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SOLAR RADIATION AND FOREST FUEL MOISTURE

BY

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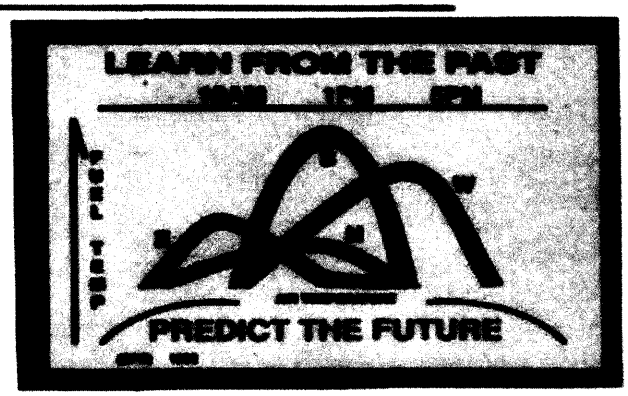
(Contribution from Forest Service)

Reprinted from JOURNAL OF AGRICULTURAL RESEARCH
Vol. 67, No. 4 : : : Washington, D. C., August 15, 1943
(Pages 149–176)



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U. S. GOVERNMENT PRINTING OFFICE : 1943

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Published with the approval of the Director of the Budget. Issued on the 1st and 15th of each month. This volume will consist of 12 numbers and the contents and index.

Subscription price:

Entire Journal:	Domestic, $3.25 a year (2 volumes)
	Foreign, $4.75 a year (2 volumes)
Single numbers:	Domestic, 15 cents
	Foreign, 20 cents

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SOLAR RADIATION AND FOREST FUEL MOISTURE[1]

By George M. Byram, *associate meteorologist*, and George M. Jemison, *senior silviculturist, Appalachian Forest Experiment Station, Forest Service, United States Department of Agriculture*

INTRODUCTION

A major contribution to progress in forest fire prevention and control during the past 10 years has been the development and widespread application of methods of rating forest fire danger.[2] Fire danger rating systems are now in use in all the forest regions of the United States. They have been described by Gisborne (*8*, *9*),[3] Brown and Davis (*2*), Curry et al. (*4*), Matthews (*13*), Jemison,[4] and others. Under each of these systems the major factors affecting fire danger are measured and the measurements are integrated by means of charts, tables, or some mechanical device into ratings, on a numerical scale, which are free from the serious errors common in estimates of fire danger based on personal judgment alone. The numerical ratings are usually defined in terms of probable fire behavior or of manpower required for suppression. They serve as a guide to efficient distribution of fire-control funds and personnel.

All these fire-danger rating systems include measurement of wind velocity and of fuel moisture content. Wind velocity, an extremely important factor whenever fuels are dry enough to burn, is usually measured with standard instruments. Fuel moisture content is more difficult to determine, because of the complex nature of fuels. Lightweight materials such as fallen leaves, needles, and twigs and dead grass respond readily to changes in atmospheric conditions. The condition of this litter[5] is determined indirectly from measurements of air temperature and humidity or, more commonly, is determined directly by means of calibrated "wood sticks," the moisture content of which changes in harmony with that of natural fuels similarly exposed. The moisture content of heavy fuels, such as large branches, logs of all sizes, snags, and deep, buried layers of duff, changes slowly, and its measurement requires different techniques. In some regions it goes through a seasonal cycle, so that calendar date is a good index of cumulative drying. Elsewhere, elapsed time since rains of different amounts serves as an index. The seasonal cycle differs between north- and south-facing slopes and between steep and gentle slopes, according to the

[1] Received for publication December 7, 1942.

[2] "Forest fire danger" as used here, is a general term signifying the combination of variable elements that determines whether fires will start, and if so, the probable rate of spread and extent of damage.

[3] Italic numbers in parentheses refer to Literature Cited, p. 175

[4] Jemison, G. M., the measurement of forest fire danger in the eastern united states and its application in fire prevention and control. Appalachian Forest Exp. Sta. Tech. Note 50, 59 pp., illus. 1942. [Processed.]

[5] Litter is the uppermost layer of organic materials in the forest floor, the structure of which has not been materially altered by decomposition.

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position of the sun, hence, the effectiveness of radiation. Another important element in fuel moisture conditions is stage of development of forest vegetation—the living fuel. This is ordinarily gaged by calendar date, ocular estimate, or actual measurement in the laboratory.

Determination of the best methods for measuring the moisture content of all types of fuels requires a knowledge of the interplay of controlling factors. For example, standards of how, where, and when to measure litter moisture and heavy fuel moisture cannot be established unless the controls of rates of drying and moisture equilibria are understood.[6] The weight that each fire-danger element should carry in the final rating, also, can be determined accurately only when the interactions of all controlling factors are known. The significance of season, elapsed time since rain, and similar indirect indices of fuel moisture depends on how the complex fuels of a given region react to the combined effect of the atmospheric factors. Furthermore, knowledge of the interaction of controls is needed in applying the ratings. In order to utilize efficiently the manpower available for fire suppression, a dispatcher needs to know how to adjust the rating available for his locality to allow for variations in temperature, humidity, and radiation brought about by variations in cover or topography in other parts of his district not served by a danger station. A fire boss on the fire line needs to be able to adapt danger ratings based on measurements taken elsewhere to fuel and weather conditions for areas in the path of the fire.

Although considerable effort has been made in the past to isolate the influence of each weather element, very little has been done to determine the effect of solar radiation on rates of drying of fuels and on the moisture equilibria of these fuels. The influence of shade on fuel and micro-climate has been discussed frequently. Stickel (*15*) obtained data confirming the importance of a timber canopy in maintaining high fuel moistures. He also found that in the mixed-hardwood-softwood forest region of the west-central Adirondacks, evaporation, hours since rainfall, duff temperature, air temperature, depression of the dew point, and relative humidity are most closely associated with litter moisture, in the order given. Mitchell (*14*) rated the general influence of individual weather elements on fuel moisture in the Lake States and showed how forest cover modifies atmospheric factors and hence fuel moisture. Jemison (*12*) found that absolute atmospheric moisture alone explained about as much of the variation in litter moisture content as did 15 weather factors combined. The work of these and other investigators brought out only indirect evidence, however, of the importance of solar radiation as a control of fuel moisture.

Gast and Stickel (*6*) were probably the first to investigate specifically the effect of sunlight on the rate of drying of forest fuels and consequently on fire danger. They compared fuel moistures in the open with those under the shade of bobbinet screens and found that the reduced radiation resulted in slower drying rates. From these investigations they concluded that degree of cloudiness could be used to gage fire danger and also that the amount of shade-producing cover on a cut-over area is an important criterion of the relative danger (dryness) on the area.

[6] Equilibrium moisture content may be defined as the asymptotic value which the actual moisture content approaches if the litter is subjected to a given temperature and humidity for an infinite length of time.

Hayes (*11*) measured air temperature, relative humidity, wind, litter moisture, maximum litter temperature, precipitation, and soil moisture on north and south slopes at each of three elevations in northern Idaho, and made a comparison of conditions as regards the first six of these elements on north slopes with those on south slopes. His results showed significant differences between the two aspects for all six elements except precipitation. He pointed out the importance of insolation as a control of fuel moisture, as indicated by measurements of maximum litter temperature. On south slopes, he found minimum litter moisture sometimes varied less than ± 1 percent from one clear day to the next, although maximum air temperature might range from 70° to 95° F., and minimum relative humidity from 30 to 15 percent. Hayes found that beds of pine duff on south slopes had a minimum moisture content, for a median day in August, about 2 percent lower than that of comparable beds on north slopes. His data indicate appreciable differences in fire behavior indices on north and south slopes.

The importance of solar radiation as controlling fuel moisture was mentioned by Byram (*3*). Radiation caused sticks exposed in calm air to dry rapidly. On wood sticks exposed to full sunlight, the drying action of wind was more than offset by its cooling action. Gisborne (*7*) found that sticks lying on litter were drier than those supported 10 inches above the litter surface, where circulation of air was greater.

An investigation of the influence of solar radiation on the moisture equilibria and rates of drying of forest fuels was begun by the Appalachian Forest Experiment Station in 1938, at the Bent Creek Experimental Forest, on the Pisgah National Forest, near Asheville, N. C. The investigation has included study of the effectiveness of radiation as a control of fuel moisture during different hours of the day and seasons of the year, on slopes of varied steepness and aspect. Theoretical relations between solar radiation and fuel moisture equilibria have been established and have been checked by field and laboratory experiments.

Under natural conditions, of course, fuel moisture is seldom in a state of equilibrium, but is usually increasing or decreasing. However, fuels with large exposed surfaces, such as hardwood leaf litter, approach the equilibrium moisture content after rain rather quickly. The rate of loss of moisture from forest litter in the southern Appalachian region on sunny days is so rapid that this layer of fuels may be considered as being in the equilibrium state most of the time.

The following technical discussion is intended to enable fire specialists to understand better the importance of radiation as a control of fuel moisture, and indicates work yet to be done on the problem. Suggestions are offered for use of the data, which may lead to refinements in some fire-control practices.

EXPERIMENTAL APPARATUS AND METHODS

In order to supply necessary constants in equations derived in this study, as well as to establish the effect of radiation on fuel moisture under a variety of topographic and atmospheric conditions, an "artificial sun" was constructed. This apparatus is actually a weather synthesizer, simulating variations of sunshine and wind, and making it possible to obtain quickly the effect of radiation as modified by topography on fuel moisture equilibria. It renders unnecessary the impractical alternative of measuring directly in the field the response of fuel moisture to numerous combinations of weather elements on several kinds of slope throughout a year.

Two such artificial suns are shown in figure 1. The walls of the artificial sun enclose a rectangular volume divided by a horizontal glass plate into upper and lower compartments. The lower and shallower compartment, open at both ends and at the bottom, serves as a wind tunnel. At the top of the larger compartment, twelve 150-watt tungsten bulbs are placed on the perimeter of a circle to provide radiation. It has been shown mathematically that a circular source of light or radiation gives uniform distribution of energy on a surface parallel to the plane of the source and situated at a distance from that plane equal to the radius of the circle. As the radius in this case was

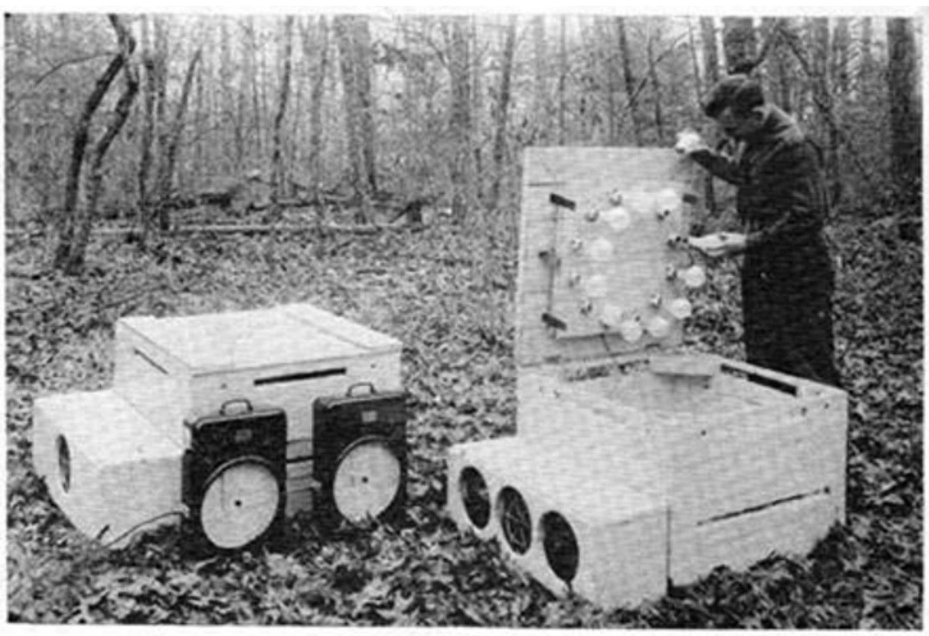

FIGURE 1.—Two artificial suns, or weather synthesizers.

9 inches, the bulbs were so placed that they were separated by a space of 9 inches from the leaf litter or other fuel tested. The whole interior of the apparatus was painted white, with the result that energy was uniformly distributed on the fuel even when only two or three bulbs were burning. The uniformity of radiation at the fuel surface was verified by careful checks with a photronic cell. The apparatus was placed directly over the natural litter in the forest or over fuel samples in the laboratory. Electric fans were used to draw air through the wind tunnel and over the fuel. Wind velocity was varied by adjusting the number of fans in operation or the openings in the box immediately behind them. Intensity of radiation was varied by turning on or off some of the bulbs; three or four bulbs, evenly spaced in the circle, were turned on or off at a time.

Usually two of the artificial-sun devices were operated simultaneously, so that results could be checked, or one of the three factors wind, radiation, and precipitation (simulated) could be varied while all other factors were held constant. Wet- and dry-bulb temperatures were taken outside the apparatus, 6 to 8 inches above the ground, with a hand-aspirated psychrometer. Within the artificial sun, surface fuel temperature was measured by means of a recording thermometer, the ⅛-inch cylindrical bulb of which was placed on the litter and covered with a single thickness of oak leaves. Leaf samples were periodically collected, weighed, and oven-dried, and the moisture content computed on the basis of oven-dry weight. Tests varied in length from 2 hours to 2 days, according to the time required for the moisture content of the fuels to reach equilibrium.

Intensity of radiation was measured with the ice calorimeter (fig. 2), a device composed of two identical ice-containing units, each unit consisting of a thin-walled copper cup blackened inside and heavily insulated. Each insulated lid has a 2-inch hole at its center. One hole is uncovered, to admit radiation; an insulated shade excludes

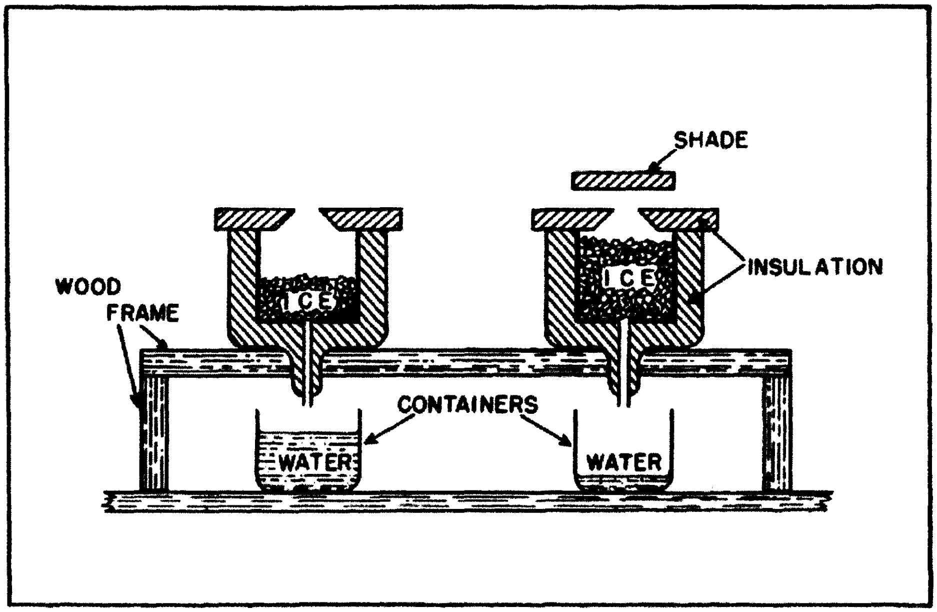

FIGURE 2.—Ice calorimeters used to measure intensity of radiation.

radiation from the other unit. Both units are exposed to the light source in the enclosed chamber of the artificial-sun apparatus. In use, each cup is two-thirds filled with ice. The difference in the number of grams of water draining from the two in a given time interval, multiplied by the heat of fusion of ice, gives the total radiant energy in calories admitted by the opening in the calorimeter lid during this interval. This energy, expressed in calories per square centimeter per minute, closely approximates the energy of solar radiation. Ten of the 150-watt bulbs gave 1.53 calories per square centimeter per minute, equivalent to very bright sunlight.

INTENSITY OF SOLAR RADIATION

The intensity of sunlight, varying with time of day, time of year, slope, aspect, latitude, and haziness of the atmosphere, can conveniently be expressed as a fraction of the theoretical maximum intensity or that received by a horizontal plane at the top of the atmosphere when the sun is at the zenith.

INTENSITY AS DETERMINED BY POSITION OF SUN, ASPECT, AND SLOPE

If atmospheric absorption is ignored, the intensity of solar radiation on a horizontal surface can be computed from the geometric position of the sun with respect to the surface. The sky may be regarded as a hemisphere, the lower boundary of which is the plane of the horizon.

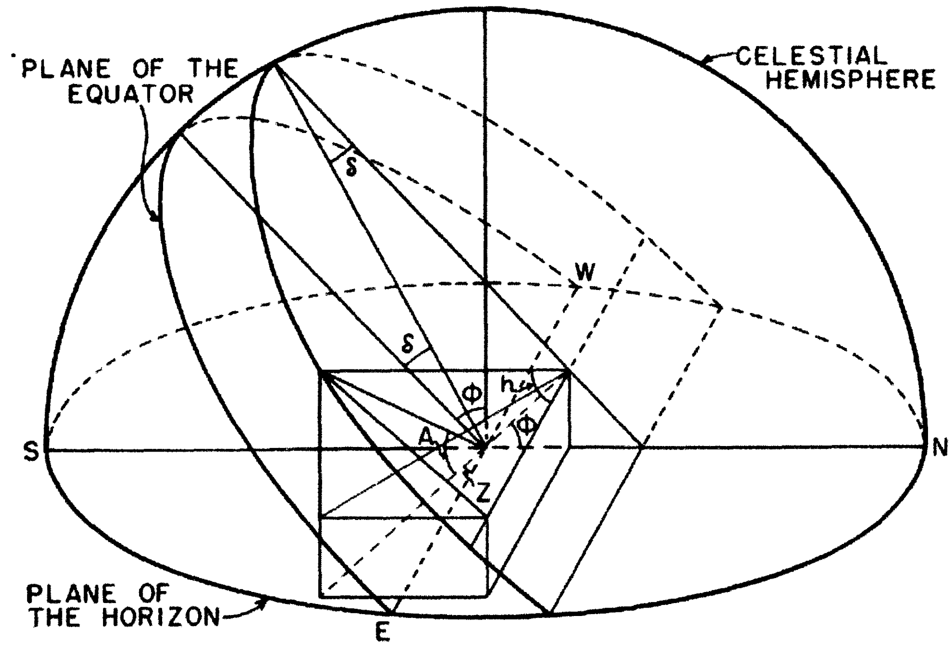

FIGURE 3.—Diagram of celestial hemisphere.

The daily paths of the sun are arcs on this hemisphere, as shown in figure 3. The angular altitude A of the sun is given by the equation

$$\sin A = \cos \delta \sin h \cos \phi + \sin \phi \sin \delta \qquad (1)$$

where δ is the solar declination, h the hour angle[7] (measured from 6 a. m.), and ϕ the latitude. The azimuth Z of the sun's position is given by the equation

$$\cos Z = \frac{\cos \delta \cos h}{\cos A} \qquad (2)$$

Figure 4 shows diagrammatically the conditions that exist when sunlight falls on a plane (mountain slope) tilted at some angle α from the horizontal and rotated clockwise through an angle β with respect to the east. The direction of the sun is along the line BC in the vertical plane CEB, and the lines BD and BE are the intersections of this plane with the tilted plane DHG and the horizontal plane EFG,

[7] In the standard equations given in a solar ephemeris or in most civil engineering handbooks or texts such as Breed and Hosmer (1), from which equations (1) and (2) can be derived, the hour angle is measured from noon and the azimuth angle is measured clockwise from north. However, in this study it was more convenient to measure the hour angle from 6 a. m. and the azimuth angle clockwise from east.

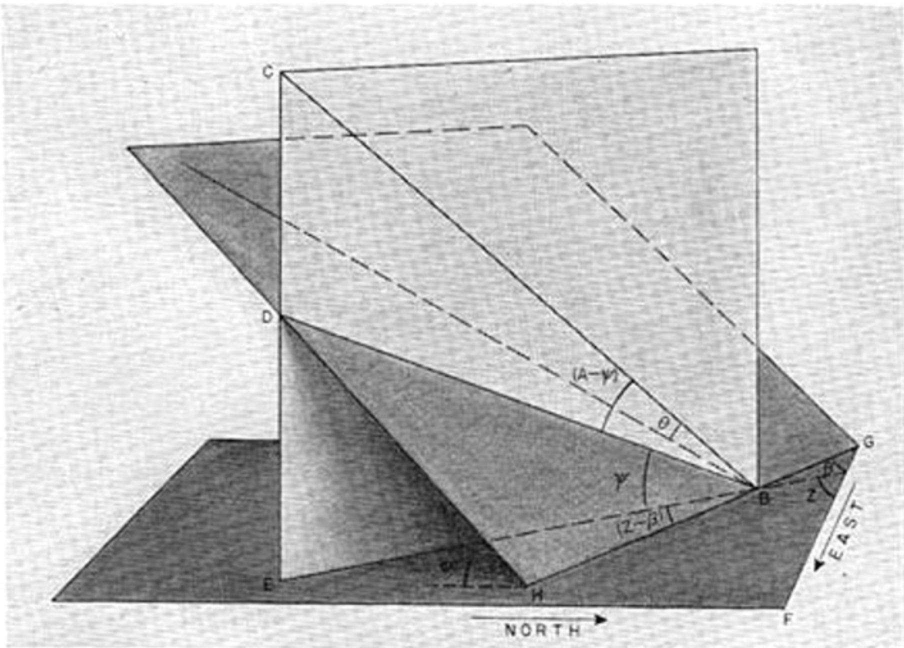

FIGURE 4.—Diagram from which the theoretical intensity of solar radiation on a tilted plane may be determined.

respectively. The angle *FGH* is the aspect angle β. For a mountain slope facing northeast, the aspect angle would be 45°; for one facing east, 90°; north, 0°; southwest, 225°. The intensity of radiation on the plane *DHG* is proportional to sin θ, which is given by the equation

$$\sin \theta = \sin (A - \psi) \frac{\cos \alpha}{\cos \psi} \tag{3}$$

the angle θ is the angle between the direction of the sun *BC* from a given point *B* in this plane and the projection of *BC* on the plane. Angle ψ is the angle between the projection of *BC* on the horizontal plane and the line *DB* formed by the intersection of the vertical plane and the tilted plane; tan ψ is given by the equation

$$\tan \psi = \sin (Z - \beta) \tan \alpha$$

which, when combined with equation (3), gives

$$\sin \theta = \sin A \cos \alpha - \cos A \sin \alpha (\sin Z \cos \beta - \cos Z \sin \beta) \tag{4}$$

EFFECTIVE RADIATION

The total amount of solar heat actually reaching the earth's surface is affected by atmospheric absorption of radiation. According to the law of absorption and Lambert's cosine law, the effective radiation received on any slope can be found from the equation

$$I = I_0 \sin \theta \, p^{\frac{1}{\sin A}} \tag{5}$$

where I is the incident intensity of radiation on a tilted plane at the surface of the earth, I_0 is the intensity of radiation at normal incidence on a horizontal surface at the top of the atmosphere, and p is the fraction of radiation transmitted at normal incidence through the atmosphere. The quantity I_0, the solar constant, equals 1.94 calories per square centimeter per minute according to Forsythe (*5*). However, it is often more convenient to express I_0 as unity so that I can be expressed as a fraction of I_0.

The absorption factor p is not constant from place to place or from day to day in a given locality, because it is affected by a large number of conditions such as water vapor, smoke, and dust in the air, and by altitude. In this study p was given an estimated value of 0.7, a reasonable average for a thin layer of rather dense haze, which is common at elevations of 2,000 feet in the southern Appalachian Mountains during the fall and spring fire seasons. In western forest regions of the United States the values of p may average somewhat higher than 0.7, although it is doubtful that they can ever be much above 0.8 except at great elevations. As defined and used in equation (5), p is independent of the vertical distribution of absorbing haze particles and the angular altitude of the sun.

The quantity I/I_0, which expresses the fraction of total possible radiation that actually reaches the earth's surface as determined from equation (5), has been presented in figure 5 as a function of time of day for typical combinations of slope, aspect, and season in the southern Appalachians. (The hour of maximum radiation intensity is that when the sun's rays approach the nearest to a 90° angle with the plane of the slope.) Curves showing fractions of maximum radiation received on 20-, 40-, and 100-percent south, north, and east slopes are plotted for June 21 and December 21, dates when the sun reaches its greatest and least angular altitudes. For the calculations represented in determining sin A, a latitude of 35°30′ was assumed. Solar declinations were obtained from a solar ephemeris, northern and southern declinations having the customary positive and negative signs, respectively.

The differences in radiation on north and south slopes brought out by figure 5 are particularly significant because direct sunlight is the greatest factor in drying exposed forest fuels. In deciduous forests or on clear-cut conifer forest areas in the eastern mountain regions, fuels are unshaded, or practically unshaded, during several months of the year. The hardwood stands are leafless from November into May, or even longer at some elevations and latitudes, and this period includes the major part of the annual fire season. On clear-cut or severely burned forest areas in the West, fuels are completely exposed to the sun throughout the fire season. Obviously, if ground fuels are partially shaded by a forest canopy, radiation intensity as represented in figure 5 is modified.

Among the southern exposures, in summer the 20-percent slope receives the greatest radiation, because this slope forms an angle of almost 90° with the sun's rays at noon. The 100-percent slope is too steep to receive maximum radiation at this hour. In winter, however, when the sun is low, the 100-percent slope receives more radiation than either the 20- or the 40-percent slope. Curves for other seasons of the year would fall between those shown for June 21 and December 21.

The picture for north-facing slopes is somewhat different. At the latitude of the southern Appalachians, where the sun approaches the zenith on June 21, 20-percent north slopes receive almost as much radiation in the summer as 20-percent south slopes. On 100-percent north slopes, however, the radiation at noon on that date is 0.38 of the maximum, as compared with 0.58 on south slopes of the same steepness. On December 21, 100-percent north slopes are in complete topographic shade, whereas 100-percent south slopes receive about 0.48 of maximum radiation at noon.

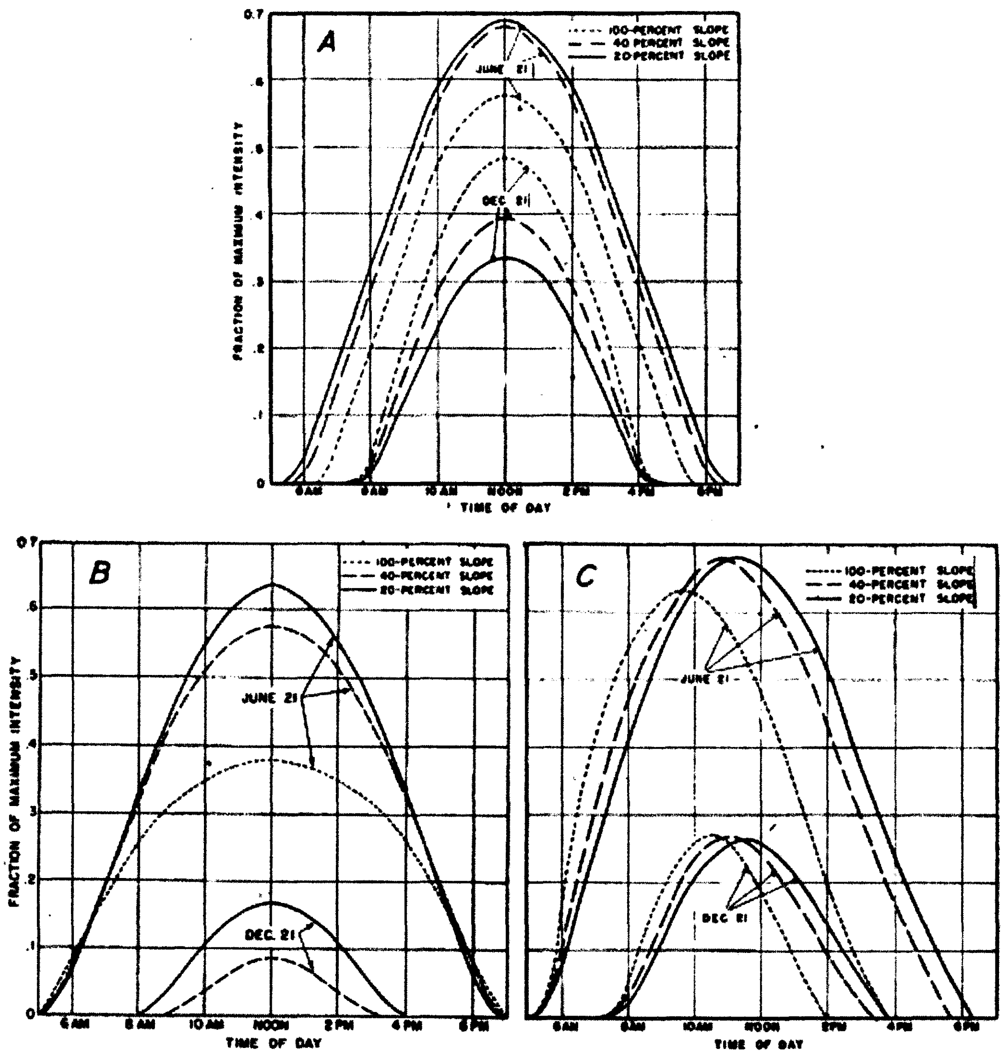

FIGURE 5.—Intensity of radiation received at different times of day on (*A*) south, (*B*) north, and (*C*) east slopes in the southern Appalachians, on June 21 and on December 21.

On east slopes, radiation intensity reaches its maximum before noon. For west slopes the curves would be mirror images of those for east slopes, the maxima occurring in the afternoon.

An example of the calculation of I, effective radiation received on a given surface, is presented as a guide to technicians who wish to adapt equations (1) to (5) to other regions of the United States.

Problem: To find radiation I, for a 20-percent east slope at 10 a.m. on June 21 at a north latitude of 35°30′.

Given: Hour angle $h=60°$ (measured from 6 a.m.).
Latitude $\phi=35°30'$ (assumed).
Aspect angle $\beta=90°$ (measured from north).
Angle of slope $\alpha=11°19'$ (for an assumed 20-percent slope).
Solar declination $\delta=23°30'$ (from solar ephemeris tables).
Solar constant $I_0=1$.
Absorption factor $p=0.7$ (assumed).

The following computations are sufficient for determining I. The sines and cosines of A and Z are found from equations (1) and (2) respectively. Sin θ is computed by means of equation 4 from the sines and cosines of A, Z, α, and β. The radiation I is then computed from equation (5). The details of these steps are as follows:

$$\text{Sin } A=\cos 23°30' \sin 60° \cos 35°30'+\sin 35°30' \sin 23°30'$$
$$=.878, \text{ and } \cos A=.478.$$

$$\text{Cos } Z=\frac{\cos 23°30' \cos 60°}{.478}$$
$$=.958, \text{ and } \sin Z=.287.$$

$$\text{Sin } \theta=.878 \cos 11°19'-.478 \sin 11°19' (.287 \cos 90°-.958 \sin 90°)$$
$$=.951.$$

$$I=.951\ (.7)^{\frac{1}{.878}}$$
$$=0.63 \text{ of maximum possible radiation.}$$

The value 0.63 thus derived checks with that plotted in figure 5, for the conditions assumed. To obtain the value I in calories per square centimeter per minute, 0.63 would be multiplied by the solar constant given by Forsythe, 1.94.

SOLAR RADIATION AND EQUILIBRIUM FUEL MOISTURE

To determine the quantitative relation between solar radiation and fuel moisture it was necessary to analyze the relations between temperatures and humidities of the fuel bed and the independent variables, air temperature, air humidity, wind, and insolation.

RELATIONS OF RADIATION AND WIND TO TEMPERATURE DIFFERENCE OF FUEL AND AIR

If $\frac{dQ_l}{dt}$ is the rate at which a fuel sample in sunlight loses heat and $\frac{dQ_g}{dt}$ is the rate at which it gains heat, then the temperature of the fuel sample remains stationary only if

$$\frac{dQ_l}{dt}=\frac{dQ_g}{dt} \qquad (6)$$

According to Newton's law of cooling, the rate of loss of heat from an object is directly proportional to the temperature difference existing between the object and its surroundings, and includes rates of loss due to free convection, conduction, and radiation. If the temperature difference is not very great, the radiation loss is small compared with the loss due to convection and conduction. This law can be generalized to give the rate of loss due to forced convection when the object is ventilated by an appreciable wind. If it is assumed that rate of loss of heat from forest fuels is directly proportional to wind velocity, it is possible to write the equation

$$\frac{dQ_l}{dt}=(aV+b)(T_f-T_a) \tag{7}$$

where V is wind velocity, T_f is fuel temperature, T_a is air temperature, and a and b are constants. The values of the constants a and b depend to a considerable extent on the nature of the fuel bed and the manner in which T_f is measured. In this study, for example, the value for T_f, the temperature of the air in the spaces under the topmost individual leaves, is considerably less than would be shown by a thermocouple with the junction cemented to the upper surface of a leaf. In addition, considerable heat is lost by conduction through the fuel bed into the ground. Radiation losses from forest fuels are small.

If I is the intensity of radiation in calories per square centimeter per minute as measured in the artificial-sun apparatus, and if this is the only source of heat, then from equations (6) and (7)

$$\frac{dQ_l}{dt}=\frac{dQ_s}{dt}=I=(aV+b)(T_f-T_a) \tag{8}$$

from which

$$T_f-T_a=\frac{I}{aV+b} \tag{9}$$

The relation between T_f-T_a and I for different wind velocities as established experimentally with the artificial-sun apparatus, is shown in figure 6 in which measured values of T_f-T_a are plotted against

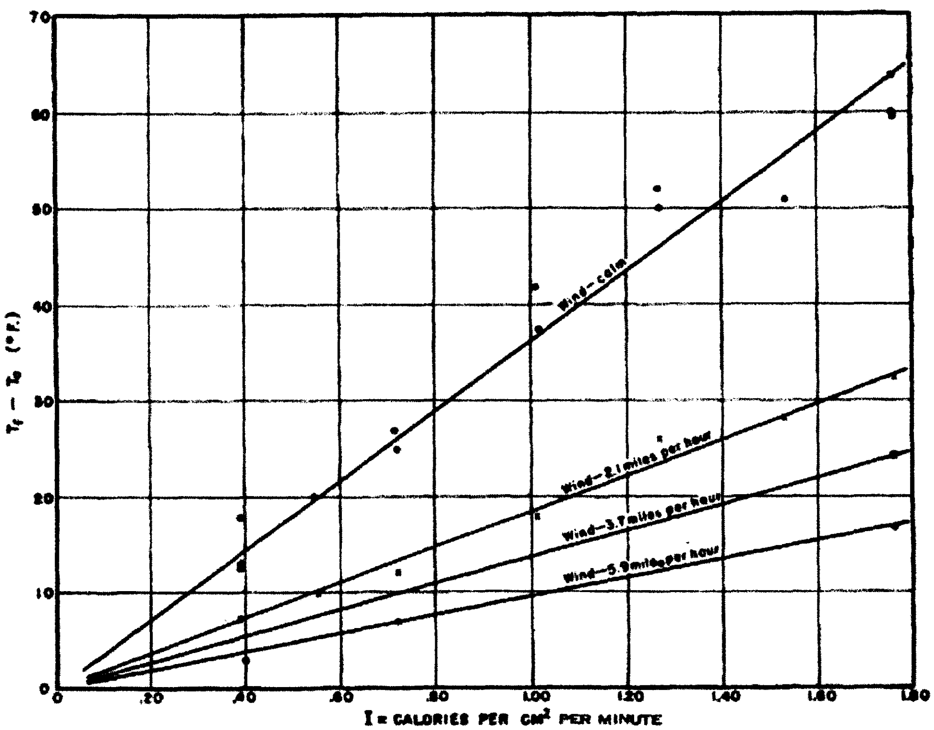

FIGURE 6.—Relation of radiation intensity I and wind velocity V to difference between fuel temperature and air temperature T_f-T_a, as established experimentally with the artificial-sun apparatus.

TABLE 1.—*Experimental data used in determining relation of $T_f - T_a$ to radiation intensity and wind velocity*

Radiation intensity, I (calories per cm² per minute)	Wind velocity, V	Air temperature, T_a	Surface fuel temperature, T_f	Temperature difference, T_f-T_a	Radiation intensity, I (calories per cm² per minute)	Wind velocity, V	Air temperature, T_a	Surface fuel temperature, T_f	Temperature difference, T_f-T_a
	M. p. h.	°*F.*	°*F.*	°*F.*		*M. p. h.*	°*F.*	°*F.*	°*F.*
0.39	0	79	92	13	1.01	2.1	84	102	18
.39	0	78	91	13	1.01	3.7	77	94	17
.39	0	79	97	18	1.27	0	74	124	50
.39	2.1	79	86	7	1.27	0	70	122	52
.39	5.9	79	82	3	1.27	2.1	74	100	26
.56	0	90	110	20	1.27	5.9	70	83	13
.56	2.1	90	100	10	1.53	0	75	126	51
.72	0	80	107	27	1.53	2.1	75	103	28
.72	0	84	109	25	1.76	0	77	137	60
.72	2.1	84	96	12	1.76	0	80	140	60
.72	5.9	78	85	7	1.76	0	83	146	63
1.01	0	77	119	42	1.76	2.1	76	108	32
1.01	0	83	120	37	1.76	5.9	83	100	17

measured values of I. The ranges in air temperature, fuel temperature, wind, and radiation under which observations were made are as follows: Air temperature, 74° to 90° F.; fuel temperature, 83° to 146° F.; wind, 0 to 5.9 miles per hour; radiation intensity, 0.39 to 1.76 calories per square centimeter per minute. Data forming the basis for figure 6 are given in table 1. Computing the constants a and b by the method of least squares gives for equation (9), when $T_f - T_a$ is in degrees Fahrenheit,

$$T_f - T_a = \frac{I}{0.015\,V + 0.026} \tag{10}$$

which adequately fits the experimental data. When a and b are determined directly from the data, it is not necessary to know the total emissivity or absorption factor of the fuel bed. It should be emphasized that, in fuel types in which loss of heat to the soil underlying the litter and loss to the air proceed at faster or slower rates than in the beds of hardwood leaf litter used in this investigation, other values for the constants a and b would be obtained.

RELATIONS OF RADIATION, HUMIDITY, AND WIND TO FUEL MOISTURE

The relation of radiation and relative humidity to fuel moisture can most easily be determined by means of the vapor pressure function. If the range of temperature is not too great, the saturated vapor pressure P_s in a given space at a temperature T is related to T approximately by the empirical equation

$$P_s = Ke^{cT} \tag{11}$$

where P_s is in millimeters of mercury, T is in degrees Fahrenheit, e is the base of natural logarithms, and K and c are constants. Table 2 shows the saturated vapor pressure of water for temperatures from 32° to 122° F. and corresponding values of Ke^{cT}, when K and c have values of 1.77 and 0.033, respectfully. That these assumed values provide a close approximation of P_s is seen by comparing the second and third columns in the table; the values agree closely except at high temperatures. The values of K and c in equation (11) could be altered slightly throughout the temperature range of, say, 60°

to 150°, which would be more suitable for use in summer, when fuel and air temperatures are high. This adjustment is unnecessary, however, because through a temperature range of 100° equilibrium fuel moisture values are changed only to the extent of about one-third of 1 percent by errors in the constant c. The constant K does not enter into determinations of fuel moisture equilibria.

TABLE 2.—*Saturated vapor pressure of water for temperatures 32° to 122° F. and corresponding values of Ke^{cT} when $K=1.77$ and $c=0.033$*

Temperature (°F.)	Saturated vapor pressure of water	Ke^{cT}	Temperature (°F.)	Saturated vapor pressure of water	Ke^{cT}
	Mm. of Hg	*Mm. of Hg*		*Mm. of Hg*	*Mm. of Hg*
32	4.58	5.09	86	31.82	30.22
41	6.54	6.85	95	42.18	40.69
50	9.21	9.22	104	55.32	54.76
59	12.78	12.40	113	71.88	73.70
68	17.54	16.69	122	92.51	99.18
77	23.76	22.47			

The vapor pressure P existing when the space is not saturated is related to P_s by the equation

$$P=HP_s \tag{12}$$

where H is the relative humidity. Hence, if P_a is the pressure of the water vapor in a given space at air temperature T_a and relative humidity H_a,

$$P_a=H_aKe^{0.033T_a} \tag{13}$$

and if P_f, T_f, and H_f refer to the same properties in a space immediately adjacent to the fuel particles,

$$P_f=H_fKe^{0.033T_f} \tag{14}$$

But when fuel moisture is in equilibrium, P_a and P_f are equal, hence (13) and (14) can be combined, which gives

$$\frac{H_f}{H_a}=e^{-0.033\ (T_f-T_a)} \tag{15}$$

Substituting (10) in (15) gives

$$\frac{H_f}{H_a}=e^{-I/(0.39V+0.85)} \tag{16}$$

Solutions for $\frac{H_f}{H_a}$ can be found from the nomographic chart figure 7. If any given values of V and I are connected with a straight edge, solutions for the ratio $\frac{H_f}{H_a}$ are given by the intersection of the straight edge with the line representing $\frac{H_f}{H_a}$. The value of H_f can be found from the ratio if H_a is known.

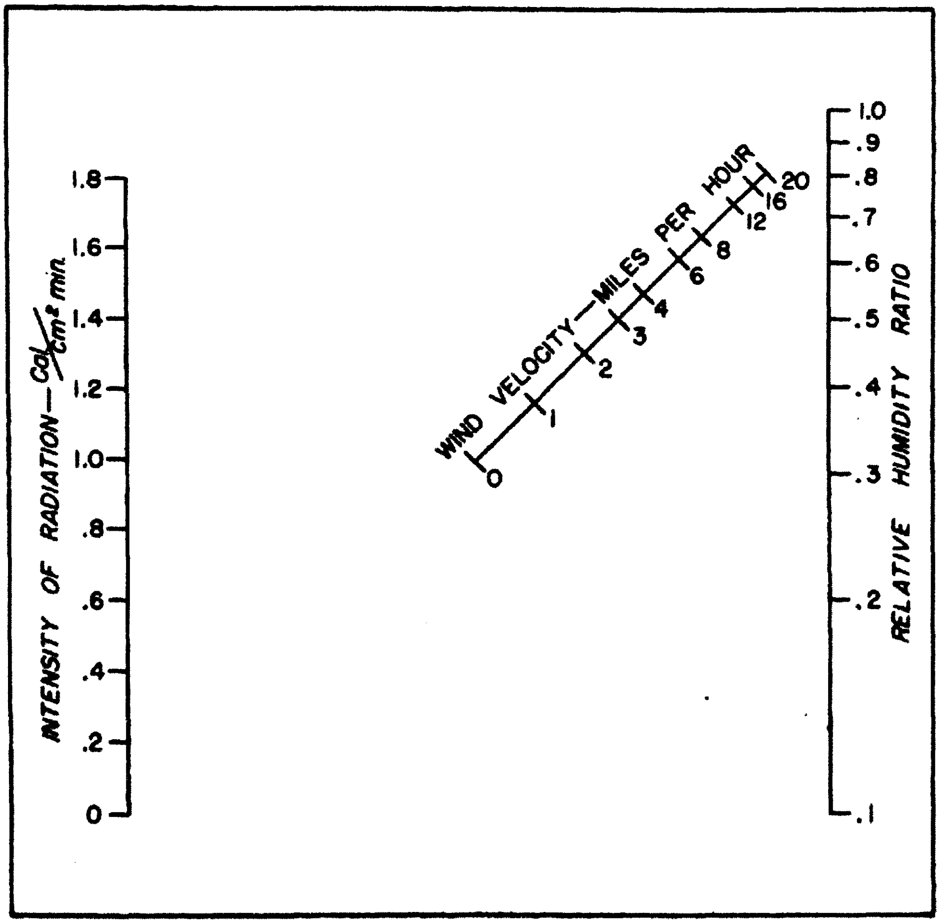

FIGURE 7.—Nomographic chart for solving the equation

$$\frac{H_f}{H_a}=e^{-I/(0.39V+0.85)}$$

The equilibrium moisture content of forest fuels (and cellulose materials in general) is determined chiefly by relative humidity, although temperature has considerable influence. From figure 8, which applies to any finely divided fuel,[8] equilibrium fuel moisture content can be found if fuel temperature T_f and fuel humidity H_f are known. With no sunlight, or if the fuel is completely shaded, fuel temperature and humidity are approximately the same as air temperature and humidity. Under either of those conditions, figure 8 may be used to find equilibrium fuel moisture by considering that $T_f=T_a$ and that $H_f=H_a$.

It is possible to determine fuel moisture equilibria for any given combination of air temperature, relative humidity, wind, and radiation by computing the effective temperature T_f and effective humidity H_f and applying these to figure 8. For example, what is the fuel moisture equilibrium when air temperature is 80°F., atmospheric relative humidity is 30 percent, wind velocity is 0, and radiation intensity is

[8] Except for high moisture contents, figure 8 checks closely with a fuel moisture equilibrium chart for Sitka spruce wood given by L. F. Hawley (*10, p. 8*), and with a series of similar relations for several kinds of light fuel reported in the following: DUNLAP, M. E. THE RELATION OF HUMIDITY TO THE MOISTURE CONTENT OF FOREST FIRE FUELS. U. S. Forest Serv., Forest Prod. Lab. 9 pp., illus. 1924. (Unpublished).

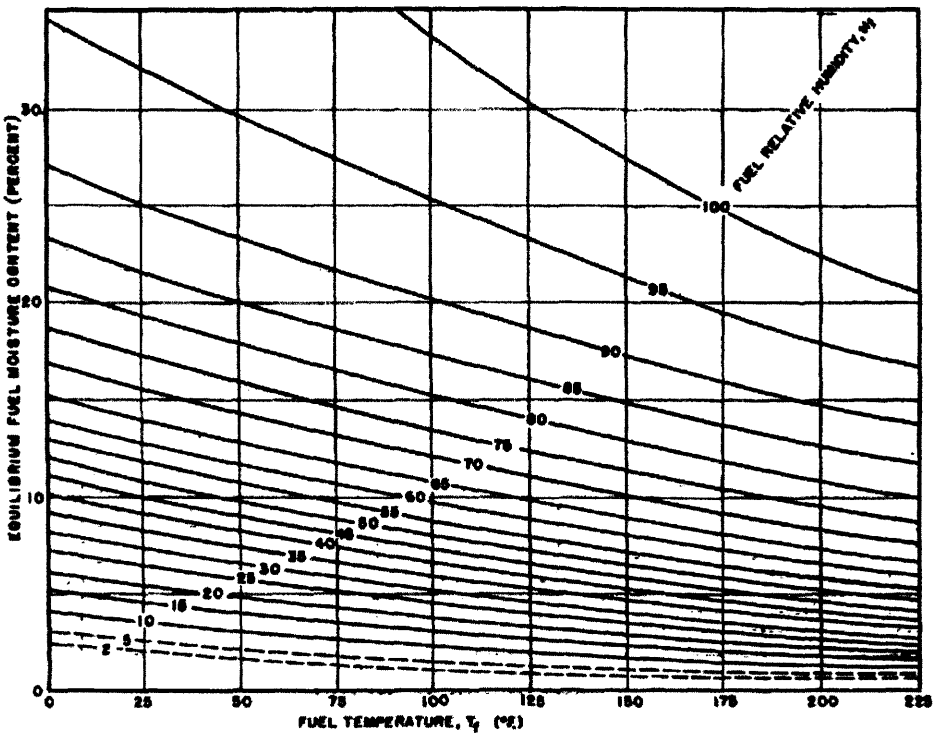

FIGURE 8.—Chart for determining equilibrium fuel moisture content on the basis of fuel humidity and fuel temperature. (Adapted from chart based on results of experimental work by the U. S. Forest Products Laboratory and published in the following: GRAY, L. G. PRELIMINARY REPORT ON FIRE HAZARD RATING STUDY. U. S. Weather Bur. San Francisco. 1933. [Processed.] The broken lines have been added by extrapolation.)

0.80 calories per square centimeter per minute on a slope fully exposed to the sun? From figure 6 the difference between litter and air temperature ($T_f - T_a$) is found to be 29°, which means that effective or fuel temperature is 109°. The relative-humidity ratio $\frac{H_f}{H_a}$ is found from figure 7 to be approximately 0.4. Effective humidity (at fuel surface) is then easily found; since

$$\frac{H_f}{H_a}=0.4 \text{ and } H_a=30$$

$$H_f=12 \text{ percent}$$

When 109° and 12 percent are used in figure 8 as the values for T_f and H_f, respectively, equilibrium fuel moisture is seen to be about 2.5 percent.

Under the conditions assumed above—air temperature of 80° F. and humidity of 30 percent—but with radiation intensity of 0, equilibrium fuel moisture as determined from figure 8 would be 6 percent. Thus, under these air conditions, where fuel in the sunlight would have an equilibrium moisture content of 2.5 percent, fuel in shade would have one of 6 percent.

Close agreement between equilibrium fuel moistures experimentally determined and those computed from figures 7 and 8 is indicated by the data presented in table 3. The experimental values are from 0

TABLE 3.—*Comparison of experimentally and theoretically determined fuel moisture equilibria for different combinations of radiation, wind, temperature, and humidity*

THIN BASWOOD SLATS

Radiation intensity, I (calories per cm.[2] per minute	Wind velocity, V	Surface fuel temperature, T_f	Air humidity, H_a	Humidity ratio, H_f/H_a	Fuel humidity, H_f	Equilibrium fuel moisture	
						Theoretical[1]	Experimental[2]
	M.p.h.	*°F.*	*Percent*		*Percent*	*Percent*	*Percent*
0.39	0	97	78	0.62	48	7.7	7.7
.39	2.1	86	78	.80	62	11.0	11.1
.56	0	110	54	.52	28	4.3	5.3
.56	2.1	100	54	.71	38	6.2	6.6
.72	0	109	30	.42	13	2.5	3.6
.72	2.1	96	30	.64	19	3.6	4.7
1.01	0	120	50	.30	15	2.6	3.8
1.01	2.1	102	50	.55	28	4.7	5.4
1.27	0	124	60	.22	13	2.5	3.6
1.27	2.1	100	60	.48	29	5.2	5.3
1.58	0	126	58	.17	10	2.0	2.9
1.58	2.1	103	58	.40	23	4.2	5.3
1.76	0	137	56	.13	7	1.8	3.6
1.76	2.1	108	56	.34	19	3.5	4.3
1.76	0	135	60	.13	8	1.9	3.0
1.76	3.7	102	60	.58	35	5.9	5.9
1.76	0	146	54	.13	7	1.5	2.4
1.76	5.9	100	54	.57	31	5.2	6.4

HARDWOOD LEAF LITTER

1.76	0	160	47	0.13	6	1.8	2.8
1.76	5.7	98	47	.55	26	4.6	5.6
1.76	0	125	53	.13	7	2.0	2.7
1.76	6.5	91	53	.58	31	6.0	7.0

[1] Computed from figures 7 and 8.
[2] Determined by use of the artificial-sun apparatus.

to 1.8 percent higher than those computed from the graphs; the average departure is 0.8 percent. Undoubtedly, this difference was due partly to a slight lag in rate of drying but mostly to hysteresis.

EFFECT OF WIND ON MOISTURE EQUILIBRIA OF IRRADIATED FUELS

From equation (16) one would be inclined to deduce that fuels exposed to both radiation and wind have higher equilibrium moisture contents than fuels exposed to radiation in still air. Although contrary to the usual ideas of drying phenomena, this deduction is conclusively borne out by the fuel moisture curves in figures 9, 10, and 11, and by the data presented in table 3. Figure 9, based on data for thin basswood slats immersed in water and then exposed in artificial-sun apparatus, shows that the slats had higher equilibrium moisture contents in wind than in calm air. Figure 10 indicates a similar contrast between slats in wind and in calm air that were started at oven dryness. Figure 11 shows the rate of drying of hardwood leaf litter having an initial moisture content of about 20 percent, a value within the inflammable range. This fuel responds in a manner identical to that of the wood slats represented in figures 9 and 10.

The higher moisture equilibria of irradiated surface fuels subjected to wind are due to the higher humidities associated with lower fuel temperatures. For irradiated fuels the cooling action of wind more than offsets its drying action. Figure 10 demonstrates that a cool fuel can absorb and hold more moisture than a hot one. (This is a partial explanation for the fact that higher moistures exist on cut-over areas bearing residual stands than on comparable clear-cut areas.)

The general conclusion may be drawn that, in regions where forest

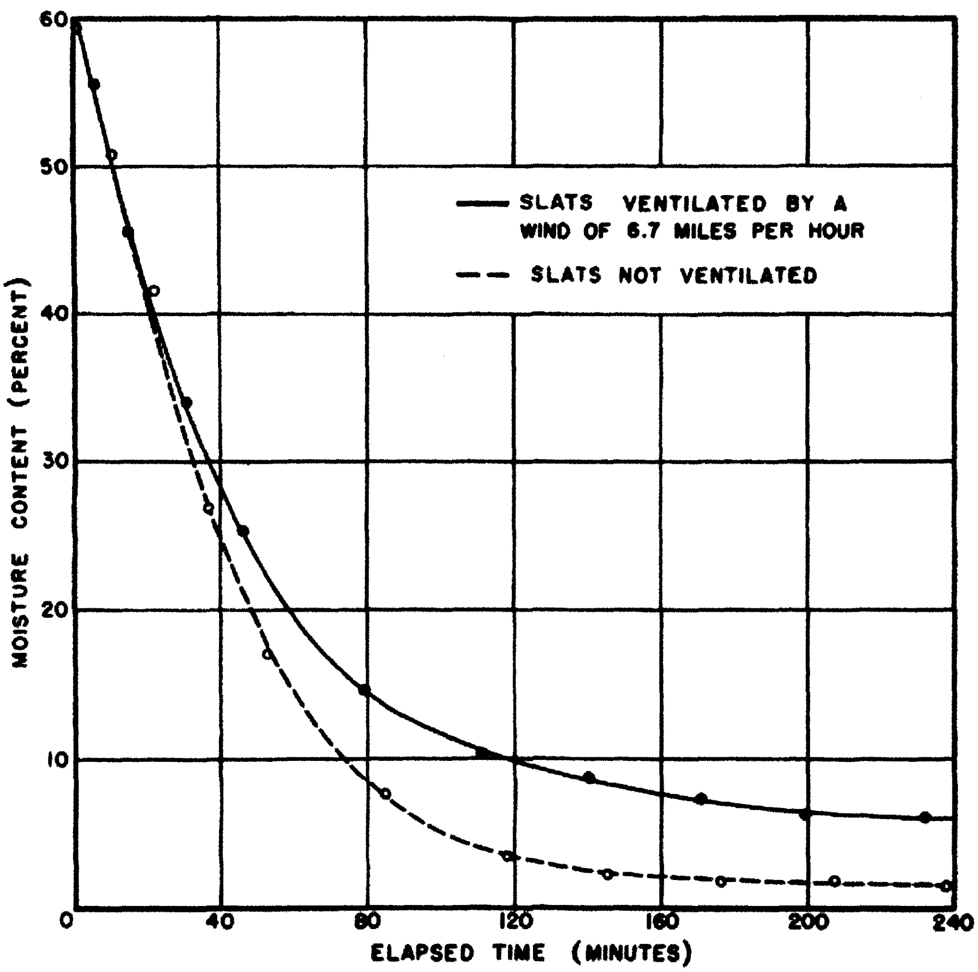

FIGURE 9.—Drying curves for irradiated wood slats exposed in calm air and for others exposed to a wind of 6.7 miles per hour. Slats were initially immersed in water. Relative humidity during test, 55 percent; air temperature, 80° F.; radiation, 1.76 calories per square centimeter per minute.

fuels are normally exposed to sunlight, higher fuel moisture equilibria are associated with clear windy weather than with clear calm weather. The difference may be as great as 6 percent, depending chiefly on levels of the atmospheric factors temperature, humidity, and wind. It is greatest for the range of fuel moisture below about 15 percent. This influence of wind operates only to a slight extent on steep north slopes, where insolation is low.

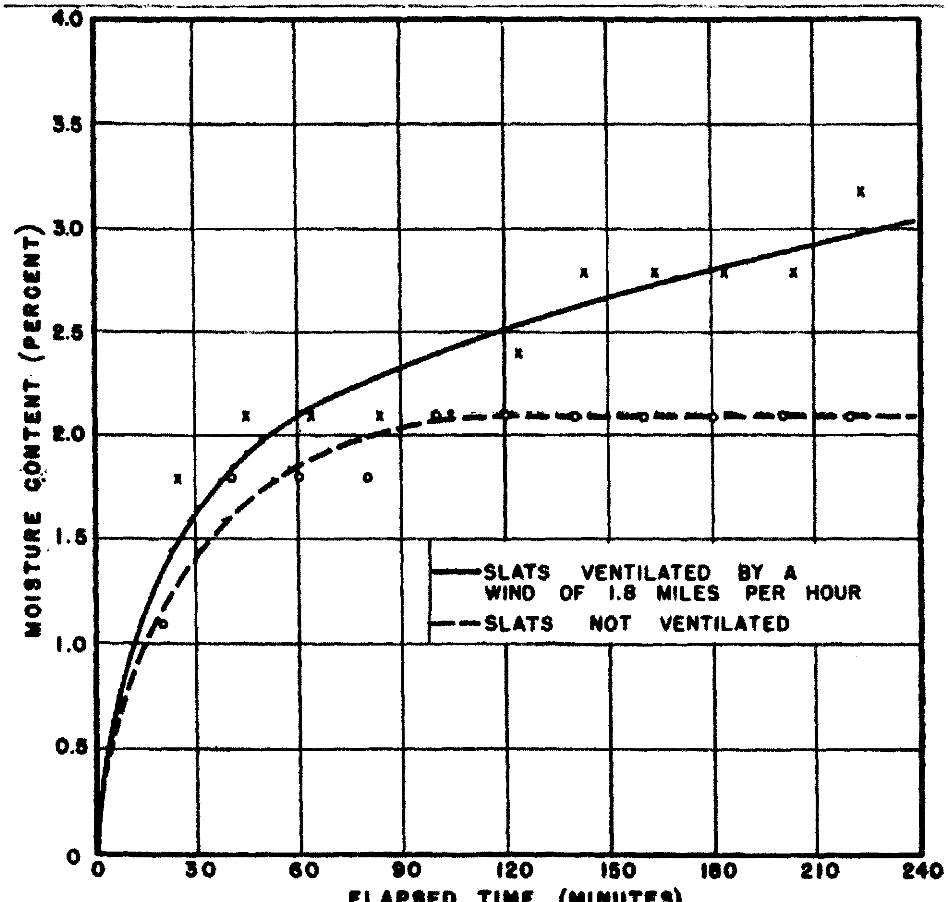

FIGURE 10.—Curves showing effect of wind on rate of gain of moisture by wood slats initially oven-dry and exposed to a radiation of 1.76 calories per square centimeter per minute. Relative humidity during test, 62 percent; air temperature, 82° F

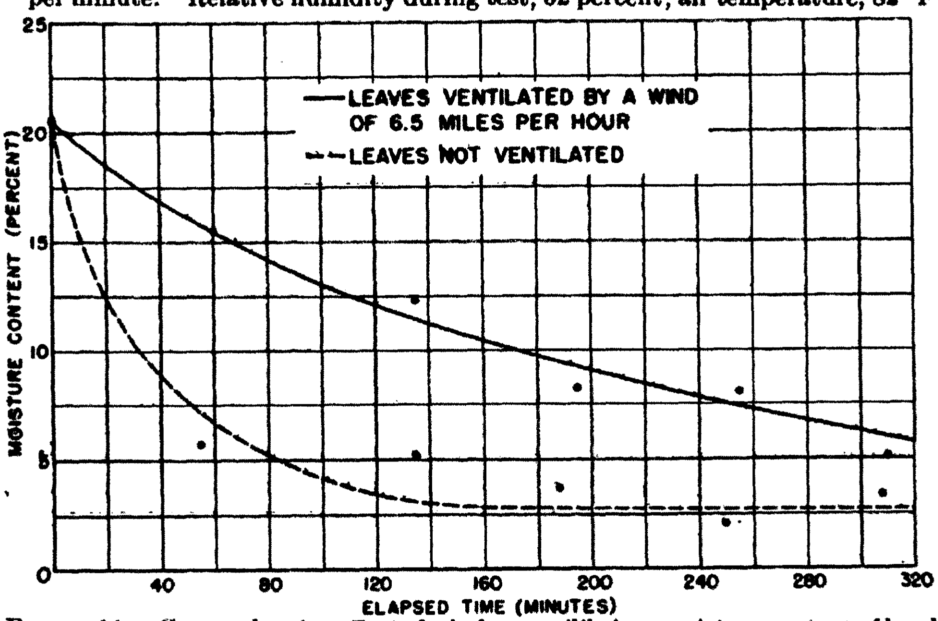

FIGURE 11.—Curves showing effect of wind on equilibrium moisture content of hardwood leaf litter exposed to a radiation of 1.76 calories per square centimeter per minute. Relative humidity during test, 51 percent; air temperature, 84° F.

SOLAR RADIATION AND RATE OF DRYING OF FOREST FUELS

As has been stated, the moisture content of the surface forest litter in the southern Appalachian region may be considered as being in the equilibrium state most of the time. The moisture content of lower layers of forest fuels, on the contrary, is not often in equilibrium with the humidity of the air immediately above the fuel bed; and it has almost as great an influence as that of the surface fuels in determining the inflammability of the total fuel layer. The rate at which subsurface fuels dry out after a rain is therefore particularly important. Only after determining the principles that govern this rate of loss of moisture can fire-research specialists supply fire dispatchers with guides that will enable them to judge when fuel is approaching an inflammable state. A complete solution of the rate-of-drying problem would find more immediate application than one of any other phase of fuel moisture studies.

Complete solution of the rate-of-drying problem is outside the scope of the present investigation, but this problem deserves discussion in connection with a general analysis of the factors upon which fuel moisture content depends. For the benefit of other investigators, some of the theoretical concepts of rate of drying of forest fuels will be outlined.

If q is the moisture content of a thin layer within a thick (about 2-inch) bed of fuel, the rate of loss of moisture from this layer should be given with reasonable accuracy by a differential equation of the form

$$\frac{dq}{dt}=-f_1(q)(P_f-H_aP_s)f_2(V)f_3(D) \tag{17}$$

where P_f is the pressure of water vapor within the fuel layer, P_s the pressure of saturated water vapor at air temperature, H_a the relative humidity of the air at the surface of the fuel bed, $f_1(q)$ some undetermined function of fuel moisture, $f_2(V)$ some function of wind velocity V, and $f_3(D)$ some function of the thickness D of the fuel above the selected thin layer.

The evaporating force is proportional to the term $(P_f-H_aP_s)$, but the rate of evaporation depends also on the vapor pressure gradient existing between the fuel layer and the space immediately above the surface of the fuel bed. The vapor pressure gradient is determined in part by the thickness and porosity of the fuel above the layer under consideration, and in part by wind velocity. The rate of evaporation depends in some complex way on the water supply or on $f_1(q)$. The vapor pressure P_f in the fuel layer is a function of the temperature of the fuel layer, which in turn is determined by air temperature, wind velocity, intensity of radiation, and rate of evaporation $\frac{dq}{dt}$. If a temperature gradient exists in the fuel bed, P_f depends also on D. If the moisture content q is below the fibre saturation point (about 30 percent) P_f is a function of q, since the water molecules in that case become partially bonded to the molecules of wood substance and this causes a decrease in P_f. For this reason equation (17) cannot easily be integrated if q is less than 30 percent. For values of q above the fibre saturation point, equation 17 can be integrated as follows, provided that the rate of loss of heat due to evaporation cooling is small compared with the intensity of radiation:

$$\int_{q_o}^{q}\frac{dq}{f_1(q)}=-(P_f-H_aP_s)f_2(V)f_3(D)\int_o^t dt$$

or

$$F(q_o)-F(q)=(P_f-H_aP_s)f_2(V)f_3(D)t \tag{18}$$

where $F(q)$ is the integral of $f_1(q)$

To find the time required for two similar layers of fuel to lose equal amounts of water under different intensities of radiation and wind velocities, it is possible to write

$$F(q_0)-F(q)=(P_f-H_aP_s)f_2(V)f_3(D)t=(P'_f-H_aP_s)f_2(V')f_3(D)t'$$

or

$$(P_f-H_aP_s)f_2(V)t=(P'_f-H_aP_s)f_2(V')t' \tag{19}$$

where P'_f, V', and t' are fuel vapor pressure, wind velocity, and time, respectively, for the second fuel layer. P_f and $P^1{}_f$ must be the saturated vapor pressures corresponding to the fuel temperatures, and should be regarded as the vapor pressures existing on the surface of individual wet leaves in the fuel layers. After substitution of the exponential relation (equation 11) for vapor pressures and simplification, equation (19) becomes

$$[e^{c(T_f-T_a)}-H_a]f_2(V)t=[e^{c(T'_f-T_a)}-H_a]f_2(V')t'$$

Substituting $\frac{I}{aV+b}$ for T_f-T_a (equation 9) gives

$$\left[e^{\frac{cI}{aV+b}}-H_a\right]f_2(V)t=\left[e^{\frac{cI'}{aV+b}}-H_a\right]f_2(V')t' \tag{20}$$

When an assumed wind velocity value of 2.5 miles per hour was inserted in equation (19) along with the values of a, b, and c previously given, the equation was simplified to

$$(e^{0.541}-H_a)t=(e^{0.541'}-H_a)t' \tag{21}$$

Values computed from this equation for relative time required for thin layers of fuel near the surface of fuel beds on north and south slopes to lose equal amounts of moisture after a rain are presented in table 4.[9]

TABLE 4.—*Relative drying time*[1] *of fuel near surface of fuel bed on north and south slopes in May and November*

Slope (percent)	May 6		November 6	
	North	South	North	South
20	2.5	2	7	4
40	2.5	2	9	3.5
60	3	2	15	3.5

[1] Calculated by use of equation (21). Wind velocity of 2.5 m. p. h. and 40 percent relative humidity are assumed. Values may be regarded as either days or hours.

[9] According to the current results of a study to determine the effect of terrestrial radiation on fuel moisture, on most forest areas the ratios of time required for drying on north slopes to that required on south slopes may be considerably greater than indicated in table 4. Under some conditions, north slopes may actually gain moisture on calm, cloudless days and nights while adjacent south slopes continue to lose moisture. Equation (17) is sufficiently general to include in its solution the effects of terrestrial radiation on fuel moisture.

The tabular value of t, relative drying time, for a given slope and season of year is the reciprocal of the area between two curves plotted on the same graph, one representing hourly values of the quantity $e^{0.541}$, the other representing values of relative humidity H_a drawn as a smooth curve from 100 percent at sunrise to 40 percent at noon to 70 percent at sunset. It was assumed that no significant drying occurred during the night. The area between the two curves represents the integrated value of $e^{0.541}-H_a$ for the daylight hours.

Experimental data obtained with the artificial-sun apparatus show

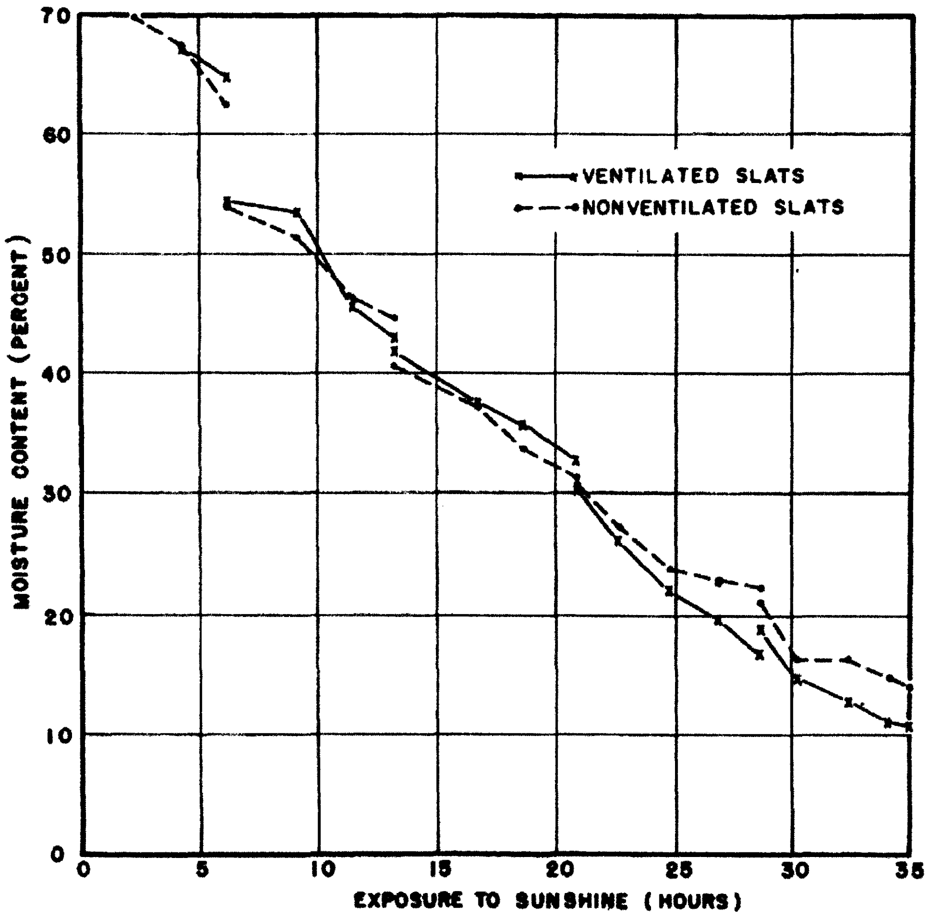

FIGURE 12.—Drying curves for lower layers of fuel exposed to radiation, as measured by thin slats buried in the lower layers of litter. (Breaks in curves indicate effect of turning off fans and lights in artificial-sun apparatus at night.)

that, in bright sunlight, winds of low velocities (1 to 3 miles per hour at the fuel surface) have no appreciable net effect on rate of drying of subsurface fuel. This is illustrated by drying curves for the lower fuel presented in figure 12. The same thing is true of basswood slats of high moisture content, as is shown by the portion of figure 9 representing moistures above the fibre saturation point. In this figure it will be noted that when their moisture content was above 30 percent, the slats dried at almost the same rate in calm air as in a wind of 6.7 miles per hour. A logical explanation is that although wind has a pronounced tendency to hasten drying this is offset, when wind velocity is low and radiation intensity is high, by its tendency to cancel the influence of radiation on temperature, just as is the wind's tendency to lower the equilibrium moisture content of surface fuels. Figure 13, which shows the effect of wind on the rate of drying of basswood slats in the absence of radiation, indicates that this explanation is correct, because the fuel in wind dried faster than that in calm air.

Probably several other factors influence the form of the basic equation (18), and the values presented in table 4 may be only rough approximations. For example, the moisture gradient within a drying fuel bed is affected by the loss of moisture from all fuel layers, not just

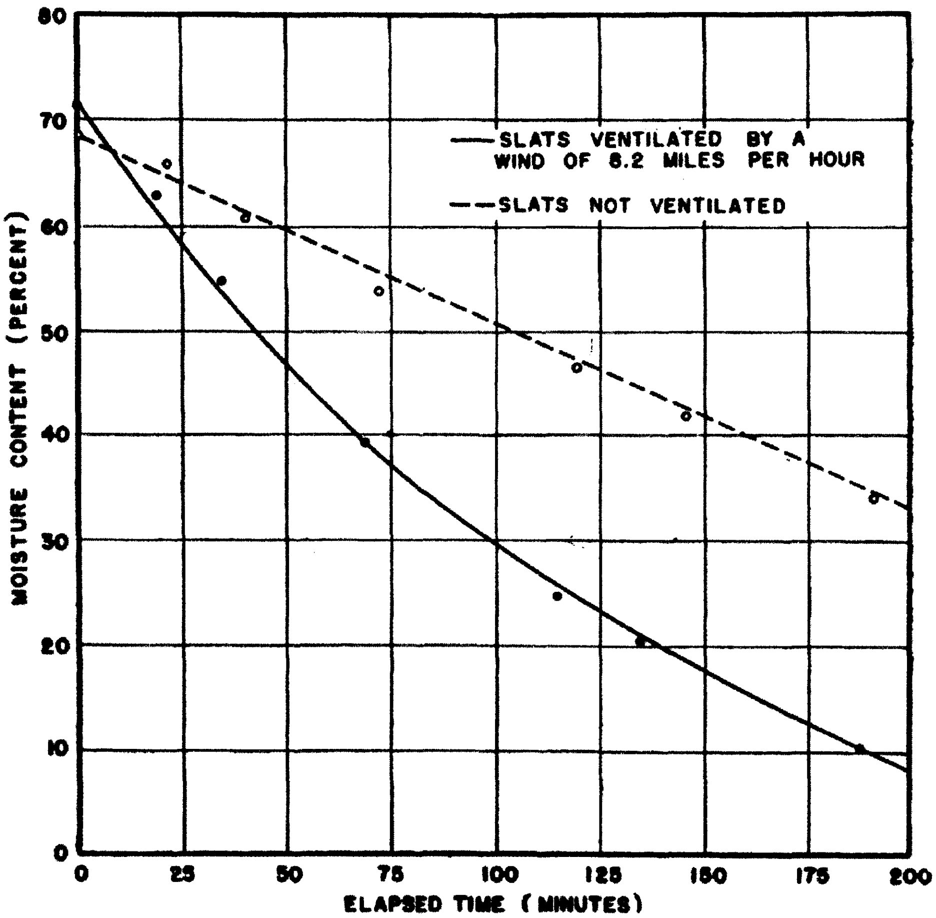

FIGURE 13.—Rates of drying of ventilated and nonventilated wood slats in absence of radiation.

one layer. However, equations (19) to (21) probably would not be changed appreciably by variation in the moisture gradient. A vertical temperature gradient also exists within a fuel bed, and $T_f - T_a$ is smaller for lower fuel layers than for layers near the surface. For thin basswood slats exposed so that the air can circulate freely about them, the rate of heat loss due to evaporation cooling is not small compared with the intensity of radiation received; it may occasionally be almost half as great as the radiation intensity. However, evaporation cooling is probably much less in fuel beds.

The development of rate-of-drying equations for moisture contents below the fibre saturation point is a phase of the problem that has received relatively little attention from technical foresters, but is one of extreme importance.

Work on the entire rate-of-drying problem is continuing at the Appalachian Forest Experiment Station.

SIGNIFICANCE AND APPLICATION OF FINDINGS

As was mentioned in the introduction, fire-danger ratings are used as guides in the employment and disposition of fire-control personnel. When the weather becomes dry and windy, more lookout men and suppression crews are required—especially in the drier and windier parts of a forest. Danger ratings help fire-control administrators to estimate how many men they need and to distribute their forces advantageously. In order to increase the refinement with which forest fire-danger ratings are made and applied, one necessity is to gain a better understanding both of the influence of topography and of "season of the year" on fire danger. In the United States the significance of seasonal changes in radiation intensity is particularly great in northern latitudes; in hardwood forest types that are leafless during late spring, when radiation is intense; on areas of rugged topography; and on western burned-over areas where dead forest fuels are exposed to sunlight during the summer months. This paper provides technicians in all regions with a general technique and equations for computing moisture equilibria of surface fuels for any combination of date, hour, slope, aspect, air temperature, air humidity, and wind, and with information on some of the basic relations governing rate of drying. This should lead to a better understanding regarding these factors on the part of workers engaged in perfecting fire-danger rating systems. Eventually, by acquiring and using a knowledge of radiation effects, it should be possible to modify the several measurements made at a skeleton network of fire-danger stations to fit all topography adjacent to the stations, thus greatly reducing the labor and cost of danger measurements.

Rates of drying of forest fuels calculated in this study can be used as a partial correction for ratings of fire danger at key stations, to make them apply to areas where conditions cannot be measured. Table 4, compiled in connection with the theoretical development of rate-of-drying relations, brings out differences in rate of drying for several aspect-slope-season combinations. After a rain in early May, it indicates, the fuel on a 60-percent south slope in the southern Appalachians loses as much moisture in 2 days as that on a corresponding 60-percent north slope loses in 3 days. Likewise in November the fuel on the south slope dries from a saturated condition down to an inflammable one in 3½ days, but the fuel on the north slope does not reach this point until after 15 days of the same type of weather.

Rate-of-drying data will become especially valuable to fire-control administrators when more is learned about variations in effect of wind corresponding to topographic variations and about variations in temperature and humidity corresponding to variations in elevations. Hayes (*11*) has worked on the latter problem in the northern Rocky Mountains, and similar studies have been in progress for 3 years in the southern Appalachians. Thus far, the most important variation isolated in these studies is that of ground wind velocity with elevation and aspect.

An example will indicate to fire specialists how the findings of this study may eventually be applied, at the same time indicating deficiencies in present knowledge and a direction for future work.

A small portion of the Pisgah Ranger District of the Pisgah National Forest, in western North Carolina, has been used for this illustration. For May 6 and November 6, near the peak of the spring and fall fire seasons, a typical set of conditions has been assumed; namely, air temperature of 70° F., relative humidity of 40 percent, no wind at the litter surface, and the hour of 2 p. m., when the moisture content of light fuels is likely to be close to the equilibrium point. Usually, on those dates, a typical hardwood forest at the average elevation of the Pisgah district, about 4,000 feet, is leafless and a maximum of sunlight penetrates the stand and reaches the fuels of the forest floor.

To illustrate in detail the variations in fuel moisture equilibria associated with topography, due to unequal insolation, lines passing through points of equal surface fuel moisture equilibria as determined according to the findings of this study have been superimposed on an enlarged contour map of this area, which is roughly 2½ miles square, for May 6 and November 6 (fig. 14). The variation brought out emphasizes the problem confronting one who must locate fire-danger stations to sample "representative" conditions of fuel moisture. Knowledge of this variation, however, should help him choose locations that meet the specifications set up. The spread in equilibrium fuel moisture on November 6 is 5 percent, a difference particularly significant in such a low range of fuel moisture as that represented here. On May 6 fuel moistures are lower and there is less difference between north- and south-facing slopes, because the sun is higher and its rays are more effective.

Table 5, showing the relative portions of the area on which equilibrium surface fuel moisture content was theoretically of given classes on the two dates, emphasizes the significance of the seasonal differences brought out in figure 14. In the southern Appalachian system of danger rating, fuel moisture of less than 4 percent is classed as critical. In May, equilibrium moisture content falls in this extreme class on 76 percent of the area used in the illustration; in November, under exactly the same atmospheric conditions it does so on only 9 percent. In other words, in November it is likely that fewer fires will start and those that start will spread more slowly and be easier to control on much more of the area than in May, even though all atmospheric conditions are the same for both dates.

Basic information such as that used to construct figure 14 can be tabulated as in table 6 to gain an appreciation of the range in equilibrium fuel moistures that may be expected in mountainous country and to facilitate its use by field men.

TABLE 5.—*Fuel moisture classification of sample area for May 6 and November 6*

Equilibrium fuel moisture content (percent)	Proportion of total area		Equilibrium fuel moisture content (percent)	Proportion of total area	
	May 6	November 6		May 6	November 6
	Percent	*Percent*		*Percent*	*Percent*
Less than 3	53	0	Less than 7		88
Less than 4	76	9	Less than 8		97
Less than 5	96	49	Less than 9		100
Less than 6	100	70			

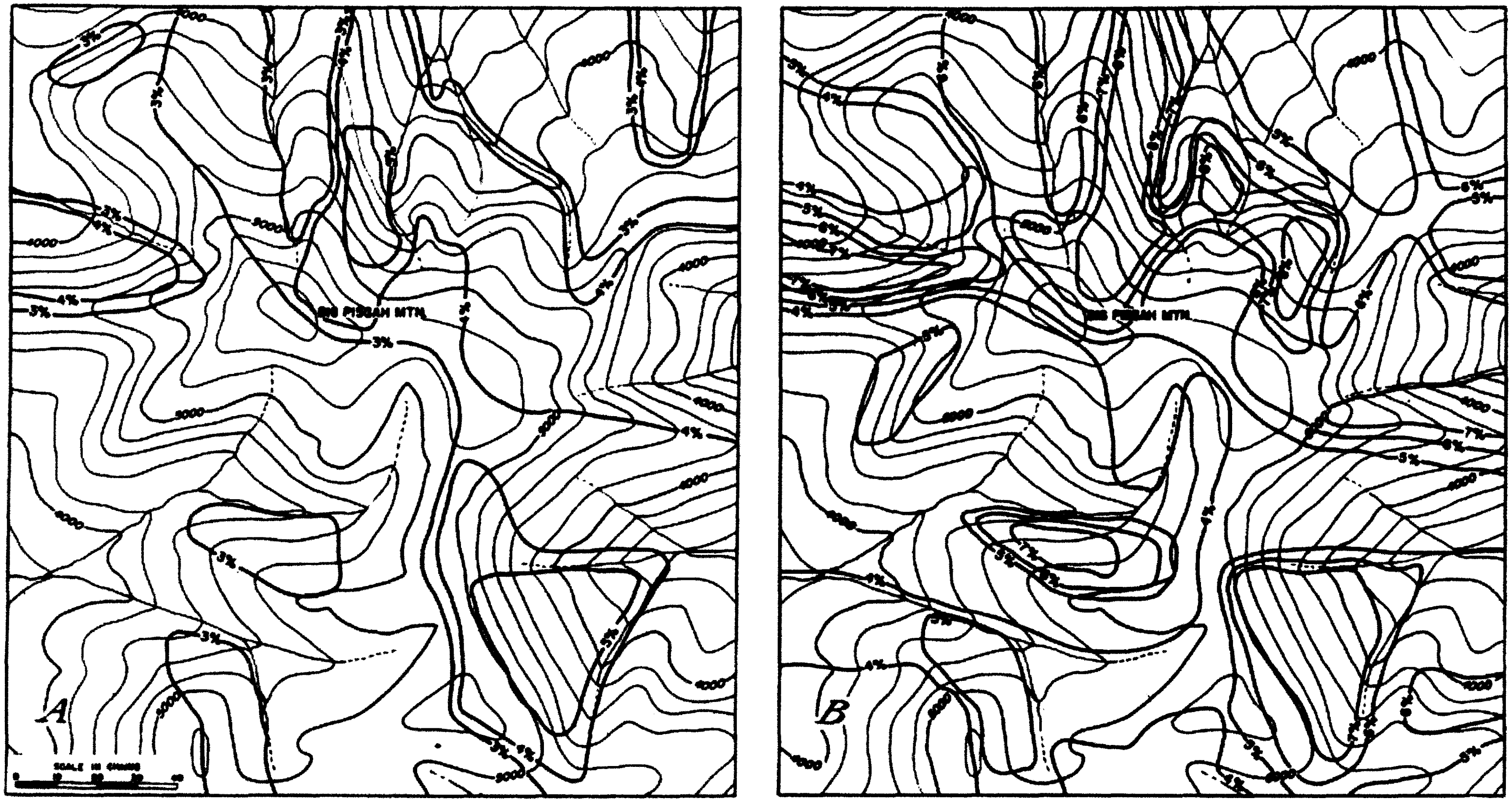

FIGURE 14.—Fuel moisture equilibrium maps for a representative portion of the Pisgah National Forest, N. C.: *A*, May 6; *B*, November 6.

TABLE 6.—*Fuel moisture equilibria for sample area, by aspect, slope, and wind class, when air temperature is 70° F., relative humidity is 40 percent, and hour is 2 p. m.*

MAY 6

Aspect[1]	Fuel moisture by steepness of slope (percent) and velocity of wind									
	20		40		60		80		100	
	0 mph	3 mph	0 mph	3 mph	0 mph	3 mph	0 mph	3 mph	0 mph	3 mph
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
N	3	5	3	5	4	6	4	6	4	6
NE	3	5	4	5	5	6	5	6	6	7
E	3	5	3	5	5	6	5	6	5	7
SE	3	5	3	5	4	5	4	5	4	6
S	2	4	2	5	3	5	3	5	3	5
SW	2	4	2	4	2	4	2	4	2	4
W	2	4	2	4	2	4	2	4	2	4
NW	3	5	3	5	3	5	3	5	3	5
NOVEMBER 6										
N	5	7	6	7	7	8	8	8	8	8
NE	5	7	6	7	8	8	8	8	8	8
E	5	6	6	7	6	7	7	8	8	8
SE	4	6	4	6	4	6	4	6	5	6
S	4	6	4	6	3	5	3	5	3	5
SW	4	6	3	5	3	5	3	5	4	5
W	4	6	4	6	4	6	4	6	4	6
NW	5	6	5	6	5	6	6	7	6	7

[1] For flats, the fuel moisture percent is as follows: Wind of 0 mph, 2 percent on May 6, 4 percent on Nov. 6; wind of 3 mph, 5 percent on May 6, 6 percent on Nov. 6.

Obviously, one condition that complicates the application of the findings regarding equilibrium fuel moisture relations to a heterogeneous forest area is the variation in air temperature, air humidity, and wind from one locality to another. Until more is known about such differences, much of the significance of the relation of radiation to equilibrium fuel moisture must lie in the basic theory developed rather than in everyday application by fire-control administrators. Nevertheless, the importance of determining the variations of atmospheric factors with topography becomes more evident when the potential differences in actual rate of spread of fires resulting from the extremes of fuel moisture noted in figure 14 are estimated. The rate-of-spread figures vary not only with atmospheric factors, but also with steepness of slope, fuel type, and perhaps other factors. On the average slope, on a calm day, and in leaf litter typical of the southern Appalachians, fires burning in fuel with 4 percent moisture would increase their perimeter about 4 or 5 chains per hour faster than fire burning in fuel with 8 percent moisture. All other things being equal, a dispatcher recognizing such a difference in fuel moisture would have to send two or three more men to a fire in the drier fuels than to a similar fire in the more moist fuels, if control were to be accomplished in the average length of time.

It must be emphasized that several other considerations influence manpower requirements for fire control to a much greater extent than 4- or 5-percent differences in fuel moisture. It must be remembered also that only for the very light surface fuels is moisture content frequently near equilibrium with that of their surroundings; therefore, the data presented here do not apply to fuels heavier than hardwood leaves, dead grass, and surface layers of pine needles.

SUMMARY

Forest fire-danger rating systems, now in use in all forest regions of the United States, are based chiefly on measurement of wind and of fuel moisture. While many workers have investigated atmospheric and related elements that control fuel moisture, little research has been done on solar radiation and its influence on fuel moisture equilibria and rates of drying. With a view to contributing to the refinement of fire-danger rating systems and application of the ratings, a study of solar radiation and fuel moisture was begun in the southern Appalachians in 1938.

A method has been developed whereby radiation intensity can be determined for any season of year, hour of day, slope, and aspect. Examples are given showing the widely different radiation intensities that are to be expected under different combinations of these factors even though atmospheric conditions are the same. The relation of solar radiation intensity to surface fuel moisture equilibria and, to a lesser extent, its relation to rates of drying have been established on the basis of theory and of data obtained by use of an "artificial sun" apparatus, a specially constructed weather synthesizer. This apparatus permits both field and laboratory observation of moisture equilibria and rates of drying under various combinations of radiation, wind, and humidity. Formulae have been developed so that for any combination of air temperature, relative humidity, and wind velocity, equilibrium moisture content of forest litter can be derived for any season, slope, and aspect. These formulae can be used universally, provided radiation intensities are adjusted for latitude.

The influence of wind on fuel drying is emphasized. In bright sunlight, contrary to popular belief, wind maintains levels of fuel moisture higher than those in calm air. The reason is that for fuels in the sun the wind's cooling action more than offsets its drying action. This is important in some regions where fuels are fully exposed to sunlight during the fire season.

Fuel moisture equilibrium maps are presented showing variations with season, aspect, and slope that result from variations in radiation intensity alone. A table is presented showing differences in drying rates caused by differences in radiation.

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U. S. GOVERNMENT PRINTING OFFICE: 1943