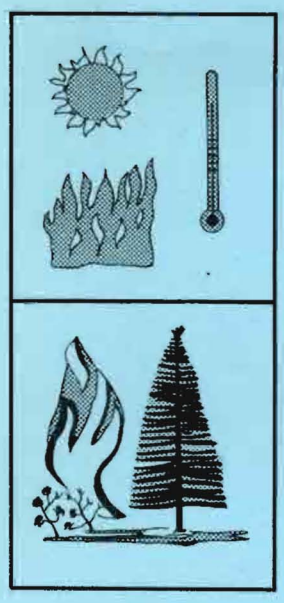
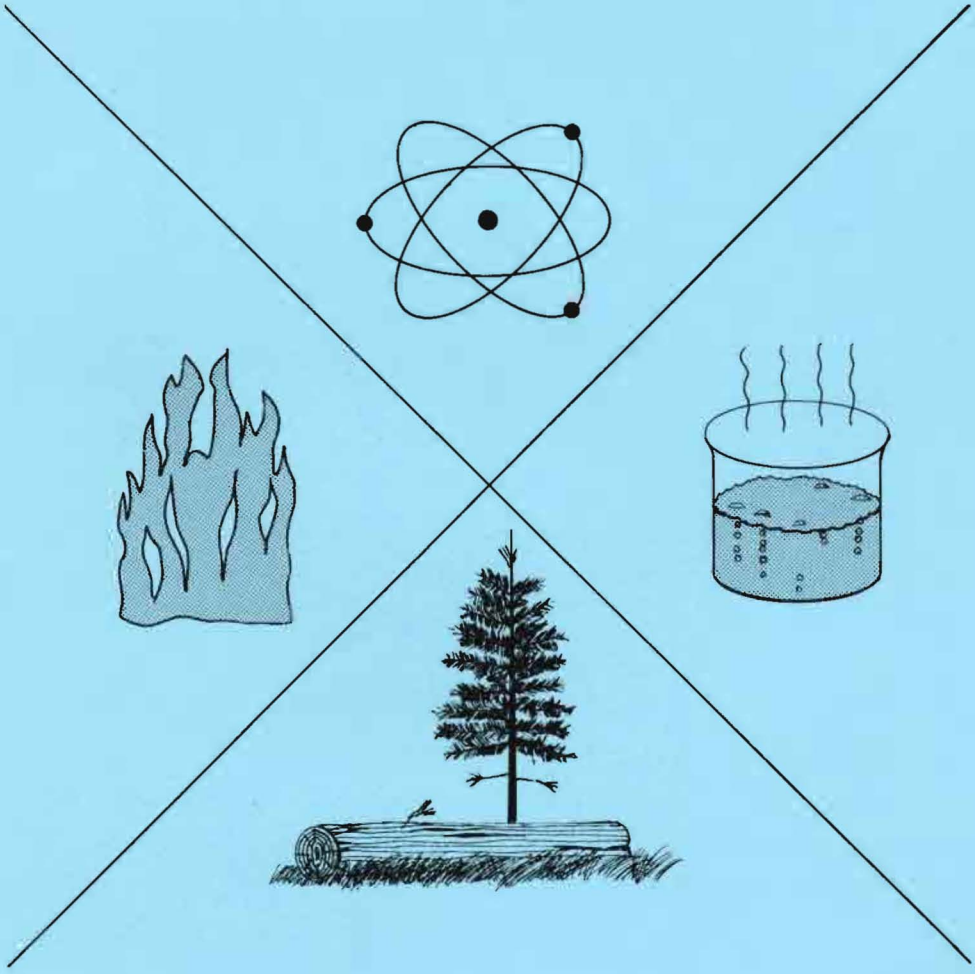


HEAT—ITS ROLE IN WILDLAND FIRE—Part 1

THE NATURE OF HEAT

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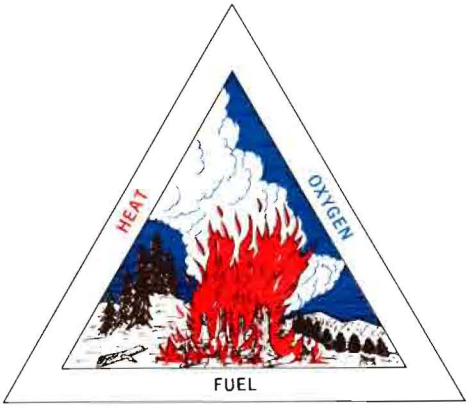
This Humidity Business: What It Is All About and Its Use in Fire Control. 1971 (blue)
Fire Whirls . . . Why, When, and Where. 1971 (blue)
Carbon Monoxide: A Firefighting Hazard. 1971 (yellow)
The Fire Environment Concept. 1972 (blue)
Heat–Its Role in Wildland Fire (blue)
Part 1–The Nature of Heat. 1975



THE NATURE OF HEAT

Three ingredients are essential for a wildland fire to start and to burn. First, there must be burnable fuel available. Then enough heat must be applied to the fuel to raise its temperature to the ignition point. And finally, there must be enough air to supply oxygen needed to keep the combustion process going and thus maintain the heat supply for ignition of unburned fuel. These three indispensable ingredients—fuel, heat, and oxygen—make up the fire triangle. All must be present if there is to be fire. In the following discussion, we will examine some of the basic characteristics of the heat segment of the fire triangle—the nature of heat itself.

The science of heat is relatively new

Everyone knows how heat feels, and is well aware of its many applications in daily life. Heat from the sun is the basic control of our weather, and this heat is also essential in the growing of food crops and other vegetation. Without the sun's heat, life could not exist on the earth.

Through the science of thermodynamics, heat has a place in many of the industrial processes that bring us the conveniences of modern life. But as recently as 200 years ago, the true nature of heat was not understood. In the early days of science the phenomena associated with heat were ascribed to a mystical and intangible fluid called "caloric." This fluid was believed to have the power of penetrating and expanding materials, sometimes melting or dissolving them, and converting some substances to vapor. Heat produced by friction or the compression of gases was attributed to stored caloric that was squeezed or ground out of the material. The caloric fluid was considered intangible, since even the most careful experiments in adding or subtracting heat by nondestructive heating or cooling of a substance failed to produce any changes in its weight.

Heat is energy

We know now that heat is not a fluid, nor a substance at all, but is really one of the several forms of energy. Other common forms are electrical energy, radiant energy, chemical energy, and the mechanical or kinetic energy possessed by moving materials and objects, such as falling water or a rotating wheel. Atomic and nuclear energy are still other forms. Heat is often labeled *thermal energy*.

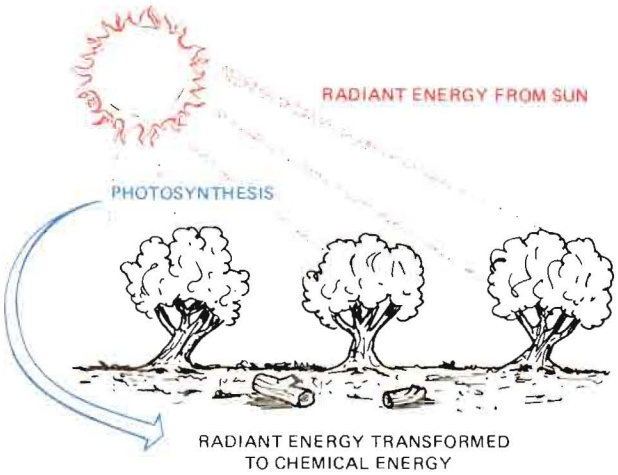
According to molecular theory, all substances are made up of molecules, and as long as the temperature of the substance is above absolute zero (−469° F), these molecules are in some degree of motion. When heat is applied to a substance, the molecular activity increases and the temperature rises. Conversely, if a substance loses heat, the molecular activity decreases and so does the temperature. We can think of heat, then, as the energy of molecules in motion.

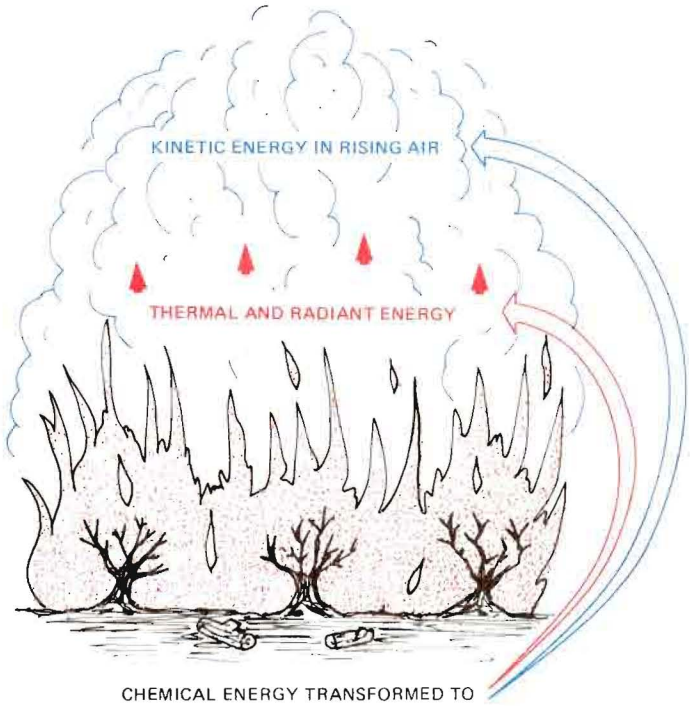
Energy cannot be created or destroyed in any way that we know. But it can be changed from one form to another, and this transformation is constantly going on, both in nature and through the activities of man. For example, *radiant* energy from the sun is transformed by the process of photosynthesis to stored *chemical* energy in vegetation. When the vegetation is burned, the chemical energy is transformed to *thermal* energy, radiant energy, and the *kinetic* energy in the rising air in the convection column over the fire. The kinetic energy in falling water can be used to generate electrical energy, which in turn can be changed back to thermal and radiant energy by an electric heater, or to kinetic energy again through the use of an electric motor.

The joule is the standard unit of heat

Because water is one of the most abundant compounds on earth and was believed to have constant characteristics, early scientists frequently used water as a standard for the measurement of characteristics of other materials. And the standard unit of heat was first based on the amount of heat needed to increase the temperature of water. In the metric system of measurement, the unit of heat was the *calorie* and was defined as the amount of heat required to increase the temperature of one gram of water by 1° C. The British Thermal Unit (Btu) was the heat unit in the English system, and was defined as the quantity of heat needed to raise the temperature of a pound of water (about a pint) by 1° F.

Unfortunately, water did not prove to be a good standard for heat measurement, for it was soon found that the amount of heat required to raise water temperature changes with the initial temperature of the water. The amount of heat needed to raise water temperature from 40° to 41° for example, is





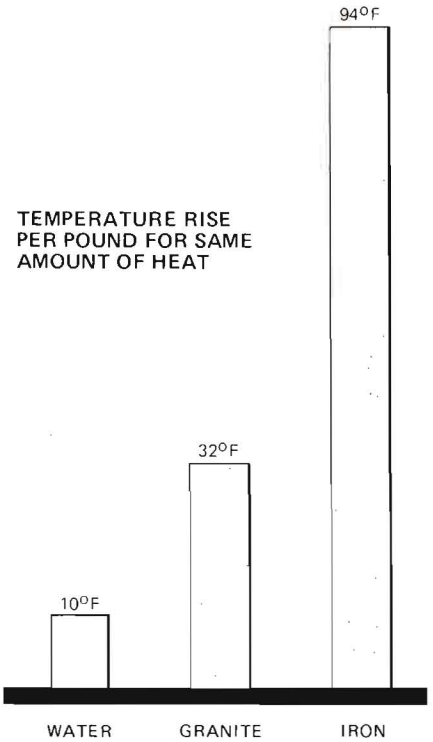
not the same as that needed to raise it from 90° to 91°. Because standards of electrical voltage and of resistance are maintained at national standardizing laboratories throughout the world, scientists agreed internationally to use the heat produced in one second by a current of one ampere through a resistance of one ohm as the standard unit of heat. This heat unit is called the *joule,* in honor of the early English physicist, James Joule.

Although the joule has been used as the standard unit of heat in most scientific work for a long time, the terms "calorie" and "Btu" have continued to be used in industrial and other practical applications, particularly in countries where the metric system of measurement has not yet been adopted. Because of the continued use of these terms, the

calorie has now been arbitrarily defined as equal to 4.1840 joules, which is nearly equivalent to the quantity of heat needed to raise the temperature of a gram of water from 14.5° to 15.5° C. One Btu equals 1055 joules or 252 calories. But by definition and derivation, the calorie and Btu are no longer connected in any way with the properties of water.

Molecular structure affects temperature change

Heat measurement units, as we have seen, are defined in terms of a temperature change brought about by heating. But the same amount of heat applied to different materials does not necessarily bring about the same temperature change—it is well known that some materials can be heated or cooled more quickly than others. These differences are the result of variations in the number of molecules in different substances and the way these building blocks of matter are put together. The variation in temperature change in different substances that accompanies the addition or subtraction of a given quantity of heat can be quite large. For example, the amount of heat needed to raise the temperature of a pound of water by 10° will increase the temperature of a pound of granite by 32° and that of a pound of iron by about 94°. Because of the variation in the amount of temperature rise when the same amount of heat is applied to different substances, a warm object may actually have less heat than a cooler one. Temperature indicates only the average molecular activity in a substance—its relative degree of hotness or coldness—and heat units must be used to measure the amount of heat it contains or can absorb.



The quantity of heat required to increase a unit weight of a substance by one degree is the *specific heat* of the substance, and is usually given as Btu per pound per degree Fahrenheit (Btu/lb/°F) or as calories per gram per degree Celsius (cal/g/°C). Materials with high specific heats require a large amount of heat to increase their temperature, and hence contain more heat at a given temperature than do materials with low specific heats. The specific heat of many materials varies considerably with temperature, so the temperature at which the specific heat was determined is usually specified. Water, with a specific heat of 1.0 Btu/lb/°F at ordinary atmospheric temperatures has one of the highest specific heats of common substances. The specific heat of most metals is low. Lead, for example, has a specific heat of only 0.031 Btu/lb/°F at 32°F, and requires very little heat to increase its temperature. Most wildland fuels have specific heats in the range of 0.45 to 0.65 Btu/lb/°F.

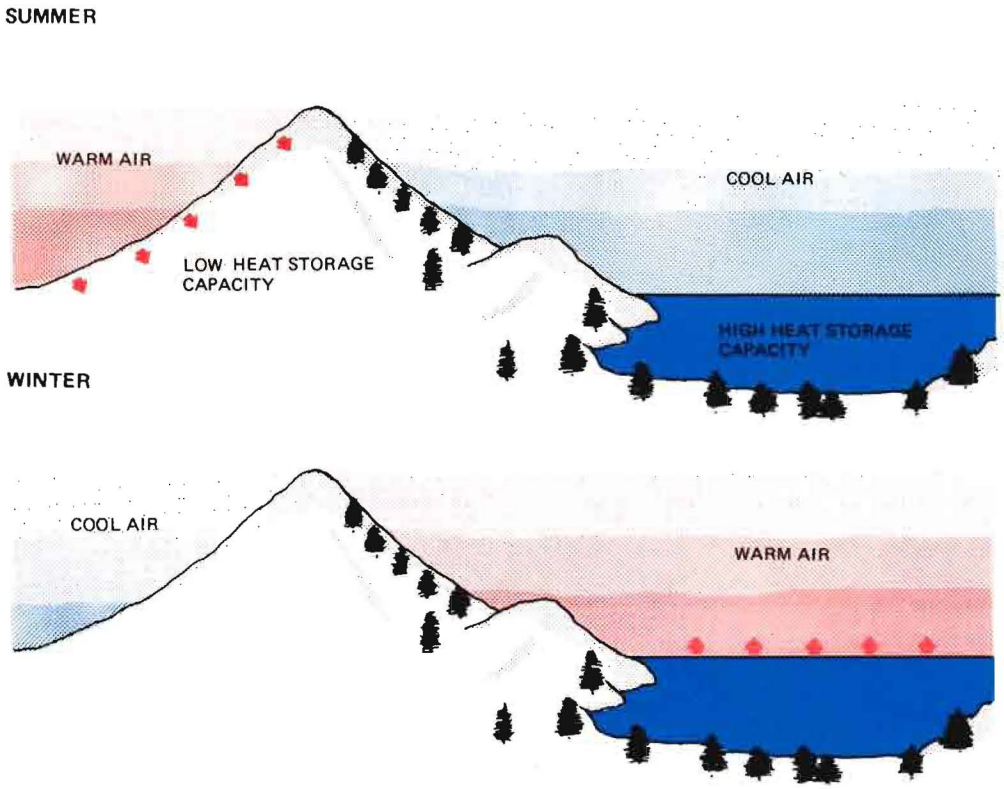
Often information on the amount of heat needed to produce a given temperature change in some *volume* of a material is needed. In wildland fire, for example, we are interested in the amount of heat needed to raise the tempera-

ture of a layer or volume of the fuels, because this helps determine the characteristics of a firebrand that can ignite a particular fuel. The amount of heat required to raise the temperature of a unit volume of a substance by one degree is its *heat capacity*. In English units, this is given in Btu per cubic foot per degree Fahrenheit (Btu/ft^3/°F).

Heat capacity varies with density and specific heat

Heat capacity is calculated from the density and the specific heat of a substance. Density is the weight of a unit of volume whereas specific heat indicates how much heat is required to increase the temperature of each unit of weight by one degree. Both density and specific heat vary widely in different substances; hence the heat capacities of these substances also vary widely. And since specific heat often varies with temperature, so also does heat capacity.

Materials with high heat capacities can absorb and lose large quantities of heat without much temperature change. Conversely, relatively little heat is needed to change the temperature of materials with low heat capacity. At ordinary temperatures, the heat capacity of air is about 0.017 Btu/ft^3/°F—little heat is needed to change its temperature. Under similar conditions, the heat capacity of dry soil and rock is 19 to 20 Btu/ft^3/°F, and that of water is about 62 Btu/ft^3/°F. The high heat capacity of water is one of the reasons why the climate near oceans and large lakes is often more



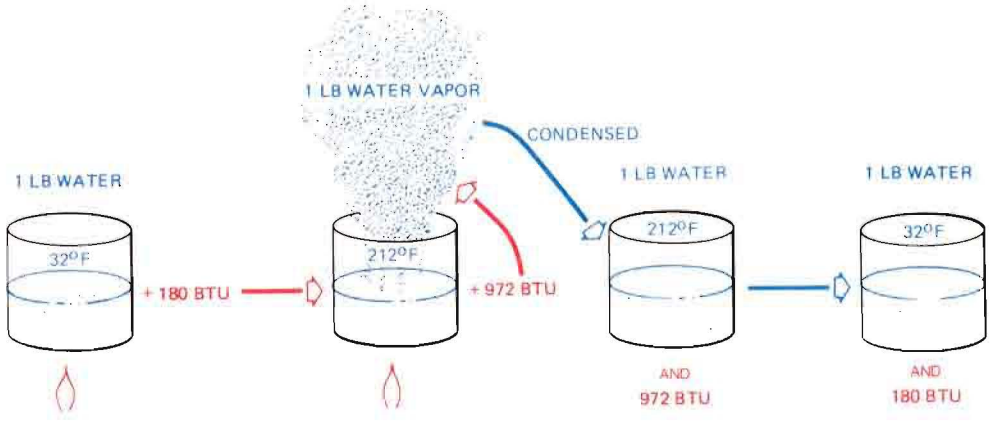
moderate than that of the climate further inland. The water absorbs and stores large quantities of heat during the summer without much change in temperature, and this tends to keep the air over the adjacent land relatively cool. In the winter the stored heat is released and warms the air over nearby land areas.

Because the specific heat of most wildland fuels varies over a relatively narrow span, differences in heat capacity of the fuels depend chiefly on their density. The differences in density of wildland fuels are quite large, and hence variations in heat capacity are also. Solid oak wood, for example, has a density of about 48 lb/ft^3, while that of punky and decayed wood may be only 6 or 7 lb/ft^3. The oak wood, then, requires a considerable amount of heat to raise its temperature to the ignition point, but decayed wood requires a relatively small amount. Thus, heat capacity is important in the ignition of wildland fuels.

Much energy is involved in changes of state

Thus far in our discussion of heat and energy, we have been concerned with the addition and subtraction of heat that does not result in a change in the physical structure or "state" of a substance—the kind of change that occurs when ice melts or water is turned to vapor. But heating or cooling if carried far enough can cause such a change, and considerable amounts of heat are frequently associated with this change. In the combustion of wildland fuels, for example, there is a change in state of the fuel being burned, during which large quantities of energy are released.

The heat associated with the changes of state of water is of major importance in our daily lives, and also affects wildland fire, both directly and indirectly. If a pan of ice water at 32°F is heated, the temperature of the water rises until it reaches 212°F, and 180 Btu per pound of water are absorbed in the heating. If the heating is continued, the water begins to boil and to vaporize, but there is no further increase in the



water temperature. Thus, a quantity of heat in addition to that required to raise the temperature of the water is needed to change the state of liquid water to vapor. At sea level, this additional heat amounts to 972 Btu per pound of water—more than 5 times the amount required to raise the temperature from 32° to 212°F. However, this thermal energy is not lost, for when the water vapor condenses back to liquid the 972 Btu is released as heat. Water also changes to vapor at temperatures below 212°, but the amount of heat required increases as the temperature decreases. At 104°F, about 1035 Btu/lb are needed, and this increases to 1066 Btu/lb at 50°F. The heat required to change a liquid to vapor, or that is released when the vapor changes back to a liquid is the *heat of vaporization.*

Heat of vaporization is used in many of the activities of man. For example, the evaporative type air conditioner, or "swamp cooler," depends directly on the heat of vaporization of water for its operation. As warm outside air flows through water soaked excelsior pads, some of the water vaporizes, and much of the heat needed for this vaporization is drawn from the incoming air, thus cooling it. Cooling towers used to cool water in industrial processes operate in much the same way.

The heat of vaporization of water is important in natural processes also. Many living creatures, including man, depend on the cooling effect of water evaporating from the skin or lungs to regulate their internal body temperature. The evaporation of water into vapor and the condensation of the vapor back into water in the form of clouds or precipitation has a major effect on our weather and climate. Because of the large volumes of water and vapor involved, enormous amounts of thermal energy can be released or stored. Lightning storms depend greatly on the heat released from condensing water vapor for their development, and much of the tremendous energy of a hurricane comes from the same source.

In addition to indirectly affecting wildland fire through its influence on weather, the heat of vaporization of water also has a more direct bearing on fire. Water vapor is formed in the combustion process and from the moisture in the burning fuel. This vapor is carried aloft in the smoke or convection column of the fire, and frequently condenses at the top of the column to form a white "cap". The heat released when the vapor condenses can add significant amounts of energy to the convection column, increasing its strength and adding to the fire activity. The condensation of enough water vapor to form 8 pounds of liquid water releases about the same amount of heat as burning 1 pound of wildland fuel. As we shall see in a future report, the heat needed to vaporize the moisture in fuels has an important effect on the ignition of fuel and the rate at which it burns.

Heat transfer is needed for a fire to burn and spread

Earlier we saw that three ingredients–fuel, heat, and oxygen–are needed for a fire to start and to burn. Enough oxygen for combustion is almost always available in our wildland areas, and fuel is usually abundant. However, we cannot have a fire until the third ingredient, heat, is added–usually in the form of a firebrand of some sort. But the mere presence of a heat source does not necessarily mean that a fire will start. For a flaming or hot firebrand to start a fire, some of its heat must be *transferred* in some way to the fuel. And if the fire is to continue to burn and to grow, heat must be transferred to the unburned fuel around the fire. Hence, heat transfer is essential for wildland fire.

In this discussion, we have been concerned only with some of the basic characteristics of heat itself. In future reports the elements of heat transfer and its effects on the combustion process, fire behavior, and fire control will be explored.

SUMMARY

Heat is a form of energy called *thermal energy*. It results from molecular activity in a substance. Energy cannot be created or destroyed, but can be converted from one form to another–a process that is continually going on.

The temperature of a substance depends on its average molecular activity, and will increase as the molecular activity increases and decrease with decreasing molecular activity. The quantity of heat that a substance contains depends on the sum, or total, of its molecular activity. Since the number of molecules varies in different substances, the total molecular activity must also vary. Hence, temperature can only indicate the relative degree of hotness or coldness of a substance, and not the quantity of heat it contains.

The standard unit of heat is the *joule*, derived from the heat produced by a standard electrical voltage applied to a standard resistance. Other units of heat in common use are the calorie and the British Thermal Unit (Btu). The *calorie* is arbitrarily defined as 4.1840 joules, and is very nearly equivalent to the amount of heat needed to raise the temperature of one gram of water from 14.5° to 15.5° C. A Btu is equal to 1055 joules or 252 calories. *Specific heat* is the quantity of heat needed to raise the temperature of a unit *weight* of a substance by 1°, while heat capacity is the quantity of heat required to raise the temperature of a unit *volume* by 1°.

A considerable amount of heat is often involved in the change of state of a substance. The amount of heat needed to change a liquid to a vapor, or released when the vapor is converted to a liquid, is the *heat of vaporization*. Heat released or absorbed in the changes of state of water is of major importance in weather processes and in the combustion of wildland fuels.

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