HEAT AND WILDLAND FIRE—Part 2

HEAT CONDUCTION

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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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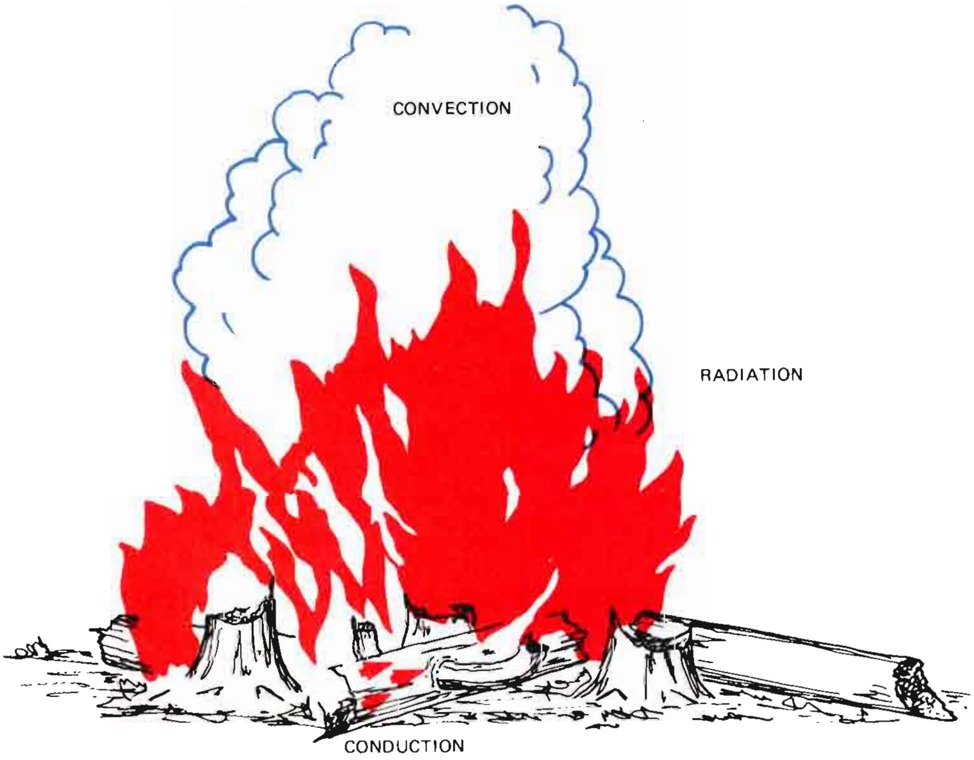
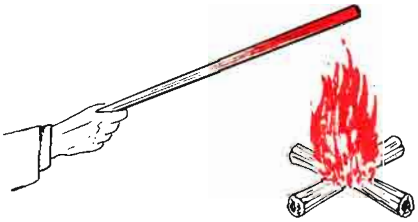
This Humidity Business: What It Is All About and Its Use in Fire Control. 1971 (blue)
Fire Whirls . . . Why, When, and Where. 1971 (blue)
Carbon Monoxide: A Firefighting Hazard. 1971 (yellow)
The Fire Environment Concept. 1972 (blue)

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
  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

HEAT CONDUCTION

Heat transfer is of paramount importance in wildland fire behavior and control. For a fire to start, heat must be transferred from a firebrand to the fuel. If the fire is to continue to burn and spread, heat must be transferred to the unburned fuel around the fire. And controlling a fire chiefly involves the prevention or slowing of heat transfer. Heat can be transferred in three ways—by conduction, by radiation, or by convection. Usually all three methods of heat transfer are operating at the same time in a wildland fire.





In Heat—Part 1, we learned something of the nature of heat—what it is, how it is measured, and some of its characteristics. In the following discussion we will examine the process of heat transfer by conduction. Future reports will deal with the role of conduction in wildland fire and with heat transfer by radiation and convection.

Conduction is the transfer of heat by molecular activity

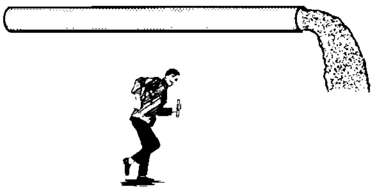
When a substance is heated, it absorbs thermal energy or heat, and the molecular activity within the substance increases. The gain in molecular activity is accompanied by an increase in temperature. If one end of a metal rod is held in a fire, the molecular activity and temperature in that end of the rod increases. But some of the activity is quickly imparted to adjacent molecules and from these molecules to others in a chain reaction. As this process continues, heat moves along the road and the other end soon becomes warm and then hot. This flow of thermal energy as a result of changing molecular activity is *heat conduction.* The transfer of heat is accomplished without appreciable movement or displacement of the substances.

Heat conduction is an essential and commonplace part of our daily lives, in industry, and in nature. Whenever heat needs to be transferred through an opaque substance, the transfer must be by conduction. In a hot-water heating system, for example, heat from burning fuel is transferred by conduction through the iron or steel of the boiler to heat the water. Heat from a burner on a stove is conducted through the bottom of utensils to cook food. In nature, the surface of the earth is heated by the sun, and some of this heat is conducted to deeper layers of the soil during the day and back to the surface at night—the varying ability of different kinds of soil and water to absorb and conduct heat received from the sun has a profound effect on local and worldwide weather and climate. Conduction of heat is essential in the combustion of solid fuels like those found in wildlands.

Substances vary in ability to conduct heat

Early scientists did not realize that heat is a form of energy and for a long time regarded it as some sort of mystic fluid that could not be seen, but whose effects were readily discernible. It is likely that some of the perceptible characteristics of heat transfer by conduction were responsible for this misconception of heat, for in many respects heat conduction is similar to the flow of fluids—such as the flow of water in pipes.

GOOD CONDUCTORS



TRANSFER HEAT OR WATER RAPIDLY

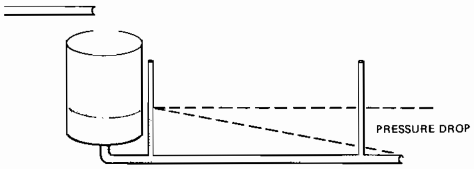
POOR CONDUCTORS

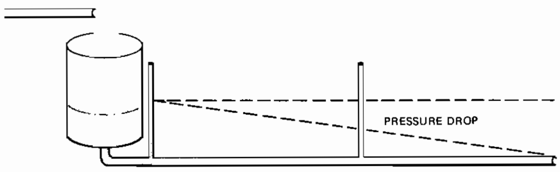
TRANSFER HEAT AND WATER SLOWLY

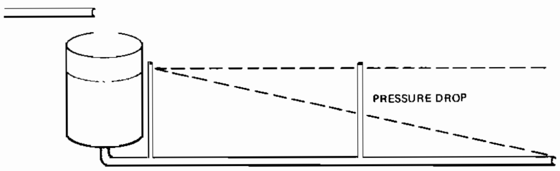
If a water pipe is smooth, the water moves easily and is quickly transferred from one point in the pipe to another. But if the pipe is bent and rough, the flow of water is impeded, and the more battered and rough the pipe, the less its ability to conduct water. It is much the same with heat conduction. Because of differences in molecular structure, some substances can conduct heat better than others—they impede or hinder the flow of heat less. Metals are usually good conductors, and some are better than others. Copper is an excellent heat conductor, and it is frequently used where rapid conduction of heat is desired. Soldering irons, for example, are usually made of copper, and the bottom of cooking utensils are often covered with copper to quickly and evenly distribute heat over the bottom of the pan. Most gases, including air, are poor conductors. Dirt, rocks, wood and wood products such as paper, all conduct heat slowly. Wildland fuels in general are poor heat conductors.

Temperature gradient affects conduction rate

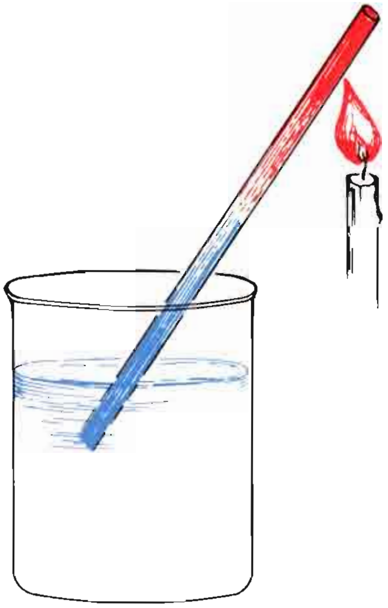
Physical factors operate to control the rate of heat conduction much as they do to control the rate of water flow. Suppose we have a water tank with a smooth, open-ended pipe connected to the bottom. Provided the water level in the tank is maintained at a fixed point, the water pressure at the pipe inlet remains constant, and the water flows through and out of the pipe at a constant rate. If we measure the pressure at several points along the pipe, we find that the pressure



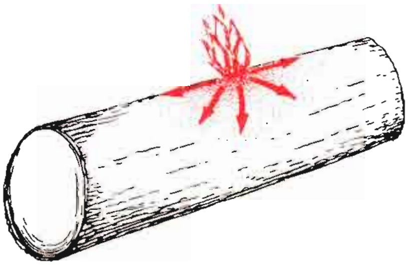




decreases as the distance from the inlet increases, and becomes zero at the outlet. The decrease in pressure is primarily the result of friction of the water with the pipe which impedes the flow. The rate at which the pressure decreases per unit length of pipe is the *pressure gradient* in the pipe. If the pipe is lengthened, the pressure gradient is smaller, because the same total pressure difference between the inlet and outlet must be distributed over the greater pipe length. And the rate at which the water flows is also reduced. However, increasing the pressure at the inlet by raising the water level in the tank increases the pressure gradient and the rate of water flow out of the pipe.



Heat conduction behaves in much the same way. Suppose we immerse one end of an iron rod in a tank of water. If we heat the other end of the rod it quickly reaches the temperature of the heat source, and the temperature increases along the length of the rod. But if the water is circulated so that its temperature remains constant, the immersed end of the rod remains at the temperature of the water. Thus, a *temperature gradient* is set up in the rod. As long as the temperatures of the heated and immersed ends of the rod are not changed, the temperature gradient and the rate of heat conduction from the heat source to the water will also remain constant. Increasing the length of the rod lengthens the path through which the heat must travel, and decreases the temperature gradient and the rate of heat transfer. Raising the temperature of the heated end of the rod increases the temperature gradient and rate of heat conduction—provided, of course, that the temperature of the water is still kept constant. If we substitute a rod of material with less ability to conduct heat than iron, the rate of heat conduction decreases, just as substituting a rough pipe for a smooth one reduces the rate of water flow.



Unlike the confined flow of liquid in a pipe, the transfer of heat by conduction is not confined to one direction in a substance, but can move in all directions from the area where the heat is applied. This is an important factor in the ignition of wildland fuels. Heat is not transferred just to the volume of fuel covered by the firebrand, but is conducted away from the firebrand in all directions, and hence to a larger fuel volume. As a result, a small firebrand applied to a large piece of fuel may not contain enough heat to raise the temperature of the fuel volume to which heat is transferred to the ignition point. On the other hand, the same firebrand applied to a small piece of fuel can cause ignition because of the smaller volume of fuel that has to be heated.

Quantity of heat conducted varies with area

In the foregoing section, the effect of temperature gradient on heat conduction was compared to the effect of pressure gradient on the flow of water through a pipe connected to a water tank. Suppose now that instead of only one pipe, several pipes of different sizes are connected to the bottom of our water tank. If we disregard possible variations in friction losses in pipes of different sizes, we can say that the speed of water flow is then the same in all of the pipes. This speed remains constant as long as the level of the water is maintained at the same point in the tank. But the *quantity* of water delivered to the ends of the pipes must obviously increase with pipe size, since the area through which the water is flowing at the constant speed is greater in the larger pipes.

It is the same with heat conduction. If we replace the iron rod with one end immersed in a water tank with a larger diameter rod, more heat will be conducted to the water for the same temperature gradient. The larger area through which heat is conducted transfers a greater quantity of heat, just as a greater quantity of water is delivered to the end of a larger diameter pipe when the rate of water flow is the same.

In our analogy of water flow in pipes to heat conduction, we have seen that the amount of water delivered at the end of a pipe will depend on the ability of the pipe to conduct water, the pressure gradient, and the size of the pipe or area through which the water flows. So it is with heat conduction, for the quantity of heat transferred depends on the ability of a substance to conduct heat, the temperature gradient, and the area through which heat flows. These factors are brought together in the term *thermal conductivity,* which expresses the quantity of heat transferred per unit of area per unit of time per degree of temperature gradient. Thermal conductivity is often expressed as Btu per hour per square foot per degree of temperature change per foot of distance (Btu/(hr)(ft^2)(°F/ft).

Thermal conductivity increases with fuel density

The *density* of a substance is its weight per unit of volume, such as pounds per cubic foot or grams per cubic centimeter. Often the density of a substance is indicated by its *specific gravity,* which is the ratio of the weight of a given volume of a substance to that of an equal volume of water. Although the density of water varies somewhat with its temperature, this variation is of little consequence at ordinary temperatures, and the specific gravity of water is usually taken as 1.0. Hence, if a substance has a specific gravity of less than 1.0 it is lighter than water and will float in water, and if its specific gravity is greater than 1.0 it is heavier than water and will sink.

In our discussion of the nature of heat (Part I), we saw that the heat capacity of wildland fuels increases with their density. The ability of wildland fuels to conduct heat is also closely related to fuel density; the greater the density, the higher the thermal conductivity. Thus, heat conduction in heavy fuels can be considered analogous to the flow of water in a smooth pipe—these fuels impede the conduction of heat much less than do low-density fuels.

Density, or specific gravity, varies considerably in wildland fuels, and consequently so does thermal conductivity. The decayed sapwood of white fir, for example, weighs only about 1/10 that of an equal volume of water (specific gravity 0.10), and has a thermal conductivity of 0.02542 Btu/hr(ft^2)(°F/ft). Dead ponderosa pine needles have a density about 5 times that of the fir, and a thermal conductivity nearly 3 times as great—0.07262 Btu/(hr)(ft^2)(°F/ft). Solid white pine has a thermal conductivity of 0.06536 Btu/(hr)(ft^2)(°F/ft), as compared with 0.08437 and 0.09199 for more dense oak and maple wood.

Temperature increase depends on thermal diffusivity

Thermal conductivity indicates the rate at which heat can be conducted into a substance. Therefore, the volume of material through which a given amount of heat is distributed in some time period depends on the thermal conductivity of the substance. Specific heat establishes the temperature increase that occurs when a quantity of heat is added to a unit weight of a substance—the higher the specific heat, the less will be the temperature increase. And the density of a substance determines the number of weight units that must be heated in a given volume. Thus, when heat is applied to a substance, the amount and rate of temperature increase at any given point is controlled by the thermal conductivity, specific heat, and density of the substance. Taken together, these factors determine the *thermal diffusivity* of the substance. The greater the thermal diffusivity, the less is the amount of heat needed to raise the temperature at any given point by a given amount. The relationship among these factors can best be shown in equation form:

$$\text{Thermal diffusivity} = \frac{\text{Thermal conductivity}}{\text{Density x Specific heat}}$$

We have seen that the thermal conductivity of wildland fuels increases with fuel density or specific gravity. But this increase is not directly proportional; doubling of the fuel density, for example, will increase the thermal conductivity by only about 1.5 times. Relatively little is known about the specific heat of various kinds of wildland fuels. However, specific heat appears to increase somewhat with increasing density, although there does not seem to be much difference among common fuel types. Thus, higher fuel density results in lower thermal diffusivity—the denominator in the equation increases more rapidly with increasing density than does the numerator. As a result of their higher thermal diffusivity, the surface layers of low-density fuels can be raised to ignition temperature with less heat, or in a shorter time with the same amount of heat, than can fuels of greater density. Differences in thermal diffusivity is one of the chief reasons why low-density fuels like decayed wood can often be ignited with a spark, while solid wood requires a much larger firebrand.

The terms thermal conductivity and thermal diffusivity are often confused and sometimes mistakenly used interchangeably. However, thermal conductivity indicates the rate at which *heat* can be conducted through a substance, whereas thermal diffusivity is concerned with the amount or rate of *temperature* increase that a given quantity of heat will produce. Thermal conductivity and thermal diffusivity represent different concepts and cannot be interchanged, just as heat and temperature do not mean the same thing and cannot be used interchangeably.

SUMMARY

Heat conduction is the transfer of thermal energy by molecular activity from one part of a substance to another part, or between substances in contact. The energy is transferred without appreciable movement or displacement of the substance as a whole. Different substances vary widely in molecular structure and the number of molecules they contain. Consequently, the ability of various substances to conduct heat also varies over a wide range. Metals are usually good conductors, but substances like air, wood, glass, water, and soil conduct heat slowly. Wildland fuels in general are poor heat conductors.

The rate at which heat can be conducted depends on the ability of a substance to conduct heat and on the temperature gradient within and between substances—the larger the temperature gradient, the more rapid the conduction rate. The quantity of heat conducted depends also on the area through which the heat is transferred. These factors are brought together in the term *thermal conductivity,* which expresses the quantity of heat transferred per unit of area per unit of time per degree of temperature gradient. Thermal conductivity is often given as Btu per square foot per hour per degree F per foot of distance (Btu/(hr)(ft^2)(°F/ft).

When heat is applied to a substance, the amount and rate of temperature rise at any given point in the substance is controlled by the thermal conductivity, specific heat, and density of the substance. Taken together, these factors establish the *thermal diffusivity* of the substance. The greater the thermal diffusivity, the less the amount of heat needed to raise the temperature. The relationship of thermal diffusivity to thermal conductivity, specific heat, and density is given by the equation:

$$\text{Thermal diffusivity} = \frac{\text{Thermal conductivity}}{\text{Density x Specific heat}}$$

The thermal conductivity of a substance increases with density, but at less than a directly proportional rate. Specific heat of wildland fuels also tends to increase with increasing density. Consequently, thermal diffusivity decreases as the fuel density becomes greater. Because fuels with low density have higher thermal diffusivity, low-density fuels can usually be ignited with less heat, or in a shorter time with the same amount of heat, than can fuels of greater density.

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