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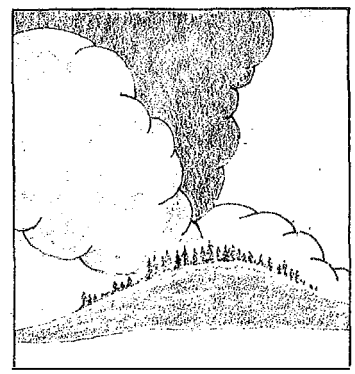
THERMAL PROPERTIES OF FOREST FUELS



DIVISION OF FIRE RESEARCH
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

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THERMAL PROPERTIES OF FOREST FUELS

by

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This study is part of a group research project of the Division of Fire Research, Forest Service, U. S. Department of Agriculture, conducted at the California Forest and Range Experiment Station.

Most of this detailed analysis was made by G. M. Byram with technical corroboration and checking by F. M. Sauer, W. L. Fons, and R. K. Arnold. Fuel measurements were made by C. C. Chandler. W. Lai drafted illustrations.

Agriculture--Berkeley

CONTENTS

ILLUSTRATIONS

TABLES

CHAPTER 1

INTRODUCTION

Forest fuels are heterogeneous mixtures of a number of green and dead woody substances. Most common are leaves, grass, conifer needles, moss, bark, and wood. As a result of past fires, an area may also contain some charcoal. With the exception of charcoal, these materials are in various stages of decay or decomposition. Logs, limbs, and decayed wood in an advanced stage of decay are referred to as punk. Mixtures of decayed needles, leaves, and grass are usually called duff.

Green fuels in the crowns of living trees, brush, and grass often are not available for combustion because a high rate of energy release is needed in the dead fuels on the ground to ignite crowns.

Woody materials have a number of properties which control or influence their ignition and initial combustion as well as the behavior of the resulting fire. This report is concerned primarily with properties as they influence ignition and initial combustion rather than subsequent fire behavior. Its main purpose is to make available to those who are interested in thermal properties of wood, and other materials which burn like wood, some of the current information and ideas of workers in forest fire research.

On two problems at least, certain conclusions and procedures are suggested which do not as yet have a complete experimental or theoretical basis. The first of these problems concerns specific heat of a wood-water system and its relation to bonding energies of the two component substances. The second problem relates to the heat of decomposition of wood and possible factors on which it depends. For the usual technical research paper, work on problems of this type would ordinarily be carried to a more finished state. However, preparation of this report is based on the assumption that in some instances other investigators would prefer to exchange a certain degree of completeness for earlier availability of information even though some questions remain unanswered.

CHAPTER 2

FUEL MOISTURE

All plant and animal fibers contain moisture. Water in these substances is not all free water, but some is in a bound or partially bound state. Properties of bound water are considerably different from those of free water. Its vapor pressure is lowered and boiling temperature is increased. Its freezing temperature is lowered, and the density of bound water is greater than that of free water. Because the vapor pressure of bound water is less than that of free water, a woody material, initially oven-dry, will take up water until vapor pressure of the adsorbed water equals the pressure of water vapor in the surrounding atmosphere. As more water is taken up by the material, bonding energies become less. In a space saturated with water vapor they ultimately become zero and vapor pressure of the adsorbed water equals the saturation pressure of water at that same temperature. The moisture content at which this occurs is defined as the "fiber saturation point." Moisture in excess of this quantity is free water. These relationships are shown more clearly in Figures 2.1 and 2.2, taken from Stamm and Loughborough (1).[1/] Figure 2.1 shows equilibrium moisture content as a function oft relative vapor pressure (relative humidity). The upper curve shows values obtained when relative humidity is being lowered at constant temperature and moisture content is decreasing. This is a desorption process. The lower curve shows the relation when relative humidity is being increased at constant temperature and moisture content is increasing (adsorption process). The intermediate curve represents equilibrium moisture contents obtained by the oscillating vapor pressure method,t which combines desorption and adsorption processes. 't

Equilibrium moisture content of wood substances is a function of temperatre as well as relative humidity. Figure 2.2 shows the relation between moisture content, relative humidity, and temperature. These curves were obtained by the oscillating vapor pressure method.

The heating of wood which contains moisture is a desorption process. This report deals with heating phenomena only, so the desired humidity-equilibrium moisture curves are those for desorption conditions rather than those for oscillating vapor-pressure conditions by which the curves of Fig. 2.2 were obtained. Detailed data on equilibrium moisture contents for desorption conditions at different temperatures were not available, so the curves of Fig. 2.2 were modified to approximate those which would be obtained if relative humidity

1/ Numbers underlined in parenthses refer to Bibliography, page 34.

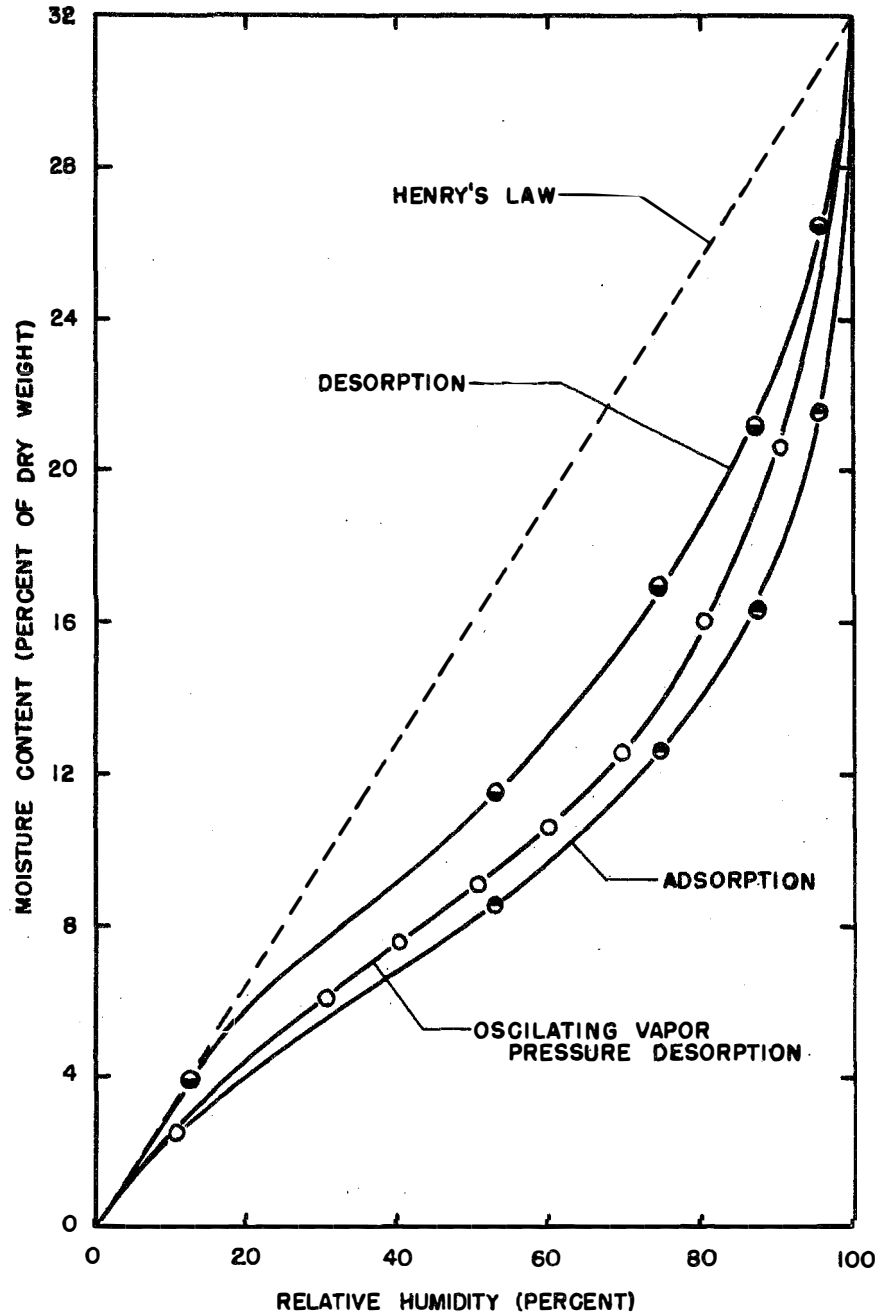

Fig. 2.1 Moisture Content as a Function of Relative Humidity (from Stamm and Loughborough (1)) for a surround temperature of 25°C

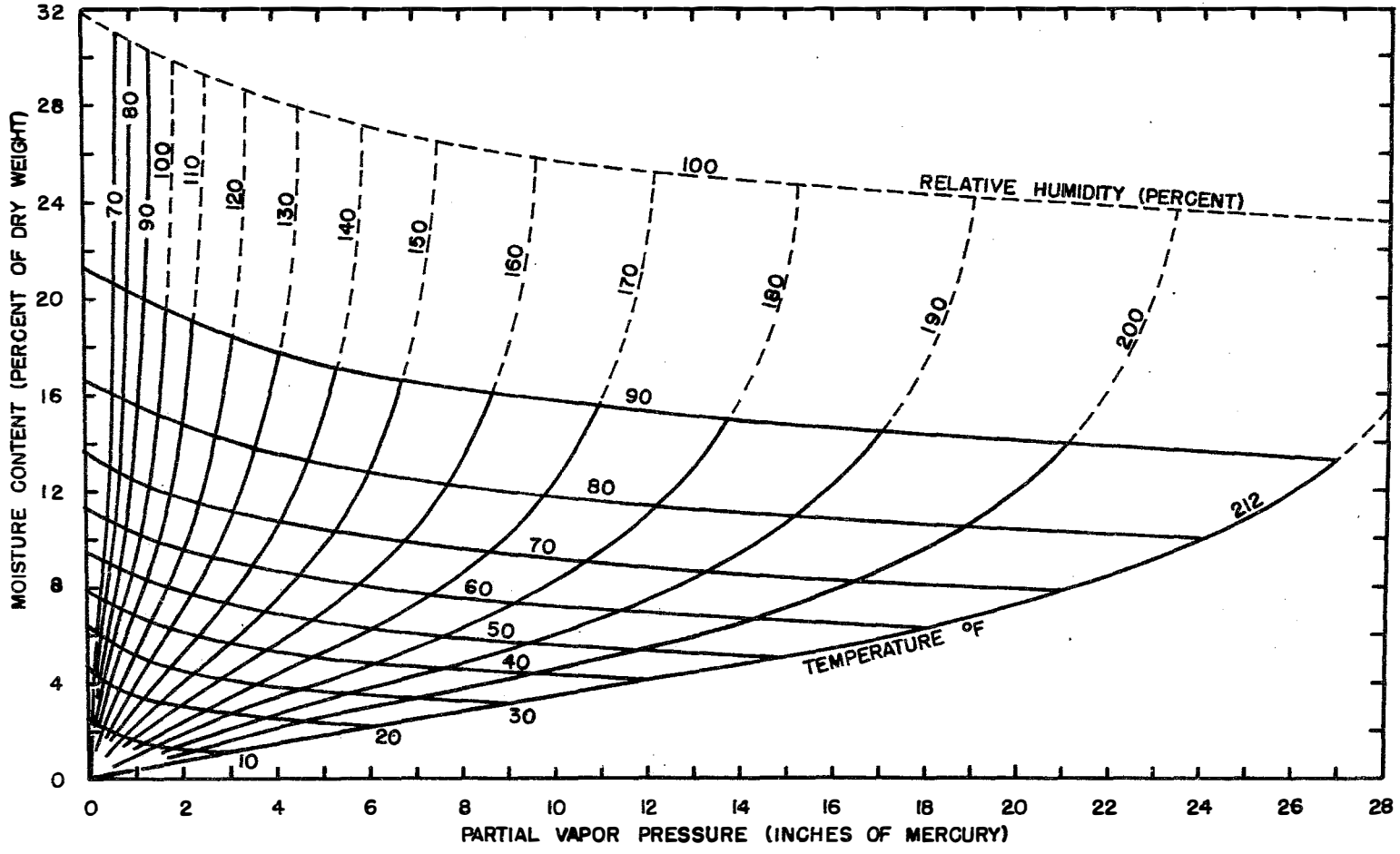

Fig. 2.2 Relation Between Equilibrium Moisture Content, Relative Humidity, Temperature, and Partial Vapor Pressure (from Stamm and Loughborough (1)). Data Obtained by Oscillating Vapor Pressure Method.

were to be lowered gradually at constant temperature. This modification was based on the assumption that

$$P(\Delta M)_{f,T} = P_o(\Delta M)_{f,T_o} \qquad (2.1)$$

in which ΔM is the difference between equilibrium moisture contents for desorption and oscillating vapor pressure conditions at a relative humidity f and temperature T; ΔM_o represents the difference for the same relative humidity f and a temperature T_o. Pressures P and P_o are saturated water vapor pressures at temperatures T and T_o respectively. The difference ΔM_o was read from Fig. 2.1 for the desired humidity and ΔM calculated for different temperatures. By adding values of ΔM to equilibrium moisture curves obtained by the oscillating vapor-pressure method, a new set of curves was obtained which was assumped to approximate desorption conditions. These curves (Fig. 2.3) closely approximate straight lines when the logarithm of equilibrium moisture content is shown as a function of temperature for different relative humidities. If plotted in this manner curves for oscillating vapor-pressure conditions, or for adsorption conditions, nearly coincide with those in Fig. 2.3 at high temperatures, but for lower temperatures equilibrium moisture contents are less. This means that the area of the hysteresis loops should decrease with increasing temperature if equation 2.1 is valid.

Moisture content is one of the most important factors in ignition and combustion of wood. Effects of moisture on ignition are brought about in two different ways. First, presence of water in wood increases the amount of heat required to bring wood up to ignition temperature, because the water as well as wood must be heated up to the temperature at which water boils off. Second, additional heat is required to separate bound water from wood and to vaporize this water.

In addition to the ignition phenomena just described, water has a pronounced effect on combustion of wood. This is a smothering effect which results from dilution of oxygen or even almost complete exclusion of oxygen at high moisture contents. When moisture content is high, the partial pressure of water vapor surrounding the burning material may approach atmospheric pressure. The limiting moisture content at which combustion can continue depends to a considerable extent on compactness of fuel, size of burning particles, and efficiency of ventilation and self-heating by radiation. Fairly compact beds of pine needles have a limiting moisture content for combustion in the neighborhood of 20 per cent (dry weight basis), while dense stands of dead grass may burn when moisture content is 60 or 70 per cent. Under a forced draft, sawdust in a furnace may be burned at much higher moisture contents. Arrangement of fuel and efficiency with which combustion products and water vapor are carried away are important factors controlling dilution of oxygen.

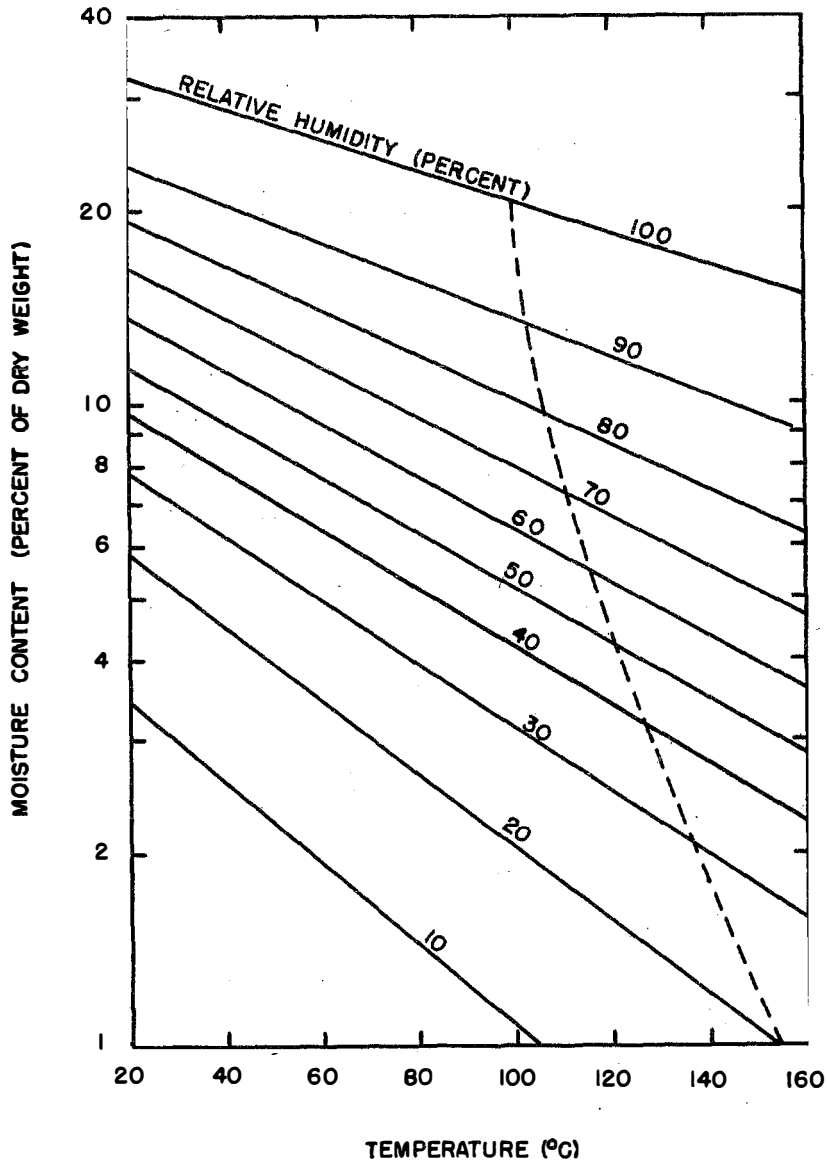

Fig. 2.3 Equilibrium Moisture Content for Desorption Conditions As a Function of Temperature for Different Relative Humidities. Dashed Line Represents Boiling Temperature at 760 mm Pressure.

CHAPTER 3

SPECIFIC HEAT CAPACITY

The heat capacity of woody materials containing moisture is not equal to the sum of heat capacities of the component substances, as one might expect, but exceeds this sum by a considerable amount. The specific heat of a wood-water system is related in a complex manner to energies bonding the wood substance and water. Elevation of the specific heat can be computed from heats of desorption (or adsorption if the wood-water system is being cooled).

The heat of desorption, H(M), represents the amount of heat required to release all water from 1 gram of wood substance initially at moisture content M and absolute temperature T. The differential heat of desorption at constant temperature $\left[\frac{\partial H(M)}{\partial M}\right]_T$ is related to the equilibriumt relative humidity, f, through the Clausius-Clapeyron equation (1):

$$\left[\frac{\partial H(M)}{\partial M}\right]_{Tt} = -\frac{R}{m}\left[\frac{\partial (\ln f)}{\partial (1/T)}\right]_{Tt} \qquad (3.1)$$

in which R is the gas constant and m the molecular weight of water. Stamm and Loughborough (1) computed heats of swelling of wood from curves based on oscillating vapor pressure conditions (Fig. 2.2) and found agreement with values obtained from calorimetric measurements.

Curves of Fig. 2.3 were replotted as logarithm of relative humidity vs reciprocal of the absolute temperature for various moisture contents, and differential heats of desorption were determined from slopes of the resultant curves using equation 3.1. Figure 3.1 shows the differential heat of desorption as a function of moisture content for a number of temperatures.

The heat of desorption

$$H(M)_T = \int_0^M \left[\frac{\partial H(M)}{\partial M}\right]_T dM \qquad (3.2)$$

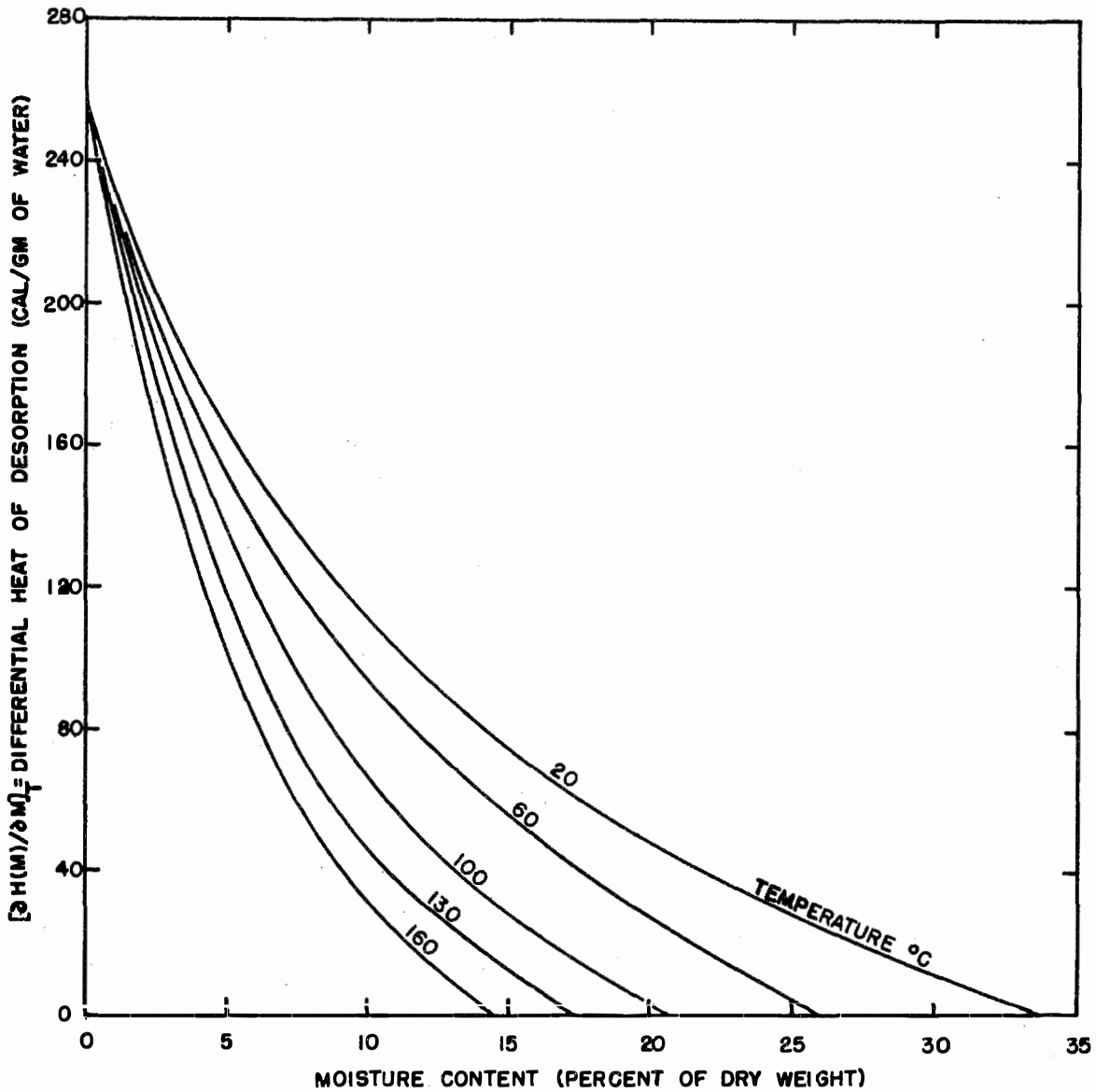

Fig. 3.1 Computed Values of Differential Heat of Desorption Shown As a Function of Moisture Content for Several Temperatures. Based on 100 Gm of Dry Wood, Ordinates Represent the Amount of Heat Required to Decrease the Moisture Content by 1 Per Cent or 1 Gm at Temperature T.

for any temperature T can be found by measuring the area under the corresponding curve in Fig. 3.1 from M = 0 to M = M. Heats of desorption determined in this manner are displayed in Fig. 3.2.

Stitt and Kennedy (2) have measured specific heat of several dehydrated vegetables at different moisture contents and have found that their specific heats are higher than they would be if heat capacities of the two components were additive. The term

$$C_f + MC_w - \left[\frac{\partial H(M)}{\partial T}\right]_{Me}$$

represents a generalized specific heat, and is the specific heat that would be obtained in an experiment designed to measure specific heat of a wood sample with moisture content M. Because H(M) decreases with increasing temperature, the term $-\left[\frac{\partial H(M)}{\partial T}\right]_M$ is positive and specific heat of a wood-water mixture is greater than it would be if heat capacities of the wood and water components were additive. Elevation of the specific heat, ΔC_p, can be determined by means of the equation

$$\Delta C_p = -\left[\frac{\partial H(M)}{\partial T}\right]_M \qquad (3.3)$$

A discussion of equation 3.3 is given by Stitt and Kennedy (2). Figure 3.3 shows ΔC_p as a function of moisture content for temperatures of 45° C, 80° C, and 140° C. These curves were computed from equations 3.2 and 3.3 by use of an intermediate plot (not shown) of H(M) vse temperature. The plotted points of Fig. 3.3 represent data from specific heat measurements of Stitt and Kennedy (2) for dehydrated potatoes.

The generalized specific heat indicates the possibility of wood having two specific heats, depending on whether temperature of the wood is decreased or increased during the experiment. If $\left[\frac{\partial H(M)}{\partial T}\right]_M$ is not the same for adsorption and desorption conditions, then wood substance should have two specific heats. For example, if the specific heat of a wood specimen were determined when its temperature dropped from T_1 to T_2, the value might be less than in a similar experiment in which its temperature increased from T_2 to T_1. The difference should be more pronounced at high moisture contents (30 to 35 per cent) and low temperatures. This question could be settled by a carefully designed experiment.

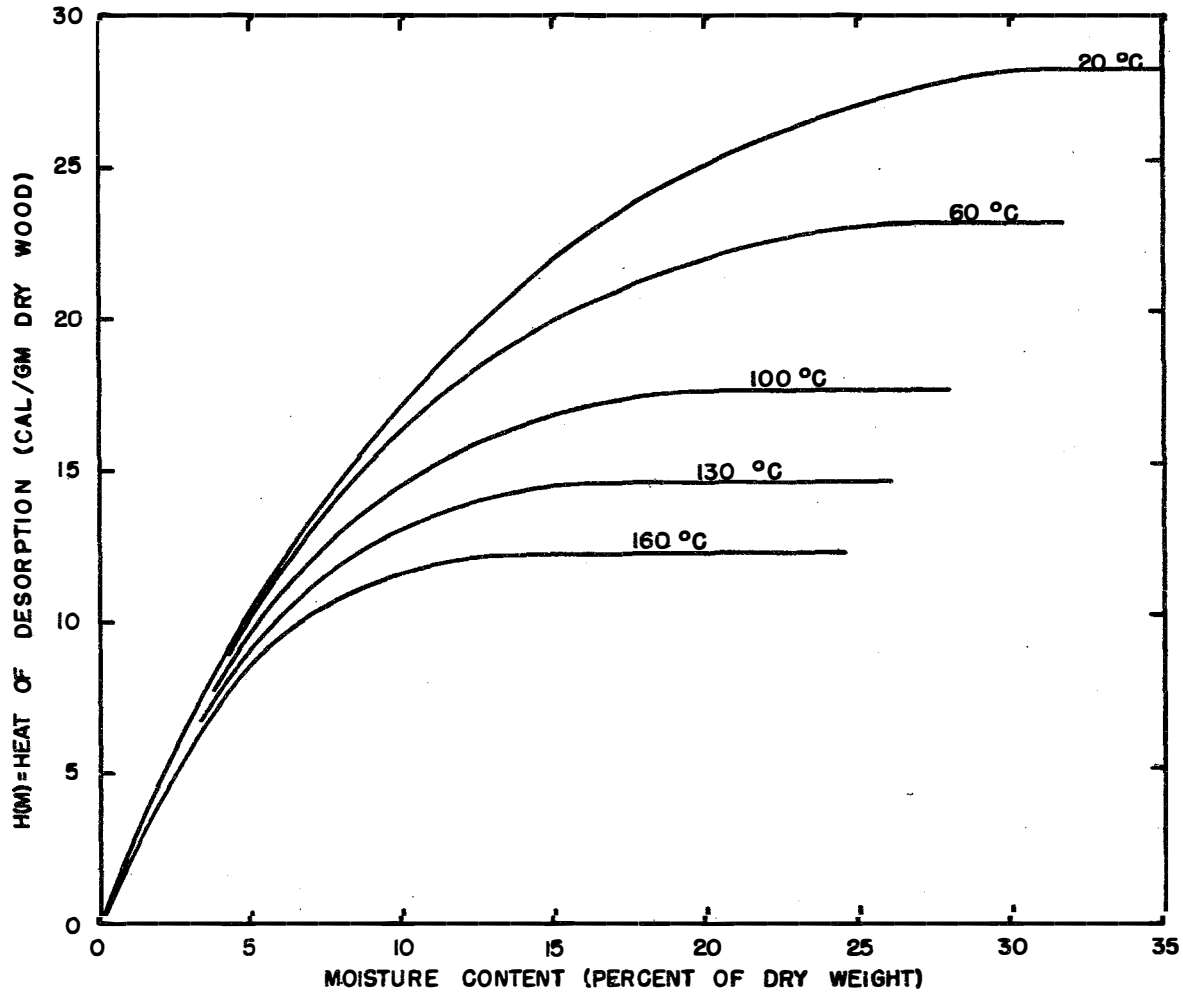

Fig. 3.2 Computed Values of Heat of Desorption Shown As a Function of Moisture Content for Several Temperatures

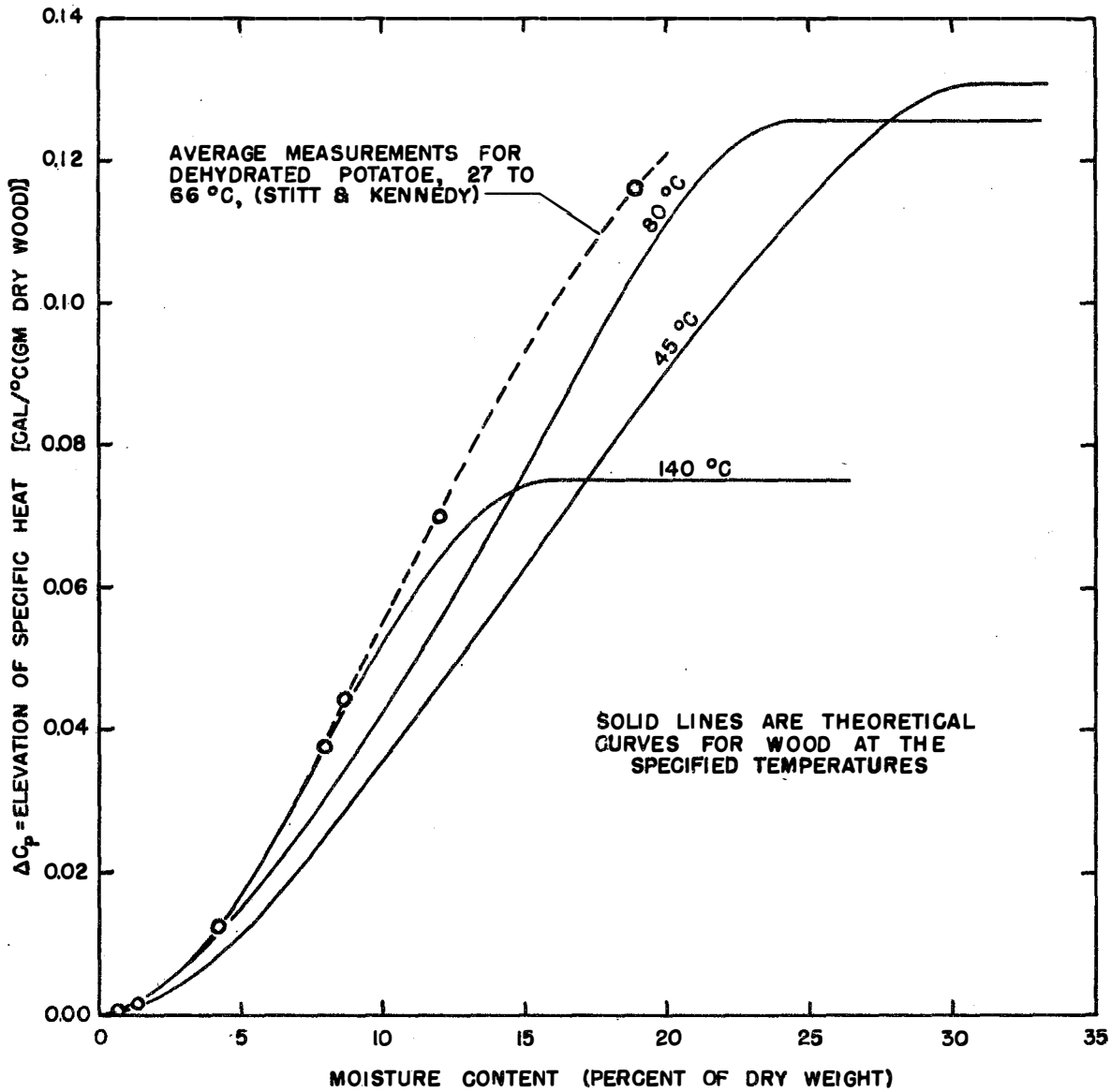

Fig. 3.3 Elevation of Specific Heat for Desorption Conditions As a Function of Moisture Content and Temperature. Curve Through Plotted Points Represents Data of Stitt and Kennedy (2).

CHAPTER 4

NET HEAT REQUIRED TO IGNITE WOOD

The net amount of heat required to ignite wood containing moisture can be estimated analytically. If a quantity of heat dQ is added slowly to a wood-water system there will in general be a change in temperature dT and a change in moisture content dM. For 1 gram of wood substance (dry weight basis) this relation may be written as

$$dQ = \left[C_f + MC_w - \frac{\partial H(M)}{\partial T}\right] dT + \left[\frac{\partial H(M)}{\partial M} + L_t\right] dM \qquad (4.1)$$

where C_f is the specific heat of oven-dry fuel or wood, C_w the specific heat of water, M the moisture content, H(M) the heat of desorption at moisture content M, and L_t the latent heat of vaporization of water.

Extremely rapid heating will approach a process carried out at constant moisture, dM = 0; hence to heat a wood-water system from a temperature T_1 up to the temperature T_2 where the fiber saturation point is reached requires the heat Q (cal/gm of wood substance)

$$Q = (C_f + MC_w)(T_2 - T_1) - \int_{T_1}^{T_2} \frac{\partial H(M)}{\partial T} dT = (C_f + MC_w)(T_2 - T_1) + H(M)_{T_1} - H(M)_{T_2} \qquad (4.2)$$

A heating process at constant moisture is equivalent to a heating process at a zero vapor-pressure difference between water in the wood sample and water vapor in the immediately surrounding space. For a sample heated at atmospheric pressure, moisture content cannot remain constant if the vapor pressure of water in the wood at a temperature of T_2 exceeds atmospheric pressure. To keep the vapor pressure difference equal to zero in this case would require heating in a saturated atmosphere under pressure. However, if heating is carried up to ignition temperature T_i at atmospheric pressure, the net amount of heat required may be written to a close approximation as

$$Q = (C_f + MC_w)(T_2 - T_1) + C_f(T_i - T_2) + C_w \int_{T_2}^{T_i} M dT + H(M)_{T_1} + \int_0^M L_t dM \quad .e \qquad (4.3)$$

The term $H(M)_{T_i}$ is dropped because it may be assumed M = 0 when the temperature reaches T_i.

Boiling temperature is a function of moisture content M, hence a relation may be written relating boiling temperature T and M as

$$T = \varphi(M) + 100 \tag{4.4}$$

from which

$$dT = \varphi'(M)dM$$

The first integral in equation 4.3 may therefore be written as

$$\int_{T_2}^{T_i} M dT = \int_{M}^{0} M\varphi'(M)dM = - M\varphi(M) + \int_{0}^{M} \varphi(M)dM$$

Equation 4.4 may be expressed as

$$M = \psi(T - 100)$$

or

$$dM = \psi'(T - 100)\, dT$$

hence the second integral in equation 4.3 becomes

$$\int_{0}^{M} L_t dM = \int_{T_i}^{T_2} L_t \psi'(T - 100)\, dT$$

Equation 4.3 thus takes the form

$$Q = C_f(T_i - T_1) + C_w\left[M(T_2 - T_1) + \int_0^M \varphi(M)dM - M\varphi(M)\right] + \int_{T_i}^{T_2} Lt\,\psi'(T - 100)dT + H(M)_{T_1} \qquad (4.5)$$

For calculation of the net energy required for ignition, only two parameters of the desorption process must be known: heat of desorption at temperature T_1 for moisture content M — the function $H(M)_{T_1}$, and the relation between moisture content and boiling temperature — $\varphi(M)$. The function $(T - 100)$ can be found directly from $\varphi(M)$, because

$$\psi(T - 100) = \varphi^{-1}(T - 100)$$

where φ^{-1} is the inverse function of φ. The functions $\varphi(M)$ ore $\psi(T - 100)$ can be determined from the curve in Fig. 2.3 which is drawn across the equilibrium moisture content lines. This curve shows the boiling temperature (at 760 mm pressure) for any moisture content.

Heating of wood is a desorption process even when moisture content is held constant. Heating wood shifts the equilibrium of the system in such a way that energy is required or work is done against bonding forces. Conversely, the cooling of wood at constant moisture content is an adsorption process in which equilibrium of the system is shifted in such a way that energy is released.

Very rapid heating closely approximates a heating process with zero vapor pressure difference or at constant pressure except when atmospheric pressure is exceeded. Slow heating of wood approximates a heating process carried out in an atmosphere of constant vapor pressure. Net energy required to reach ignition temperature would be less in the second case than in the first. This slow type of heating will not be considered in this report.

CHAPTER 5

HEAT OF DECOMPOSITION

When wood and many other organic substances decompose at high temperatures, heat is evolved. Studies of ignition and combustion of organic substances show, however, some uncertainty as to the amount of heat evolved or how this varies with rate of heating.

Bamford, Crank, and Malan (3)give temperature-time histories in wood slabs heated by gas flames. As both surfaces of the wood were exposed to flame, temperatures in slab centers were measured at intervals during the heating period. At a temperature from 550° K to 600° K the temperature rose rapidly and then tended to level off at a temperature of about 750° K. From the magnitude of this temperature rise, it is possible to make a crude estimate of the amount of heat released during the exothermic reaction. Bamford, Crank, and Malan estimate this value as 86 cal/gm of volatile products evolved. If one assumes that the products are 70 per cent of the wood substance by weight, then the exothermic heat of reaction is about 60 cal/gm of oven-dry wood. This value is small compared to the heat of combustion, about 4800 cal/gm of dry wood.

A temperature-time curve for heating of 1-cm cube blocks of Douglast fir (Fig. 5.1) is given in the British publication "Fire Research" (4) for 1948. The temperature of the surrounds (oven temperature) is also shown. These two curves provide another way to estimate rate of energy release in the exothermic heating process as well as an approximation of the total amount of exothermic heat evolved. If $\frac{dT}{dt}$ is rate of temperature rise in a 1-cm block and $\frac{dQ}{dt}$ the rate of heat release within the block, then approximately

$$\frac{dQ}{dt} = C_p \gamma V \frac{dT}{dt} + \epsilon \sigma (T_1^4 - T_2^4) \qquad (5.1)$$

where C_p is the specific heat of the wood, γ its density, V its volume (1.0 cm^3), T_1 the temperature of the block, T_2 the temperature of the surround or oven, ϵ the emissivity, and σ the Stefan-Boltzman constant. The quantities $\frac{dT}{dt}$, T_1, and T_2 are determined directly from Fig. 5.1 and $\frac{dQ}{dt}$ is then computed from equation 5.1. This quantity is plotted in Fig. 5.2 as a function of time of heating. If it is assumed that in

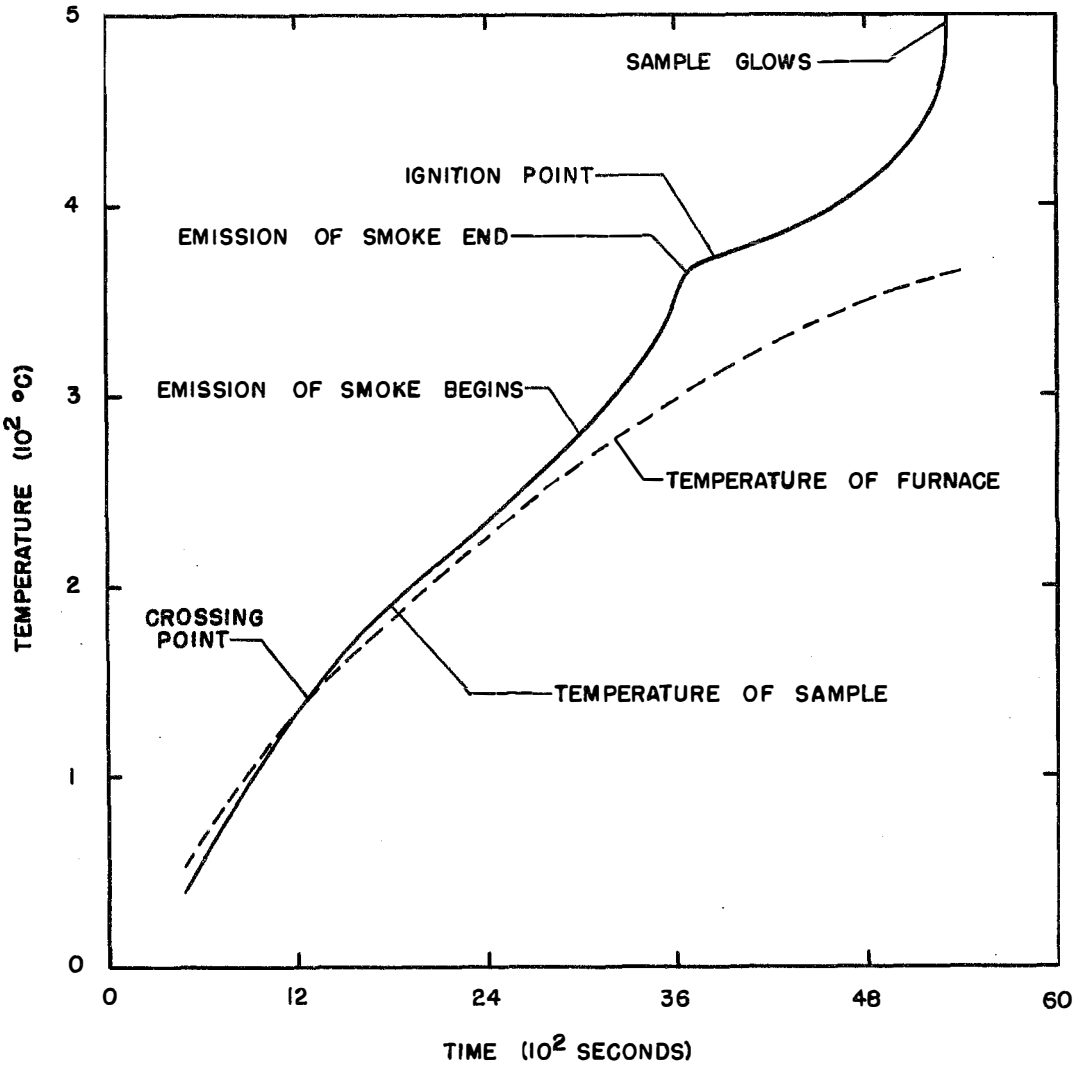

Fig. 5.1 Temperature-Time History for 1-Cm Douglas Fir Cube Heated In Furnace

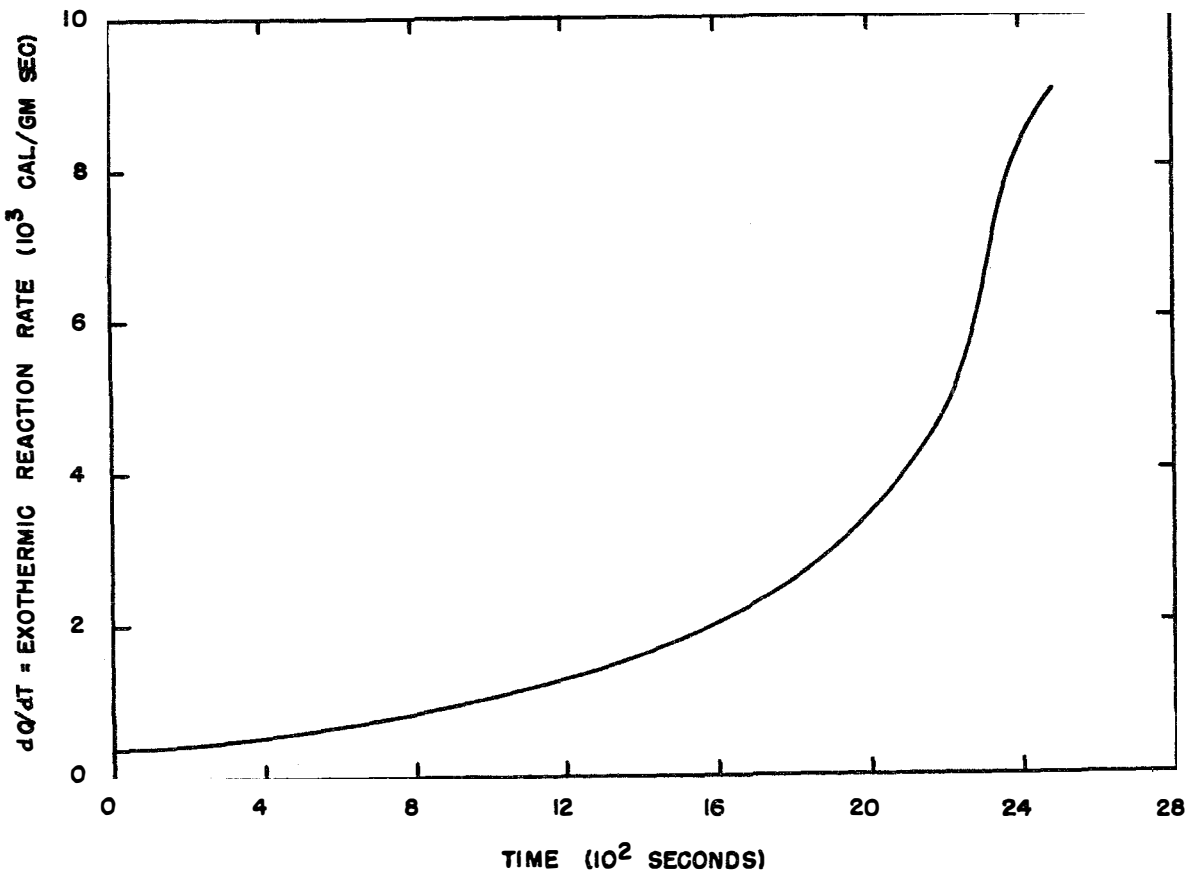

Fig. 5.2 Calculated Rate of Energy Release Due to Exothermic Heating of 1-Cm Douglas Fir Cube

this particular instance the exothermic reaction is essentially completed at a temperature of 637° K, then the area under the curve in Fig. 5.2 gives total heat evolved in the process. This estimate of exothermic heat should be reduced 10 to 15 per cent to account for the fact that the temperature of the cube surface is less than the value read from Fig. 5.1 because of temperature gradients within the cube.

This analysis indicates, then, that total exothermic heat is about 400 cal/gm of oven-dry wood — nearly seven times higher than the corresponding estimate of Bamford, Crank, and Malan. Several reasons for this discrepancy may be advanced.

The gas flame used by Bamford, Crank, and Malan could have prevented oxygen from coming in contact with the wood surface. On the other hand, air had free access to the cubes heated slowly in the oven, and oxidation which would increase the total heat evolved might have been taking place even at temperatures below 625° K.

A more likely explanation of this discrepancy lies in the fact that the heating rate was much higher in the study by Bamford, Crank, and Malan. If end products of the decomposition process were always the same, then exothermic heat yield should be independent of rate of heating. However when rate of heating is sufficiently rapid, primary substances may be distilled off before they can complete their exothermic decomposition.

Stamm[2/] has computed exothermic heat yield for dry glucose sugar under nonoxidizing conditions which give a number of different possible end products. These computations show that the yield (about 330 cal/gm) does not vary greatly with different decomposition products. In a similar computation for wood, but with one group of decomposition products, he estimates exothermic heat as slightly less than 300 cal/gm of wood. This value is nearly midway between the 400 cal/gm estimate previously given and the highest value given by Klason (5).

Klason found that exothermic heat yield varied considerably with time of distillation and pressure. For distillation carried on for a period of 14 days at atmospheric pressure the exothermic heat was 169.2 cal/gm of wood. For a distillation period of 8 hours it dropped to 96.7 cal/gm. For rapid distillation in a vacuum, the exothermic heat yield was -47.6 cal/gm. Products of rapid distillation in a vacuum were also different from those distilled slowly at atmospheric pressure.

2/ Letter from Alfred J. Stamm, Forest Products Laboratory, Madison, Wisconsin, to George M. Byram, Southeastern Forest Experiment Station, Asheville, North Carolina, dated March 12, 1952.

Yield of tar was much higher and charcoal and gas yield correspondingly lower. When the vacuum tar was heated it decomposed exothermically between 230°C and 275° into ordinary tar, gas, and tar coke.

Hawley and Wise (6) discuss thermal decomposition of wood, including comments on Klason's work. They suggest that decomposition of wood consists of two reactions: (1) A primary reaction which is not exothermic forms primary tar and primary charcoal; (2) a secondary reaction in which the primary tar is decomposed exothermally into secondary reaction in which the primary tar is decomposed exothermally into secondary tar and gas (both of which are volatile) and a tar coke delosited in the charcoal when the heating process is slow. If the above concepts describe thermal decomposition of woody materials, they are highly significant in a heating process in which ignition temperature is reached in only a second or two. It seems likely that primary volatile products would boil off before they had time to decompose exothermally within the wood. In theoretical calculations of the net energy required to ignite wood, it seems best to neglect exothermic heat provided that the heating process is very rapid. Actually it might be more reasonable to use a negative heat value which would correspond to a latent heat of vaporization. Possibly the negative value obtained by Klason may represent the latent heat or part of the latent heat of vaporization of primary products distilled from wood. This negative heat yield would approach the latent heat of vaporization as time of heating approaches zero. At the other extreme the yield may approach the value estimated by Stamm as the heating period becomes infinitely long.

CHAPTER 6

THERMAL CONDUCTIVITY

Ignition characteristics of materials which have very low thermal conductivity and are in the form of semi-infinite solids such as decomposed wood differ greatly from those of thin non-decayed materials. Even the ignition process seems to be different. For substances such as leaves and non-decayed wood, ignition by radiation probably occurs when residual charcoal reaches a temperature (tentatively placed at 900° K) which ignites the distilled gases. In punk distilled gases probably do not contribute as much to ignition or combustion as they do in non-decayed fuels. Punk seems to burn more like carbon or powdered charcoal. Its ignition temperature may be as low as 600° K. Due to low thermal conductivity, isolated smoldering spots on the surface tend to conserve their heat and spread slowly throughout the volume of the material. This slow process also favors the contribution of exothermic heat. Fire may smolder in decayed wood for days or weeks before igniting material in which fire spreads rapidly.

Byram and others (7) found that thermal conductivity of wildland fuels was primarily a function of specific gravity. These data are summarized in Fig. 6.1, which may be used for estimating purposes along with the equation of MacLean (8). ;This equation is

$$K = \left[(4.78 + 0.097\ M)S + 0.568\right] \times 10^{-4}; \quad (0 < M < 40)^e$$
$$K = \left[(4.78 + 0.13\ M)S + 0.56\right] \times 10^{-4}; \quad (M > 40)^e \qquad (6.1)$$

where K is thermal conductivity in cal/cm^{2}sec (^{o}C/cm), M is moisture content in percent of oven dry weight, and S is specific gravity based on oven dry weight and wet volume at current moisture content.

Specific gravities and corresponding thermal conductivities computed from equation 6.1 are displayed in Table 6.1.

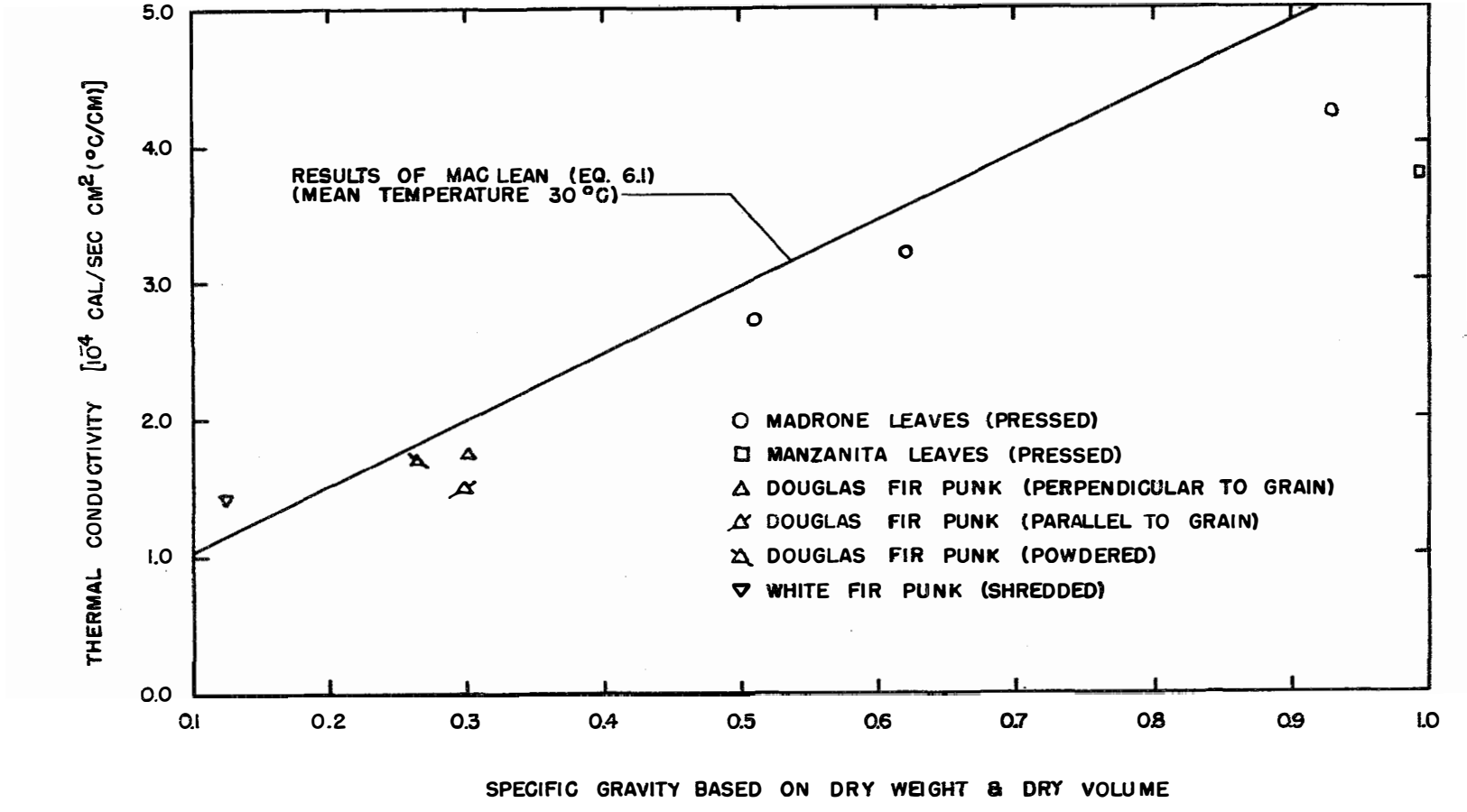

Fig. 6.1 Thermal Conductivity of Some Common Forest Fuels at Zero Per Cent Moisture

TABLE 6.1

Specific Gravity and Thermal Conductivity of Forest Fuels—Oven Dry

Specific Gravity	Thermal Conductivity (10^{-4} cal/cm^2 sec (°C/cm))	Material
0.10	1.05	White fir punk—sapwood (*Abies concolor*)
0.25	1.75	Douglas fir punk (*Pseudotsuga taxifolia*)
0.25	1.75	aWhite fir punk—heartwood(*Abies concolor*)
0.35	2.25	Wheatstraw (*Triticum* sp.)a
0.37	2.35	Cheatgrass (*Bromus tectorum*)a
0.37	2.35	Chestnut oak (*Quercus montana*)a
0.39	2.45	Beech (*Fagus* sp.)a
-	2.45	European beech (*Fagus sylvatica*)a
0.39	2.45	Harding grass (*Phalaris tuberosa* var.a *stenoptera*)a
0.42	2.60	Redwood (*Sequoia sempervirens*)a
0.44	2.70	Knobcone pine (*Pinus attenuata*)a
0.45	2.75	Madrone (*Arbutus menziesii*)a
0.46	2.80	Coulter pine (*Pinus coulteri*)a
0.48	2.90	Manzanita—weathered (*Arctostaphylos patula*)a
0.50	2.95	Rhododendron (*Rhododendron catawbiense*)a
0.51	3.00	Sedge (*Carex geyeri*)a
0.51	3.00	Ponderosa pine (*Pinus ponderosa*)a
0.52	3.05	Shortleaf pine (*Pinus echinata*)a
-	3.05	Scotch pine (*Pinus sylvestris*)a
-	3.10	White pine (*Pinus strobus*)
0.53	3.15	Desert stipa (*Stipa* sp.)a
0.54	3.15a	Chinquapin (*Castanopsis chrysophylla*)a
0.54	3.15a	Sugar pine (*Pinus lambertiana*)a
0.55	3.20	White fir (*Abies concolor*)a
-	3.20	Norway spruce (*Picea excelsa*)a
0.56	-	White bursage (*Franseria dumosa*)a
0.56	-	Jointfir (*Ephedra* spp.)a
0.57	3.30	Snowbrush (*Ceanothus velutinus*)a
0.57	3.30	Lodgepole pine (*Pinus contorta*)a
0.59	3.40	Scarlet oak (*Quercus coccinea*)a
0.64	3.65a	Manzanita—newly fallen (*Arctostaphylosa patula*)
0.65	3.70a	Horsehair lichen (*Alectoria jubata*)
0.67	-	Wiregrass (*Aristrida stricta*)

CHAPTER 7

DIMENSIONS AND STRUCTURE OF COMBUSTIBLE MATERIAL

Ignition of thin materials by radiation is determined by those factors which affect the rate of temperature rise within the material. If a substance in the form of a flat plate is thin enough, the temperature difference between its two sides when one is irradiated will not be great, and it can be considered as having heat capacity per unit area. Therefore density, specific heat, and thickness will be the factors which determine the rate of temperature rise for a given rate of energy absorption on the surface and within the material. Because specific heat and density values have narrow ranges, thickness is probably the dominating factor in determining ignition. In fuel mixtures containing leaves, grass, and various kinds of thicker materials, the thinnest materials in the mixture will determine whether the whole mixture will ignite by radiation. However, ignition of thicker materials by thinner components in the mixture will depend to some extent on compactness of the mixture and the relative positions of thin and thick materials.

Moisture content should be mentioned again as a factor in ignition. Theoretical calculations show that when materials are 0.002 inches or less, moisture content has less effect on ignition than it does for thicker materials. However, this does not lessen the importance of moisture content as a factor in ignition. Even though thin fuels may ignite at comparatively high moisture contents, a higher proportion of spurious ignitions would occur than would be the case when fuels were dry. Also, probability of ignited thin material causing thicker fuels to ignite would be much lower at higher moisture contents.

Mean thicknesses of some forest fuels are displayed in Table 7.1.

TABLE 7.1

Mean Thickness of Forest Fuels

Thickness (Cm)	Material
0.002	Horsehair lichen—branchlet hairs (Alectoria jubata)
0.003	Cheatgrass—seedpod (Bromus tectorum)
0.007	Wiregrass (Aristrida stricta)
0.007	Desert stipa (Stipa sp.)
0.008	European beech (Fagus sylvatica)
0.009	Beech (Fagus sp.)
0.010	Dogwood (Cornus sp.)
0.011	White bursage (Franseria dumosa)
0.012	Jointfir (Ephedra sp.)
0.013	Red maple (Acer rubrum)
0.014e	Chestnut (Castanea sp.)
0.014	Walnut (Juglans sp.)
0.015	Harding grass (Phalaris tuberosa var. stenoptera)
0.016e	Sourwood (Oxydendrum arboreum)
0.016	Hickory (Carya sp.)
0.017e	Post oak (Quercus stellata)
0.017	Sedge (Carex geyeri)
0.018e	Chestnut oak (Quercus montana)
0.018	Scarlet oak (Quercus coccinea)
0.025	Rhododendron (Rhododendron catawbiense)
0.028	Madrone (Arbutus menziesii)
0.037	Wheatstraw (Triticum sp.)
0.038	Ponderosa pine (Pinus ponderosa)
0.039	White pine (Pinus strobus)
0.044	Scotch pine (Pinus sylvestris)
0.046	Redwood (Sequoia sempervirens)
0.058	Shortleaf pine (Pinus echinata)
0.066	Coulter pine (Pinus coulteri)
0.084	Norway spruce (Picea excelsa)

CHAPTER 8

THERMAL ABSORPTIVITY

Energy received from a radiant source contributes to the ignition process only if this energy is absorbed by the fuel particle. A fraction of incident energy is reflected, a fraction transmitted through the fuel (if it is thin enough), and the remainder absorbed. The ratio of the absorbed energy to the incident energy is called the thermal absorptivity.

Absorptivity for any given fuel is dependent on the spectral quality of the incident radiation. The value associated with radiation occurring at a single wave length is called the monochromatic absorptivity, α_λ , and is related to the monochromatic transmissivity, t_λ , and reflectivity, r_λ , by the equation

$$\alpha_\lambda = 1 - t_\lambda - r_\lambda \tag{8.1}$$

The total or average absorptivity integrated over the spectrum of the incident radiation is defined as

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_2} \alpha_\lambda \, E_\lambda \, d\lambda}{\int_{\lambda_1}^{\lambda_2} E_\lambda \, d\lambda} \tag{8.2}$$

where E_λ is the spectral distribution of the energy received from the radiant source and λ is wave length.

These definitions of total and monochromatic absorptivity do not specify how the energy is absorbed. For forest fuels the fraction of energy represented by α_λ is probably absorbed internally. Calculations concerning the temperature distribution within forest fuels should take this into consideration (i.e. fuels should be considered diathermanous).

Measurements of spectral distribution of reflectivity and transmissivity have been made (9) on several common forest fuels (Table 8.1) which represented the visual range of color found among these dry fuel

types. Harding grass represented "straw colored" materials while weathered manzanita represented dark brown materials. Extreme value ranges are presented in Fig. 8.1. Equation 8.1 was used to determine absorptivities from measured transmissivities and reflectivities.

TABLE 8.1

Absorptivity of Some Common Forest Fuels[a/]

Fuel		Side Measured	Absorptivity[b/] (Per Cent)	
Sample No.	Kind		Total	Group Average
WEATHERED				
1	Sycamorer	Top	74	
2	Sycamore	Under	75	
3	Sycamore	Under	63	73
4	Sycamore	Top	65	
5	Manzanita	Under	83	
6	Manzanita	Top	77	
NEWLY FALLEN				
7	Sycamore	Top	67	
8	Sycamore	Under	60	
9	Madrone	Under	47	58
10	Madrone	Top	53	
11	Madrone	Under	61	
GREEN				
12	Sycamore	Under	69	70
13	Sycamore	Top	71	
STRAW-COLORED				
14	Harding Grass	Top	46	48
15	Harding Grass	Under	50	

a/ Air-dried state.
b/ Spectral source distribution equivalent to that received at 2,000 yards through normal atmosphere from 10,000°K Planckian radiator.

Spectral dependence of absorptivity on color of fuel is apparant only in the region 0.4 to 2.0 microns (see Fig. 8.1). Weathered fuels have a higher absorptivity in this region. The newly-fallen and light-colored fuels have progressively lower absorptivities. For wave lengths

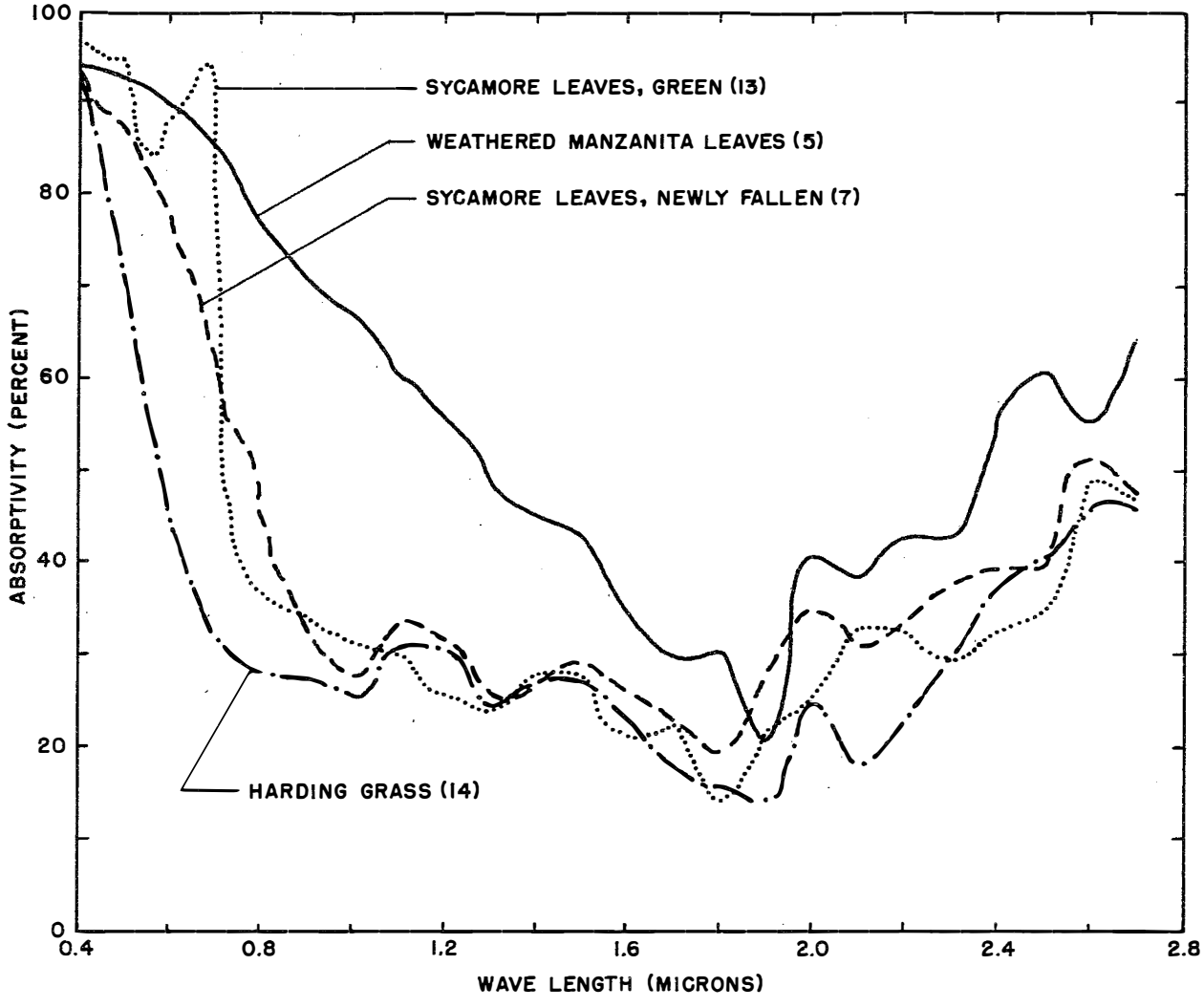

Fig. 8.1 Representative Spectral Absorptivities of Forest Fuels, Air Dry

greater than 2.0 microns, all fuels have approximately the same absorptivity. The amount of energy transmitted ranges from 5 to 15 per cent and is fairly constant in the wave length range investigated.

Table 8.1 lists total absorptivities computed (9) for a high-temperature source (T = 10,000°K) attenuated in the ultra violet and visible due to the atmosphere. This represents a special case where differences in total absorptivity due to spectral differences should be maximized. Fuels in Table 8.1 have been grouped according to visual classifications. Since variations about the average of 15 to 20 per cent appear, caution should be exercised in using these average values.

Effect of moisture on absorptivity has not been considered. All fuels were in equilibrium with the ambient air, but relative humidity at time of test was not recorded. Evidence of moisture is found in the increased absorptivity at 1.4-1.5 and 1.9-2.0 microns corresponding to the water absorption bands at these wave lengths.

Since total absorptivity for any given fuel depends on the spectral distribution of energy received (Equation 8.2), absorptivity will vary in accordance with spectral concentration of incident energy. Distribution of energy for Planckian (ideal) radiation depends on the absolute temperature of the radiator. Table 8.2 serves to illustrate the region of importance when evaluating the total absorptivity for Planckian radiation. The region $2200 < \lambda T < 4800$ (microns °K) contains half the total energy. Table 8.3 shows this region in terms of temperature and wavet length.

TABLE 8.2

Energy Distribution for a Planckian Radiator

λT (Microns °K)	Per Cent of Total Energy
Less than 2200	10
2200 - 4800	50
4800 - 7000	20
Greater than 7000	20

TABLE 8.3

Temperature and Wave Length Corresponding to Region $2200 < \lambda T < 4800$ (microns °K)

T (°K)	(Microns)
7000	0.31 - 0.68t
5000	0.44 - 0.96t
3000	0.73 - 1.6
1000	2.2 - 4.8t
300	7.3 - 16.0

With low-temperature radiation such as received from a wood flame ($T = 1000°K$), Table 8.3 and Fig. 8.1 indicate that differences in ignition due to absorptivity may be as high as 50 per cent between extremes. Spectral distribution measurements should be extended in order that these differences may be determined.

Calculation of emissivity for determination of back radiation during ignition also requires greater wave length range ($\lambda \leq 20$ microns) than presented here.t

At the temperature of carbon plate laboratory radiators ($T = 3000°K$) rather significant differences in total absorptivity should be noted between weathered fuels and others, as shown in Fig. 8.1. Sufficient spectral range is available but average values have not been determined for this temperature.

During ignition, decomposition and charring of the surface changes the spectral characteristics of the fuel and consequently the absorptivity. No information as to the magnitude of this effect is available for forest fuels at the present. However, initial absorptivity should serve as an index of the average absorption characteristics during ignition time.

BIBLIOGRAPHY

(1)t Stamm, A. J., and Loughborough, W. K. "Thermodynamics of thet Swelling of Wood," Journal of Physical Chemistry, XXXIX (1935)t 121-132.t

(2)t Stitt, Fred, and Kennedy, Evelyn Krause. "Specific Heats of De-t hydrated Vegetables and Egg Powder," Food Research, X (1945)t 426-436.t

(3) Bamford, C. H., Crank, J., and Malan, D. H. "The Combustion of Wood,t Proceedings Cambridge Philosophical Societyt XLII (1946), 166-182.t

(4)t Department of Scientific and Industrial Research and Fire Offices't Committee. Report of the Fire Research Board for the Year 1948. London: H. M. Stationery Office, 1949.

(5)t Klason, Peter. "Versuch einer Theorie der Trockendestillation vont Holz," Journal für praktische Chemie, XC (1914), 413-447.

(6)t Hawley, L.F., and Wise, Louis E. The Chemistry of Wood. New York:t The Chemical Catalog Co., Inc., 1926.

(7)t Byram, G.M., Sauer, F.M., Fons, W.L., and Arnold, R.K. Thermal Conductivity of Some Common Forest Fuels. U.S. Dept. Agriculture, Forest Service, Division of Fire Research. Interim Technical Report AFSWP-405, to be submitted November 1, 1952.

(8)t MacLean, J. D. "Thermal Conductivity of Wood," Heating, Piping,t Air Conditioning, XIII (1941), 380-91.

(9)t Cooper, B. E., and Derksen, W. L. Spectral Reflectance and Transmittance of Forest Fuel Materials. Material Laboratory, New York Naval Shipyard. Technical Report NS 081-001, 27 March 1952.