of burning for several minutes while being carried forward by the upper winds. Decayed punky material, charcoal, bark, clumps of dry duff, and dry moss are efficient firebrands (Chap. 6). Leaves and grass tend to be inefficient firebrands except over short distances. On the basis of their capacity to cause ignition, firebrands can be put in two definite classes: (1) flaming and (2) glowing. Although flaming firebrands have a far higher ignition probability than the glowing type, the latter is much more common. The type of firebrand material should partly determine whether or not it will be flaming or glowing, but a more important factor may be duration of flight. Flaming firebrands should be of most significance over the shorter distances. Fortunately, only a very small fraction of the firebrands spotting over long distances are of the flaming type.

### *Ignition Temperature*

Temperature of firebrands is an important factor in ignition. It is well known that dropping a flaming match in dry leaves or grass is much more likely to start a fire than dropping a lighted cigarette, or glowing piece of charcoal, in the same material. The difference in the ignition capabilities of the two types of firebrands is due primarily to their different temperatures. Glowing material quickly forms a film of ash which partially excludes oxygen. The resulting reduction in the burning rate of the ember lowers its temperature, which may be in the neighborhood of 1200°F—considerably lower than the flame temperature of 1600 to 1800°F.

There appears to be no definite temperature at which a solid fuel can be said to ignite, and any attempt to measure this quantity will depend to a considerable extent on how it is defined and how it is measured. If glowing and smoldering are the ignition criteria, then the ignition temperature may be somewhere in the temperature range from 400 to 700°F. If the appearance of flame is taken as a criterion, then the ignition temperature is higher. From measurements on the internal temperatures of rapidly heated wood cylinders, Fons (1950) estimates their surface tem-

perature to be about  $650^{\circ}\text{F}$  when they ignite. He found that cylinders placed in a heated atmosphere would glow but would not flame until the temperature of the surrounding atmosphere was between  $800$  and  $900^{\circ}\text{F}$ . This temperature probably corresponds to the ignition temperature of the gases distilled from the wood cylinders and is in good agreement with the ignition temperatures of the vapors of the liquid hydrocarbon fuels, most of which range from  $700$  to  $1100^{\circ}\text{F}$ .

### EARLY LIFE HISTORY OF A FIRE

To conclude discussion of combustion and basic fire behavior, it is worthwhile to consider the sequence of events in the early life history of a fire. From the standpoint of fire control, the most important period in the life of any fire might be described as its infancy or the time from ignition until the fire has developed a definite pattern of spread, direction of travel, and rate of buildup of intensity. During this early period, the opportunities for control and extinguishment are greatest.

The pattern of initial spread, as well as the principal direction of spread, is determined mostly by the speed and direction of the surface wind and by topography, which have a marked influence on heat transfer

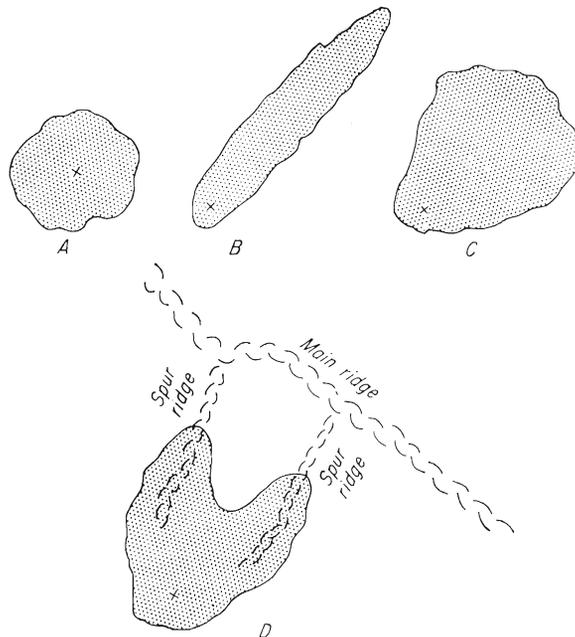


Fig. 3.5. Characteristic shapes of fires in initial spread. A. No wind and flat terrain. B. Effect of wind and/or slope. C. Variable wind. D. Initial fire spread pattern when fire advances up two spur ridges simultaneously.

by radiation and convection. Local variations in fuel and cover type also have some effect, but their contribution is usually less than that of wind and topography. They are important, however, in the rate of buildup of intensity.

In the absence of wind and in flat terrain, a fire will spread at about the same rate in all directions so that the initial spread pattern is an approximately circular area with the point of ignition in the center as shown in Fig. 3.5A. If there is a wind which maintains a constant direction, the burned area will assume the shape of an elongated ellipse, with the long axis parallel to the direction of the wind as shown in Fig. 3.5B. The ratio of the two diameters of the elliptical area will depend on the surface wind speed. Often the direction of the wind is not constant but may vary through an angle of 30 or 40°. In this case, the initial pattern of spread will assume a fan-shaped area as indicated by Fig. 3.5C. An extreme but infrequent example of a variable wind is a situation in which there is no definite prevailing wind direction. This condition can occasionally exist on sunny days when the atmosphere is turbulent and gusty winds can come from almost any direction. The initial spread pattern will resemble that of Fig. 3.5A but will be larger and have a more irregular perimeter.

In mountainous terrain, both wind and topographic factors control the pattern of initial spread and direction of travel. In the period just following ignition, wind may be the dominant factor, but as the fire intensity builds up, topography is more likely to dominate, especially on the steeper slopes. A fire starting on a slope will have an initial spread pattern similar to that of Fig. 3.5C, with the long axis pointed upslope. The pattern may be modified somewhat if a general slope or drainage has a number of spur ridges running down from a primary high ridgetop. A fire on a lower slope will tend to form a head which will travel rapidly up a spur ridge. This tendency can create a pattern of spread which has resulted in men being trapped even on small fires. The pattern is illustrated in Fig. 3.5D. The fire is burning slowly in flat or gently sloping terrain near the base of two spur ridges. After spreading from the indicated ignition point or origin, it may start to run up both ridges simultaneously. Since the two heads may spread along the ridgetops faster than a man can travel upslope, the U-shaped area between the heads becomes a trap. The rapid upslope spread can occur very suddenly, and the fire can travel from 3 to 6 miles per hour and even faster on steep slopes.

All fires, large and small, must have an early burning period. The majority of fires remain in what would be termed the small-fire class, but a few become conflagrations. The last features in the early life history of a potential conflagration, the rate of buildup of fire intensity and the beginning of fire propagation by transfer of ignition points, introduce the main field of fire behavior and its many complex problems. These are considered in Chap. 4.