HEAT CONDUCTION AND WILDLAND FIRE

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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
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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
    Part 4—Radiation. 1976
    Part 5—Radiation and Wildland Fire. 1976
Heat and Wildland Fire (yellow)
    Part 1—The Nature of Heat. 1977
    Part 2—Heat Conduction. 1977
    Part 3— Heat Conduction and Wildland Fire. 1977

HEAT CONDUCTION AND WILDLAND FIRE

Wildland fire involves both chemical and physical processes. In the burning of wildland fuels, their stored chemical energy is converted to thermal energy or heat through a series of complex chemical reactions. But for the combustion process 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 by reducing or eliminating heat transfer.

STORED CHEMICAL ENERGY	+	CHEMICAL REACTIONS	▶	THERMAL ENERGY (HEAT)
FUEL	+ OXYGEN + HEAT ▶			FIRE
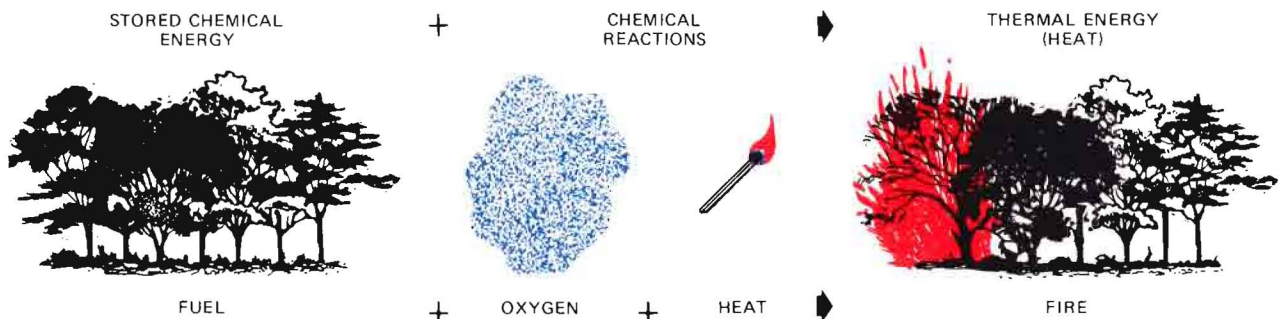
In earlier publications, we explored the nature of heat and the process of heat transfer by conduction. In the following discussion, we will look at the combustion process and the part that heat conduction plays in it, and how heat transfer by conduction can be checked in fire control operations.

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.

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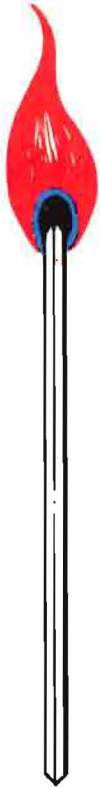
Wildland fuels do not burn directly

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 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 chemical reactions in char are different than in solid wood. Char can burn directly—mostly by glowing combustion—without first being pyrolyzed into gases. Because the ash is very fragile, it usually falls from the surface, seldom forming more than a thin layer.

ASH

CHAR

PYROLYSIS ZONE

UNBURNED WOOD
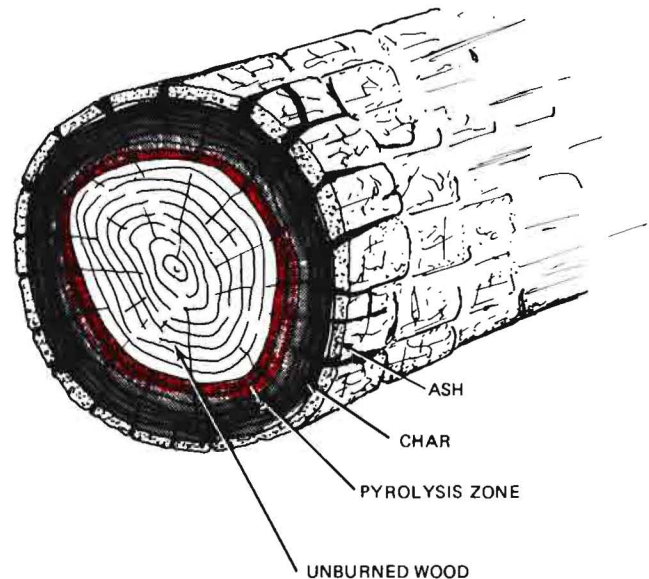
Thus, if we examine a cross section of a partially burned piece of wood we see from the surface inward first a thin layer of ash, next a layer of char, then a layer, usually shading from dark to light brown, where the pyrolysis has been taking place, and finally unburned wood. The speed with which the 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 do significant amounts of combustible gas begin to appear, and the fuels begin to discolor or char. At about this temperature too, the pyrolysis begins to become *exothermic*—the chemical reactions themselves produce heat. If the heat losses are small, the pyrolysis may become self-sustaining, and the temperature continue 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 or wood chips 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 become more strongly exothermic, reaching a peak about 600° 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° F 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 the gases must come in contact with something that is hot enough to ignite them. For example, a lighted match held close to smoldering logs in a fireplace can cause them to suddenly burst into flame. In wildland fires, the flames from other burning fuels can provide an ignition source for the gases from the heated fuel.

The maximum temperature that can be produced by the burning 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° F 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 cooler air. As a result, flame tem-

°F

900°

800°

FLAME

GLOW

400°

COMBUSTIBLE GASES

212°

WATER VAPOR

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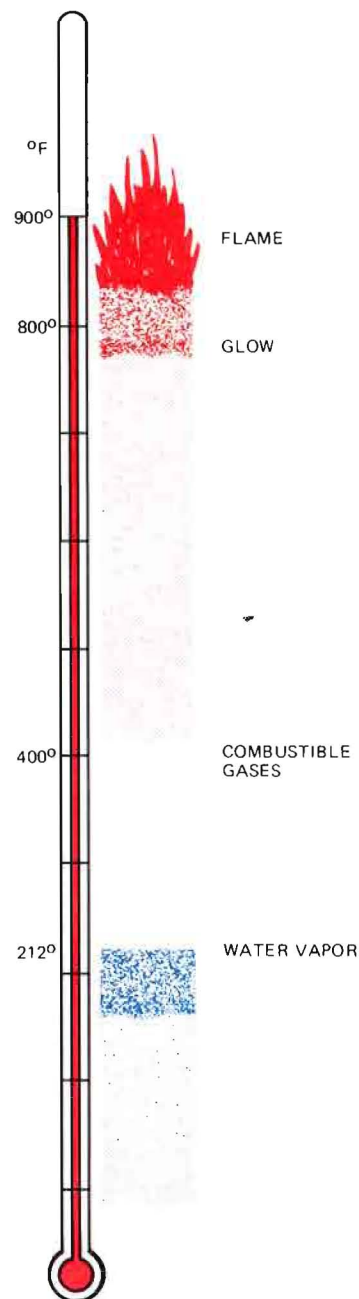
peratures in the range of 1800° to 2500° are more common. This is well above the temperature needed to ignite the gases, so once flaming starts, it continues as long as sufficient gas is produced.

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 with 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 be applied long enough to raise the temperature of a fuel layer thick 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.

HEAT   FUEL   +   TIME   =   IGNITION

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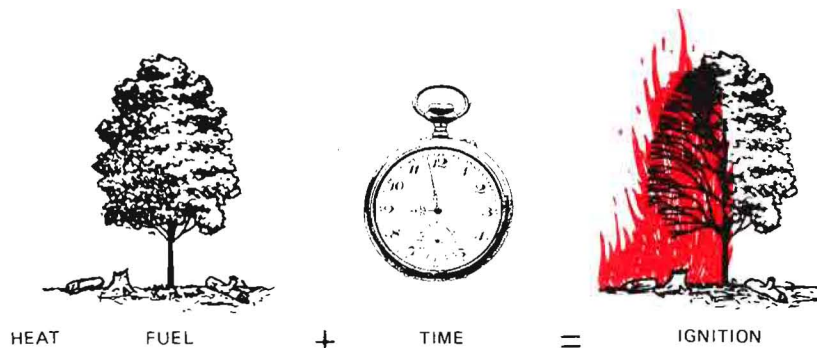
Moisture slows pyrolysis and ignition

In Part I, The Nature of Heat, we saw that when water is heated to the boiling point its temperature will 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 measuring device into a piece of wood and then subject the wood to strong heating, we will find that the temperature will rise to 212°, and then remain nearly constant until all of the moisture at the point of measurement has been vaporized. If the exterior temperature is high enough, 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 the burning rate of wildland fuel, and sometimes determine whether it will ignite or burn at all. When the fuel moisture content is high, large amounts of heat are needed to vaporize the moisture in the surface layer and to raise its temperature to a point where combustible gases are produced or sustained glowing combustion can begin. Thus, as the moisture content increases, the ignition time is greater 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.

The effect of moisture on the pyrolysis of wood can be illustrated from the results of an experiment with two half-inch wooden dowels. Temperature sensors were placed in the dowels at a $^3/_{16}$-inch depth. Dowel A had a moisture content of 2.4 percent and Dowel B about 20 percent. The dowels were inserted into a muffle furnace heated to 1200° F. The change in temperature with time of the two dowels is shown in the figure.

Dowel A, with its low moisture content, required about 20 seconds to reach a temperature of 212° F at the $^3/_{16}$-inch depth, while Dowel B required about 32 seconds. The temperature of Dowel A remained at 212° for only 9 seconds, but Dowel B stayed at this temperature for 21 seconds.

The cooling effect of heat absorption of water vapor is also

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illustrated by the temperature-time record of the dowels. Dowel A required 61 seconds to increase in temperature from 212° to 800°—the temperature where visible glowing usually begins to appear. Dowel B needed 81 seconds to reach this temperature. The total time for the dowels to reach 800° from the time of insertion in the furnace was 90 seconds for Dowel A and 135 seconds for Dowel B. Thus, Dowel A was burning about 1.5 times faster than Dowel B.
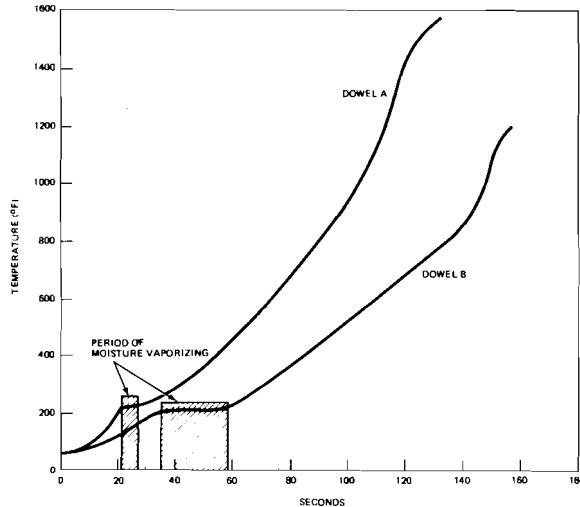
Not all of the water vapor moves out of the burning fuel immediately. Some of it diffuses toward the interior and condenses in the unburned part—the moisture content of the fuel tends to increase as it burns. Although the heat used to vaporize the moisture is released when it condenses, the increasing moisture content slows the temperature increase 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 combustion, and at the same time reduces the rate at which heat is generated.

Char slows pyrolysis

The layer of char that forms on the burning fuel has a strong effect on the burning rate, particularly for larger 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 and reduces heat production. 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, further lowering heat production. The relatively slow heat conduction, reduced heat production, and large heat losses from the flaming zone tend to prevent the pyrolysis from sustaining itself in the larger fuels. As a result, large fuels usually do not burn well, or stop burning—unless an additional heat source is available, the piece of fuel itself does not produce enough heat for continued pyrolysis. Fuels larger than about 1-inch in diameter seldom burn completely unless heat is supplied by other burning fuel or heat losses are reduced in some way.

Thermal diffusivity affects ignitability and burning rate

The thermal diffusivity of a substance is indicative of the amount of heat needed to increase the temperature of the substance at any point—the higher the thermal diffusivity, the less is the quantity of heat required. Because both the ignition of fuel and the continuation of pyrolysis depend on increasing the fuel temperature above some critical level, the ease of ignition and rate of burning increases with increasing thermal diffusivity.

The thermal diffusivity of wildland fuels decreases as their density or specific gravity increases. Consequently, fuels with low specific gravity can be ignited with less heat than can those with a higher specific gravity. Decayed wood, for example, has a very low specific gravity and can often be ignited with a spark, but solid wood with a greater specific gravity and therefore lower thermal diffusivity requires more heat for ignition. The burning rate is also slower for fuels with a high specific gravity and low thermal diffusivity. In investigating the charring rate of Douglas-fir timbers, the U.S. Forest Products Laboratory found that for material with the same total amount of moisture, the charring rate of timbers with a specific gravity of 0.60 was nearly one-third less than those with a specific gravity of 0.35.

One reason for the easier ignition and faster burning of low-density fuels is simply that there is less material per unit of volume, and hence less heat is needed to raise the temperature of a given layer of the fuel. However, the thermal conductivity of wildland fuel also increases as the density becomes greater. Therefore, a given amount of heat is conducted through a deeper layer of high-density fuel and hence raises the temperature less than for fuels with low density. As a result, the time for the fuel temperature to become high enough to vaporize the moisture and to produce

combustible gases is greater for the high-density fuels. This slows ignition and pyrolysis, particularly in the larger sizes of fuel where the mass of material is great enough to absorb a large quantity of heat.

HEAT CONDUCTION AND FIRE CONTROL

When the three ingredients needed for fire—fuel, heat, and oxygen (air)—are brought together in the proper proportion, 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 unburned 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 ensure that more heat will be needed to ignite the fuel than can be transferred from the fire.

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 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 in-

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LARGE SURFACE AREA
PER VOLUME

SMALL SURFACE AREA
PER VOLUME
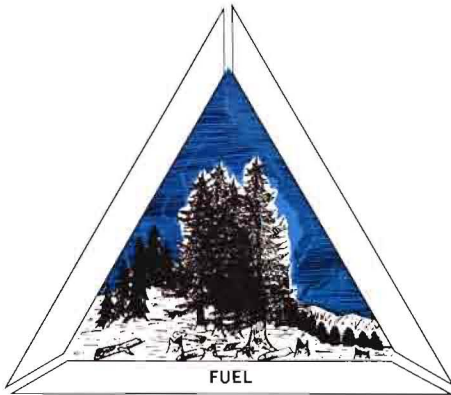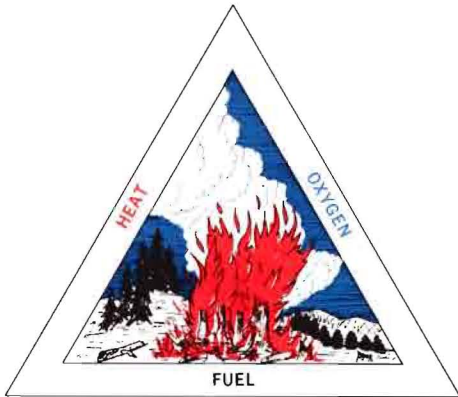
crease the chance of wildfire, particularly from small fire-brands.

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 rapidly becomes less 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 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
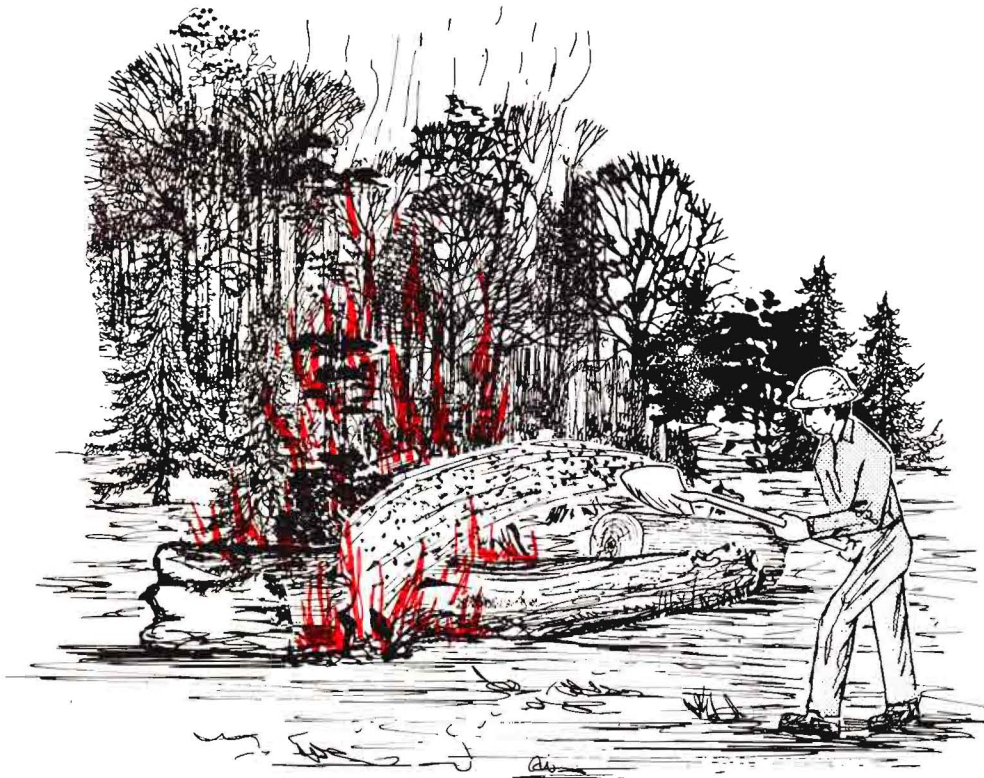
be used singly, but more often are used in various combinations.

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.
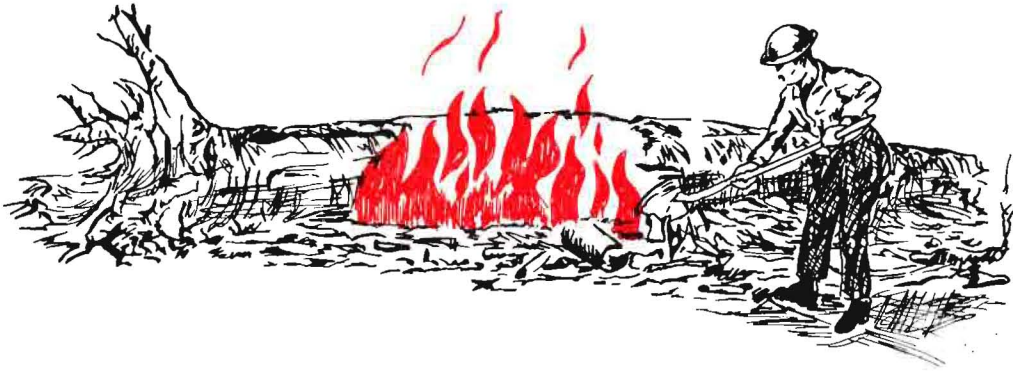
In fuel types where there are large as well as small fuels in the fuel bed, much of the large fuel stops burning once the small fuels have been consumed, since the additional heat needed to keep the large fuels burning is no longer available. But in the usual wildland situation, some of these fuels continue 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 pyroly-

sis 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 in 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 ensure 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.

Fire retardants affect pyrolysis

When fire retardants mixed with water are applied to burning fuel, a large part of the effect of the mixture on fire intensity is due simply to the cooling by the water—the retardants in common use do not change the heat capacity of water much. But the water can soon evaporate, and then the effect that the retardants have on pyrolysis becomes important in fire control, particularly for fuel treated ahead of the fire. Because little is gained by adding retardants to water for direct fire extinguishment, fire retardants are of greatest value in pretreating fuel in situations where water will not remain effective.

Fire retardants now in use on wildland fires can generally be grouped into two types. The first type depends for its effectiveness mainly on the insulation the material provides and the mechanical effect the retardant coating has on slowing the escape of combustible gases from the fuel. Some chemical pyrolysis inhibiting effect may also be present, but this is usually relatively small. This type of retardant, of

which borate is an example, tends to increase the ignition time of fuel exposed to heat, reduce the rate of combustion, and diminish the amount of fuel consumed.

The second type of retardant has a direct effect on pyrolysis. Materials that break down under heat to form phosphoric acid as one of the by-products, such as monoammonium phosphate or diammonium phosphate (DAP), are the most common retardants of this type. Phosphoric acid itself is an excellent fire retardant, but too hazardous to use in wildland fire control operations. In general, the effect of this type of retardant is to reduce the temperature at which pyrolysis takes place, thus favoring glowing over flaming combustion, and increasing the amount of char formed. Although applied only to fuel surface, some of the retardant migrates inward so that the flame inhibiting effect continues as long as pyrolysis is taking place. Because the pyrolysis takes place at a lower temperature, thus reducing heat requirements, treated fuel often burns more completely than untreated fuel, even though less flaming occurs and the rate of heat production is less. The lower temperature needed for pyrolysis also results in more rapid ignition when the fuel is exposed to strong heating. Fuel treated with phosphoric acid, for example, will ignite in about one-half the time of untreated fuel. However, flaming is less, and the fuel quickly reverts to mostly glowing combustion when the heat source is removed.

Both types of retardants are effective in reducing rate of fire spread and fire intensity—the mechanical type by increasing ignition time and slowing the rate of combustible gas production, the chemical type by reducing flaming and heat production. Where heavy fuels inside the firebreak are a problem, as is often the case with slash fuels, the chemical action type of retardant can be used to reduce fire intensity and lessen the chance of fire escape. But because the chemical action type may cause ignition at a lower temperature, the mechanical action type of retardant can be the most effective in protecting fuels outside the firebreak. The effectiveness of both types decreases rapidly as the fire intensity increases, however, and hence retardants are most effective on small and slow burning fires and portions of the fire edge on larger fires where heat production is not likely to be great.

SUMMARY

Organic materials, such as wildland fuels, do not burn directly, but must first be converted to gases by pyrolysis, a chemical process brought about by heat. Radiation and convection can transfer the necessary heat to the surface of the fuel, but transfer of heat into the interior is almost entirely by conduction. Control and extinguishment of a wildland fire hinges upon stopping the chemical reactions of pyrolysis, and about the only way we have of doing this is by interrupting or reducing heat transfer.

Ignition of wildland fuels requires a finite quantity of heat, and this heat must be supplied at a rate adequate to generate sufficient gases to produce a flammable mixture, and at a temperature high enough to cause the gases to flame or the char to glow. Moisture in fuel increases the ignition time and slows the pyrolysis process by increasing the amount of heat required to raise the fuel to a temperature where combustible gases are produced, by absorbing part of the heat otherwise available for pyrolysis, and by diluting the gases produced by pyrolysis.

The thermal diffusivity of most wildland fuels increases with increasing specific gravity or density of the fuel. When the thermal diffusivity is high, more heat is needed to raise the fuel temperature at any point. As a result, fuels with low specific gravity tend to ignite more readily, and often burn more rapidly for the same size than do fuels with high specific gravity. This effect is most important in the larger fuels where there is sufficient mass to absorb significant quantities of heat. The formation of char with its low thermal conductivity on the surface of the fuel also slows pyrolysis by reducing the rate of heat conduction into the fuel.

Three ingredients are needed for fire—fuel, heat, and oxygen. Together, these ingredients form the fire triangle. To extinguish a fire, one (or more) of the essential ingredients must be removed or modified in such a way that it cannot perform its needed function—the fire triangle must be broken. Basically, all of the methods we have of breaking the fire triangle in the suppression of a wildland fire involves interfering with heat production and heat transfer.

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

surrounding hot material.

Heat transfer to unburned fuel can be prevented by removing fuel in a firebreak around the fire. Pyrolysis may be slowed or stopped and heat conduction reduced by cooling burning fuels with water or dirt. Mechanical type fire retardants diminish heat production by insulating fuel against heat and slowing the production of combustible gases. Chemical action retardants interfere with the normal pyrolysis process by permitting the chemical reactions to take place at a lower temperature. This favors glowing over flaming combustion and increases the amount of char, thus reducing the rate of heat production and the quantity of heat available for transfer. However, these retardants can shorten ignition time under strong heating. The efficiency of both types of retardants decreases rapidly with fire intensity, hence retardants are most effective on small or slow burning fires and portions of large fires where heat production is not great.

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