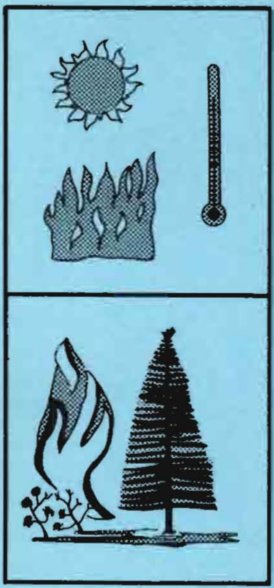
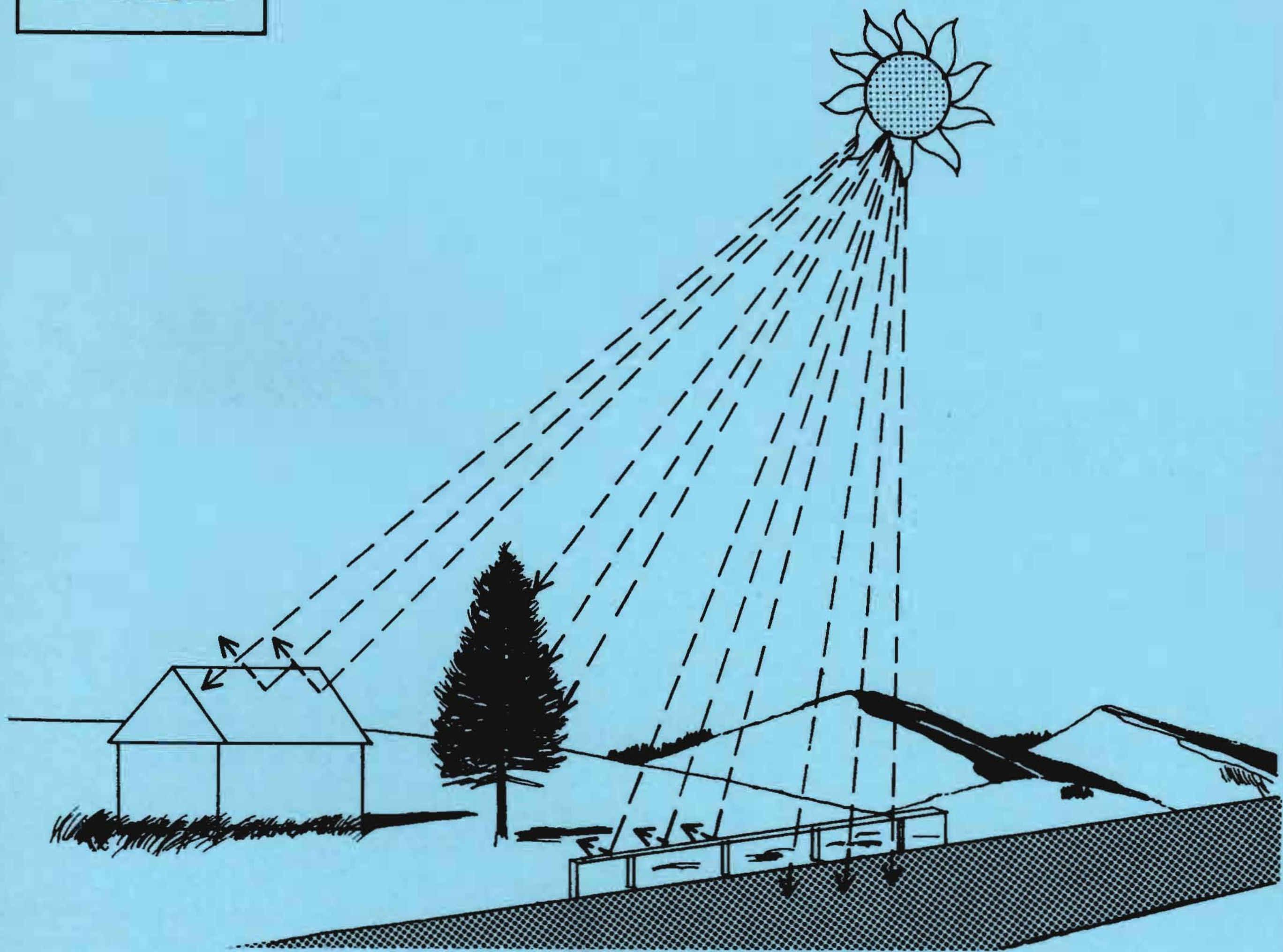


HEAT—ITS ROLE IN WILDLAND FIRE—Part 4

RADIATION

Clive M. Countryman



PACIFIC SOUTHWEST
Forest and Range
Experiment Station

1976

FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE
P.O. BOX 245, BERKELEY, CALIFORNIA 94701

The Author

CLIVE M. COUNTRYMAN heads fire behavior studies at the Pacific Southwest Forest and Range Experiment Station, with headquarters at the Forest Fire Laboratory, Riverside, Calif. He earned a bachelor's degree in forestry at the University of Washington in 1940, and joined the Forest Service the following year.

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:

Director
Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701
Attention: Publication Distribution

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)

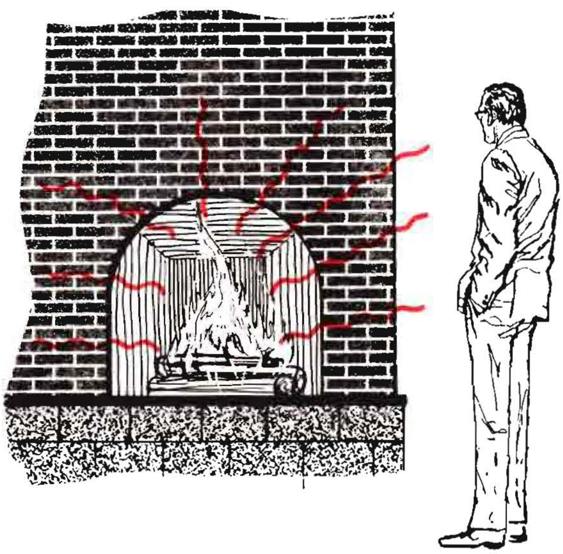
- Part 1–The Nature of Heat. 1975
- Part 2–Heat Conduction. 1976
- Part 3–Heat Conduction and Wildland Fire. 1976
- Part 4–Radiation. 1976

RADIATION

Wildland fire is dependent on heat transfer. For a fire to start, heat must be transferred from a firebrand to the fuel. If the fire is to burn and grow, heat transfer to the unburned fuel around the fire must continue. The way a fire burns and behaves is closely related to the manner and rate of heat transfer. The speed with which fire spreads, for example, depends greatly on how quickly sufficient heat for ignition can be transferred to the unburned fuel.

Heat can be transferred from one point to another in three ways—by conduction, by radiation, or by convection. In Parts 1 and 2 of this series, the nature of heat and transfer of heat by conduction were examined. Here we discuss heat transfer by radiation.

Radiation is energy in the form of electromagnetic waves



In Part 1, we learned that heat is a form of energy called *thermal energy.* Often we sense radiation as heat too, such as when standing in front of a fire in a fireplace or near a black-topped road on a hot summer day. But radiation is not heat—it is an entirely different form of energy. Radiant energy exists as *electromagnetic waves,* similar in form to the waves of alternating current electrical energy. These waves travel at the speed of light—186,000 miles per second. All substances at temperatures above absolute zero (−469°F), produce radiant energy. On earth, absolute zero can be approached only in the laboratory and with special apparatus. For all practical purposes, then, we can consider that all materials we ordinarily deal with are radiating energy—even cold ones.

Radiant energy travels outward in all directions from the emitting substance until it encounters something capable of absorbing it. The absorbed radiation increases the molecular activity in the substance, thereby increasing its temperature and the amount of heat it contains—this is why we frequently sense radiation as heat. The heated substance radiates energy too, and this energy can be absorbed by other substances and converted to heat. And this two-way process is continually going on. It is the interconvertibility of radiant and thermal energy that makes heat transfer by radiation possible.

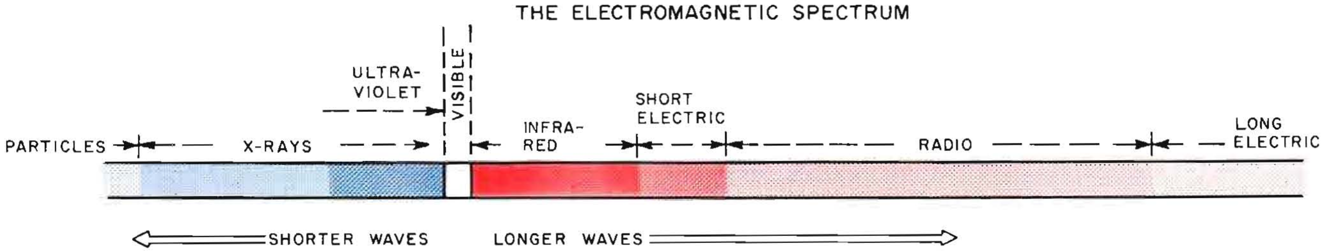
Radiation is the only means of heat transfer that does not require an intervening substance between the heat source and receiving substance. Radiant heat transfer can operate in a vacuum. A prime example is the heating of the earth by the sun—only radiation can transfer the sun's heat through outer space.

Radiation varies in wavelength

The electromagnetic waves of radiant energy vary in length—the distance between crests of successive waves—from very long electric and radio waves to extremely short X-rays, gamma rays, and cosmic rays. All of the radiant energy arranged in the order of wavelength forms the *electromagnetic spectrum* of radiant energy.

Most radiant energy is invisible, and its wavelength and often its presence can be detected only with special instrumentation. Visible light occupies a narrow band near the middle of the spectrum, and its wavelengths can be readily

THE ELECTROMAGNETIC SPECTRUM



distinguished because light waves of differing lengths are visible as different colors. Radiation from the sun includes all visible wavelengths. Sunlight directed through a glass prism will be separated by wavelength to give a display of colors ranging from violet (shortest visible waves) through blues, greens, yellows, to reds (longest visible waves). In the same way, sunlight shining through raindrops under certain conditions may be seen as a rainbow.

Radiation intensity and wavelength change with temperature

Substances at ordinary atmospheric temperatures emit thermal radiation that is mostly in the long wave or infrared range. As the temperature of a substance becomes higher, the total amount of radiation becomes greater. But the amount of radiation in the shorter wavelengths increases more rapidly with rising temperature than does that in the longer wavelengths. Therefore, as the temperature of a substance increases, the wavelength of maximum radiation intensity shifts more and more toward the shorter wavelength part of the spectrum.

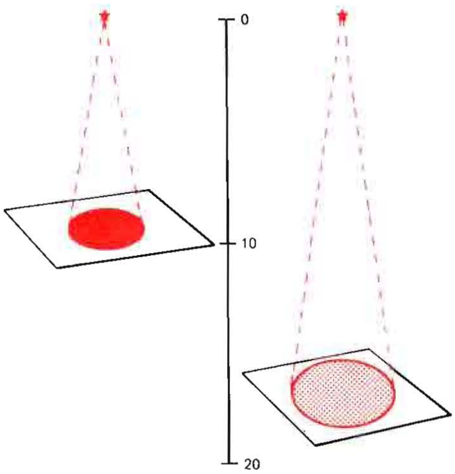
The sun radiates as a very hot body, and much of its radiation is in the shorter wavelengths. About half is in the visible band, and the human eye is adapted to make most efficient use of this radiation. Generally, thermal radiation is not visible when the temperature of a substance is less than

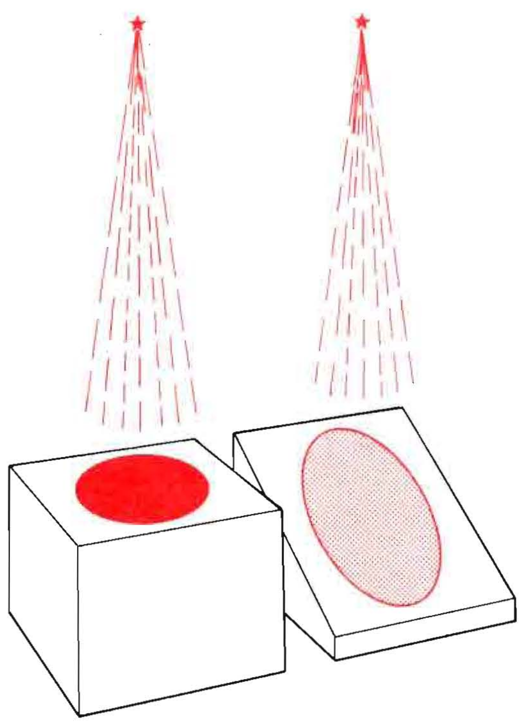
1000°F. If we heat a substance, such as an iron rod, it appears dull red when it first becomes hot enough to emit visible radiation. Continued heating causes it to change in color to bright red, and then to orange, yellow, and white as its temperature increases and the maximum radiation intensity shifts toward the shorter wavelengths.

The color change that accompanies a change in temperature of a substance has a number of practical applications. In tempering steel, for example, a blacksmith frequently uses the color of the heated metal to determine the proper temperature that will produce the desired degree of hardness in the finished product. Sensitive and accurate instruments utilizing the color change have been devised to measure the temperature of materials without contacting them. Such instruments are often used where temperature measurements with more conventional devices are not practical or are hazardous.

Radiation intensity changes with distance and angle

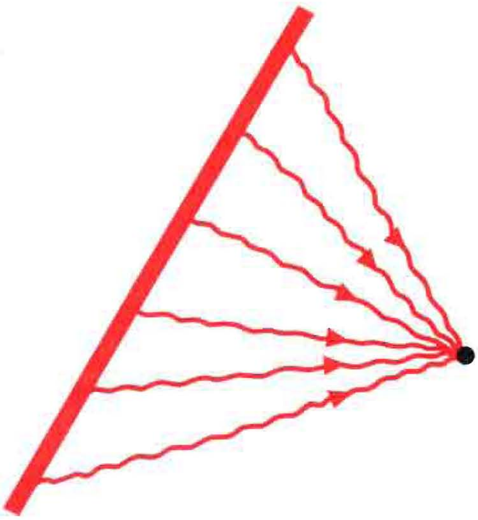
The intensity of radiation received by an object depends not only on the temperature of the radiation source, but also on the object's distance from the source and the angle at which the radiation strikes. For a point source of radiation,



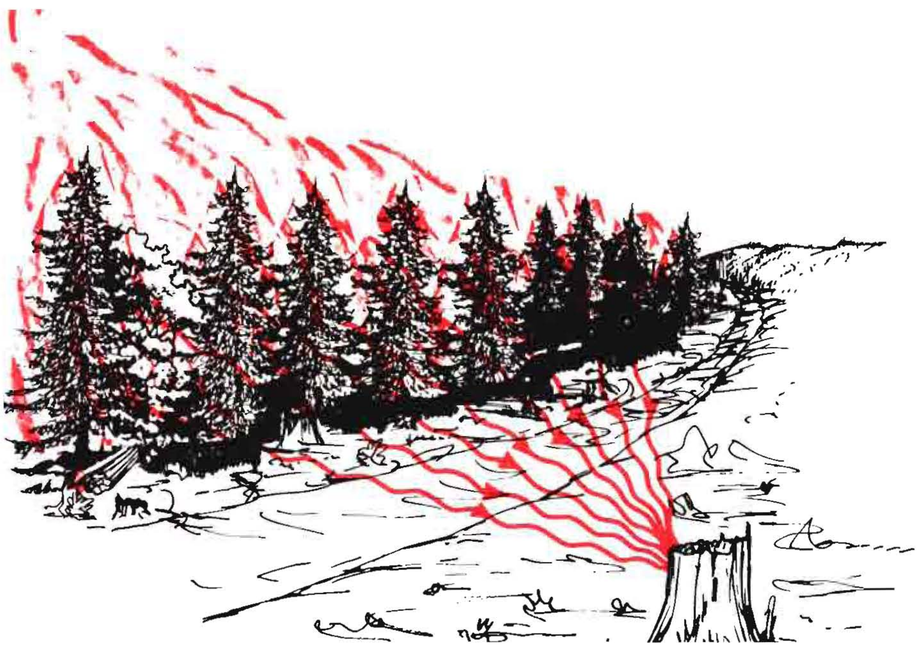


the radiation intensity decreases inversely as the square of the distance. This means the radiation intensity 20 feet from the source is only one-fourth that at 10 feet. Intensity decreases so rapidly because the radiant energy waves travel only along straight paths. As the distance from the source increases, the same total amount of radiation is spread over a greater area, hence the amount received per unit of area is less. The same thing happens as the angle of radiation varies. The greatest intensity occurs when the receiving surface is perpendicular to the source, but as the angle of radiation departs from the perpendicular the same total radiation must cover a larger area.

For a line source of radiant energy, such as a hot wire, the decrease in intensity with distance is less rapid. We can consider a line source as a series of point sources, each radiating energy along straight paths. The receiving object will receive radiation from all of the points; most from the point perpendicular to the object, and lesser amounts from the other points because of the different angles and distances. Because the receiving object can receive more radiation from a line source than a point source, the intensity varies inversely with the distance instead of the square of the distance as it does for a point source. The intensity at 20 feet will therefore be one-half that at 10 feet.



In wildland fires, we are seldom concerned with either point or line sources of radiation, for flames usually have considerable surface area. However, we can think of the flame surface as being made up of a large number of adjacent point sources. Radiation strikes the receiving object from all of the points—in greatest intensity from points perpendicular and closest to the object, and in lesser intensity from the other points. Because so many points are producing radiant energy, the decrease in intensity with distance from a flame source is less than that from a line source and much less than that from a point source. The number of points from which



radiation can be received also increases rapidly with the area of the radiating surface. Thus, the amount of thermal radiation that fuel—and firefighters—receive increases rapidly as the flame heights increase.

Substances differ in ability to emit and absorb radiation

Different kinds of substances vary greatly in capability to emit and to absorb thermal radiation. Substances that are good radiators are also usually good absorbers. Opaque materials are better radiators than transparent materials, and nonmetals are usually more efficient in emitting and absorbing thermal radiation than metals, particularly at low temperatures. The ideal radiator is one capable of emitting and absorbing *all* thermal radiation. Since black surfaces most often approach this capability, a perfect radiator is called a *black body*.

The term *black body* is somewhat misleading, because some substances that are not black are almost perfect radiators and absorbers of radiation. And a perfect black body, if it is hot enough to radiate in the visible light range, does not appear black. Thick flames in a wildland fire, for example, can come as close to emitting thermal radiation as a black body. But generally, most dark-colored substances are better radiators and absorbers than are light-colored ones. This is why it is better to wear white rather than dark clothing on a hot day, and why a dark-colored car parked in the sun is noticeably warmer to the touch than a white car parked next to it. In some of the early nuclear tests in the South Pacific, dark-colored birds were killed by thermal radiation from the nuclear bomb, whereas white birds survived because they absorbed less of the thermal radiation.

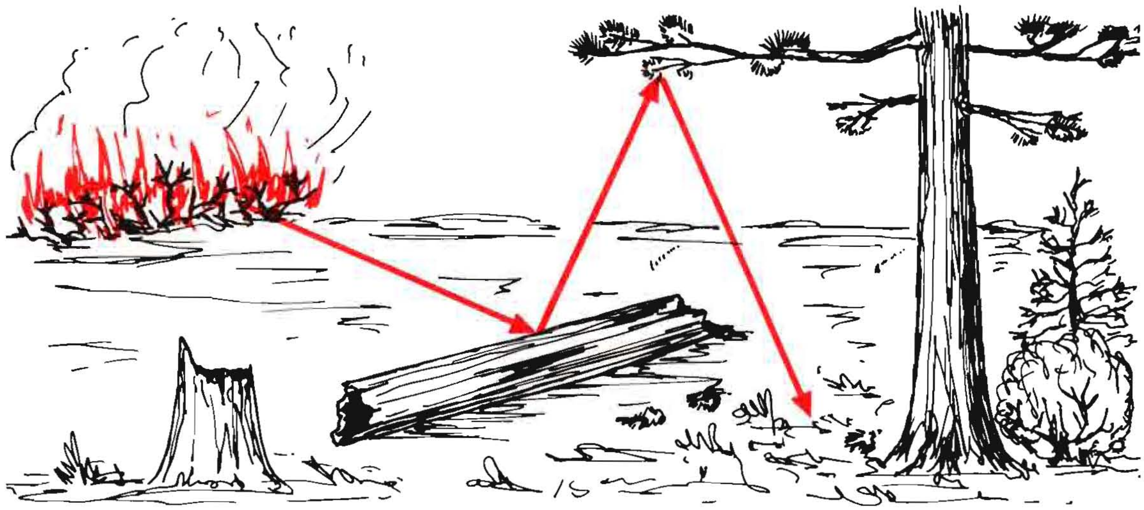
Not all thermal radiation is absorbed

Only a perfect black body can absorb all the thermal radiation that reaches it—other substances absorb only part of the radiation. Clear, translucent, and very thin opaque materials can absorb some wavelengths while allowing others to pass through unchanged. Glass, for example, transmits most wavelengths in the visible light band, but absorbs those in the infrared range. Thus, a glass window in a house will admit the shortwave light radiation, but block longwave radiation from lower temperature materials inside the house.

Substances that are selective in the radiation wavelengths they absorb or transmit are said to be *transparent* to the wavelengths they do not absorb. Gases are particularly selective: different kinds of gases absorb and transmit different wavelengths. This peculiarity of gases is often used to identify unknown materials. The unknown substance is converted to a gaseous state and its spectrum of absorbed and transmitted wavelengths is compared with those of known materials. As we shall see later, this characteristic of gases affects the way we receive thermal energy from the sun.

Some radiation is reflected

Not all the thermal radiation received by a substance is absorbed or transmitted through it—some is usually reflected. This applies to radiation in the invisible part of the spectrum



as well as to light. Reflection does not change the wavelength of the radiation, only its direction of travel. Some other substance can absorb part and again reflect part of the reflected radiation, and this process of partial absorption and reflection can continue. Only the thermal radiation that is reflected or radiated to space can be considered "lost."

Reflection of light is essential to the visual perception of substances. We could not see a substance if it did not reflect light—unless it is warm enough to emit radiation in the visible wavelengths. Selective reflection of light wavelengths determines the apparent color of a substance; a substance has a certain color because that wavelength is being reflected and the others absorbed. Thus, a red object appears red because it is reflecting light in the red wavelengths. Pure white is seen when all visible wavelengths are being reflected, and pure black is seen when all visible wavelengths are being absorbed and none reflected. Actually, we cannot see a truly black object, only the blackness from lack of reflected light in contrast to the light reflected from other substances.

In a complex way, the amount of thermal radiation reflected depends on the characteristics of the surface of the substance, the radiation wavelength, and the angle at which the radiation strikes the surface. In general, however, smooth, light-colored surfaces reflect more radiation than do dark, rough surfaces. A highly polished, smooth surface such as a mirror or chrome on a car, reflects a large part of the thermal radiation, but a black-topped road surface reflects very little. About 36 percent of the solar radiation received on the earth, taken as a whole, is reflected, but this percentage varies greatly with the kind of surface. Clean, fresh snow reflects about 80 percent of the sun's radiation, dry sand about 30 percent, and dark coniferous forests about 5 percent. Dead wildland fuels usually reflect less than 30 percent. The tops of clouds reflect a large part of the solar radiation—40 to 80 percent. Thus, the diminished sunlight on a cloudy day is not due so much to absorption by the clouds as to reflection back to space.

Substances tend to attain a common temperature

We have seen that all substances above a temperature of absolute zero emit radiation. If two objects with different temperatures are placed in an evacuated and perfectly insulated enclosure so no heat can be lost or external heat gained, they can radiate energy only to each other. But because radiation intensity increases with temperature, the warmer object therefore loses heat, and its temperature decreases—part of its heat is transferred to the other object. Conversely, the cooler object receives more radiation than it is emitting and its amount of heat and temperature increases. Eventually, both objects attain the same temperature—their radiant energy gain and loss just balances. Thus, if a substance receives more radiation than it is losing, it gains heat and becomes warmer, but if it is radiating more energy than it is receiving, it loses heat and becomes cooler. When you place your hand near a cold object, a sensation of cold is felt, as if the object were radiating cold. Actually, your skin is losing more thermal radiation than it is receiving, and this produces the cold sensation. Because all substances radiate energy, they are always tending to move toward a common equilibrium temperature.

Only absorbed radiation is converted to heat; the reflected and transmitted radiation is not. In opaque materials, such as wildland fuels, the conversion of radiant to thermal energy takes place in a very thin layer at the surface. Heating of deeper layers must usually be accomplished by conduction.

SUMMARY

Radiation is energy in the form of *electromagnetic waves* moving at the speed of light. All substances radiate energy when their temperature is above absolute zero. Radiant energy is not the same as thermal energy or heat, but radiant energy can be converted to heat and heat can be converted to radiant energy. Heat transfer by radiation is accomplished through this interconvertibility of radiant energy and heat. Radiation is the only means of heat transfer that does not require an intervening substance between the heat source and the receiving substance.

Radiant energy varies greatly in wavelength. All of the radiant energy arranged in order of wavelength forms the electromagnetic spectrum of radiant energy. *Thermal radiation* ranges from the longest infrared wavelengths to the shortest ultraviolet waves. The intensity of thermal radiation increases with an increase in temperature of the emitting substance, and the wavelength of the most intense radiation shifts toward the shorter wavelengths as the temperature increases.

The electromagnetic waves of radiant energy move only along straight paths. Hence, the intensity of radiation received depends on the angle of the incoming radiation and the distance from the source. Radiation perpendicular to the receiving surface is most intense. For a point source of radiation the intensity decreases inversely with the square of the distance from the source. But for a surface source the decrease with distance is smaller. The amount of decrease depends on the area of the radiating surface—the greater the surface area, the less the decrease.

Different kinds of substances vary in ability to emit and to absorb radiation. Generally, substances that are good emitters are also good absorbers. Dark-colored materials are usually better emitters and absorbers of radiation than are light-colored materials, and opaque materials are better than transparent ones. A substance capable of emitting and absorbing all thermal radiation is called a *black body*.

Not all thermal radiation reaching a substance is absorbed. Part of the radiation may be transmitted unchanged through the substance, and some may be reflected. Reflection does not change the wavelength of the radiation, only its direction of travel. Only absorbed radiation is converted to heat.

GPO 792-203