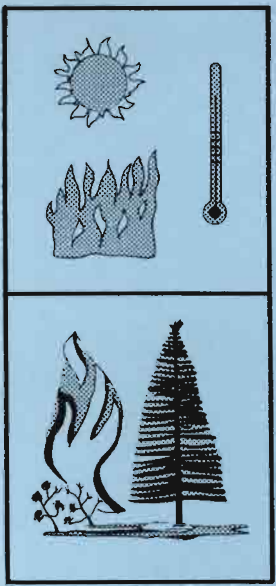

HEAT—ITS ROLE IN WILDLAND FIRE—Part 2

HEAT CONDUCTION

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PACIFIC SOUTHWEST
Forest and Range
Experiment Station

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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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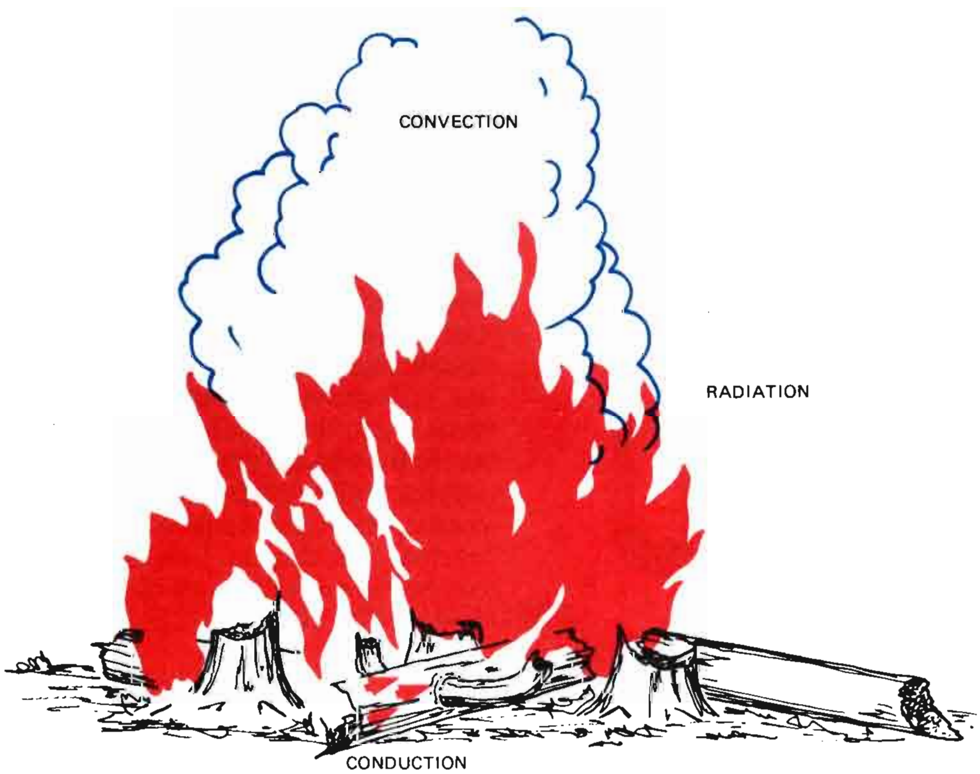
This Humidity Business: What It Is All About and Its Use in Fire Control. 1971 (blue)
Fire Whirls . . . Why, When, and Where. 1971 (blue)
Carbon Monoxide: A Firefighting Hazard. 1971 (yellow)
The Fire Environment Concept. 1972 (blue)
Heat–Its Role in Wildland Fire (blue)
Part 1–The Nature of Heat. 1975
Part 2–Heat Conduction. 1976

HEAT CONDUCTION

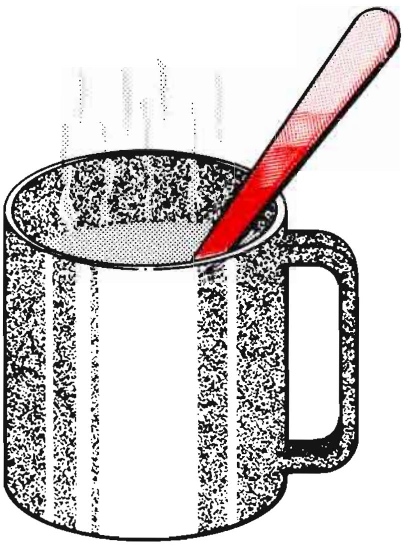
Heat, or *thermal energy*, is one of the three ingredients essential to fire–the other two are oxygen and fuel. Enough oxygen for fire is almost always available in wildlands, and fuel is usually plentiful. But the mere presence of a heat source does not necessarily result in a wildland fire. Before a hot or flaming firebrand can ignite the fuel, some of its heat must be imparted to the fuel in some way. And for a fire to continue to burn and to spread, heat must be transferred from the fire to unburned fuel.



Heat can move from one point to another in three basic ways: by conduction, by radiation, or by convection. Most often, all three methods of heat transfer are operating at the same time in a wildland fire. In the following discussion, we will examine the characteristics of one of these methods by which heat can move–the transfer of heat by conduction.

Conduction is the transfer of heat by molecular activity

In Heat–Part 1, we learned that when a substance is heated it absorbs thermal energy or heat, and the molecular activity within the substance increases. The increase in molecular activity is accompanied by an increase in temperature. If only part of an object is heated, the molecular activity and temperature are increased only in that part at first. 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 toward those parts of the object that have a lower temperature. This flow of thermal energy as a result of changing molecular activity is *heat conduction*. Heat can be conducted from higher to lower temperature regions within an object, or between objects in contact when they are at different temperatures. The transfer of heat is accomplished without appreciable movement or displacement of the substances. Whenever heat is transferred through an opaque solid substance, the transfer must be by conduction.

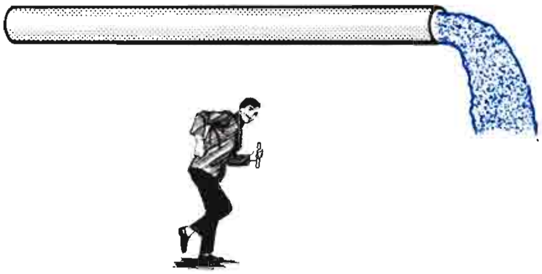


Conduction of heat is a commonplace occurrence in our daily lives, in industrial processes, and in nature. If a metal spoon is dipped in a cup of hot coffee, the spoon handle soon becomes warm and then hot–some of the heat in the coffee is conducted along the spoon. Heat from a burner on a stove is conducted through the bottom of utensils to cook food. In a steam engine or hot-water heating system, heat from burning fuel is transferred by conduction through the iron or steel of the boiler to heat water. In nature, the sun heats the earth's surface and this heat is conducted to deeper layers of soil and water during the day and back to the surface at night–the varying ability of different soils and of water to absorb and conduct heat has a profound effect on local and worldwide weather and climate. Conduction of heat is essential for the combustion of solid fuels like those found in wildlands.

Heat conduction and fluid flow are alike

Before heat was recognized as a form of energy, early scientists regarded heat as some sort of mystic fluid. Probably some of the perceptible characteristics of heat transfer by conduction was responsible for this misconception of heat, for in many ways heat conduction appears similar to the flow of fluids. Consider the flow of water in a pipe, for example. If the pipe is straight and smooth, the water can move 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 or hindered, and the more battered and rough the pipe, the less is its ability to conduct water.

GOOD CONDUCTORS



TRANSFER HEAT OR WATER RAPIDLY

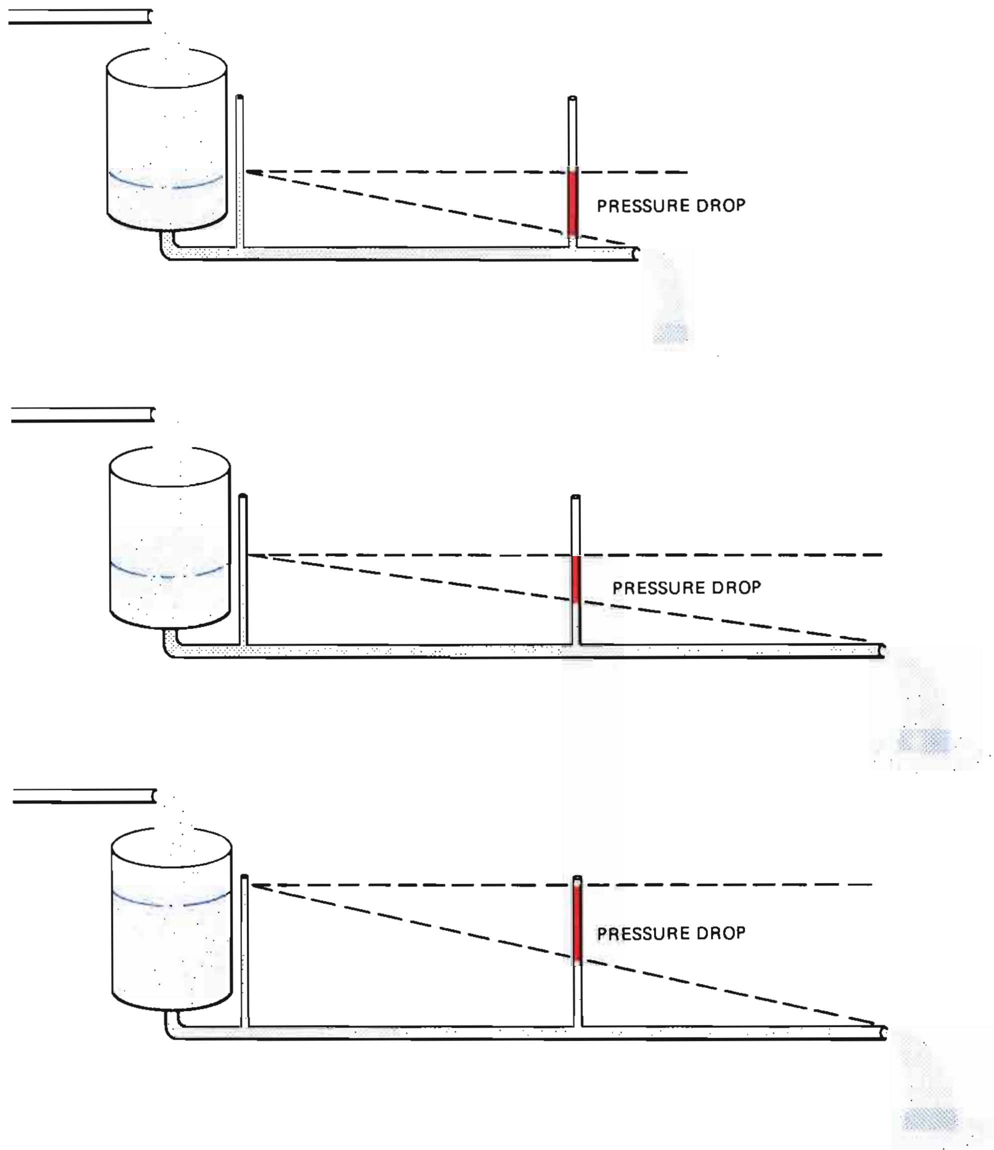
POOR CONDUCTORS

TRANSFER HEAT AND WATER SLOWLY

So it is with heat conduction. Because of differences in number of molecules and molecular structure, some materials impede the conduction of heat more than others. 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 distribute heat quickly and evenly over the bottom of the pan. Most gases, including air, are poor conductors. Water and many other liquids do not conduct heat well. Wildland fuels in general, wood, and wood products conduct heat slowly, and so do soil and rocks.

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

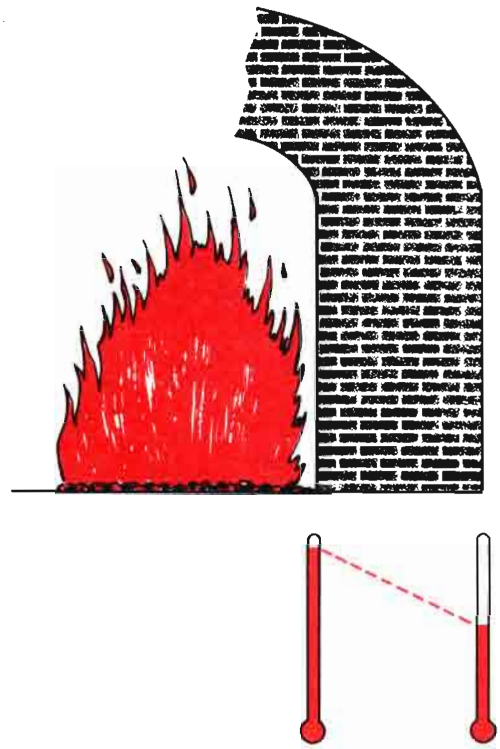


the same total pressure difference between the inlet and outlet must be distributed over the greater pipe length. And the rate at which the water flows is also reduced. However, increasing the pressure at the inlet by raising the water level in the tank increases the pressure gradient and the rate of water flow out of the pipe.

Heat conduction behaves in much the same way. Consider a brick-walled furnace. If the temperatures at the inner and outer wall surfaces at two opposite points are measured, the outer wall is found to be cooler than the inner wall–a *temperature gradient* exists in the wall. This can be measured as degrees per foot of distance between the two surfaces. As long as the temperature at the heated side of the furnace wall is kept constant, the temperature gradient and the rate of heat conduction also remain constant. Increasing the thickness of the wall lengthens the path through which the heat must travel, decreasing the temperature gradient and the rate at which heat appears at the outside surface. Raising the temperature in the furnace increases the temperature gradient and the rate of heat conduction, much as raising the inlet pressure increased the rate of flow of water in the pipe.

If we substitute a rough pipe for the smooth one connected to the water tank, the rate of flow of water is reduced for the same inlet pressure and pipe length. Similarly, substituting a material with less ability to conduct heat for the brick wall reduces the rate of heat conduction.

The rate of heat conduction, then, depends on both the ability of a substance to conduct heat and on the temperature gradient.



TEMPERATURE GRADIENT

Quantity of heat conducted varies with area

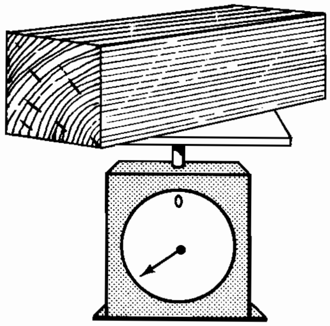
Suppose now that instead of only one pipe, several pipes of different sizes are connected to the bottom of our water tank. Neglecting possible variations in friction losses in pipes of different sizes, we can say that the speed of water flow is then the same in all pipes, and this speed remains constant 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 the area through which heat is conducted at a constant rate increases, the quantity of heat transferred must also increase. Thus, the *rate* at which heat is conducted depends on the ability of a substance to conduct heat, and on the temperature gradient, but the *quantity* of heat conducted depends on the area through which the heat is transferred as well. These factors are all brought together in the term *thermal conductivity*, which indicates the quantity of heat transferred per unit of time per unit of area per degree of temperature gradient. Thermal conductivity is often expressed as Btu per hour per square foot per degree of temperature change per foot (Btu/(hr)(ft^2) (°F/ft).

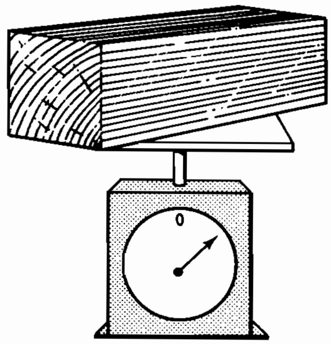
The thermal conductivity of different substances varies over a very wide range. The thermal conductivity of poor conductors is low; that of good conductors is high. As indicated earlier, air is a poor conductor–at 68°F its thermal conductivity is only 0.0148 Btu/(hr)(ft^2)(°F/ft). Water is also a poor conductor, with a thermal conductivity of 0.0346, whereas that of copper, a good conductor, is 227.6 Btu/(hr)(ft^2)(°F/ft). Thus, copper conducts heat more than 15,000 times better than air, and 6,500 times better than water.

Fuel density affects thermal conductivity

In our discussion of the nature of heat (Part 1), we saw that the heat capacity of wildland fuels increases with their density, or weight per unit of volume. 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 such as oak and maple



HEAVY FUELS =
HIGH THERMAL CONDUCTIVITY =
SLOW IGNITION + SLOW BURNING



LIGHT FUELS =
LOW THERMAL CONDUCTIVITY =
FAST IGNITION + FAST BURNING

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. For example, the decayed sapwood of white fir is one of the lightest of wildland fuels, with a density of 6 to 8 pounds per cubic foot. Its thermal conductivity is about one-third that of ponderosa pine needles that have about 5 times the density, and only about one-fourth the thermal conductivity of the still more dense maple wood.

Because of their greater thermal conductivity and heat capacity, dense fuels usually require more heat for ignition than do low-density fuels. Heat can be conducted more rapidly into deeper layers of the high-density fuels, thus slowing the temperature rise at the surface so that more heat is required to raise the surface temperature to the ignition point. More heat is also required to raise the temperature of the surface layer because the dense fuel has greater heat capacity. This difference in heat requirements for ignition is one of the reasons that fuel like decayed wood can often be ignited with a spark, but solid and dense wood requires a larger firebrand.

SUMMARY

Conduction is the transfer of heat by molecular activity from one part of a substance to another part, or between substances in contact, without appreciable movement or displacement of the substance as a whole. Different substances vary widely in molecular structure and in the number of molecules they contain. Therefore the ability of various substances to conduct heat also varies over a wide range. Most metals are good conductors, but substances like wood, air, glass, water, and soil conduct heat slowly.

The rate at which heat can be transferred by conduction depends on the ability of a substance to conduct heat and on the temperature gradient. 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 time per degree of temperature gradient. Thermal conductivity is often given as Btu per square foot per hour per degree F per foot (Btu/hr)(ft^2) (°F/ft).

The thermal conductivity of wildland fuels becomes greater as the density of the fuel increases. Because heat capacity of the fuels also increases with density, high-density fuels usually require more heat for ignition than do low-density fuels.