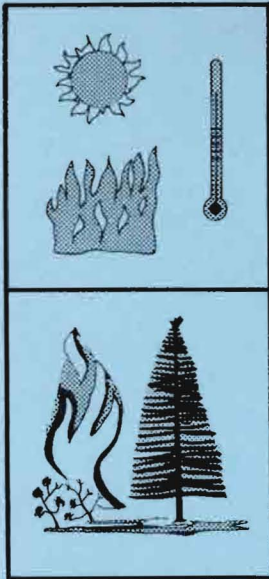


HEAT—ITS ROLE IN WILDLAND FIRE—Part 3



HEAT CONDUCTION AND WILDLAND FIRE

Clive M. Countryman

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NOTE

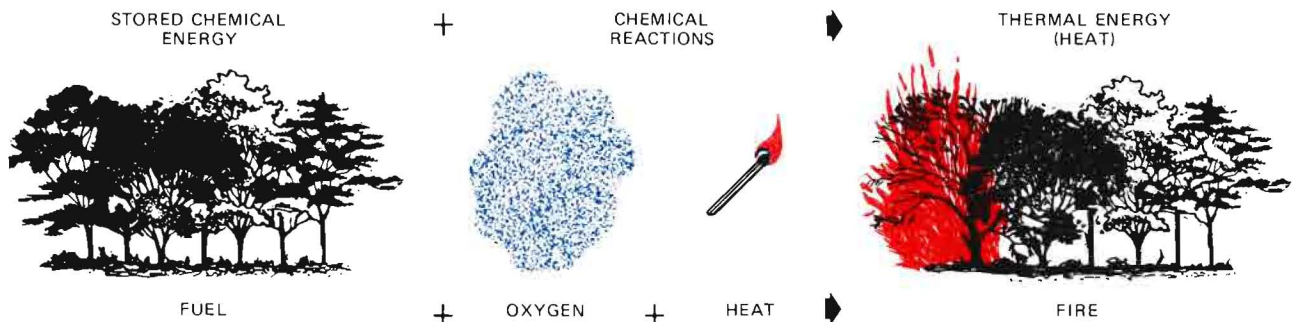
This publication is part of a group designed to acquaint fire control personnel, wildland managers, and forestry students with important concepts of fire behavior and the application of these concepts to wildland fire problems. The level of difficulty of the treatment of topics in these publications varies, as signaled by the color of the cover: the blue cover group is generally elementary and the yellow cover group is intermediate. The following publications, by Clive Countryman, are available on request to:

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Fire Whirls . . . Why, When, and Where. 1971 (blue)
Carbon Monoxide: A Firefighting Hazard. 1971 (yellow)
The Fire Environment Concept. 1972 (blue)
Heat—Its Role in Wildland Fire (blue)
 Part 1—The Nature of Heat. 1975
 Part 2—Heat Conduction. 1976
 Part 3—Heat Conduction and Wildland Fire. 1976

HEAT CONDUCTION AND WILDLAND FIRE

Wildland fire involves both chemical and physical processes. When wildland fuel burns, its stored chemical energy is converted to thermal energy or heat through complex chemical reactions. But for the reactions to be started, heat must be physically transferred from a firebrand to the fuel, and heat transfer to unburned fuel must continue if the fire is to keep on burning and spreading. Control and extinguishment of a wildland fire hinges upon the interruption of the



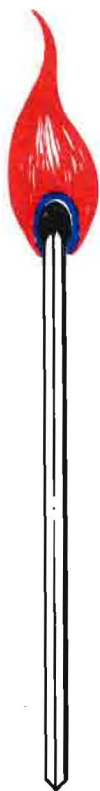
chemical reactions. And about the only way we have of doing this is to reduce or eliminate heat transfer.

In earlier publications, we explored the nature of heat and the process of heat transfer by conduction. In the following discussion, we will look at the combustion process and the part that heat conduction plays in it, and how heat transfer by conduction can be checked in fire control operations.

HEAT CONDUCTION AND COMBUSTION

All three methods of heat transfer—conduction, radiation, and convection—are usually operating at the same time in a wildland fire. But radiation and convection can transfer heat only to the fuel surface. The only way that heat can get into the interior of opaque materials like wildland fuels is by conduction. Hence, conduction of heat is of major importance in the combustion process, particularly for the larger fuels.

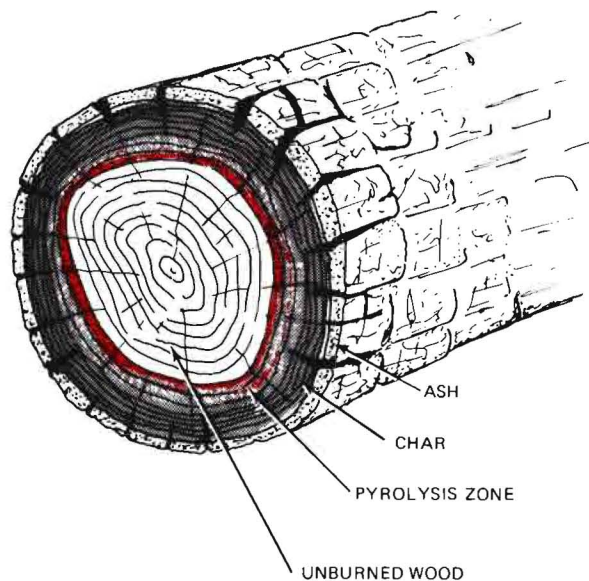
Wildland fuels do not burn directly



If we look closely at a piece of burning wood, such as a lighted match, we see that the flames are not attached directly to the wood surface, but are separated from it by a thin layer of vapor or gas. This happens because solid organic materials do not burn in flaming combustion directly, but must first be decomposed or *pyrolyzed* by heat and chemical reactions into various gases—some combustible and some not. The combustible gases do not contain enough oxygen to burn when emitted from the fuel, and must first mix with the surrounding air before a flammable mixture is produced. If the pyrolysis is slow, not much gas is generated and the flames are short and intermittent. But when large amounts of fuel are burning rapidly, the volume of gas is large and some must move a considerable distance from the fuel before the mixture becomes flammable. Long and massive flames are produced in this process. Thus, fire intensity depends greatly on the rate at which pyrolysis is taking place.

Burning wood has four zones

When a piece of wood is first ignited, the pyrolysis takes place in a thin layer at the surface. But as the combustion continues, a char layer forms on the surface and deepens as the pyrolysis penetrates into the wood. The char also burns from the surface inward to form a white or gray ash, but at a slower rate than that of the wood during much of the combustion process. Unlike wood too, the char burns directly without being pyrolyzed into gases. Because the ash is very



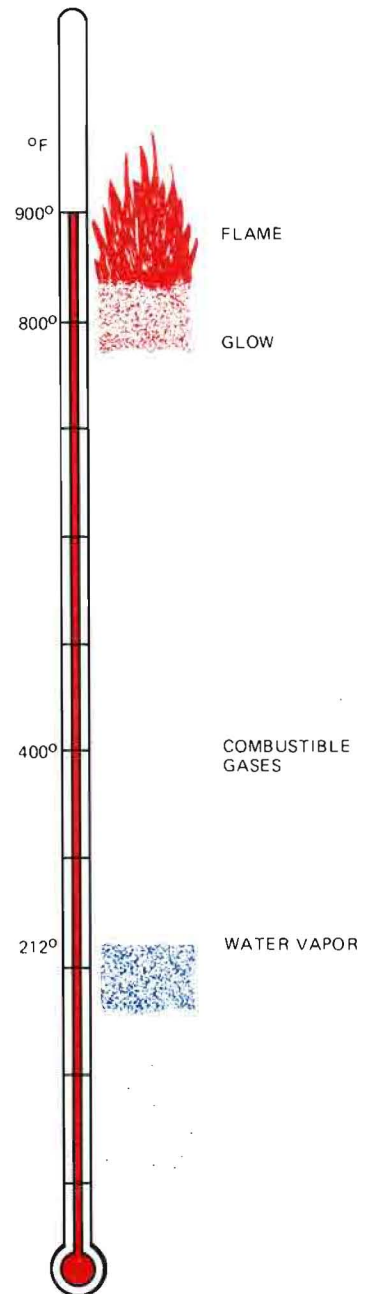
fragile, it usually falls from the surface, seldom forming more than a thin layer. Thus, if we examine a cross section of a partially burned piece of wood we see from the surface inward first a thin layer of ash, next a layer of char, then a layer, usually shading from dark to light brown, where pyrolysis has been taking place, and finally unburned wood. The speed with which the pyrolysis layer moves through the wood determines its burning rate.

The combustion process

Wildland fuels have a very complex and varied chemical structure, and their chemical reactions when heat is applied are also complex. Different reactions take place at different temperatures. When heated, the fuels first produce water vapor and other gases that are mostly noncombustible. Not until the fuel temperature reaches 400°F or more does significant amounts of combustible gas begin to appear. At about this temperature too, the chemical reactions themselves begin to generate heat; then if heat losses are small, the pyrolysis may become self-sustaining, the temperature continuing to rise without an outside heat source. These heat-producing reactions at relatively low temperatures are important in the spontaneous combustion of fuels. The decay of some fuels under conditions allowing little heat loss can produce enough heat to start active pyrolysis. It is not unusual for deep layers of sawdust to be ignited in this way.

As the temperature of the fuel continues to rise, combustible gases are produced more rapidly and the chemical reactions produce more heat, reaching a peak about 600°F. Visible glowing begins to appear at the fuel surface around 800°F. Although combustible gases are generated at temperatures above 400°F, they will not flame, even when mixed with air, until their temperature reaches 800° to 900°F. For flaming combustion, then, the pyrolysis must continue long enough to raise the temperature above the ignition point of the gases, or they must come in contact with something hot enough to ignite them. A lighted match held close to smoldering logs in a fireplace, for example, can cause them to suddenly burst into flame. In wildland fires, the flames from other burning fuel can provide an ignition source for the fuel being heated.

The maximum temperature that can be produced by the burning in air of gases generated from wildland fuels is believed to be between 3500° and 4000°F with an ideal mixture of gas and air. And temperatures exceeding 3000° have been measured in exceptionally intense fires. The ideal mixture of gas and air is not likely to occur often during most wildland fires, however, and there is usually considerable cooling of the flames by mixing with outside air. As a result,

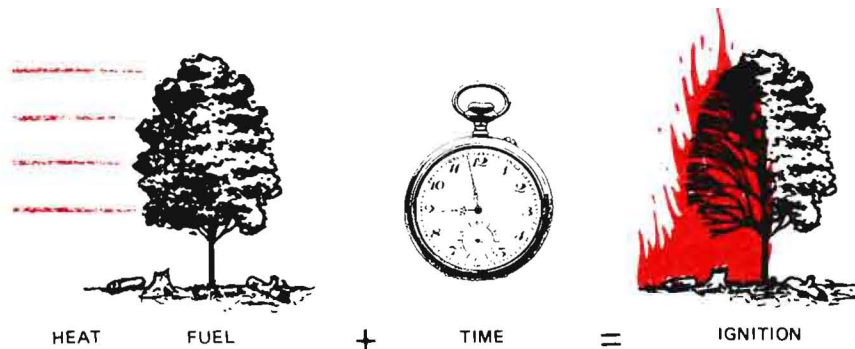


flame temperatures in the range of 1800° to 2500°F are more common. This is well above the temperature needed to ignite the gases, so once flaming starts it continues as long as sufficient gas is produced.

Ignition depends on temperature and heat quantity

The chemical reactions of heated fuels vary with the temperature; hence the ignition temperature depends on the stage of pyrolysis at which the fuel is considered to be actually ignited. Charring can begin at relatively low fuel temperatures, and once started can continue if there is little heat loss. This sometimes occurs in deep layers of compact, fine dead fuel. Glowing combustion requires higher fuel temperatures to begin, and may proceed without flames in some types of fuel. Ground-up grass, compact duff, peat, and decayed wood often chars and glows until consumed without ever bursting into flame. So does tobacco. High fuel temperatures are needed to initiate flaming, but flaming combustion also produces the greatest amount of heat and the highest fire temperatures.

In all types of combustion, however, fuel ignition requires that the fuel temperature be raised to some minimum level by the application of heat. And the heat must also be applied long enough to raise the temperature of a fuel layer deep enough to permit the pyrolysis to become self-sustaining—some *quantity* of heat is required for ignition. If the time the heat is applied is too short, the necessary quantity of heat



cannot be supplied, and the fuel will not ignite regardless of the temperature of the heat source. For example, a piece of wood moved quickly through a hot flame will not ignite—the time it is in the flame is too brief for the required amount of heat to be transferred to the wood. If a firebrand is to cause ignition, then, it must be both hot enough and contain enough heat to start the pyrolysis process. Fuel characteristics and the conditions under which the heat is applied greatly affect the capability of a firebrand to ignite wildland fuels and also the time required for ignition.

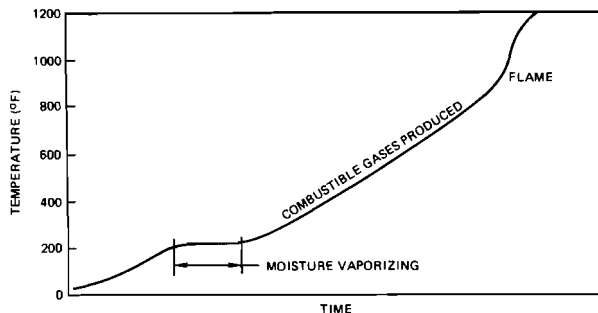
Ignition and combustion take longer in dense fuels

In earlier publications (*Parts 1 and 2, Heat—Its Role in Wildland Fire*), we saw that both the thermal conductivity and heat capacity of wildland fuels increase as the fuel density (weight per unit volume) becomes higher. Because of the greater thermal conductivity of the more dense fuels, heat applied at the surface is conducted into a deeper layer in a given time than it is for less dense fuels. Consequently, the rate of temperature rise in dense fuels is slower—a larger volume of fuel must be heated. Also, because the heat capacity of dense fuels is higher, more heat is required to raise the temperature of a given volume of fuel. Thus, the greater thermal conductivity and heat capacity of dense fuels acts to increase the amount of heat needed for ignition and the fuel ignition time. Low-density fuels such as decayed wood can be ignited with smaller firebrands, or in less time with larger firebrands, than can high density fuels.

Fuel density also affects the rate of penetration of the pyrolysis zone into the fuel. Because of the greater conductivity and heat capacity of dense fuels, the burning rate of fuels of the same size decreases as the density increases. For example, in investigating the charring rate of Douglas-fir timbers, the U.S. Forest Products Laboratory found that timbers with a density of 37 pounds per cubic foot charred at a rate nearly one-third less than timbers with a density of 22 pounds per cubic foot.

Moisture affects pyrolysis and ignition

In *Part 1, The Nature of Heat*, we saw that when water is heated to the boiling point its temperature does not increase above 212°F, and that considerable thermal energy (heat of vaporization) is required to change the water to vapor. Moisture in wildland fuel behaves in the same way. If we insert a



TEMPERATURE HISTORY OF HEATED FUEL

temperature-measuring device in a piece of wood and then subject the wood to strong heating, we find that the temperature rises to 212°, and then remains constant until all of the

moisture has been vaporized at the point of measurement. The temperature of the wood then continues to increase.

The delay in temperature increase while the moisture is being vaporized and also the amount of heat required to vaporize it, affect the ignition time and burning rate of wildland fuel, and sometimes determine whether it will burn at all. When fuel moisture content is high, large amounts of heat are needed to raise the temperature of the surface layer to a point where combustible gases are produced. Thus, as the moisture content increases, the ignition time increases and firebrands capable of producing more heat are needed to ignite the fuel.

Even after the surface layer is hot enough to generate combustible gases, the moisture still has an effect. The pyrolysis layer moves more slowly into the moist fuel, reducing the rate of heat production. Also, the released water vapor must pass through the hot char, where it can absorb part of the heat that otherwise would contribute to pyrolysis. Outside the fuel, the water vapor dilutes the combustible gases and delays the production of a flammable mixture, or prevents it entirely. When flaming is established, the water vapor reduces flame temperature through heat absorption and by reducing the flammability of the air and gas mixture.

Not all of the water vapor moves out of the burning fuel immediately. Some of it diffuses toward the interior and condenses in the unburned part—the moisture content of the fuel tends to increase as the fuel burns. Although the heat absorbed in vaporization is released when the moisture condenses, the increasing moisture content slows the temperature rise of the unburned fuel. As a result, the pyrolysis rate tends to slow as the fuel burns.

Overall, then, moisture in the fuel increases the heat requirements for ignition and pyrolysis, and at the same time reduces the rate at which heat is generated from the fuel.

Char slows pyrolysis

The layer of char that forms on burning fuel has a strong effect on the burning rate, particularly for large fuels. The thermal conductivity of char is low—usually one-half to two-thirds that of the solid fuel. Consequently, the char forms an insulating layer around the fuel that reduces the conduction of heat from the flaming exterior into the unburned fuel. This slows down pyrolysis. As the char layer deepens it becomes more effective as an insulator, until eventually the pyrolysis proceeds at the same rate as the char is burned away at the surface. The combustible gases also react chemically with the hot char and become less flammable when they emerge from the fuel. The relatively low heat production, slow heat conduction, and large heat losses from the

flaming zone tend to prevent the pyrolysis process from sustaining itself in the larger fuels. As a result, large fuels usually do not burn well unless heat is available from sources other than the burning piece of fuel. Fuels larger than about 1 inch in diameter seldom burn completely unless heat is available from other burning fuel or unless heat losses are reduced in some way.

HEAT CONDUCTION AND FIRE CONTROL

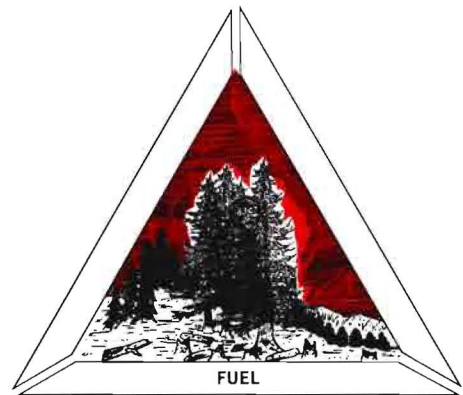
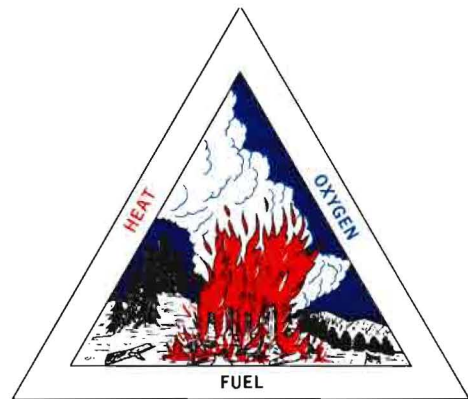
When the three ingredients needed for fire—fuel, heat, and oxygen (air)—are brought together in the proper proportions, a fire can start and burn. Symbolically, this can be represented by a triangle—the fire triangle. To extinguish a fire, we must remove or modify one or more of the essential ingredients so that it cannot perform its needed function—we must break the fire triangle. In suppressing a wildland fire, we can remove the fuel in a band or firebreak around the fire to deprive it of the fuel ingredient, or we can put water, chemicals, or dirt on the burning fuel to reduce the amount of heat and to decrease the supply of oxygen.

Basically, all of the methods we have for breaking the fire triangle involve modifying or interfering with heat transfer in some way. Thus, when we construct a firebreak around a fire, we prevent heat transfer to unburned fuel. To determine the firebreak width, we must consider the amount of heat being produced and the amount of heat that must be transferred to ignite the particular unburned fuel. Water, chemicals, and dirt applied to the burning fuel reduce the amount of heat available for transfer to unburned fuel and for sustaining pyrolysis in the burning fuel itself. Similar treatment of fuel surrounding the fire is intended to insure that more heat will be needed to ignite the fuel than can be transferred from the fire.

Compared to convection and radiation, heat transfer by conduction is slow and of minor direct consequence in the rate of spread of wildland fire. In the combustion process, however, and in the intensity and persistence of fire, heat conduction plays a major role. We can halt fire spread by reducing or preventing heat transfer by convection or radiation. But to extinguish a fire completely, we must eliminate heat transfer by conduction.

Small fuels are most important

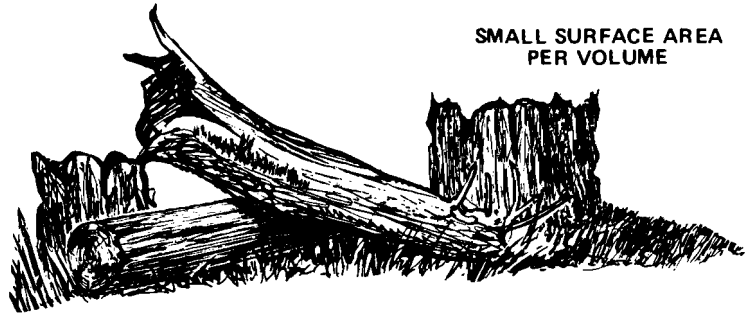
Anyone who has started a fire is well aware that small or thin fuels ignite more readily than do larger fuels, and such “kindling” is usually needed to start the larger fuels burning



at all. The reason lies in the rapidity with which small fuels can be heated and ignited. All of the heat that gets into a piece of fuel must go through the surface. Hence, the time required to heat the fuel enough to ignite it depends greatly on how much surface area the fuel has compared to its volume. And this ratio increases rapidly as the fuel size decreases. A cylindrical piece of fuel 2 inches in diameter has 1



LARGE SURFACE AREA
PER VOLUME



SMALL SURFACE AREA
PER VOLUME

square inch of surface area to each cubic inch of volume. But fuels one-half inch in diameter have 8 square inches, and those one-eighth inch in diameter have 32 square inches, per cubic inch. Thus, small fuels present in an area greatly increase the chance of a wildfire, particularly from small firebrands.

Small fuels also burn more rapidly than large fuels—a given weight of fuel in small-sized material releases its heat in a shorter time and produces a more intense fire. The more rapid burning is due largely to the greater ratio of surface area to volume. However, char formation is also important. Only a thin layer of char can form on small fuels, and its effect is small compared to the thick char layer on large fuels.

Many of our wildland fuel beds in their natural state are made up of a mixture of fuel sizes. These sizes may range from a small fraction of an inch to 4 or 5 inches in diameter in brush fuels, or to several feet in diameter in timber types. But because of their relatively slow burning rate, the large fuels usually contribute little to heat production in the early stages of a fire. For example, in dead and fairly dry large fuels, the pyrolysis characteristically penetrates at the rate of

1 to 2 inches per hour into the fuel. A 2-inch limb may require up to 2 hours to burn completely. On the other hand, the burnout time for a half-inch stick is usually 3 to 4 minutes, and decreases sharply for smaller fuels. Thus, only a thin layer of the large-sized fuels can burn before the small fuels are entirely consumed. As a result, the smaller fuels—generally those less than one-half inch in diameter—contribute most to heat production in the main flame wave of a spreading fire in most wildland fuels. And it is this main flame wave that largely controls fire behavior and determines how difficult it is to stop fire spread.

To stop the fire, stop pyrolysis

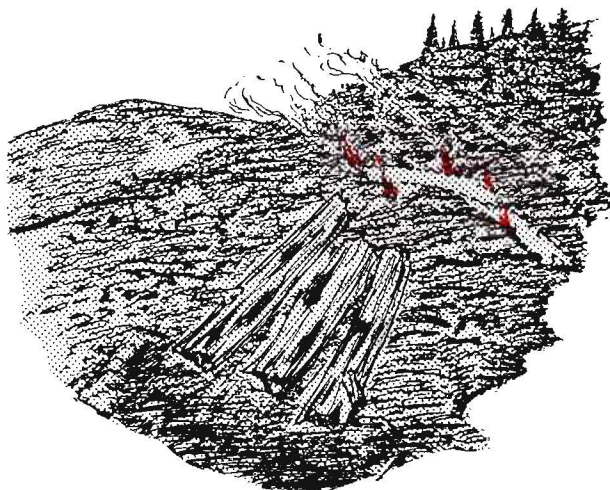
There are only three practical ways to stop the pyrolysis of wildland fuel once it has started: (1) Cool the fuel below the temperature that sustains pyrolysis; (2) Modify the fuel so that it cannot burn, or its heat production is below that required for continued pyrolysis; (3) Allow the fuel to burn out. In controlling a wildland fire these basic methods may be used singly, but more often are used in various combinations.

In stopping fire spread, cooling the fuel with water or dirt and modifying the fuel with chemicals or water are methods often used. More frequently, however, the fuel is scraped away to form a firebreak around the fire and the fine fuel

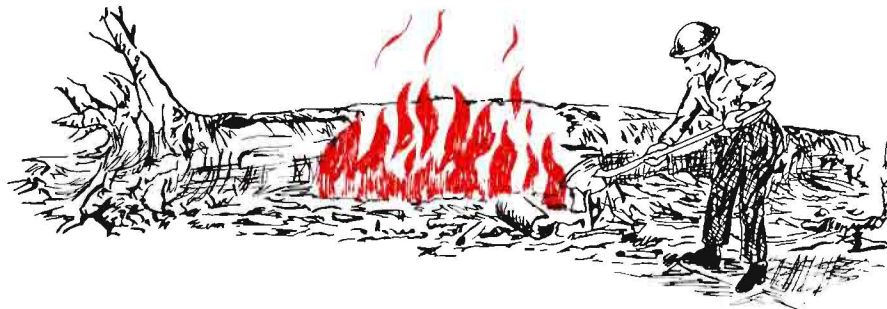


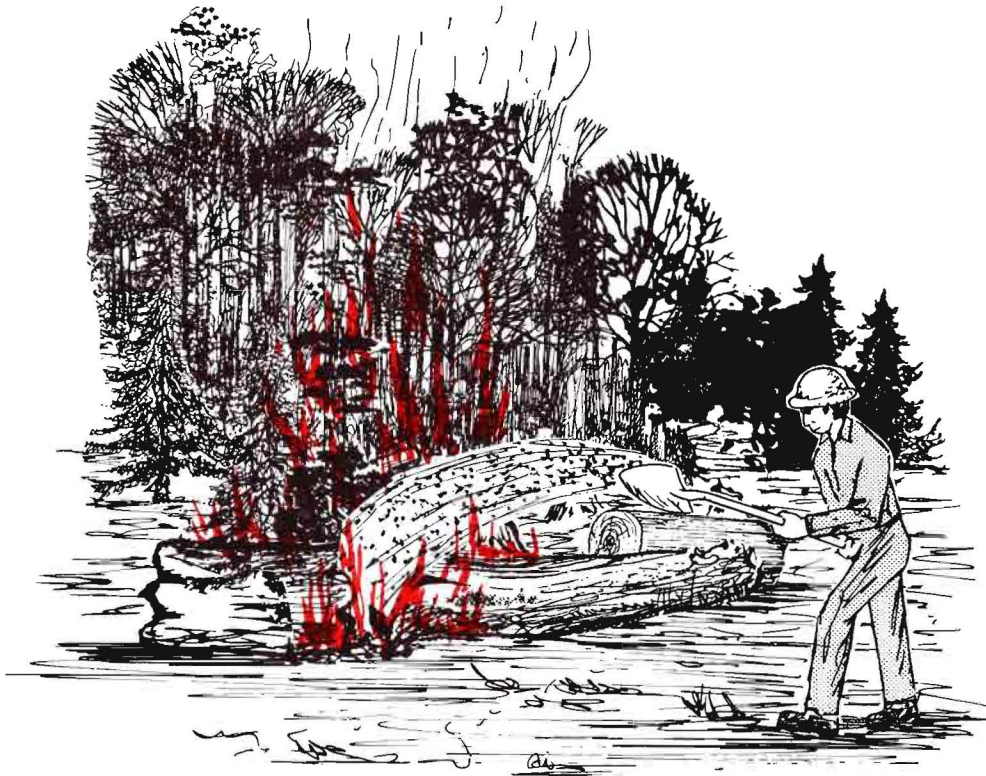
within the break allowed to burn out. Since the burning time of these fuels is short, heat production is soon drastically reduced, and the chance for further fire spread greatly diminished.

In fuel types where there are large as well as small fuels in the fuel bed, much of the large fuel stops burning once the small fuels have been consumed, since the additional heat needed to keep the large fuels burning is no longer available. But in the usual wildland situation, some of these fuels continue to burn because they are close enough together to supply heat to each other, or are lying in hot coals or ashes. Also, when the larger fuels are extremely dry they continue to burn for a longer time—less heat is lost in evaporating moisture and from heat absorption by the water vapor. As long as the slow-burning fuels are producing heat, they pose a threat of fire escape, and must be extinguished to assure fire control. Because of their long burning time, it is not often feasible to allow them to burn out, and stopping the pyrolysis by cooling or other means of heat removal is necessary.



There are several ways to cool large fuels below the temperature needed for pyrolysis, or to deprive them of the heat required. Fuels lying close together frequently stop burning if they are simply moved farther apart. Similarly, fuels in hot coals and ashes can be moved, or the hot material can be scraped away to deprive them of heat.





Water is highly efficient as a cooling agent because of its great heat-absorbing capacity, in both liquid and vapor form. It is not always available, however. Dirt can also be used to cool the fuel, but some caution is required of its use. Dirt has a low thermal conductivity, hence is a good insulator. Although covering the fuel with dirt stops the flaming and removes some heat, the dirt layer also serves to prevent escape of heat from the interior of the fuel. This may permit glowing combustion to continue—there is usually enough oxygen in most fuels for glowing combustion if enough heat is being generated. Thus, when dirt is used for cooling it should be scraped away and fresh dirt applied repeatedly until the pyrolysis has been stopped. The fuel should then be left uncovered to insure detection of any fire that may have been missed. Char is also a good insulator, and the effectiveness of water and dirt for cooling can be greatly increased if as much as possible of the char is scraped away.

Compact fine fuels, such as deep litter and duff, burn in much the same way as large fuels, and similar methods can be used on them to check pyrolysis. They can be cooled with water, or dug out and mixed with dirt to reduce the heat.

SUMMARY

Wildland fuel does not burn in flaming combustion directly. The fuel must first be converted to gases through *pyrolysis*, a chemical process brought about by heat. Fuel *ignition*, or the initiation of self-sustaining pyrolysis, requires a finite quantity of heat. This heat must be supplied at a rate adequate to generate enough gases to produce a flammable mixture with air, and from a source hot enough to cause the gas mixture to flame or the char to glow. Radiation and convection can transfer the heat necessary for pyrolysis to the surface of the fuel, but transfer of heat to the interior must be by conduction.

Moisture increases the amount of heat required to raise the fuel temperature to a point where combustible gases are produced; it absorbs part of the heat otherwise available for pyrolysis; and it dilutes the gases produced. Thus, moisture in wildland fuels increases their ignition time and decreases their burning rate.

The thermal conductivity of most wildland fuels increases as the density of the fuel increases. When the thermal conductivity is high, the available heat is transferred through a deeper layer of fuel in a given time than when the thermal conductivity is low. And there is more material to heat per unit of volume in the dense fuels. As a result, fuels with low density tend to ignite more readily, and often burn more rapidly than do high-density fuels. This effect is most important in the larger fuels, which have sufficient mass to absorb significant quantities of heat. Char, with its low thermal conductivity, also slows pyrolysis by reducing the rate of heat conduction from the surface into the interior of the fuel.

Small fuels ignite more easily and produce heat at a faster rate than large fuels because their greater ratio of surface area to volume and their thinner layer of char permit more rapid heat conduction. Small fuels in fuel beds of mixed sizes contribute most to the main flame wave that largely controls fire behavior and determines the difficulty of suppressing the fire. Large fuels usually require an external heat source for complete combustion, and frequently stop burning when the fine fuels have burned out. Large fuels can also be deprived of heat by moving them farther apart or by scraping away surrounding hot material.

We can slow down or stop pyrolysis and reduce heat conduction by cooling burning fuels with water or dirt. Because dirt is a good insulator, however, it should be scraped away and fresh dirt applied repeatedly until pyrolysis has been stopped. Removal of char increases the effectiveness of both water and dirt as cooling agents.