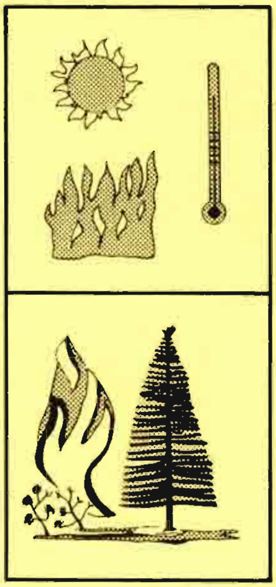
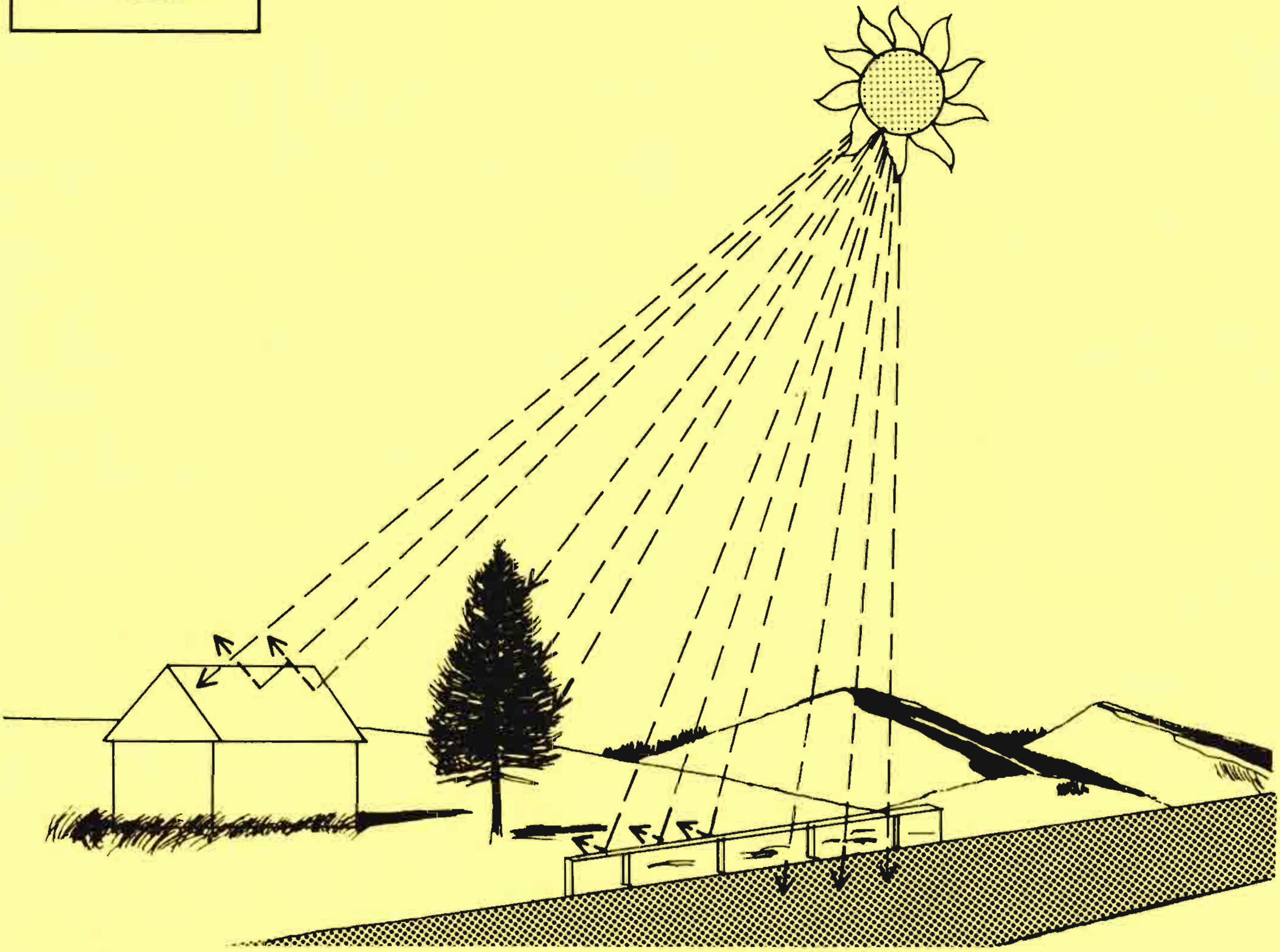


HEAT–ITS ROLE IN WILDLAND FIRE–Part 4

RADIATION

Clive M. Countryman



PACIFIC SOUTHWEST
Forest and Range
Experiment Station

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FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE
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The Author

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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:

Director
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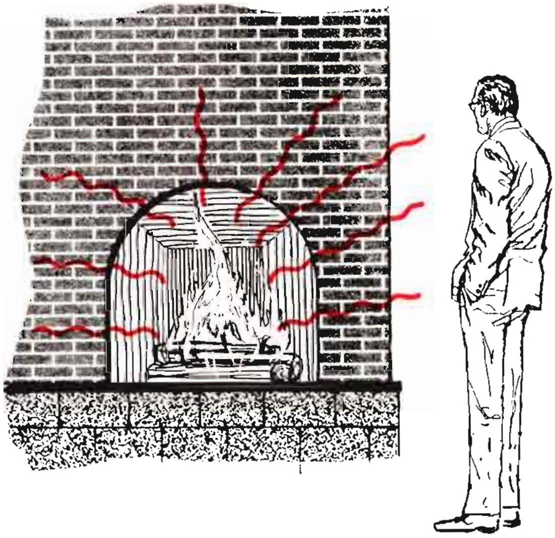
This Humidity Business: What It Is All About and Its Use in Fire Control. 1971 (blue)
Fire Whirls . . . Why, When, and Where. 1971 (blue)
Carbon Monoxide: A Firefighting Hazard. 1971 (yellow)
The Fire Environment Concept. 1972 (blue)
Heat–Its Role in Wildland Fire (blue)
    Part 1–The Nature of Heat. 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
    Part 3–Heat Conduction and Wildland Fire. 1977
    Part 4–Radiation. 1978

RADIATION

The way that a wildland fire burns and behaves, and the difficulty of controlling it, are 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 unburned fuel around the fire. And control of a wildland fire hinges on preventing or reducing heat transfer, reducing the heat available for transfer, or modifying the fuel so that more heat is needed for ignition and pyrolysis than is available.

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

The Nature of Radiation



In Part 1, we learned that heat is a form of energy called thermal energy. We often sense radiation as heat too, such as when we stand 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 give off radiant energy when their temperature exceeds absolute zero (-460°F), the temperature at which molecular action ceases. On earth, absolute zero can only be approached in the laboratory and with special apparatus, so for all practical purposes we can consider that all materials we ordinarily deal with are radiating energy — even cold ones.

Radiant energy travels outward along straight paths 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.

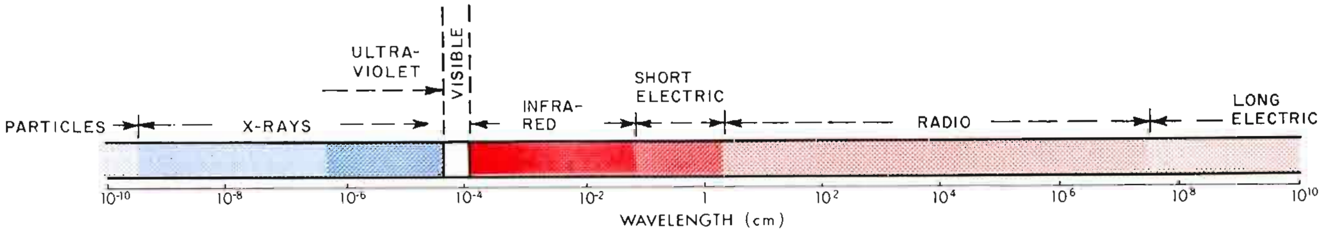
Radiation Varies in Wavelength

The electromagnetic waves that transfer radiant energy vary in wavelength — the distance between the crests of successive waves — from very long electric and radio waves to extremely short X-rays, gamma rays, and cosmic rays. Wavelengths are usually measured in *microns* (u) or in *Angstroms* (A). A micron is 0.0001 centimeter, while the Angstrom is a much smaller unit and is equal to 0.00000001 centimeter. When all of the radiant energy is arranged in the order of the wavelength, we have the *electromagnetic spectrum* of radiant energy. Visible light is radiant energy too, and occupies a narrow band of wavelengths near the middle of the electromagnetic spectrum.

Most radiant energy is invisible, and its wavelengths can be detected only with special instrumentation. But the wavelengths in visible light can readily be distinguished, for the color light depends on its wavelength. Sunlight directed through a glass prism will be segregated by wavelength to give a display of colors ranging from violet in the shortest visible wavelengths, through blues, greens, yellows, to reds in the longest visible waves. This same display is found in nature where under some conditions sunlight shining through raindrops will be separated by wavelength to form a rainbow.

All radiation can be converted to heat. In heat transfer, however, we are concerned mostly with the part of the spectrum from the longest infrared weavelengths, through visible light, to the shortest ultraviolet waves. Radiation from this part of the spectrum is called *thermal radiation*.

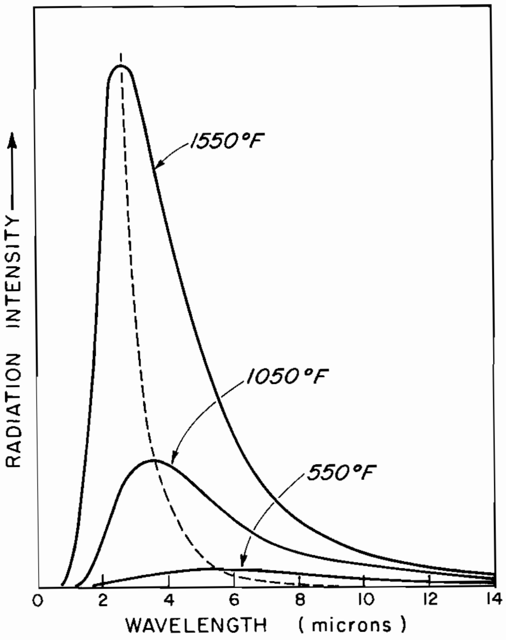
THE ELECTROMAGNETIC SPECTRUM



Radiation Intensity and Wavelength Changes With Temperature

Thermal radiation emitted by substances at ordinary atmospheric temperatures is mostly in the longwave 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.

In the visible light band, the shift toward shorter wavelengths is accompanied by a color change. If we heat an iron rod, for example, it will appear dull red when it first becomes hot enough to emit visible radiation. Continued heating will cause the rod to change to bright red, and then to orange, yellow, and white as its temperature increases and the maximum radiation shifts toward the shorter wavelengths. The sun radiates as a very hot body (between 10,000° and 11,000° F), and most of its radiation is in the shorter wavelengths. About half of the sun's radiation — including that of maximum intensity — is in the visible wavelength band. Generally, thermal radiation is not visible when the temperature of a substance is less than 1000° F.

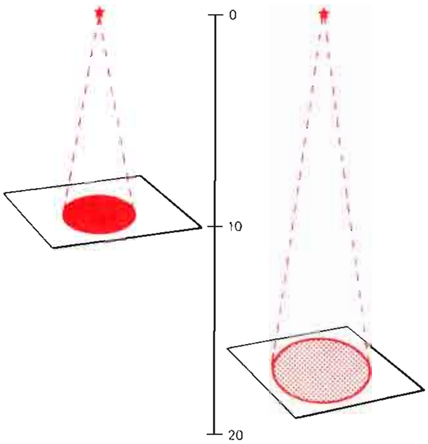


The change in intensity of radiation with variations in the temperature of a substance is proportional to the fourth power of the absolute temperature (°F plus 460°). Therefore, radiation intensity increases rapidly as the temperature increases. A substance of 1000°F, for example, will radiate more than 46 times as much energy as it will at a temperature of 100°F. At 2000°F — a temperature flames in a wildland fire often attain — the radiation intensity will be 373 times that at 100°F.

The shift in wave length of radiationthat accompanies a change in the temperature of a substance has several 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 range of hardness in the finished product. Instruments have also been devised to use the shift in wavelength and change in radiation intensity to measure temperatures accurately. Some of these instruments use the color change in the visible light band, while others use the shift in wavelength and intensity in invisible radiation as well. Because radiant energy is transmitted through space or transparent media, the temperature of a substance can be determined without direct contact and often from a considerable distance with these instruments. In this way temperatures can be measured under conditions that would be difficult or impossible with the more usual methods. Such instruments are used extensively in some industries, such as metal ore smelting and plastic manufacture. Temperatures of distant celestial bodies are determined from their radiation spectra, and some space vehicles have used instruments sensitive to infrared radiation to determine the temperature patterns of the earth.

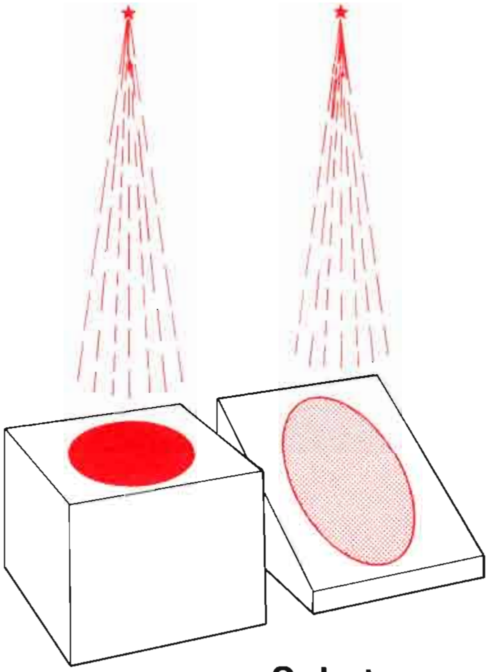
Radiation Intensity Varies With Distance and Angle

In addition to the temperature of the radiator, the intensity of the radiant energy received depends on the distance of the receiving material from the source, the angle at which the radiation strikes the receiver, and the geometrical shape of the heat source. For a point source of radiant energy, the intensity of radiation decreases inversely as the square of the distance. The intensity of radiation 20 feet from the source, for example, will be only one-fourth that at 10 feet. The intensity decreases so rapidly because radiant energy travels only in straight paths. As the distance from the source



increases, the same total amount of energy must be spread over a greater area. The same thing happens as the angle of radiation changes. The greater intensity occurs when the receiving surface is perpendicular to the source, but as the angle of radiation departs from the perpendicular the same amount of radiation must cover a greater area.

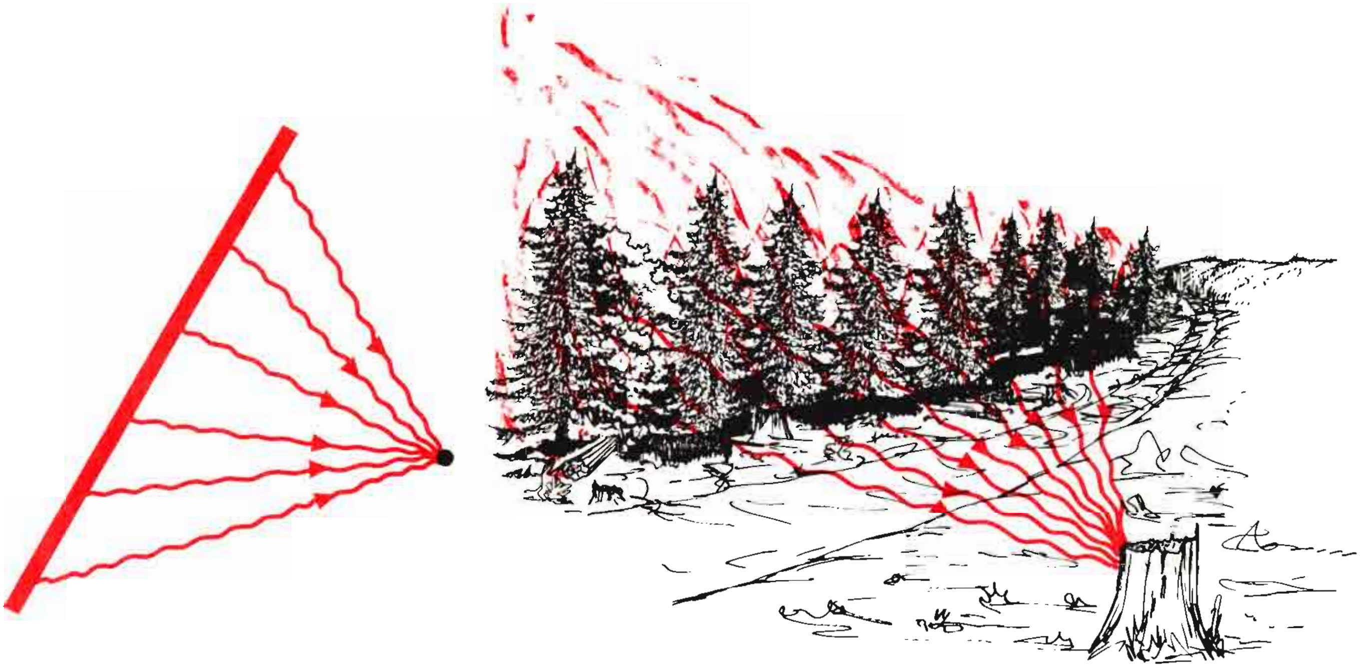
For a line source of radiant energy, such as a hot wire or line of fire with very short flames, the decrease in intensity with distance is less rapid than for a point source. We can think of a line source of radiant energy as a continuous series of point sources, each radiating energy in all directions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



Area sources of radiation can be considered to be made up of many point sources in both horizontal and vertical directions. Consequently, an object exposed to an area source of radiation will receive radiation from many directions, and the decrease in radiation intensity with distance is less than for a line source, and much less than for a point source. The number of points from which radiation is received also increases rapidly as the area of the radiating surface increases. Wildland fire flames are area sources; therefore, the amount of radiation received at a given distance from the flames increases at the flame heights become greater. Since flame heights usually increase as fire intensity increases, the width of firebreak needed to contain a fire and the difficulty of holding the fire within the firebreak will increase rapidly as the fire intensity increases. And the amount of thermal radiation that fuel—and firefighters — receive also increases rapidly as flame heights increase.

Substances Differ in Ability to Emit and Absorb Radiation

Different kinds of substances vary greatly in their 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 radiation than metals, particularly at low temperatures. The ideal radiator and absorber is one capable of emitting and absorbing *all* thermal radiation. Such a substance is called a *black body*. The term black body is somewhat misleading, however, because some substances that are not black in color can radiate and absorb thermal radiation nearly the same as a perfect black body. And a perfect black body if hot enough to radiate in the visible light range will not be black. 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 the reason why a



dark-colored car parked in the sun will be noticeably warmer to the touch than a white car parked next to it. In some of the early nuclear bomb tests in the South Pacific, dark-colored birds were killed by thermal radiation, while white birds survived because they absorbed less of the radiation.

The amount of energy radiated from a surface per unit of surface area per unit of time is the *emissive power* of the substance. The term may be applied to radiation in all wavelengths or to a particular wavelength or wavelength band. The ratio of the emissive power to that of a perfect black body under the same conditions is the *emissivity* of the substance. Emissivity varies with both temperature and wavelength. Since a black body emits all radiation, the highest emissivity value is 1.0 and this value decreases as the ability of a substance to emit radiation decreases. Lamp black has an emissivity of 0.95, smooth oak wood 0.90, and rusted iron 0.65. Polished aluminum can emit little radiation — its emissivity is only 0,08, or 8 percent of that of a black body. Thick flames in a wildland fire approach the emitting capability of a black body, and the emissivity of such flames is often taken as 1.0. However, the emissivity of thin flames may be considerably less.

The radiant energy absorbed per unit of area per unit of time is the *absorption rate* of the substance. It depends on the incident radiation and the surface characteristics of the substance. Absorption rate can apply to the entire spectrum, a band of wavelengths, or a single wavelength. The fractional part of the radiation that can be absorbed by a substance is its *absorptivity*. Like emissivity, the maximum value of absorptivity is 1.0 for a black body, and less for substances that can absorb less of the incident radiant energy. Like emissivity too, absorptivity depends on the temperature of the substance and the wavelengths of the radiation.

The absorptivity of fuels helps determine how quickly they can be heated by radiation from fuels already burning or from some types of firebrands. The absorptivity of wildland fuels varies widely. Weathered hardwood leaves, for example, may have absorptivities of 0.60 to 0.80, while that of newly fallen leaves can range from 0.45 to 0.55. The absorptivity of cured and dry grass usually varies from 0.45 to 0.55.

Not All Thermal Radiation is Absorbed

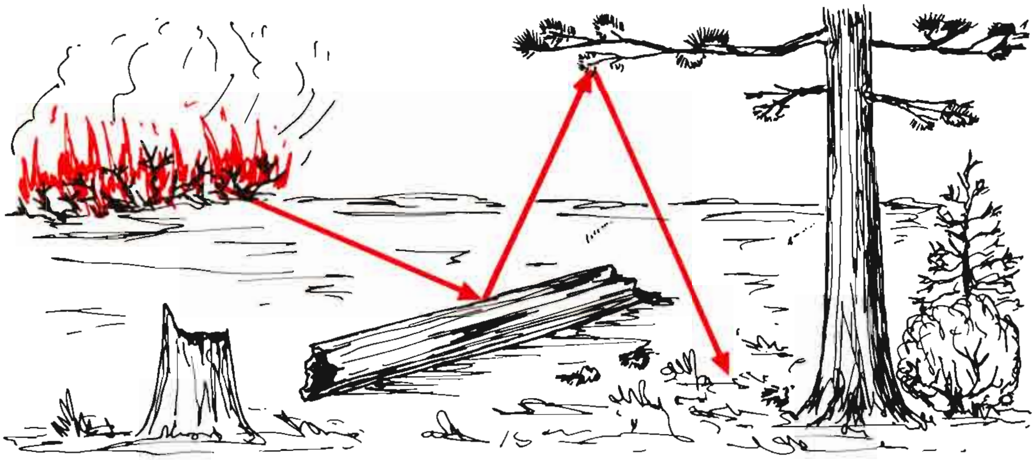
Only a perfect black body absorbs all of the thermal radiation that reaches it — other substances absorb only part of the radiation. Clear, translucent, and very thin opaque substances can absorb some wavelengths while allowing others to pass through unchanged. Glass, for example, transmits most wavelengths 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 from the sun, but blocks the longer wave radiation from lower temperature materials inside the house.

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

Some Radiation is Reflected

Not all of the thermal radiation received by a substance is absorbed or transmitted through it — some part is usually reflected. This characteristic 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. Also, the part of the radiation that is reflected is not converted to heat by the reflecting substance. However, 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 reflected to space can be considered "lost."

The amount of radiation reflected depends on the angle at which the radiation strikes the surface, the wavelength of the radiation, and the characteristics of the receiving surface — smooth, light-colored surfaces tend to reflect more. The term *albedo* is used to indicate the relative capability of a substance to reflect radiation. Numerically, the albedo can range from 1.00 when all of the incident radiation is reflected, to 0 when none is reflected. The albedo of the earth, taken as a whole, is approximately 0.36. Thus, about 36 percent of the radiation received by the sun is reflected, but this percentage varies greatly with the kind of surface. Clean, fresh snow will reflect about 80 percent of the solar radiation, dry sand about 30 percent, and dark coniferous forests about 5 percent. The tops of clouds can reflect a large part of the solar



radiation — 40 to 80 percent. Hence, the reduced amount of sunlight on a cloudy day is not due so much to absorption by the clouds as to the reflection of sunlight back to space. Because of its high albedo, extensive snow cover can have a marked effect on the climate. For example, the cold winter of 1972-73 in the temperate zones is believed to have been partly caused by the widespread snow cover in the winter of 1971-72, which slowed warming of the earth the following summer and gave winter a headstart in the fall.

The reflection of light is essential to the visual perception of substances and of their color. If substances did not reflect light, we would not be able to see them — unless they are warm enough to emit radiation in the visible wavelengths. Selective reflection of light wavelengths determines the apparent color of a substance; an object 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. White color indicates that all visible wavelengths are being reflected, and black indicates all wavelengths are being absorbed and none reflected. We can see a truly black object only because of the lack of reflected light in contrast to the surrounding reflection of light from other substances.

Substances Tend to Attain a Common Temperature

We have seen that all substances above a temperatures of absolute zero emit radiation. If two objects with different termperatures 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 radiates more energy to the cooler one than it receives. 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 balance. 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

All substances radiate energy when their temperature is above absolute zero. This energy is in the form of electromagnetic waves that travel only in straight lines and at the speed of light. Radiation does not require the presence of an intervening material to transfer energy. The radiant energy varies greatly in wavelength, but the wavelengths of greatest interest in heat transfer range from the longest infrared waves, through visible light, to the shortest ultraviolet waves. This band of wavelengths is called *thermal radiation*. Thermal radiation that is absorbed by a substance is converted to thermal energy or heat, and it is the interconvertibility of radiant energy to thermal energy and thermal energy to radiant energy that heat transfer by radiation is accomplished.

A substance capable of emitting and absorbing all wavelengths of thermal radiation is designated as a *black body*. The amount of energy radiated from a surface per unit of surface area is the *emissive power* of the substance, and the ratio of the emissive power to that of a black body under the same conditions is the emissivity of the substance. Emissivity values range from 0 to 1.0.

The radiant energy absorbed per unit of area per unit of time is the absorption rate of the substance. The fractional part of the radiation received that can be absorbed by a substance is its *absorptivity,* and like emissivity, it ranges from 0 to 1.0. Only a black body can absorb all the radiation that reaches it (absorptivity 1.0). Other kinds of substances may be transparent to some wavelengths and capable of absorbing others. And part of the incident radiation is usually reflected from the surface of the substance. Reflection does not change the wavelength of the radiation, and reflected radiation is not converted to heat by the substance from which it is reflected.

The intensity of radiation from a substance is proportional to the fourth power of the absolute temperature, and as the temperature increases the wavelength for maximum radiation intensity shifts toward the shorter waves. Because radiation can travel only in straight lines, the intensity of radiation decreases with distance from the source and with the angle at which the radiation strikes the receiving surface — the intensity is greatest when the radiation is perpendicular to the surface. For a point source, radiation intensity decreases as the square of the distance, while with a line source the decrease with distance is inversely proportional. The decrease in radiation intensity with distance from a surface source depends on the area of the surface.

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