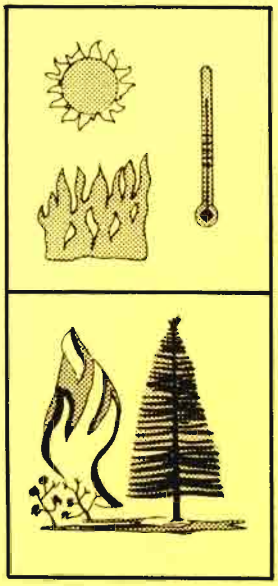
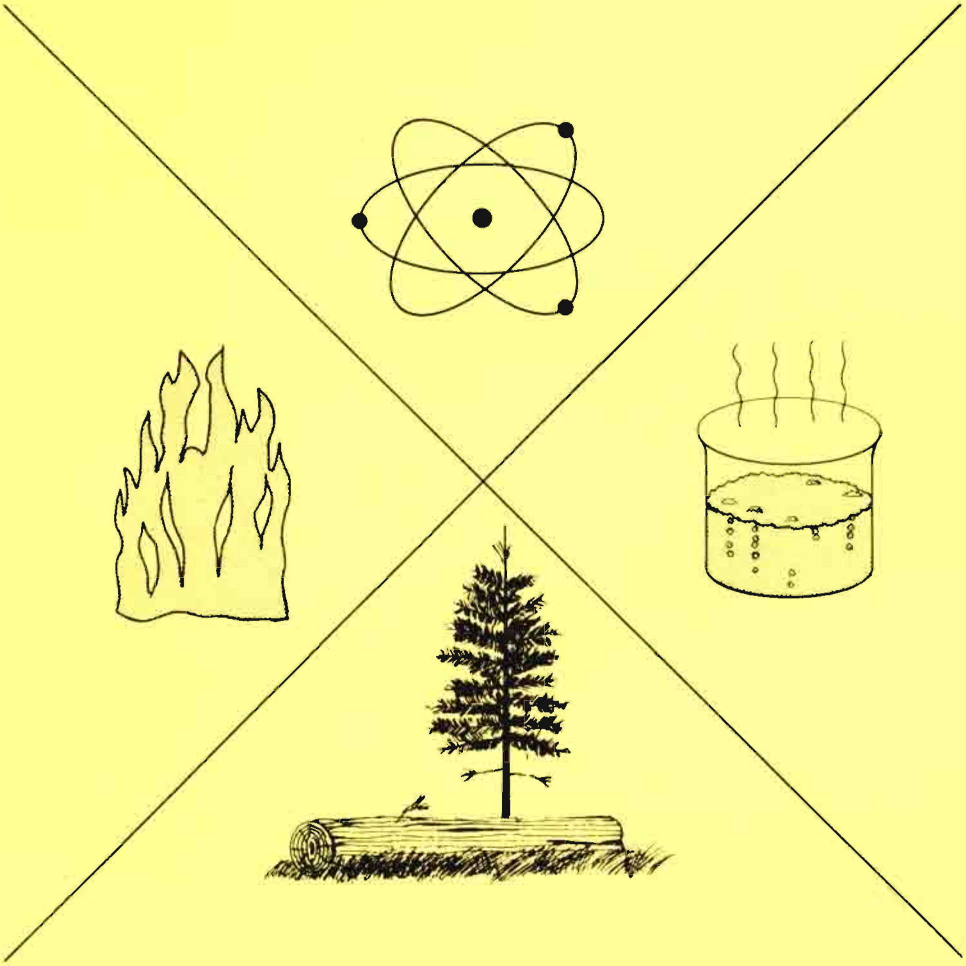


HEAT AND WILDLAND FIRE—Part 1

THE NATURE OF HEAT

Clive M. Countryman



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P.O. BOX 245, BERKELEY, CALIFORNIA 94701

PACIFIC SOUTHWEST
Forest and Range
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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:

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P.O. Box 245
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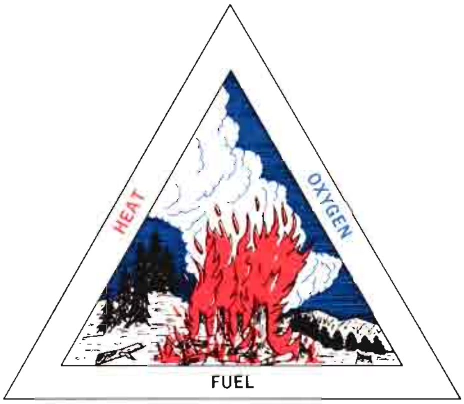
- This Humidity Business: What It Is All About and Its Use in Fire Control. 1971 (blue)
- Fire Whirls . . . Why, When, and Where. 1971 (blue)
- Carbon Monoxide: A Firefighting Hazard. 1971 (yellow)
- The Fire Environment Concept. 1972 (blue)
- Heat–Its Role in Wildland Fire (blue)
  - Part 1–The Nature 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

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 the oxygen needed to keep the combustion process going and thus maintain the heat supply for ignition of unburned fuel. These three essential 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 triangle—the nature of heat itself.

Heat is indispensable

Everyone knows how heat feels, and is well aware of its many uses and applications in our lives. Heat is used to warm our houses and to cook our food. Heat is necessary in many industrial and manufacturing processes—most products we utilize or consume involve the use of heat somewhere along the line in their production. Modern power sources often depend on heat; internal combustion and steam operated engines, for example. And heat is often used to generate the electrical power so important in the present way of life. Heat received at the earth's surface from the sun is the basic control of our weather, and this heat is also essential in growing food crops and other vegetation, including wildland fuels. Without the heat received from the sun, life could not exist on the earth.

Heat science is relatively new

The science of heat (thermodynamics) has brought an understanding of many of the physical laws governing heat and heat phenomena. 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 an intangible and mystical 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. The caloric fluid was considered intangible, since it could not be seen and even the most careful experiments failed to show that non-destructive heating or cooling of a substance would produce any changes in weight.

The early theory of heat as a fluid was simple in application and difficult to refute, for in some respects heat does behave like a fluid. The theory satisfactorily explained the results of elementary experiments of the time in heat, and many of the manifestations of heat in daily life. Heat produced by friction or the compression of gases, for example, was attributed to latent or stored caloric that was squeezed or ground out of the substance. The abraded material produced in drilling or grinding was assumed to be not capable of holding as much caloric as the parent material, thus accounting for the heat produced in such operations.

The idea of heat as an intangible fluid was useful in helping to conceive of an abstract phenomenon that makes itself apparent in concrete ways. But in many respects, the idea was misleading, and the persistence of the caloric theory for many years severely retarded the understanding of the true nature of heat and the science of thermodynamics.

Heat is energy

We know now that heat is not a fluid, nor a substance at all, but is really a form of energy called *thermal energy*. Other common forms of energy 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 or nuclear energy is still another form. Simply defined, *energy* is the capacity to do work, and in the science of physics "work" is the transfer of energy from one object to another that results in the motion of displacement of the object acted upon.

Energy cannot be created or destroyed in any way that we know. But it can be changed from one form to another, and also transferred from one substance to another. And this transformation and exchange of energy is constantly going on—both in nature and through human activities. Consider, for example, the operation of a coal-burning steam pile driver. Radiant energy from the sun is transformed by the process of photosynthesis into stored chemical energy in vegetative material. The vegetation is converted by natural processes into coal, which is another type of stored chemical energy. When burned in a pile driver firebox, the stored chemical energy is converted to heat, which is transferred to the water in the boiler. thereby changing it into steam. While stored under pressure, the steam has stored or potential energy. When released into the steam cylinder, the expanding steam does work on the piston and gives kinetic energy to it.

This kinetic energy is transferred through the connecting rod and gear train to the hoisting drum, allowing work to be done in raising the driving weight. While poised in the air, the energy used in raising the weight appears as potential energy, and this is transformed into kinetic energy when the weight is released and permits work to be done in driving the pile into the ground.

Not all of the energy of the coal is applied toward driving the pile. Some of the thermal energy escapes through the firebox, boiler, and steam cylinder, and is absorbed by the air and surrounding objects, increasing their thermal energy. Part of the kinetic energy is changed back to thermal energy by friction in the machinery. The impact of the driving weight on the pile changes some of the kinetic energy to thermal energy that increases the temperature of both the weight and the pile and the amounts of their thermal energy. Some of the kinetic energy of the moving pile is also converted to thermal energy by friction with the ground, and potential energy is imparted to the earth displaced by the pile. In all of this complex transformation and transfer, none of the original radiant energy received from the sun is destroyed—it simply appears in different forms.

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 without changing its state—such as occurs when ice is changed to water or water to vapor—the molecular activity increases and the temperature rises. Conversely, if a substance loses heat without change of state, the molecular activity decreases and so does the temperature. We can think of heat, then, as the energy of molecular motion.

The joule is the standard unit of heat

Because water is one of the most abundant compounds on earth, it is perhaps not surprising that early scientists frequently compared the physical characteristics of various substances with those of water, and often used the attributes of water as a standard of measurement. 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 1 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 increase the temperature of a pound of water (about a pint) by 1° F.

Water did not prove to be a good standard for the measurement of heat quantity, however, for it was soon found that the amount of heat required to raise its temperature varied with the initial temperature of the water. The amount of heat needed to change the temperature by 1 degree at 40°, for example, is not the same as when the water temperature is 90°. This characteristic of water led to several "kinds" of calories. For example, if the water temperature change is from 3.5 to 4.5° C—the temperature at which water has its greatest density—the unit of heat was the *small calorie.* The amount of heat required to change the temperature of a gram of water from 14.5 to 15.5° C was the *normal calorie,* and was the unit of heat most commonly used. The *mean calorie* was 1/100 of the amount of heat needed to raise the temperature of a gram of water from 0° to 100° C. And a *large calorie* was equal to 1000 small calories.

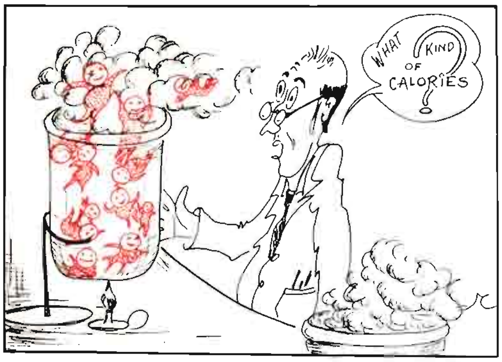
The numerous heat units, each representing a different quantity of heat, caused a great deal of confusion and required that the heat unit be defined each time it was used. To correct this problem, it was agreed internationally to define the standard unit of heat as the amount of heat produced when an electrical current of one ampere flows through a resistance of 1 ohm for 1 second. Standards of electromotive force (voltage) and resistance are maintained at the national standardizing laboratories, and the mean solar second is used as the time standard. This new heat unit is called the *joule* in honor of James Joule, an early English physicist.

Although most theoretical and experimental work in heat since 1910 has been based on the joule, the terms "calorie" and "Btu" continued to be used in industrial and other practical applications requiring the measurement of heat. Results of research were usually converted from joules to some kind of calorie, giving the incorrect impression that the unit of heat was still in some way connected with water, and required that the kind of calorie still be specified. To solve this difficulty, it was agreed internationally to arbitrarily define the calorie as equivalent to 4.1840 joules. This calorie, sometimes known as the *thermochemical calorie,* is very nearly identical in size with the normal calorie. The thermochemical calorie has been used in nearly all thermodynamical and thermochemical work in the United States since 1930. By definition and derivation, the calorie is not connected in any way with the properties of water and does not vary in size.

Because the term "Btu" is so commonly used in practical applications of heat units in the United States, it will be used in this discussion. One Btu equals about 1055 joules or 255 calories.

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 substances does not necessarily bring about the same temperature change—it is well known that some materials can be heated or cooled more easily 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. Adding 1 Btu to a pound of water will increase its temperature by only 1° F. But adding 1 Btu to a pound of iron will increase its temperature by about 9°, and the same amount of heat added to a pound of lead will cause a 32° F increase.

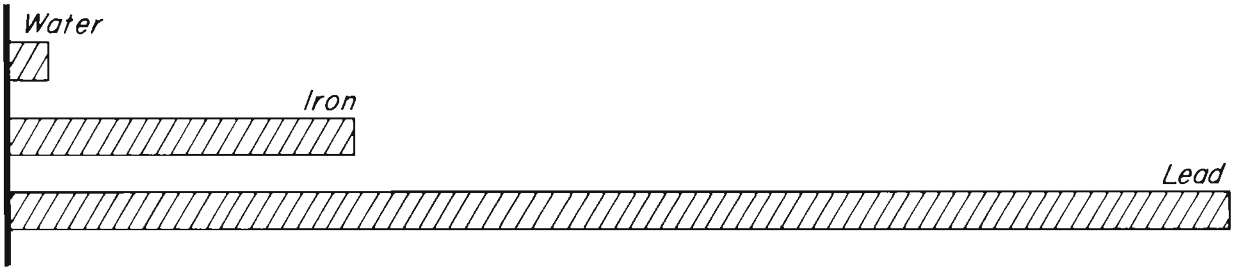


For a unit weight of a substance, the ratio of added heat to the temperature rise is the *specific heat* of the substance:

$$\text{Specific heat} = \frac{\text{Added heat}}{\text{Temperature increase}}$$

In English units, specific heat is expressed as Btu per pound per degree F of temperature change (Btu/lb/° F).

Substances with high specific heats require more heat to increase their temperatures than those with low specific heats. Hence, a substance with a high specific heat will contain more heat at a given temperature than will a substance with a low specific heat. Specific heats for many substances can be found in engineering and other references. The specific heat often varies with temperature, so that 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. Dry air at a constant pressure has a specific heat of 0.24—the same amount of heat added to a pound of air and a pound of water will increase the temperature of the water only 24 percent as much as the air. Some metals have very low specific heats. Copper, for example, has a specific heat of 0.0919 Btu/lb/° F, and that of gold is 0.0305. Such metals need little heat to increase their temperature. Most wildland fuels have specific heats in the range of 0.45 to 0.65 Btu/lb/° F.

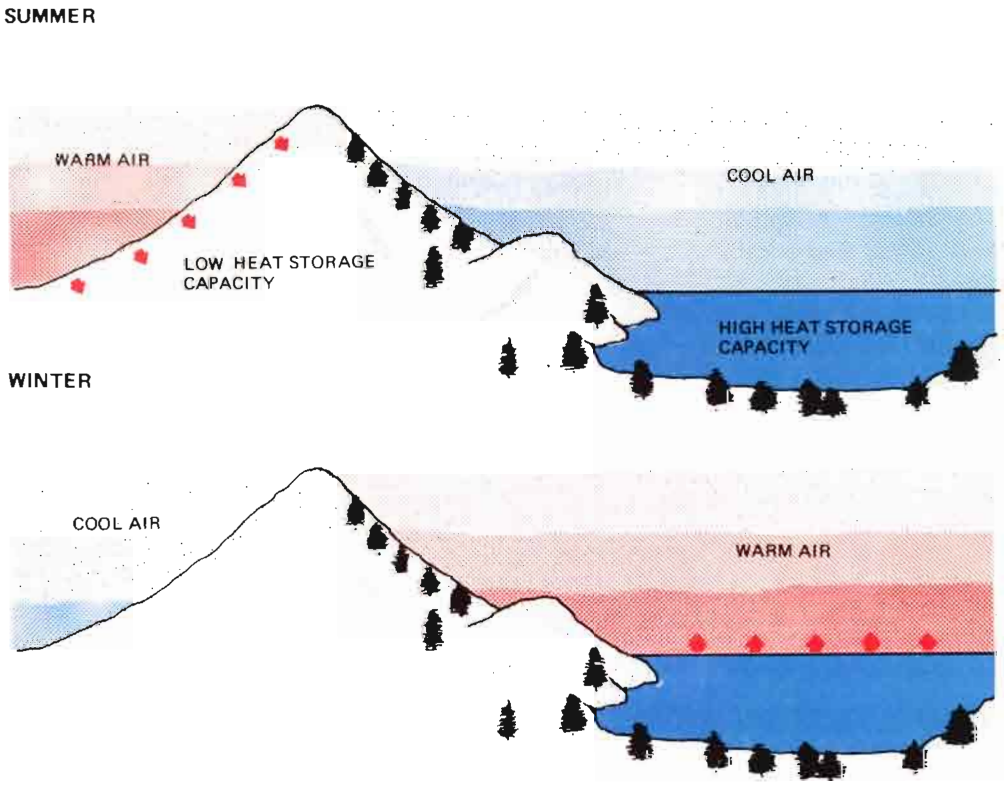


TEMPERATURE INCREASE PER POUND FOR 1 BTU ADDED HEAT

Specific heat gives the amount of heat needed to raise the temperature of a unit *weight* of a substance by 1 degree. Often, however, information on the amount of heat needed to produce a given temperature change in some *volume* of a substance is needed. In wildland fuel, for example, we are interested in the amount of heat needed to raise the temperature of a layer or volume of fuel because this helps determine the characteristics of a firebrand that can ignite it. The amount of heat required to raise the temperature of a unit volume of a substance by 1 degree is the *heat capacity* of the substance. In English units, this is expressed in Btu per cubic foot per degree Fahrenheit of temperature rise (Btu/ft^3/° F).

Heat capacity varies with density and specific heat

The density of a substance indicates its weight per unit of volume, while its specific heat establishes how much heat is required to increase the temperature of each unit of weight by 1 degree. Therefore, the heat capacity of a substance can



be calculated from the simple equation:

Heat capacity = Density x Specific heat

If the density and specific heat of a substance is known, its heat capacity can readily be determined. Solid oak wood, for example, has a specific heat of 0.57 Btu/lb/° F and a density of 48 lbs/ft^3. Its heat capacity is then 27 Btu/ft^3/° F (0.57 x 48 = 27)—it will absorb 27 Btu per cubic foot for each degree of temperature rise.

Both the density and specific heat of different substances have a wide variation, and consequently, their heat capacities also vary widely. And since specific heat often varies with temperature, so does the heat capacity. Substances 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 a substance with a 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. With similar temperatures, 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 keeps the air over the water and nearby land areas relatively cool. In the winter the stored heat is released and warms the air over the water and adjacent land. The ability of water to absorb and transport large quantities of heat also makes it useful in heating and cooling systems—hot water heating systems in buildings and cooling systems in automobiles, for example.

Because the specific heat of most wildland fuels varies over only a relatively narrow span, differences in heat capacity of the fuels depend chiefly on their density. The difference in the density of wildland fuels is quite large, and hence variations in heat capacity are also. Solid oak wood 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, will require considerably more heat to raise its temperature to the ignition point than will the decayed wood. Thus, heat capacity is an important factor in the ignition of wildland fuels.

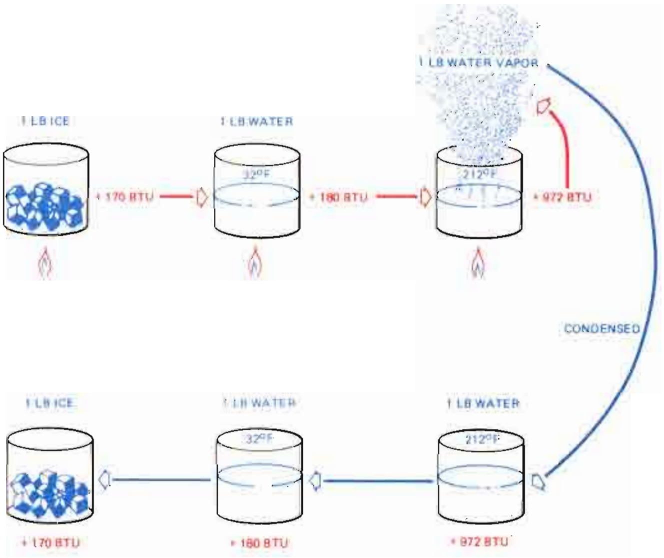
Much energy is involved in changes of state

Thus far, our discussion of heat and energy has been concerned with the addition and subtraction of heat that does not change the physical structure or "state" of a substance. But heating or cooling if carried far enough can cause a change in state of a substance, and considerable amounts of energy are frequently associated with this change. The combustion of wildland fuels, for example, involves a change of state in the fuel being burned during which large quantities of thermal energy are released.

If a block of ice is heated, its temperature will rise until it reaches the melting point of 32° F. Continued heating will cause the ice to melt, but there will be no further increase in temperature until all of the ice is melted. Thus, additional heat is required to change the state of ice to water. Heating of the water from the melted ice will result in a temperature rise of the water until it reaches 212° F. The water will then begin to boil and to vaporize, but there will be no further increase in its temperature with continued heating. Again, additional heat is needed to change the state of water to vapor.

To change ice to water, or water to vapor, heat is needed from an outside source. But if the process is reversed and the vapor is changed to water or water to ice, an equivalent amount of heat is released. The heat required to change a solid to a liquid, or that released when a liquid is converted to a solid, is the *heat of fusion.* And the heat needed to change a liquid to vapor and that is released in changing a vapor to a liquid is the *heat of vaporization.*

Both the heat of fusion and heat of vaporization of different substances vary over a wide range. The heat of fusion of aluminum is 170 Btu/lb and its heat of vaporization is 3591 Btu/lb. The heats of fusion and vaporization of nitrogen are 11 and 86 Btu/lb respectively, while those of butane are 34 and 166. The heat of fusion of water is 144 Btu/lb, and at sea level the heat of vaporization of water is 972 Btu/lb. Water will change to vapor at temperatures below 212° F, but the heat of vaporization increases as the tempera-



ture decreases. At 104° F it is 1035 Btu/lb, and this increases to 1066 Btu at 50°.

The heat involved in changes of state of water is of major importance in daily life, and also affects wildland fire, both directly and indirectly. Many living creatures, including humans, regulate their internal body temperature through the heat used in evaporating water from the skin or lungs. Heat of vaporization is important in many industrial processes and in air conditioning. The evaporative type air conditioner, or "swamp cooler" depends on the heat needed for water vaporization for its operation. As warm outside air flows through water soaked excelsior pads, some of the water vaporizes, and part of the heat needed for this vaporization is drawn from the incoming air. The evaporation of water into vapor, and the condensation of the vapor back to water in the form of clouds and precipitation, has a major effect on our weather and climate. Because of the large volumes of water and vapor involved, enormous amounts of energy can be released or stored. Thunderstorms depend greatly on the energy released by 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 effect on weather, the heat of vaporization of water also has a more direct bearing on fire. Frequently, large fires develop a white "cap" at the top of the convection column. This is condensed water vapor, produced from vapor created in the combustion process and from moisture in the fuel, and carried aloft in the convection column. 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 will release 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 moisture in fuels has an important effect on the ignition of fuel and the rate at which it burns.

Heat in wildland fuel can be measured

The amount of heat that can be obtained from fuel when it burns is known variously as its caloric value, heat of combustion, heating value, or sometimes heat content. Fuel oil will produce 18,000 to 22,000 Btu per pound when it is burned, and gasoline about 21,000 Btu per pound. The heating value of most wildland fuels falls within a range of 8000 to 9500 Btu per pound, but there are some exceptions. Pitch pine produces more than 11,000 Btu per pound, while plants with high mineral content, such as some of the saltbushes, produce only 6500 to 7000 Btu per pound.

Some of the constituents of wildland fuels, such as resins, waxes, and oils, have a much higher heating value than the rest of the fuel. In chamise, for example, these high energy constituents have heating values ranging from 17,000 to 24,500 Btu per pound—about the same as fuel oil and gasoline. Consequently, the parts of a plant that contain most of the resins, waxes, and oils will have a higher heating value than the rest of the plant. For example, the needles and small twigs of pinyon pine have a heating value of more than 9500 Btu per pound, while that of the tree trunk is about 8800 Btu per pound.

The heating value for various fuels is determined through laboratory procedures for dry fuels and complete combustion. This value represents the maximum amount of heat that can be obtained from the fuel. Under wildfire conditions, the actual heat production is likely to be considerably less. Some flammable gases produced from the fuel may be carried into the convection column unburned, and complete oxidation of all the fuel chemicals may not occur. This is likely to be of most consequence in intense fires in which the convective activity is strong and the air flow turbulent—in very intense fires only 50 to 60 percent of the potential heat from the fuel may actually be realized.

Moisture in the fuel also reduces the heat production. The heating value for fuel containing moisture can be calculated from an equation developed by the U.S. Forest Products Laboratory:

$$H_w = H_d \times \frac{100 - \frac{M.C.}{7}}{100 + M.C.}$$

where H_w = Heating value of moist fuel

H_d = Heating value of dry fuel

M.C. = Moisture content in percent

For a fuel having a heating value of 8500 Btu per pound when dry, a moisture content of 5 percent will reduce this value to 8274. At 20 percent moisture content, the heating value will be reduced to 6881 Btu, and at 80 percent moisture to 4183 Btu per pound. Since living fuels often have moisture contents exceeding 80 percent, they produce much less heat than dead and dry fuels.

SUMMARY

Heat is a form of energy called *thermal energy*. Energy cannot be created or destroyed, but it can be converted from one form to another, and transferred from one place to another and between substances. This conversion and transfer of energy is constantly going on, both in nature and through the activities of man.

The standard unit of heat is the joule, which is based on the amount of heat produced by a current of one standard ampere through a standard resistance of 1 ohm in 1 second. The thermochemical calorie is arbitrarily defined as equivalent to 4.1840 joules. The thermochemical calorie is nearly the same in size to the normal calorie which is the amount of heat required to raise the temperature of 1 gram of water from 14.5° to 15.5° C. One British Thermal Unit (Btu) is equal to 1055 joules or 252 thermochemical calories.

For a unit weight of a substance, the ratio of added heat to the temperature rise is the specific heat of the substance. In English units specific heat is given as Btu per pound per degree Fahrenheit of temperature rise (Btu/lb/°F). The heat capacity of a substance is defined as the ratio of added heat to the temperature increase of a unit volume of the substance (Btu/ft^3/° F). Heat capacity is strongly affected by the density of a substance, and is related to specific heat by the equation:

$$\text{Heat capacity} = \text{Density x specific heat}$$

Much energy is involved in the change of state of a substance, such as occurs when ice is changed to water, or water to vapor. The heat absorbed when a solid is changed to a liquid, or that is released when a liquid is changed to a solid is the heat of fusion. The heat required to change a liquid to a vapor and that is released when a vapor changes to a liquid is the heat of vaporization. In wildland fire, the heat of vaporization of water is of major importance through its effect on water processes, heat needed for ignition, and the burning rate of fuels.

The maximum amount of heat that can be obtained from a fuel when it burns is its heating value. For most wildland fuels the heating value ranges from 8000 to 9500 Btu per pound. However, fuels with large amounts of resins, oils, or waxes may have higher heating values, while those with high mineral content can be lower. Only part of the heating value of fuels is realized from a wildland fire, and the heating value decreases as increasing moisture content increases.

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