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MEASURING FOREST-FIRE DANGER IN NORTHERN IDAHO

"SPOT FIRES"—A SYMPTOM OF GREAT FIRE DANGER

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MEASURING FOREST-FIRE DANGER IN NORTHERN IDAHO

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FOREST-FIRE STUDIES, PAST AND PRESENT

In most of the forest regions of the United States the fire problem is the greatest forest problem. Wasteful methods of logging and lumbering may result in the loss of a large proportion of the remaining forest growth, but the land will usually produce a new crop of timber without undue delay, unless fire occurs.

In the northern Rocky Mountains, as in other regions, fire makes " idle land and costly timber." The intense heat of slash fires following logging destroys the duff or forest litter in which seeds are stored. Fire following logging kills the trees that have escaped the ax and consumes the seed in the cones. Fire, by the destruction of the humus, renders the soil more liable to washing, leaching, and erosion. Fire turns cut-over but producing land into dead and idle land producing nothing and promising nothing for years to come. If the principal object of the practice of forestry is the production of timber, then the greatest enemy of forestry and of lumbering is fire (*16*).[1]

Fire is a natural phenomenon, occurring in accordance with natural laws. The first problem in dealing with fire is, therefore, to discover these laws; and this naturally resolves itself into the problem of isolating and measuring each factor that influences fire and determining its relative importance. The ultimate scope of forest-fire studies is limited only by the number of these factors.

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[1] The italic figures in parentheses refer to " Literature cited," p. 62.

2786°—28——1

The purpose of this publication is to present some of the facts determined by a study of fire danger in northern Idaho, facts which, although they constitute but a first step toward the ultimate definition and measurement of forest-fire danger, may be of immediate value both in improving forest protection and as a basis for further investigation.

In this study the endeavor was to record on an extensive scale as many as possible of the factors controlling fire behavior and to make at least a beginning of the broader study that must be carried to completion if fire danger is to be fully defined and measured. Intensive study, however, was concentrated on a few phases of the entire problem, selected because they appeared to be of the most immediate importance and promised the most usable results.

Because of the evident need for some sort of measurement to check and eventually to replace mere opinion, a strong effort was made to find some one factor or condition fluctuating in close accordance with forest-fire danger which could be regarded as a criterion and which could be measured easily and perhaps predicted. In making this effort it was recognized that no measurement of any single factor could be expected to be an accurate criterion in all instances, for forest-fire danger involves at the same time the activity of fire-starting agencies, the character, volume, and arrangement of the materials that burn, and the moisture content and inflammability of these materials. Also it is modified by the climate, topography, and other general conditions of the particular area.

Investigations were confined almost entirely to northern Idaho, where a large part of the land is more valuable for the production of timber than for the growing of any other crop. This region is the home of the extremely valuable western white pine (*Pinus monticola*), and has suffered very heavily from forest fires in the past. The field of investigation in this locality was restricted mainly to the relation of the weather elements to the moisture content of fuels, and the effect of moisture content on the inflammability of fuels.

This attack on the problem is the logical extension of the work done in previous investigations.

What probably represents the pioneer effort in forest-fire studies in this country, undertaken by the earlier Bureau of Forestry, is noted in the 1901 report (*37*) of the Forester:

> An extended study on the ground was made of forest fires and reproduction in the North Park and Medicine Bow Mountains of Colorado. Special attention was given to this subject in the reserves of Arizona, California, Oregon, Washington, and Wyoming. In the historical study of forest fires, records of about 1,800 fires were added during the year, bringing the total number recorded to over 10,000.

In 1902, however, when Fernow published his Economics of Forestry (*12*), he gave less than two pages to the forest-fire problem in the United States, thereby showing how relatively unimportant it appeared at that time. By 1903 and 1904 a few of the more progressive States were publishing the reports of their foresters, describing, as does the Massachusetts report (*1*) for 1904–1906, how fire injures the forest, the annual loss due to fires, the "methods of extinguishment and prevention," the duty of the public, and the laws on the subject.

It was not until 1907 that the results of studies of forest fires began to appear in print with any frequency, and these were generally of the type represented by The Control of Forest Fires at McCloud, California, by Cooper and Kelleter (*9*). The features of the problem dealt with were largely the causes of these fires, the amount of damage resulting, methods of preventing fires from starting, and the best methods of putting out fires that do start.

By 1910 investigations were being made of the most effective methods of preventing and extinguishing fires. This stage is best represented by Protection of Forests from Fire, by Graves (*14*), then Forester, and Better Methods of Fire Control, by W. B. Greeley, later Forester (*15*). The main purpose of both publications was the strengthening of the Forest Service organization for the suppression of forest fires. Colonel Graves, however, produced in his bulletin the first comprehensive analysis of the conditions controlling the behavior of forest fires, and of how man may take advantage of these conditions. Several of his conclusions have since received a large amount of intensive investigation and are now recognized as of fundamental importance in forest protection.

Although the statistical study of the occurrence of forest fires, their causes, costs, and damages has necessarily been continued, more and more attention has been given recently to the natural factors which permit or prevent their occurrence. It is being recognized more clearly that for the most efficient forest protection the protective organization must be as flexible as the natural controls of fire are variable, and that a flexible organization can be produced only if the variations of the controls are recognized.

The first analysis of the occurrence of large forest fires as affected by the weather in the United States was published in 1914 (*4*), not by a forester or timber owner but by a trained meteorologist, District Forecaster E. A. Beals, of the United States Weather Bureau, who recognized the possibility of using weather forecasts as a basis in preparing for great fire danger. The first intensive experiments devoted to the explanation of why forest fires burn more fiercely at certain times, and what controls their behavior, were the work of S. B. Show, of the Forest Service, in California in 1915 (*32*). A year later Messrs. Beals and Williams published further information on the relation of weather to forest fires in their articles entitled, "Fire-weather Warnings," "Droughts and Hot Weather," and "How the Weather Bureau Can Help" (*5*, *6*, *39*). At about the same time, and later, J. A. Larsen was also studying the effect of atmospheric conditions on the inflammability of forest materials on the Priest River experimental forest in northern Idaho. His principal publications on this study are Climate and Forest Fires in Montana and Northern Idaho, 1909 to 1919 (*22*), and the results of his study of the effects of altitude on the length of the fire season (*21*).

In later years Munns (*28*) and Bates (*3*) called attention to the important effect of the evaporating power of the atmosphere on the behaviour of forest fires, and Osborne (*30*), and Hofmann and Osborne (*17*) to the importance of relative humidity.

Previous to 1922 little was known of the effects of temperature, humidity, and evaporation on fire danger beyond the fact that high temperature, high evaporation, and low humidity caused high fire danger, whereas low temperature, low evaporation, and high humidity caused the forest fuels to be less inflammable. Larsen had concluded that 2 inches of rain per month is necessary to allay fire danger in northern Idaho, and Show had found that the rate of spread of fire varies approximately as the square of the wind velocity, other conditions being constant. No attempt had been made to state as exactly as possible what temperatures were safe, slightly dangerous, dangerous, or extremely dangerous. No danger lines or zones had been drawn for either humidity or evaporation. Yet it was well known that the daily fluctuations of these factors cause a large part of the fluctuations of fire danger which, occurring without warning, frequently strain the forest-protective organization to the breaking point.

In 1922 the study of conditions that control the behavior of forest fires was made a definite research project of the Forest Service, and since then studies have been carried on at a number of the regional forest experiment stations. In addition, private foresters and timber protective organizations have begun to devote considerable time to similar research. The Weather Bureau has continued to contribute its very valuable assistance. Prominent among the men contributing new information bearing on the forest fire problem are: Alexander, Weidman, Joy, Show, Flint, Hofmann, and Bates (*2*, *3*), Osborne (*17*), Kotok (*33*, *34*, *35*), McCarthy (*24*, *25*), Gisborne (*13*), and still more recently, Cowan (*10*), Norquest (*29*), Dague (*11*), Munger (*27*), and Simpson (*36*). The chief contributions by these men have been theories and and substantiating evidence dealing with the relation of the weather elements to the inflammability of the fuels and to the occurrence and behavior of forest fires.

The present trend of investigations into the factors influencing the rate of spread of fire is almost exclusively in the direction of attempts to determine the relative importance of the various weather elements and the probable degree of fire danger according to the weather predicted. Show and Kotok (*33*, *35*) have stated very clearly the need for measurements of these weather elements and for weather forecasts as helps toward most efficient forest protection; and unpublished reports by Howard R. Flint of investigations in the northern Rocky Mountains have strongly emphasized this need.

BASIS OF THE PRESENT STUDY

There must be a clear understanding of the term "forest-fire danger" before the controlling factors can be studied systematically. For this purpose the following definition may serve as a working hypothesis.

Forest-fire danger consists of:

1. The present number of fires burning, or the probability that fires will be started.
2. The present rate of spread of fire, or the probability that fires will spread.
3. The loss occurring from existing fires, or the probability that fires will result in loss.

According to this definition there can be no danger unless atmospheric and other conditions are such that fires exist or will be started, are spreading or will spread, or are doing damage or will do damage.

If the measure of any one of these components is zero then there is no fire danger. As local conditions cause each of these natural components to increase, danger likewise increases. If each of these three components—number, spread, and damage—could be measured accurately, then fire danger, or the total of them all, could be more definitely determined.

Unfortunately, forest-fire history, as written in the annual records of number of fires started, area burned, and damage done, is not yet sufficiently particularized to permit the short-period fluctuations of fire danger to be segregated and analyzed, and so to be correlated with current weather conditions. The records for monthly or 10-day periods also fail this purpose to some extent, for even these estimate only roughly the area burned and damage done, and include many fires that started, under different conditions, the month or 10-day period preceding the period recorded. No records are available of the average rate of spread of each fire, or the area burned and damage done each day; yet the daily change in conditions controlling the degree of danger is often very great. The best available record for correlating fire danger and weather is that of the number of fires discovered each day. But number of fires alone is a very unsatisfactory criterion, and, also, few of the regular stations where weather records are obtained are sufficiently close to the area burned to make it safe to assume that the weather is always the same on the fire as at the station.

Records may in the future be more dependable. Continuous improvement in the system of recording will provide much better records. In 1901 the Forester called attention to records of 10,000 fires, obtained from various parts of the country after several years' work. Twenty years later Show and Kotok had available records of more than 10,000 fires in California alone for a period of only 10 years. Twenty years from now, if meteorological stations are established and maintained in the proper localities, the records of the start, spread, and damage of fires in Idaho and Montana may give ample basis for the correlation of fire history and meteorological conditions.

In the meantime there are other means by which the relative importance of the various factors controlling fire danger can be determined. These include measurements of the relationship between the weather and the moisture content of fuels, the relationship between moisture content and inflammability, the effect of kind of fuel on ease of ignition, and the importance of volume and arrangement of fuels. These relationships have been made the subject of the present study. As soon as the effect of any one factor is determined, measurements and forecasts of that factor can be used immediately as partial criteria of fire danger. As will be seen, this study has produced conclusions which agree very closely with those arrived at by Show and Kotok in California (*35*).

FUNDAMENTALS OF COMBUSTION

Fire is a chemical action called combustion, accompanied by light and heat. An understanding of the process of combustion is, therefore, fundamental to any study and analysis of forest-fire danger.

In order that combustion may take place in the forest there must be a fuel, or a material composed largely of carbon and hydrogen which, when heated to the kindling temperature, will combine with oxygen from the air, the supporter of combustion (*8*). Remove the fuels, prevent them from being heated to kindling temperatures, or shut off the supply of oxygen, and there will be no combustion, no fire. These are very simple facts, yet perhaps not always kept clearly in mind by those studying the behavior and suppression of forest fires.

THE PRINCIPAL KINDS OF FOREST FUELS

The common fuels of forest fires vary through a great range even in a small region such as northern Idaho. The variation includes not only the character of the material but its volume and arrangement as well.

On certain areas the fuels may consist largely of grass or dead weeds, such as Plate 1 illustrates. On these areas most of the heavier materials such as branch wood and dead timber have been consumed in previous burns, the weed crop remaining as the principal carrier of fire. The proportion of lightweight fuels on an area is very important because such materials pick up and lose moisture much more rapidly than the heavier ones. As will be shown, the inflammability of a fuel varies much as its moisture content; hence those areas bearing a large proportion of lightweight fuels are most susceptible to sudden and pronounced changes in inflammability.

On other forest areas, such as that shown in Plate 2, which have been partially cut over and from which the commercial timber has been largely removed, the principal fuels are the continuous layer of duff (dead leaves, twigs, etc., forming a compact carpet easily separable from the humus beneath), the heavier branch wood and logs left lying on the ground after logging, and the standing trees, small and large, dead and alive. A much greater variety of fuels is available on such areas to contribute toward the process of combustion and to complicate the changes in degree of inflammability.

A third common type of fuel combination consists of the green, uncut, and unburned forest either young or old, such as Plate 3 illustrates. Here the fuels vary greatly in size from fine moss to massive trees, and also in condition, from extremely dry dead material to the living tissues wet with sap. The continuous layer of duff covering the soil is a very important fuel in this type.

A fourth and exceedingly important type of fuel is illustrated by Plate 4. Previous fires have caused a tremendous accumulation of dead wood, which forms one of the most dangerous fuel types in this region, once the heavy materials are heated to the ignition temperature.

EASE OF IGNITION

The heating of the forest fuels to the kindling temperature or ignition point is the beginning of the forest fire. As the sources of heat which start forest fires vary from tiny sparks from locomotives to the great heat of lightning bolts, and as the kindling temperatures of the forest fuels differ greatly according to the kind and size of material, the study of this phase of the fire problem extends over a wide field. The fact of most immediate importance seems to be that, since each specific material must be heated to a certain temperature before the process of combustion can begin, anything that

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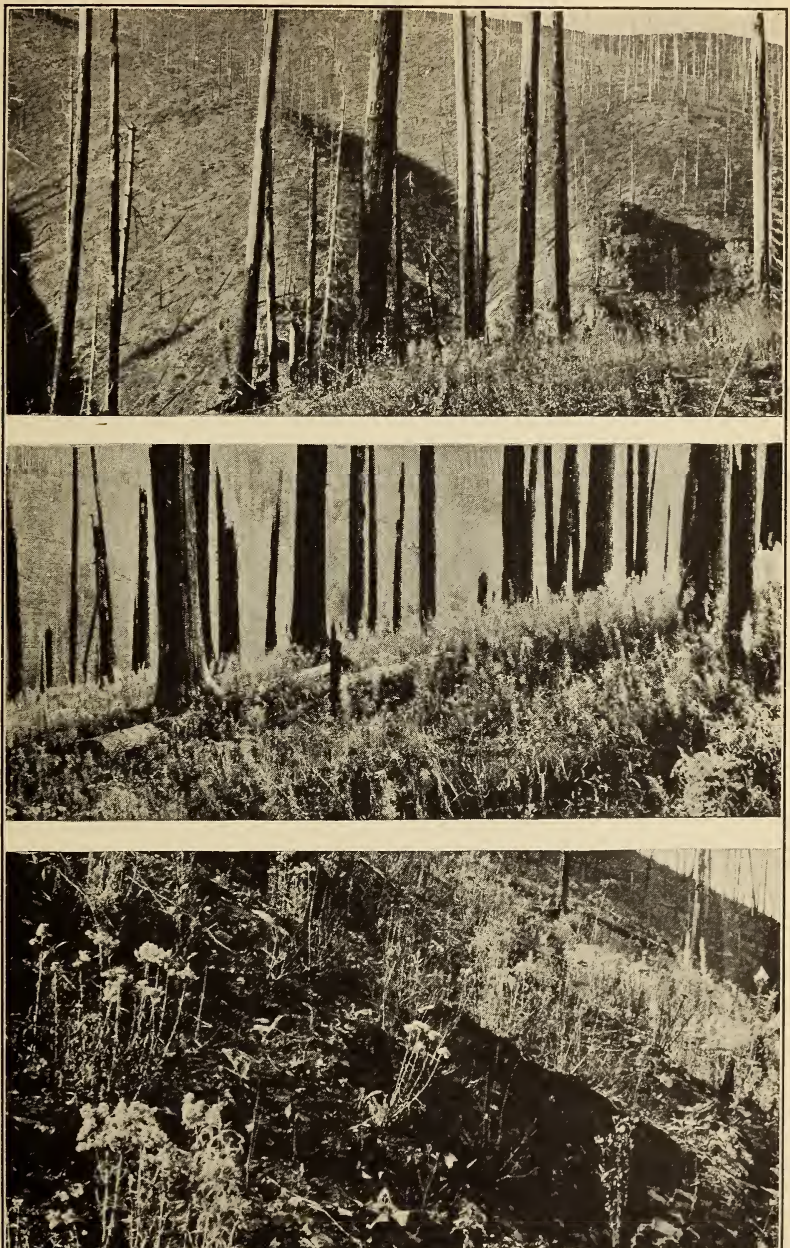
PLATE 1

F-182784, 182793, 182794

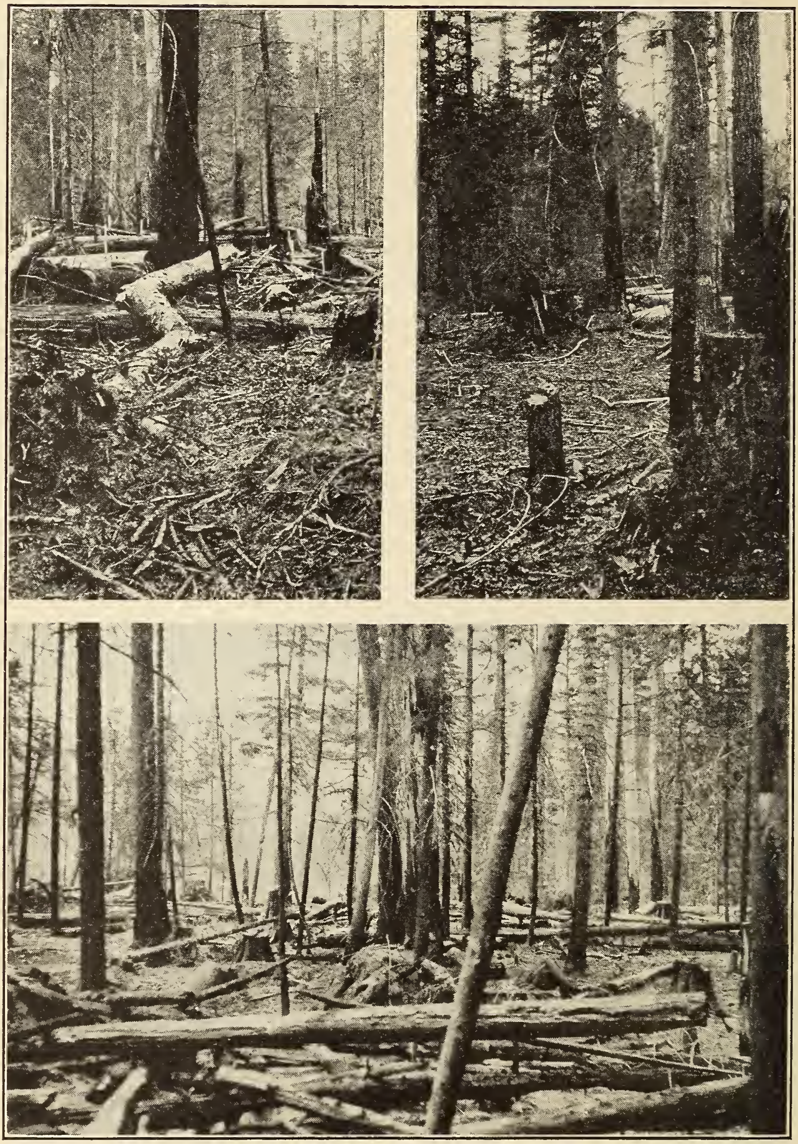


THE WEED TYPE OF FUEL

On these three typical areas on which weeds are the principal carriers of fire, intense double or triple burns have removed most of the heavier fuels. This is the usual result of repeated fires

PLATE 2

F-48483A, 48479A, 46687A



THE PARTIALLY CUT-OVER TYPE

Where the forest cover has been partially removed, as in these three areas, duff, twigs, logs, and standing dead trees are the principal fire carriers

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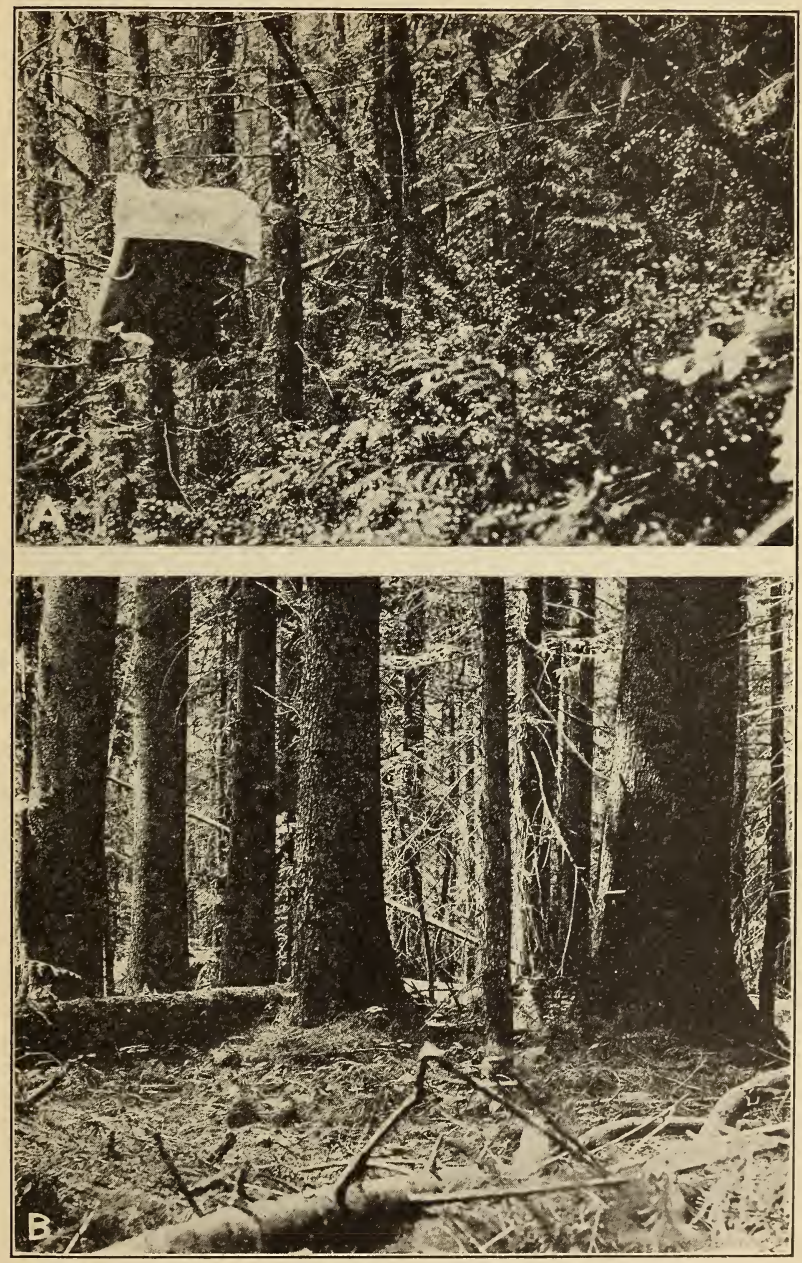
PLATE 3

F-173989, 27283A



THE GREEN TIMBER TYPE

In immature stands, A, as in the mature stands of green timber, B, the principal carriers of fire are duff, twigs, dead branches, windfalls, and snags; but here, except when exceedingly dry, the green shrubs act to retard the spread of fire

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PLATE 4

F-190947, 190936, 182799

THE DEAD AND DOWN TIMBER TYPE

An intense single burn was enough to reduce the forest to this condition on each of these areas, leaving standing snags and down timber as carriers of the next fire. There is less timber than before, but more fuel. Given dry enough conditions the highest fire danger will prevail prevents or delays this heating to the kindling temperature is favorable for the prevention of forest fires as well as for their suppression. Cold materials must, of course, be heated through a greater range than warm materials. Likewise water in or on the materials absorbs heat and prevents or delays the raising of the fuel to the ignition point (7).

The materials present may vary from those which dry out easily and ignite at comparatively low temperatures to heavy materials with high moisture and ignition points, and yet a small amount of heat may serve as the source of a large forest fire by igniting the more inflammable material first and so producing in turn the kindling temperature for the next most inflammable material. In this way combustion may be produced even in green materials wet with sap and cool from the processes of respiration. A spark may ignite tree moss in the forest, the moss may ignite dead weeds, the weeds may ignite twigs, twigs may ignite branch wood, branch wood may ignite large dead snags and windfalls, and the whole may become hot enough to cause green tree tops and branches to burst into flames; whereas the same spark falling on a green leaf might fail to leave a mark.

THE SUPPORTER OF COMBUSTION

The supply of air is, of course, nearly always plentiful, so that once fuels are heated to their kindling temperatures, the process of combustion will continue as long as the fuels last. The most familiar method of stopping the supply of air is by the use of water, which cuts off the air supply at the same time that it lowers the temperature of the fuel. Theoretically, it would also seem that smoke, composed of solid particles, would reduce the supply of air in the immediate vicinity of a forest fire. Doctor Hawley, of the Forest Products Laboratory at Madison, Wis., also has advanced the idea that a large amount of water vapor in the atmosphere must displace an equal volume of the other gases in the air and thereby tend to reduce the supply of oxygen to support combustion. Hence, although air is always present to support the combustion of forest materials, it may be shut off by a blanket of water, or it may be reduced to some extent through replacement in space by smoke particles or the presence of more than a normal amount of water vapor.

It is apparent from this brief sketch of the process of combustion that at least two of the conditions fundamental to combustion—fuels and air—are always present in the forest, and that the occurrence and behavior of unfought forest fires on any particular area depend chiefly upon the production and maintenance of the third fundamental condition—the kindling temperature. As the sources of ignition become numerous and the ease of maintaining the kindling temperature increases, the number and the size of unopposed fires increase. The presence of the sources of ignition, such as locomotive sparks, matches, cigarettes, camp fires, burning brush, lightning, etc., is being studied intensively through the compilation of records of causes of forest fires; the possibility that these sources will be effective, and that the resultant fires will spread, is the principal field of the present discussion.

IGNITION OF FUELS

In northern Idaho June 1 to September 15 is the normal fire season. During the remainder of the year there are usually very few disastrous forest fires. There can be no doubt that this normal fire season, and any variations from it, are caused largely by variations in the ease of ignition of the fuels. As the same fuels, when snow does not blanket them, and approximately the same oxygen supply prevail throughout the entire year, and as most of the sources of ignition are continuously present in some degree, the duration of the fire season must be otherwise controlled by some variable which in turn influences or controls the ease of ignition of the fuels. The most obvious variable is the moisture content of the fuels, which has been shown to affect ease of ignition both by determining how much heat is needed to raise the fuel to its kindling temperature and by governing the contact of air (oxygen) with the material.

Apparently a study of the relation of fuel moisture content to ease of ignition should explain the occurrence of the many forest fires during the dry period of the year and make clear the reason for some of the peculiarities in the behavior of forest fires. A measurement of fuel moisture content might be obtainable which would indicate the degree of fire danger by showing whether the fuel is easy or difficult of ignition. Forecasts of the weather, which controls fuel moisture content, might then be translated into terms of ease of ignition, hence chance of fire starting and the probable spread. With such information the forest-protective organization should be able to cope more successfully with the general problem of forest-fire danger.

Formerly the degree of dryness of the fuels was merely estimated and an opinion then formed of the inflammability, or ease of ignition and rate of combustion of the various materials. Experience has shown, however, that it is extremely difficult to estimate whether a piece of wood or a section of duff has a 10 per cent or a 20 per cent moisture content. And tests have proved that such a difference exerts an important effect on the inflammability of these materials. The present tendency is toward instrumental measurements and the interpretation of these measurements in terms of inflammability.

THE EFFECT OF MOISTURE CONTENT OF FUELS

Eventually all of the conditions which favor and hinder the ignition of each of the important forest fuels must be determined, not only that what natural conditions assist and interfere with the protection of the forests from fire may be known exactly, but also that current measurements of all these conditions may be made in order to determine accurately which sources of ignition must be guarded against and which can be safely ignored. The present investigation has, as yet, determined tentative conditions of safety and danger for only one of the important fuels. This work has been confined to tests of the ease of ignition and combustion of the common duff layer according to the amount of moisture in the duff.

Duff was selected as the first material to be studied because of its widespread occurrence. because it is almost the only forest fuel which is sufficiently continuous so that the kindling temperature may be carried forward uninterruptedly, and because, as will be shown, the amount of moisture in the top layer of duff is usually representative of the average moisture content of several other important materials, including twigs and slash.

The first tests answered certain direct questions: How much moisture can the duff contain without rendering a match inefficient as a source of ignition? How much moisture in the duff will prevent a match from being effective, and yet not prevent the fuel from being ignited by a camp fire, a burning slash pile, a broadcast slash fire, or a bolt of lighning? At what moisture content is the duff generally safe from ignition by any of these sources of forest fires? The answers to these questions should be of use in forest protection if combined with current measurements showing how much moisture is actually present in the duff each day.

It has already been explained that variation in the amount of moisture in a fuel is a principal control of its ease of ignition. That combustion also is appreciably affected by fuel moisture is indicated in United States Department of Agriculture Bulletin 753 (*38*), which contains the statement: "Under the most favorable circumstances the heating efficiency of a pound of wood containing 25 per cent moisture will be * * * 72 per cent of that of a pound of dry wood." Furthermore Doctor Hawley has computed the degree of heat required to sustain combustion according to the quantity of moisture in a typical forest-fire fuel. He finds that whereas two similar wood samples at 50° F., one with 20 and the other with 5 per cent moisture content, will both require 160 B. t. u.[2] to raise the wood alone to the combustion temperature; the wetter sample will require approximately 258 B. t. u. for the complete elimination of its water content (32.4 B. t. u. to raise the water from 50° to 212°, 193 B. t. u. to vaporize that water, and 32.8 B. t. u, to heat that water vapor from 212° to 540°, or the ignition temperature); and the drier sample, on the other hand, will need only about 65 B. t. u. to dispose of the water in it. Hence the amount of heat required to eliminate the water from the wood is four times as great at 20 per cent moisture content as at 5 per cent. In other words the amount of heat required is directly proportional to the amount of water in the materials. This illustrates the fact that the moisture content of materials is of paramount importance in the fire problem, and that the more accurately the moisture content is measured the more dependably will the degree of fire danger be known.

Actual tests were made with matches, small camp fires, and large slash piles as the sources of ignition of the duff. Larsen and Show have agreed that when the duff layer has less than 10 or 12 per cent moisture content—that is, less than 10 or 12 pounds of water for every hundred pounds of oven-dry duff—this material can be ignited readily with a single match. At higher moisture contents the duff is generally too wet to be ignited by this means. Over 40 match tests made by the writer confirm Larsen's and Show's results, although the method employed was slightly different. Show used samples of duff held on tin sheets, brought the samples to known moisture contents, and applied a match. Larsen raked up small

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[2] British thermal units.

heaps of top-layer needles in place in the woods, and applied a match; then collected a similar sample of duff, and determined its moisture content. The writer dropped lighted matches on the duff without disturbing it, and collected similar samples near by. Out of 13 tests, with the duff at 12 per cent moisture content, the lighted match caused the duff to ignite and fire to spread five times—twice with some wind to assist, and three times with no wind. In eight instances, or 61.5 per cent of the trials at this moisture content, there was no ignition or spread. At moisture contents of over 13 per cent the results were uniformly negative. Below 10 per cent ignition was always successful if the wind was not so strong that it extinguished the match.

From these tests it appears that whenever the topmost layer of white pine duff in northern Idaho has less than 10 per cent moisture content, any source of ignition producing the same heat as an ordinary match, or greater, will be capable of raising the temperature of the duff to its kindling point, and that combustion will then continue as long as there is a supply of this fuel in this condition and as long as the supply of air is not cut off. As mentioned above, wind has an appreciable effect, sometimes in extinguishing the source of ignition, sometimes in leveling the flames so that more of the heat is available to raise the temperature of adjacent duff. The fact of most importance, however, is that as a rule the danger of forest fires being started in the duff by matches or other less-heating sources of ignition decreases rapidly as the duff acquires more than 10 per cent moisture content. At over 13 per cent the duff is generally immune from ignition by smokers' matches, similar-sized blazing embers blown ahead of a large fire, or sparks from locomotives.

A greater volume of heat in the source of ignition would presumably remove some of the moisture in fuel of more than 13 per cent moisture content and still be capable of raising the fuel to the kindling temperature. Thus combustion in the duff would continue even after the source of ignition was exhausted.

Thirty-seven tests were made with small fires, similar to camp fires, burning 15 to 30 minutes on top of duff ranging from 10 to 22 per cent in moisture content, the full duff layer measuring from 12 to 82 per cent. Results varied from no spread at all to extremely quick spread, including some instances in which the fire spread through the top layer and not through the lower, and others in which the reverse was true. As a rule, however, the camp fires ignited the duff and caused fire to spread through it when the top layer of duff had less than 18 per cent moisture content. No ignition or spread occurred when the top layer of duff had over 18 per cent moisture content.

The results of these so-called "camp-fire tests" indicates that the duff will ignite and carry fire even when it has as much as 18 per cent moisture content, and that, so long as the material is not wetter than this, common camp fires must be regarded as dangerous sources of ignition of this fuel.

Only two measured tests were made with a volume of heat greater than that of the camp fire. These two tests each employed a compact pile of slash, consisting of twigs, branch wood, and a small log or two, covering a ground area about 5 feet in diameter, the pile being about 3½ feet high. In both these tests the fire was of such intensity that the flames leaped more than 10 feet from the pile, as is common when similar piles of slash are burned in logging operations. In one instance the top layer of duff surrounding the slash pile had a moisture content of 19 per cent and the full layer 74 per cent. In this test the duff within 2 feet of the pile was ignited and burned, but there was no further spread of fire. In the other test, made the next day, the top layer of duff had a moisture content of 16 per cent and the full layer 52 per cent. This time the fire spread through the top duff over 15 feet from the pile in less than 10 minutes and had to be extinguished to prevent a dangerous conflagration.

Although these two tests are not sufficient for determining accurately the possibility that burning slash piles will ignite the duff, the results at least corroborate the results of the camp-fire tests and indicate that such sources of ignition may be dangerous whenever the top layer of duff has 18 per cent moisture content or less. That amount is, therefore, taken as the limit of danger from slash piles.

There are four other important agencies which commonly cause forest fires and which should be tested experimentally, if possible, to determine within what limits of moisture in the fuels they are effective or noneffective. These are lighted tobacco, sparks from locomotives, broadcast-slash fires, and lightning. Pending further tests, zones of moisture content have been estimated for the top layer of duff to express the susceptibility of this fuel to ignition by two of these agencies. At less than 7 per cent moisture content, it is estimated that the top duff may be freely ignited by locomotive sparks. At 25 per cent or less, broadcast-slash fires may be effective. At more than 25 per cent it is estimated that the duff is generally safe from ignition by any of the common causes of forest fires, except possibly lightning. No instances have yet been found in which duff with more than 25 per cent moisture content was holding or carrying fire, regardless of the source of ignition.

From these experiments and from estimates based on observation, it has been possible to delineate six zones of inflammability of the top layer of duff, depending upon the effectiveness of various common causes of forest fires. These zones, which, of course, can not be sharply delimited, have been designated as follows:

Zone	Moisture content
Noninflammable	Over 25 per cent.
Very low inflammability	25 to 19 per cent.
Low inflammability	18 to 14 per cent.
Medium inflammability	13 to 11 per cent.
High inflammability	10 to 8 per cent.
Extreme inflammability	7 to 0 per cent.

Through the recognition of these zones and the measurement of the top-duff moisture content, it may be possible to state within fairly definite limits the possibility of fires being started in the duff by certain common causes. Obviously the same method of experiment must be used on the other important fuels such as twigs, slash, dead windfalls, and snags before a complete measurement of the possibility of ignition can be obtained. Meanwhile, the condition of the duff alone may serve as a partial criterion of prevailing fuel dryness.

This determination of the relation of moisture to inflammability indicates that although the possibility of combustion of duff apparently lies within a range of 25 per cent of dry weight, a much smaller difference in duff moisture content may often be extremely important. As is shown in Figure 1, a large proportion of the fluctuations of duff inflammability result from variations of duff moisture between 3 and 20 per cent. The two extremes, 25 per cent moisture and absolute dryness, may be readily distinguishable by mere inspection; but the smaller, very significant differences demand measurements rather than estimates. This explains the emphasis which the writer places upon measurements in preference to estimates of moisture content.

Figure 1 also shows how the moisture content of the top layer of duff varied on two adjacent areas during the 1925 fire season. The

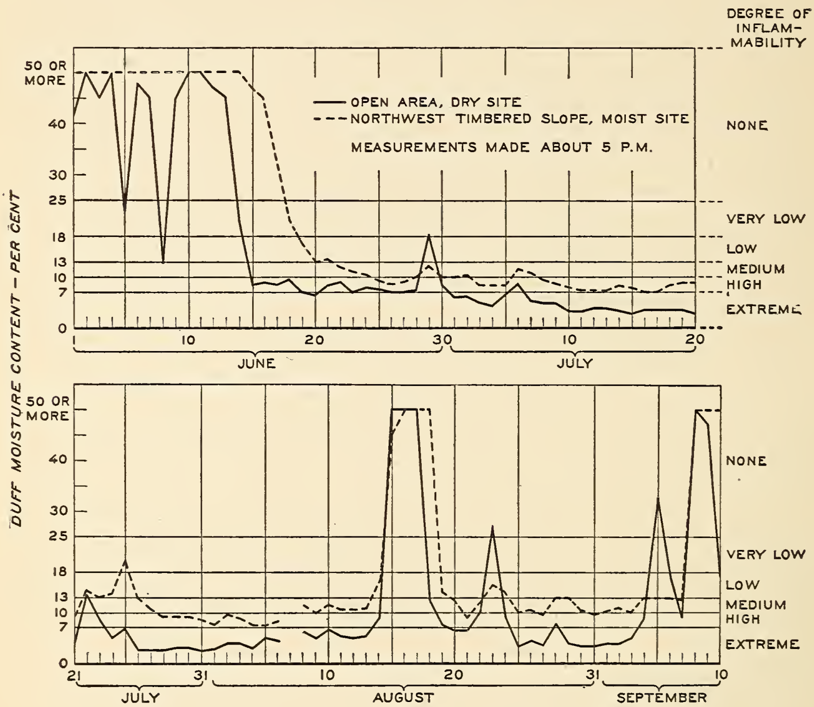

FIG. 1.—Fluctuations of duff moisture content, 1925 fire season

measurements indicated on this chart, which were made at the Priest River branch station of the Northern Rocky Mountain Forest Experiment Station, represent conditions at about 5 p. m. each day. When plotted with respect to the inflammability zones already mentioned, they visualize the daily possibility of ignition of this particular fuel. The reasons for the differences on the two areas will be discussed later. The fact of importance here is that moisture content in this fuel varies remarkably throughout each fire season and thereby produces a marked variation in inflammability. By measuring the moisture content of the important fuels each day and comparing the results with established zones of inflammability for the different fuels, it should be possible to measure, instead of estimate, the degree of prevailing inflammability.

An important step in this direction is a comparative study of the moisture content of various fuels.

MOISTURE CONTENT OF VARIOUS FUELS COMPARED

Years ago Graves (*14*) first pointed out the important influence of the moisture content of materials when he wrote:

> The condition of the litter and débris governs largely the character and severity of the fire. The most severe fires occur where the material is thoroughly dried to the mineral soil. When the material is only partially dry the fire is slow and the litter is not completely burned.

Although the experiments conducted by Show, Larsen, Hofmann, and the writer have confirmed the truth of this statement, no exact information concerning the amount of moisture in any one fuel at various intervals in the fire season has heretofore been available, nor any comparison of the amount of moisture in the important fuels through several seasons.

In order to obtain accurate information on this phase of the problem a series of comparable measurements were made for four successive fire seasons in northern Idaho. The results of these measurements are shown in Table 1.

TABLE 1.—*Moisture content of important fuels on timbered northwest slope in percentage of oven-dry weight*

Date	Twigs	Top ¼-inch of duff	Slash or heavy dead branch wood	Outside ½-inch wood from windfall	Full layer of duff
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1922					
June 5	9	12	----------	155	20
July 1	6	9	----------	30	13
Aug. 3	7	7	----------	17	9
1923					
May 7	12	18	----------	111	167
June 9	20	55	----------	216	182
July 2	14	16	----------	129	57
Aug. 4	12	14	----------	28	24
Sept. 8	16	19	----------	17	63
1924					
May 24	11	14	10	22	25
July 2	10	9	21	15	26
Aug. 12	10	10	9	16	16
Sept. 1	9	15	16	23	23
1925					
Apr. 27	140	120	127	150	320
June 8	21	64	31	44	77
July 3	11	11	12	18	19
Aug. 1	14	10	12	12	12
Sept. 1	8	12	12	15	16
Average	19.4	24.4	27.8	59.9	62.9
Average, 1924–25	26.0	29.4	27.8	35.0	59.3

The measurements were made on days selected to represent the ariest conditions existing around the first of each month during the fire season. The samples of duff and relatively sound wood were obtained from a small area having uniform timber type, density of canopy, exposure, and slope, the windfall samples being cut from a single fallen tree.

The outstanding fact made apparent by these measurements is the difference in the average moisture content of the materials. Twigs, the smallest and finest fuel, were usually the driest. The top quarter-inch layer of duff and the slash or branch wood usually had nearly equal percentages of moisture, averaging about 7 per cent more than the twigs. The full layer of duff, about 1½ inches thick, and the outside half-inch of wood from the windfallen tree also had similar average moisture content, about 42 per cent more than the twigs, or 35 per cent more than the top duff and slash. It is apparent from these results that the different kinds of material have very different moisture content, even though they occur side by side and are exposed to the same weather conditions.

The variation in moisture content of any one material is the second point of interest. The full layer of duff showed the greatest range of moisture content, varying from 320 down to 9 per cent in the 17 measurements made during these four years. In other words, a pound of oven-dry duff at one time held 3.2 pounds of water; at another time but 0.09 pound. The top layer of duff showed the least variation, from 120 down to 7 per cent. It should be noted that these are not the extreme ranges of moisture content, because none of the measurements in Table 1 were made when the materials were saturated.

The third point worth noting is the cumulative effect of the summer drouth on the heavier fuels. Though the twigs and upper duff approach minimum moisture content early in the summer, the windfalls and lower duff layers do not attain this condition until late in the season. Thus, the maximum difference between the wetness of these contrasted types of fuels occurs near the beginning of the fire period, while the minimum variation is found near the close. This emphasizes the fact that, although a few bad days may produce a condition of extreme inflammability in the lighter fuels, it takes the cumulative effect of many unfavorable days to create such a condition in the heavy ones.

All of these measurements are, of course, subject to the error of sampling and should be accepted merely as approximating the amount of moisture in these particular classes of fuels on northwest timbered slopes in northern Idaho. The major differences alone should be considered as significant, and these only in the region in which the measurements were made.

The noticeably different moisture contents of various materials obtained from a small area and undoubtedly exposed to the same weather conditions, including rainfall, temperature, humidity, wind, and sunshine, indicate that hygroscopicity, saturation capacity, and moisture-holding ability vary sufficiently to require that each class of material be studied separately. When the exact effects of each of the weather elements on moisture content are determined, it will be possible to state whether the differences in hygroscopicity and similar properties result mainly from differences in size of material, physical structure, or chemical composition, or from a combination of all three of these factors. Eventually this will be worked out for each of the important fuels. The present investigation has, so far, attempted to study the effect of the various weather elements on only one of the fuels, the top layer of duff. This study has not only determined the relative effects of each of the weather elements, but has at the same time developed methods which may be of value later in studying similar effects on the other important fuels.

METHODS OF MEASURING DUFF MOISTURE CONTENTS

As soon as attempts were made to measure duff moisture content accurately and with sufficient frequency so that its variations could be compared with the variations of its controls, it became evident that the conventional method would not serve. The ordinary way of determining the amount of moisture in any material consists of the selection of a representative sample, the determination of its weight, the drying in an oven to remove all moisture, the determination of the oven-dry weight, and the computation from these measurements of the weight of the water in the original sample and the ratio between this weight of water and the weight of the oven-dry sample. Such a procedure has the inherent weakness of sampling, no two duff or wood samples being obtainable which are exactly alike in size and composition. Furthermore, the process is very slow because of the time consumed in oven drying. Expensive equipment such as drying ovens and accurate scales for weighing also are required.

It was, therefore, necessary to develop a method which would always utilize the same sample of duff and which would be quick and simple in operation, inexpensive, and yet reasonably accurate. To meet this need, the duff hygrometer shown in Plate 5 was invented by the United States Forest Products Laboratory and developed in cooperation with the Northern Rocky Mountain Forest Experiment Station.

A detailed description of the duff hygrometer will be found in the appendix. It will be sufficient here to explain that this instrument measures the moisture by revealing changes in the length of a strip of rattan inserted in the duff. The rattan expands when the duff is wet and contracts as the duff dries, the different lengths of the rattan showing the amount of water in the duff. The relation between the length of the rattan and the moisture content of the duff is determined by calibration before the hygrometer is put in use in the field.

Duff hygrometers have been used experimentally on the Priest River experimental forest since August 1, 1923, for measuring duff moisture content during the fire seasons. The purpose has been to determine the accuracy of the instrument, to obtain daily measurements of duff moisture content on various sites, and to test the use of such information in actual forest fire protection.

Tests of the accuracy of the hygrometer have indicated that when properly calibrated it will read within 1 or 2 per cent of oven tests of samples of duff surrounding it. The range of measurement, it is true, is limited to moisture contents of less than 50 per cent, but this range includes all the determined zones of possible inflammability and therefore does not interfere with advance recognition of impending danger. Like hair hygrographs, the duff hygrometer gradually departs from its original calibration with continued use until after about four months the readings of moisture contents above 35 per cent are noticeably in error. The readings of less than 35 per cent remain reasonably accurate, even on instruments used continuously without recalibration for a full four-months fire season.

Sufficient tests have not been made to warrant a statement of the size of area that may be represented by hygrometer readings made for a single small spot. It is known, however, that as the timber type, crown density, exposure, etc., change noticeably, readings of duff moisture content at any given point fail to apply accurately. The use of additional instruments serves to reveal these very differences in the degree of moisture in the fuels on different sites, and so to reveal differences in the inflammability in different timber types and sites. Figure 1 shows how these differences were brought out by the use of two duff hygrometers on two areas within a mile of each other, both of which undoubtedly experienced the same general weather conditions.

EFFECTS OF WEATHER ELEMENTS ON DUFF MOISTURE CONTENT

As is shown in Table 1, the top layer of duff and the slash or dead branch wood had average moisture contents which were neither extremely low nor extremely high in comparison with the other classes of fuels studied. A careful study of the relation between the moisture content of one of these two materials, duff for instance, and each of the weather elements should, therefore, serve as a logical beginning in the investigation of the relation between weather and the moisture content of all the fuels. The top layer of duff is a particularly important material for this purpose because, besides being very evenly distributed in all unburned forest types and covering probably more surface area than any other single fuel, it serves as a carrier of fire between piles of slash, windfalls, and other heavy and unevenly distributed materials.

Even though duff moisture content alone can not always serve as a criterion of fire danger, it is obvious that a detailed knowledge of the controls of duff moisture content, the effect of moisture on the inflammability of the duff, and the effect of duff inflammability on the degree of forest-fire danger should be of practical advantage in any attempt either to determine the degree of existing danger or to forecast probable future danger. It will thus contribute directly to the more efficient protection of the forests. For these reasons a very large part of the present work has been concentrated on duff moisture content, its controls, and its relation to forest-fire danger. It is necessary to emphasize the fact that in all of the discussion which follows the results shown and the conclusions drawn should be accepted as applicable only for the particular timber types studied and only for the region of northern Idaho or areas with very similar weather conditions. Other regions with other classes of fuels and other weather conditions may be expected to give results which will vary from these in direct proportion as the important factors vary.

EFFECTS OF EXPOSURE

Figure 1 reveals the fact that great variations in moisture content of a certain type of fuel may be due mainly to the degree of exposure of the fuel to the weather. This fact is also brought out in the

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PLATE 5

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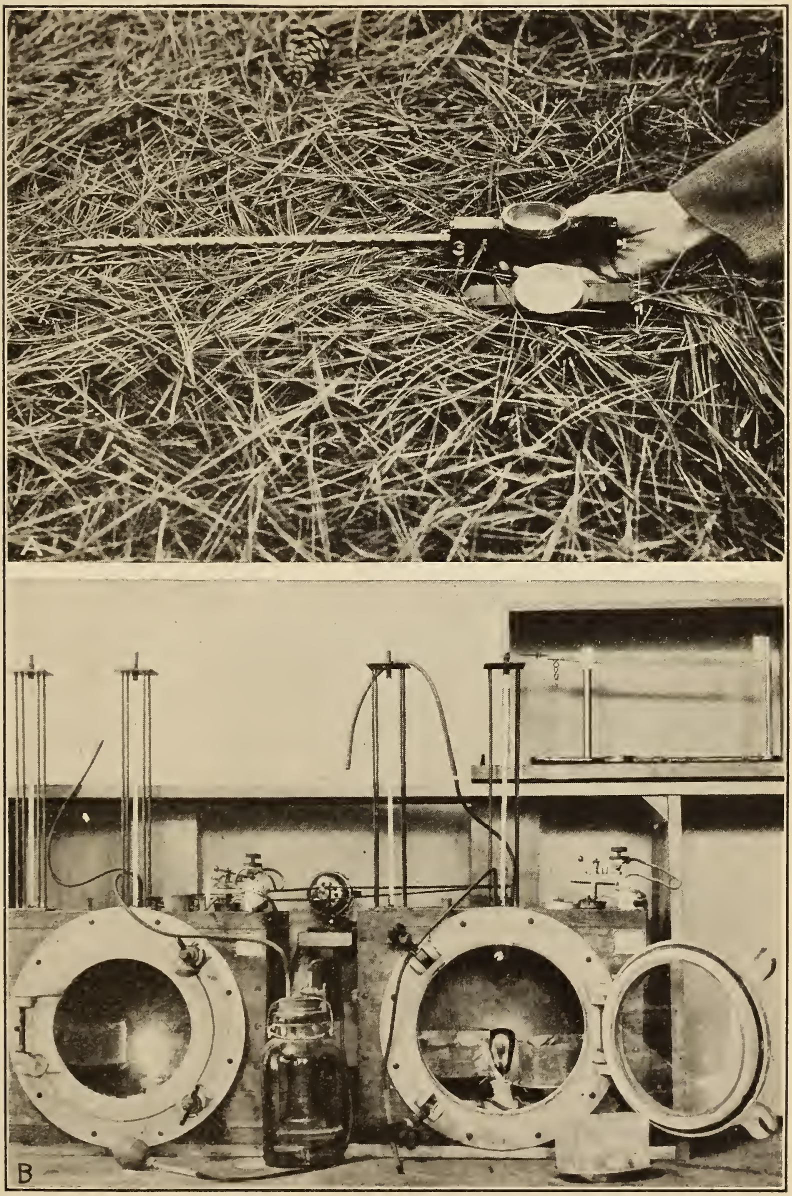

A.—The duff hygrometer. The photograph shows one instrument in place in the top layer of duff and another held above the surface for comparison

B.—Apparatus used in determining equilibrium relations between relative humidity and various fuel moisture contents. Inside the two kilns are wire baskets containing samples of duff and twigs to be tested three curves in Figure 2, which represent practically simultaneous daily measurements made during the 1924 fire season, all being for the same type of fuel within a small area subjected to the same general weather conditions. Because of the differences in moisture content the three sites in Figure 2 have been classified as moist, medium, and dry. The measurements for the moist and dry sites of 1924 are directly comparable with the 1925 measurements shown by Figure 1, the duff hygrometers having been inserted in the same spots in the same duff areas both years.

The graphs of the moist site represent duff conditions on a northwest slope, sheltered by a timber canopy of about 0.8 or 0.9 density

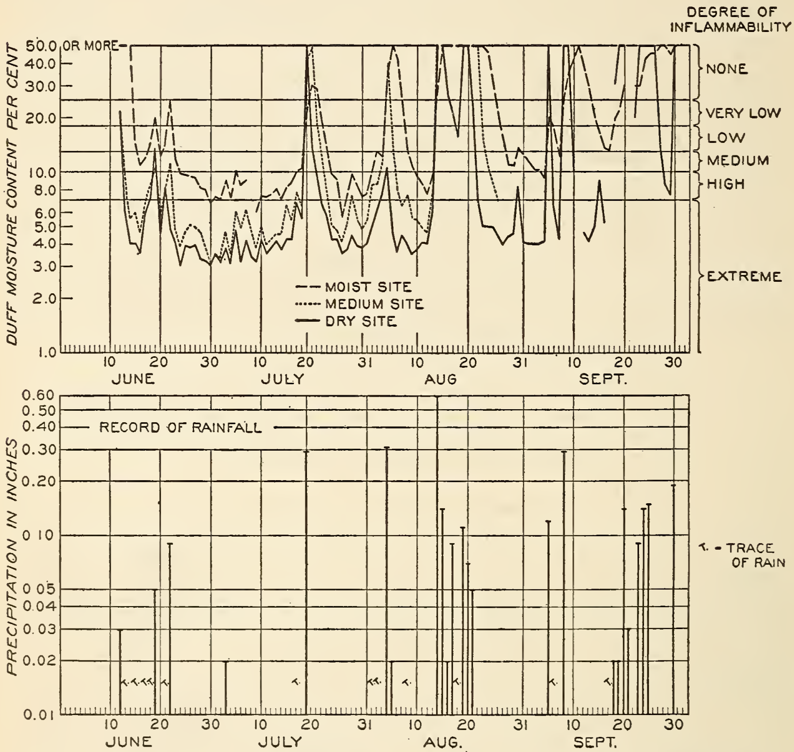

FIG. 2.—Inflammability of forest duff during 1924. Three sites at Priest River Forest Experiment Station

from most of the direct rays of the sun, from full-sunshine temperatures, from the greatest wind velocity, and also from full precipitation. The duff moisture content consequently would be expected to rise and fall more slowly on this site than on an open area fully exposed to all the weather elements, and, as the graphs show, this did occur.

The graphs of the dry site show, in contrast, conditions on a clearcut, flat area so fully exposed to the sun, wind, rain, and all the weather elements that the most rapid changes in fuel moisture content would be expected. The graphs indicate much more rapid changes here than on the moist site.

The measurements made on an area from which about half the timber had been cut are plotted in Figure 2 as the medium site. With half the shelter of the moist site and half the exposure of the dry site, the duff moisture values naturally fell about midway between the values for the other sites.

From these measurements it is obvious that although the regional weather may control the regional moisture content of fuels, the degree of exposure to the weather greatly influences the amount of moisture in specific materials. The significance of these differences within a small area is brought out more clearly by Table 2.

TABLE 2.—*Effect of exposure on duff moisture, as shown by the percentage of time from June 12 to August 30 that the duff on three different sites remained within various limits of inflammability*

Year and site	Distribution of time as between various degrees of inflammability [1]					
	Extreme	High	Medium	Low	Very low	None
1924	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Dry	76	7	3	3	4	7
Medium	57	17	5	4	2	15
Moist	5	38	16	9	7	25
Average	46	21	8	5	4	16
1925						
Dry	66	20	1	3	3	7
Moist	2	44	28	10	3	13
Average	34	32	15	6	3	10

[1] For duff moisture contents corresponding to the different degrees of inflammability, see fig. 2.

In 1924 the top duff was noninflammable more than three times as many days on the moist site as on the dry. On the other hand, this fuel on the dry site was extremely inflammable about 15 times as many days as that on the moist site. As the principal variable was exposure to the weather, the great importance of exposure is evident. A comparison with the 1925 measurements substantiates this conclusion, but it also indicates that the effect of the same exposure varies from season to season.

It is evident from these results that no positive statement can be made that certain degrees of exposure always result in certain comparative degrees of inflammability. It is perhaps noteworthy, however, that the percentage of time that the duff was fairly inflammable or worse on the dry site was the same for both seasons. Likewise the periods of high or extreme inflammability on the moist site were of about the same extent in both years. On the other hand, the difference of exposure that tripled the period of noninflammability during one fire season increased it only 85 per cent the next. The main point of interest is that actual measurements do show a pronounced effect of exposure on both the duration and intensity of the fire season on typical sites and in different seasons.

Measurements in materials other than the top layer of duff support the conclusion that exposure to the weather is an important control of the wetness or dryness and hence the inflammability of fuels. Simultaneous measurements on the timbered northwest slope and one clear-cut flat showed that the woody materials such as twigs, slash, and the outside half-inch of wood from a windfall had an average moisture content 63 per cent lower on the clear-cut area than on the timbered northwest slope. Similar classes of materials on an open south slope had at the same periods an average moisture content 84 per cent lower than on the northwest timbered slope.

From this preliminary study it is evident that density of the timber canopy, a condition greatly influenced by methods of cutting and of brush disposal, is an important factor in inflammability. In estimating the probable effects of rainfall, the duration of noninflammability following rainstorms, the rapidity of drying out to high inflammability, and the duration of periods of greatest inflammability, the exposure of the fuels to the weather elements should be given critical attention by the forest protective oragnization.

EFFECTS OF PRECIPITATION

As is shown in Figure 2, the only occasions during the 1924 fire season when the amount of moisture in the top layer of duff rose to over 25 per cent of the weight of the oven-dry material were periods immediately following rain. A comparison of the rainfall and duff-moisture records for the 1925 fire season substantiates this statement. Although increases in duff moisture of 4 or 5 per cent frequently occurred apparently as a result of changes in the other weather elements, no instances have so far been found, in over 250 daily measurements, in which large and lasting increases of duff moisture occurred except as a result of rain. If a moisture content of more than 25 per cent be assumed as necessary for complete elimination of duff inflammability in northern Idaho, the only weather element which commonly insures noninflammability is precipitation.

Larsen (*22*) found that for this region approximately 2 inches of rain per month is necessary to eliminate fire danger completely, and that, as a monthly rainfall of 2 inches is very infrequent during the summer, fire danger may be expected annually. Later studies indicate that the distribution of the rainfall throughout each summer month may cause exceptions to this general rule of Larsen's. The more even the distribution of precipitation, the less is the total amount required to prevent the drying out of fuels and to avert fire danger. Furthermore, the character of the weather following each rainstorm affects very materially the length of the period of noninflammability resulting from the rain. A storm followed by cool and humid weather will keep the forest from fire danger for a much longer period than will a storm of the same intensity that is followed by extremely hot, dry weather. It is evident that the total effect of rainfall alone can not be estimated or measured accurately under natural conditions unless proper consideration is given (1) to the amount of precipitation, (2) to its distribution, and (3) to the evaporation rate in the periods between rainstorms.

The amount of moisture in the fuel before the rain began is also important, of course, in determining how wet the material will be after the rain has ceased. Although no measurements have been made in the present investigation to determine the exact moisture content of any fuel resulting from various intensities and durations of rainfall when the fuel was fully exposed to the weather, a series of measurements of duff moisture content under a timber canopy, made immediately following measured amounts of rainfall in the open, indicates that when the duff is fairly dry before the rain its ability to absorb precipitation decreases as the rate of rainfall increases. Rains of under 0.5 inch in less than 24 hours seem to be more fully absorbed by the duff than rains of over 0.5 inch in less than 24 hours. Experience has shown that as a general rule any rain of 0.2 inch or more in 24 hours may be considered sufficient to eliminate fire danger temporarily. Although the timber canopy undoubtedly intercepts a higher proportion of the more gentle rains, it distributes the drip of the rain over a longer period and maintains a high humidity for a longer period, thus giving the duff more time to absorb moisture.

Heavy rains of short duration on the sheltered sites may, on the other hand, penetrate the tree canopy so that a greater proportion reaches the duff and other fuels on the ground; yet if this water reaches the materials faster than they can absorb it the surplus must either percolate through to the ground, evaporate back into the air, or be lost as surface run-off.

Some tests of the rate of absorption of water by fairly dry and inflammable duff indicate that from 0.6 to 0.7 inch of rain, evenly distributed throughout a period of 48 hours, is the minimum for saturation of duff in the northern Idaho white pine timber type. The same distribution of a smaller rainfall fails to produce saturation. Heavier rains, or lighter rains falling in less than 48 hours, produce more moisture than can be absorbed and result in percolation, evaporation, or run-off. As a rule the rain accompanying summer thunderstorms in northern Idaho is of sufficient volume for saturation but of too short duration to permit full absorption by the duff layer in the white pine forests.

One test of the ability of duff to absorb water from beneath indicated that even when the soil is saturated there is only an extremely slow capillary rise of water into drier duff above. In this test a sample of dry duff about 1 inch thick, held in a porous container, was immersed to a constant depth of 0.16 inch in water and the moisture content of the duff was determined periodically for 52 hours. Three hours after the beginning of this test, the sample had absorbed sufficient water to become noninflammable, and within nine hours its moisture content had increased to 74 per cent. Within 26 hours the moisture content was 108; at 49 hours it was 120, and at 52 hours 126 per cent. The saturation capacity of this duff sample was then determined as being 222 per cent.

At the rate of absorption occurring during the last 24 hours of the test, the duff would have required at least 9 days more to become completely saturated. Hence it may be assumed that soil moisture alone probably never results in saturation of the duff. A saturated soil, however, by supplying moisture to the fuel lying upon it, may have an important effect on the lower range of duff moisture contents and undoubtedly contributes toward the lowering of fire danger. Although the rain has ceased, secondary effects of marked importance may result several days later from increased soil moisture. In actual fire suppression the great value of a wet soil is generally recognized.

The duff moisture contents shown in Figures 1 and 2 can not be used as an index of the effect of varying amounts of precipitation recorded during the preceding 24 hours, since the rainfall may have occurred and ceased even as much as 23 hours before the duff moisture was measured. In the interim there may have been 10 or 12 hours of hot, dry weather which removed much of the moisture supplied by the rain; or the rain may have been followed by a cool, humid day which did not remove as much moisture from the fuels. The effect of the weather following the rain, as well as the effect of the rain, is thus included in many of these daily measurements. To supply better evidence on this phase of the problem, special readings should be made immediately before and after rains.

TABLE 3.—*Correlation between summer[1] rainfall and fires for Finnish forests*

Correlation	Correlation coefficient	Probable error
All State forests:		
Amount of summer rainfall and number of fires	−0.46	±0.13
The Pallila forest:		
Amount of rainfall and number of fires	−0.76	±0.09
Amount of rainfall and area burned	−0.53	±0.16
Number of rainy days and number of fires	−0.73	±0.10
Number of rainy days and area burned	−0.72	±0.11

[1] June to August, inclusive.

Although daily measurements of rainfall can not be used at present as a highly accurate gauge of the amount of moisture in the fuels, a comparison of records of seasonal rainfall and the number of forest fires during the same period, as in Figure 3, shows a marked relationship between the two. This relationship is so striking that the cause of exceptions should be sought in factors other than rainfall. For example, the marked departure in the summer of 1920 is largely explained by the excessive occurrence of lightning storms.

The tentative boundary lines in Figure 3 have been located merely to include about 90 per cent of the individual instances for both spring and summer conditions. The precipitation data used were obtained from the records taken at Walla Walla, Spokane, and Missoula, and the fire data from the records for the Kaniksu, Pend Oreille, Coeur d'Alene, Clearwater, St. Joe, Kootenai, Blackfeet, Flathead, Cabinet, and Lolo National Forests. The relationship between rainfall and fires, while not perfect, is sufficiently obvious to indicate that seasonal rainfall is a very important factor controlling the number of forest fires.

Further, as rainfall has been shown to influence the moisture content of fuels markedly, it probably acts as an important control of the rate at which fires spread. It is reasonable to believe that by influencing both the number of fires and their rate of spread, the amount of rain indirectly affects the damage resulting from fires. Hence rainfall alone must be recognized as a very important control of each of the components of forest-fire danger in northern Idaho.

A statistical study of the relation between rainfall and fires conducted in Finland and covering a long series of records, has shown very high correlation coefficients between the two. A report by Saari (*31*) gives the results of this phase of the Finnish study as shown in Table 3. Correlation coefficients of over 0.50 indicate an appreciable correlation between the two conditions and when equal to six times the value of the probable error they practically preclude

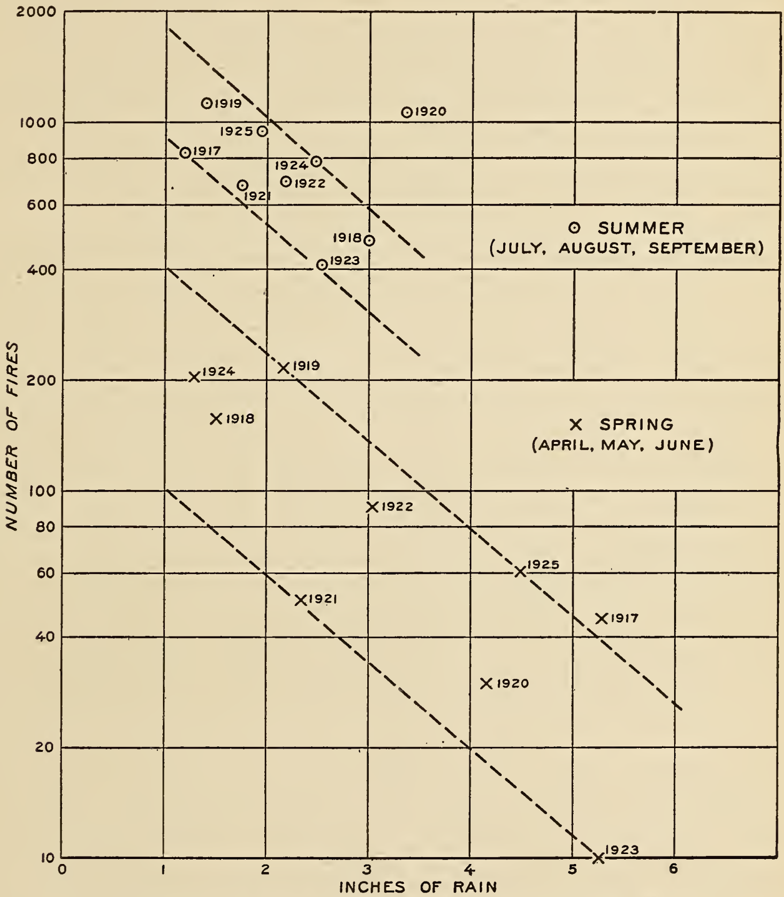

FIG. 3.—Number of fires in relation to spring and summer rainfall

the possibility of the correlation being accidental (*19*). The indication is that the effect of rainfall on fire danger in Finland is very important. A similar study should be made of our North American data as soon as the records cover a sufficient period with satisfactory accuracy.

EFFECTS OF RELATIVE HUMIDITY

As will be shown, atmospheric humidity is very important in raising the fuel moisture content from low points up to an occasional maximum of about 50 per cent, but humidity alone can not ever cause much more than 50 per cent moisture content in the fuels, whereas precipitation may produce moisture content as high as 200 or 300 per cent. In other words, humidity may put half a pound of water in every pound of duff, but rain can put from 2 to 3 pounds, or from four to six times as much water, in that fuel. On the other hand, although rain is capable of making the fuels wetter than can the water vapor of the atmosphere, rain is at best a periodic agency; whereas a certain amount of air moisture is ever present. Rain also acts only in one direction, to make fuels wetter; but under the influence of low atmospheric humidity wet fuels may within limits become drier. Hofmann and Osborne (*17*) have concluded that in western Washington and Oregon atmospheric humidity is the most important single weather element controlling the fluctuations of forest inflammability. It is extremely important in northern Idaho also.

The amount of moisture in the atmosphere is commonly measured in two ways: (1) According to the weight of the water vapor per cubic volume of space, and (2) according to the ratio between the amount of moisture in the atmosphere at its existing temperature and the amount the same space could hold if it were saturated at that temperature. The first method gives results which are expressed in grains of moisture per cubic foot of space, grams per cubic meter, or the vapor pressure in terms of height of a mercury column to balance the pressure of the water vapor. Such measurements express the absolute humidity regardless of the temperature of the air. The second method compares the amount of water vapor actually existing at any moment with the total amount possible at the prevailing temperature, and thereby expresses the relative humidity. The choice of the method employed depends upon the purpose of the measurement. In forest-fire protection the relative humidity measurement is usually employed as the simplest and most comprehensive.

In northern Idaho and western Montana the atmosphere seldom has a relative humidity as high as 100 per cent. Practically the only occasions when this condition does occur are when fog or clouds surround the point at which the measurements are made. Frequent measurements made in the course of this study have shown that although it be raining hard the air may not be saturated. Relative humidities between 60 and 80 per cent are common during rainstorms. After the storm has ceased, however, the temperature of the air may have been lowered sufficiently, and enough rain water may have evaporated back into the atmosphere to form fog and to cause a relative humidity of 100 per cent. On the other hand, the relative humidities experienced in this region seldom fall below 8 or 10 per cent. At that level the atmosphere is capable of absorbing moisture very rapidly from all wet materials and of reducing all fuels to a very dry and very inflammable condition.

The effect of humidity on the moisture content of each of the fuels will indicate the relation between humidity and inflammability of the fuel. Any additional effects of humidity on ignition and combustion of fuels, such as the possible reduction of the oxygen supply due to its replacement in space by water vapor, should also be discovered and utilized in forest-fire fighting.

The present investigation has attempted to measure fluctuations in moisture content of fuels with all the factors eliminated except relative humidity. Samples of several important fuels were collected from the forest, placed in small chambers in which the air temperature and humidity could be held constant at any desired point, and left there until measurements of their weight showed that they had ceased to absorb or lose moisture. When a sample reached this condition its moisture content was in equilibrium with the relative humidity, and the relationship could thus be ascertained for the natural range of humidity in this region.

This laboratory determination of the equilibrium relations between relative humidity of the atmosphere and moisture content of several materials was made by the Forest Products Laboratory at Madison, Wis. The apparatus used is illustrated by Plate 5, B, which shows the chambers in which the humidity was held constant, the humidity control and measuring instruments, the samples of fuels in baskets within the chambers, and the scales for weighing the samples without removing them from the chambers and without opening the chambers. A summary of the results of these tests, made by M. E.

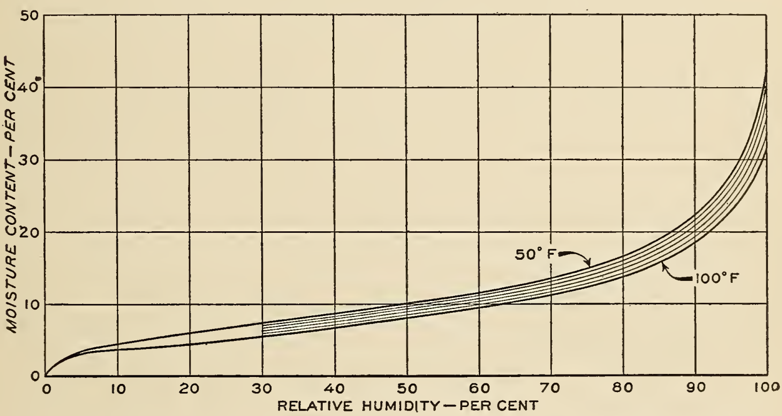

FIG. 4.—Composite curve of moisture content of various materials at different humidities

Dunlap of the Forest Products Laboratory, as given in Figure 4, indicates that the effect of relative humidity on fuel moisture content is very great, the fuel moisture varying from 0 to more than 40 per cent, and for individual fuels to 50 per cent, as the relative humidity increases from 0 to 100.

As relative humidity can not be measured independently of temperature, this summary of all materials includes tests at various temperatures between 50° and 100° F. As is apparent, the effects of temperature alone was very slight, the major changes of fuel moisture content being caused by changes in the relative humidity. The small variation in the moisture in the fuel, due to temperature alone may be neglected at present. When the rate of change of fuel moisture is studied in relation to the normal changes of atmospheric temperature and humidity, then temperature becomes much more important.

Six different materials were tested—twigs, sound and decaying wood from windfalls, duff from immature and mature white pine stands, and western yellow pine duff. Results were so nearly alike that for all practical purposes the different materials may be said to have the same equilibrium moisture content for any specific relative humidity.

If the relative humidity of the air remained constant long enough, or if the forest fuels changed their moisture content rapidly enough to insure a fairly constant equilibrium between the two, existing relative humidity alone would serve as an accurate indicator of inflammability, excepting only when precipitation caused higher moisture content than humidity alone can cause. However, instead of remaining comparatively constant, the relative humidity of the air under natural summer conditions varies rapidly from a common daily minimum of 20 to a common maximum of 80 or 90 per cent; and the various materials fail to react to these changing humidities with anything like the same speed. The typical forest fuels are usually in perfect equilibrium with relative humidity for only a few minutes about twice each day.

The greatest moisture content to be expected as a result of the highest humidity is between 40 and 50 per cent. Consequently, more than one-half pound of water per pound of fuel should never be expected as a result of high humidity even though the humidity stays constantly at 100 per cent for a period of several hours or days. On the other hand, even when the humidity is as low as 10 per cent there will still be at least 2 per cent moisture content in the fuels.

Between these extremes the potential effect of relative humidity varies. According to the composite curve shown in Figure 4, a humidity increasing from 10 to 60 per cent can be expected to raise the fuel moisture content from 4 to about 11 per cent, or a 7 per cent rise in fuel moisture for a 50 per cent increase in humidity. If the humidity then rises from 60 to 90, the fuel may be expected to pick up moisture from 11 to 20, or a 9 per cent rise in fuel moisture for a 30 per cent increase in humidity. Then if the humidity increases only 10 per cent more, i. e., to 100, the fuel may be expected to increase its moisture content from 20 to about 40 per cent. Small changes in the humidity in its higher range are therefore of much greater potential effect than equal changes in the lower range. Whether or not this potential effect produces a corresponding actual effect on the behavior of a forest fire remains to be determined by further measurements.

Figure 5 illustrates the relative changes in the moisture contents of three classes of materials—wood, the top layer of duff, and the full layer of duff—with the natural air temperatures and humidities to which these materials were exposed. This comparison of the humidity-fuel moisture relation for about nine consecutive days shows the theoretical as well as the actual effects of humidity on fuel moisture. The curve marked "equilibrum fuel moisture content" was computed from the equilibrium moisture contents shown in Figure 4, and the graphic records of temperature and humidity shown in the upper portion of Figure 5, to show how each of these three fuels would have changed moisture content if they had responded instantly and fully to the measured changes of temperature and humidity.

A comparison of this curve with the three curves of actual moisture content shows very clearly that these three materials, at least, actually pick up and lose far less moisture than they are potentially able to do. The top layer of duff responded most nearly to the potential but still with too great a lag to permit the use of humidity alone as an index of duff moisture. The wood sample responded less readily, and the full layer of duff showed a diurnal change of only 1 or 2 per cent in moisture content in contrast to an indicated possible change ten to twenty times greater.

The differences between these three curves representing actual fuel moisture content show that the different fuels do not respond similarly to changing humidity, and the comparison of these three curves with the curve representing the equilibrium condition shows that none of these important fuels changes its moisture content in close enough agreement with humidity so that humidity alone can be used as an accurate index of their moisture content. Hofmann and Osborne have stated (*17*) that moisture content changes with changing humidity much more rapidly in finer and lighter-weight materials such as dead weeds and tree moss than in the materials tested here, but that even in these more responsive materials it fails to fluctuate at all times directly with the humidity.

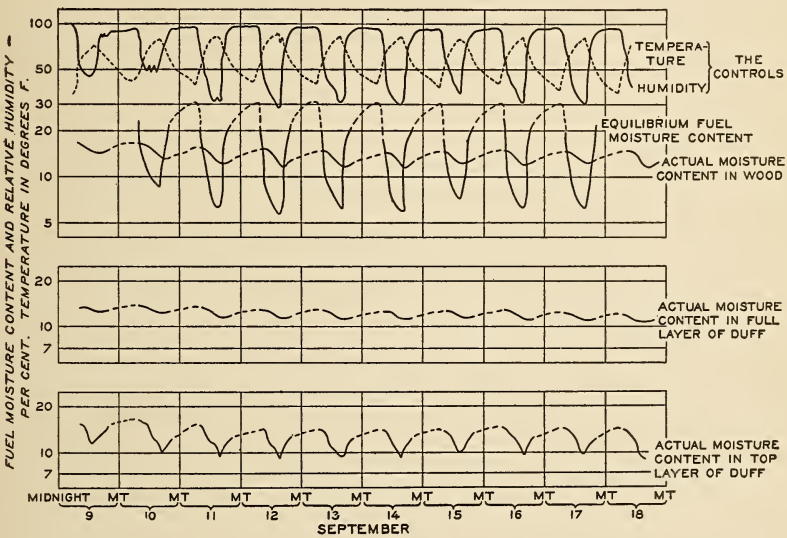

FIG. 5.—Equilibrium and actual fuel moisture content changes compared

There are occasions, furthermore, when the action of other weather elements produces effects which can not be estimated at all by the use of humidity measurements, as when rain has raised the fuel moisture content to a very high point, such as the 320 per cent for April 27, 1925, in Table 1. When the duff or other fuels are as wet as this they lose moisture to the atmosphere at any relative humidity under 100 per cent. Until the fuels dry out so that their moisture is equal to or less than the corresponding balance of moisture in the atmosphere, no measurement of relative humidity can be even a rough index of the amount of moisture in the fuels. A measurement of relative humidity can always be used, however, to show the equilibrium fuel moisture content toward which the condition of the fuel is changing. The length of time required before this equilibrium condition could be reached depends upon several other factors as well as upon the relative humidity.

The principal factor determining the rate of change of moisture between the fuel and the atmosphere is the difference between their moisture contents. When the fuel is extremely wet and the air very dry the change will be most rapid. When the fuel is very dry and the humidity very high the change also will be rapid. When the two are nearly in balance the change will be very slow.

Another factor contributing to the rate of change is the difference in degree between the wet-bulb and dry-bulb temperatures of the air. A relative humidity of 21 per cent, for example, does not always mean the same rate of drying of the fuel. According to Humphreys (*18*, *p. 247*) :

> Many observations have shown that, to at least a first approximation, the rate of evaporation is directly proportional, other things being equal, to the difference in temperature indicated by the wet and dry bulb thermometers of a whirled psychrometer.

If the dry-bulb air temperature is 41° F. at one observation and 86° at another and the relative humidity is 21 per cent on both occasions, then the depression of the wet bulb will be 11° in the first instance and 26° in the second (pressure 27 inches) ; and therefore the rate of evaporation at a humidity of 21 per cent and an air temperature of 86° will be more than double the rate at a humidity of 21 per cent and a temperature of 41°. Wet fuels can be expected to dry out to equilibrium with any humidity at high temperatures much faster than with the same humidity at comparatively low temperatures. Low humidities during cool nights are by the same token less active in drying the fuels than equal humidities during hot days.

A third factor influencing the rate of evaporation of moisture from wet fuels is the wind velocity. Large volumes of dry air passing rapidly over the wet fuels remove more moisture than small volumes of air of equal dryness passing slowly. The measurements of duff moisture content at Priest River have shown frequently that with low wind velocities the rate of drying of the fuels in dense woods, sheltered from the wind, is much slower than the rate of drying of the same class of fuels in the open, exposed to the wind. As the wind velocity increases, however, it penetrates the woods and greatly increases the rate of drying of the fuels there.

Other known factors influencing the rate of evaporation are the salinity of the water in the fuels, the barometric pressure of the air, the area of the surface of the fuels exposed to evaporation, and the temperature of the water in the fuels (*18*). The effects of these factors are minor when compared with the effects of differences between the moisture content of the fuels and the atmosphere, the depression of the wet-bulb temperature, and the velocity of the wind; but in view of all these factors, it is evident that humidity measurements alone frequently fail to indicate accurately the degree of inflammability of forest fuels.

Measurements of prevailing relative humidity nevertheless serve a very real and practical purpose in forest protection. Experienced fire fighters become familiar with the "feel of the air" on bad fire days. Their subconscious correlation of dry air and raging fires has taught them to approximate the degree of dryness of the air and the result. An instrumental measurement is certain to be more accurate in the long run than any physical sensations, and therefore should improve the accuracy of these estimates.

Instrumental measurements of humidity are of further value because, regardless of the amount of moisture in the fuels as a result of previous rains, if the atmosphere becomes drier than it has been and the psychrometer shows a greater depression of the wet bulb, the fuels are certain to lose moisture to the atmosphere and to become more inflammable. Likewise, if the atmosphere becomes more moist it will cease to extract as much moisture from the fuels each day, and may even add moisture. As the process of transference of moisture between the fuels and the air requires some time, the measurements actually show what will be most likely to happen in the immediate future as well as what is happening. The fact that these measurements of humidity can not be translated accurately into absolute terms of fuel moisture content need not prevent the recognition of whether the atmosphere is becoming more favorable for fire suppression, or more unfavorable. The trend can be judged much more accurately from this measurement than from physical sensations.

Until recently (*17*) no attempt had been made to do more than draw a single line separating dangerous from safe humidities. Results of the present investigation indicate, however, that, independent of the moisture content of fuels or the other weather elements, it may be possible to define certain zones of humidity, each of which would be generally significant of a certain most probable degree of inflammability or fire danger. These distinctions are based on a comparison of 610 simultaneous measurements of relative humidity and duff moisture content made during the 1924 and 1925 fire seasons. The measurements represent both morning and evening relationships between humidity and duff moisture, or degree of inflammability, on three areas—the moist, medium, and dry sites previously described. Figure 6 shows the relationships graphically.

From the graph it is evident that on these sites, as representative of north Idaho conditions, humidity may be classified as generally safe, slightly dangerous, dangerous, or extremely dangerous in so far as it affects duff moisture content and duff inflammability. Although in other regions and with other fuels in this region a different relation may be found, for the top layer of white pine duff in northern Idaho relative humidities of more than 70 per cent may be assumed to be generally safe, humidities between 45 and 70 per cent slightly dangerous, those between 25 and 45 per cent dangerous, and humidities of less than 25 per cent nearly always extremely dangerous.

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The degree of dependence which should be placed upon this classification varies according to the degree of danger indicated. The 105 comparisons of duff moisture with humidities of less than 25 per cent show that in every instance the duff had less than 15.6 per cent moisture content, and in 102 instances less than 12 per cent. The 189 comparisons in which the humidity was between 25 and 45 per cent revealed a greater range of duff moisture, the minimum being 2.5 per cent and the maximum 50 per cent or more. Hence all degrees of duff inflammability occurred with humidities between 25 and 45 per cent, but the average condition was one of low or medium inflammability. Likewise, for both the slightly dangerous and generally safe classes of humidity, a great range of duff moisture was actually found.

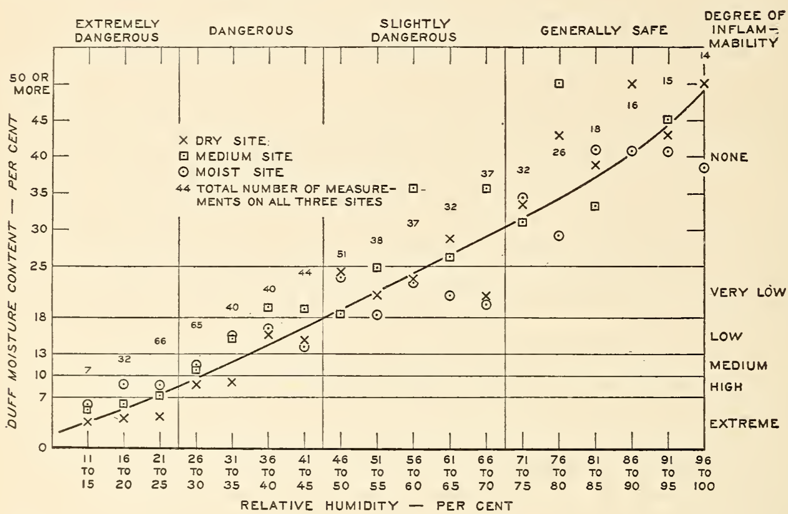

FIG. 6.—Composite curve of simultaneous relative humidities and duff moisture contents on three sites. Basis—610 simultaneous measurements of both relative humidity and duff moisture

As this comparison of humidity and duff inflammability includes daily measurements made during and following rainstorms, as well as during and at the end of long droughts, the effects of all the weather elements are included. The remarkable feature is that there should be such a distinct relationship between humidity alone and duff moisture content. The existence of this relationship does not prove that humidity controlled the duff moisture content, for a very similar relationship will be shown between temperature and duff moisture content, and one can hardly assume with reason that temperature alone can add or subtract moisture from the duff. The existence of all these general agreements between single weather elements and fuel moisture content tends to indicate merely that all the weather elements influence fuel moisture, and that measurements of each element may be used with varying accuracy as individual criteria of fuel moisture. The fewer are the weather elements measured the smaller is the degree of accuracy to be expected in determining fuel moisture and resultant inflammability.

As has been stated previously, exposure of the fuels to the weather must be given consideration in attempting to use measurements of

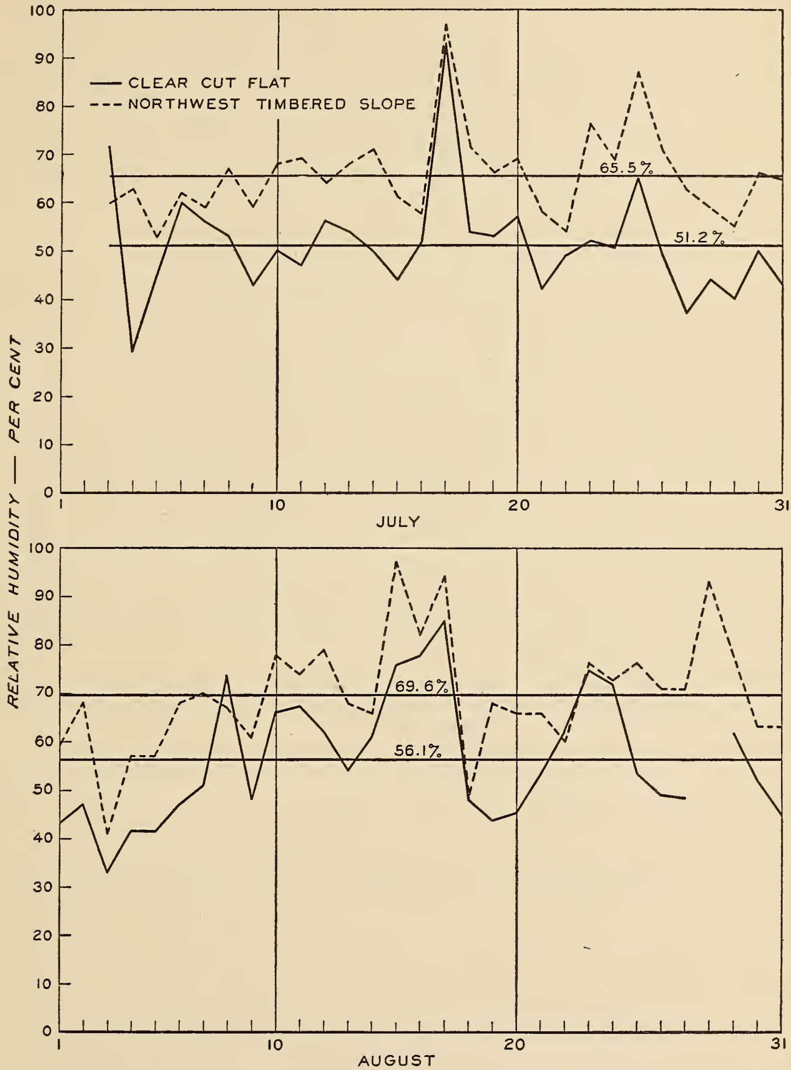

FIG. 7.—Relative humidity on two neighboring areas

single weather elements as indices of fuel moisture contents. Figure 7 serves to show the humidities occurring in adjacent areas, the differences being largely caused by different exposures to the general and regional weather.

TABLE 4.—*Comparisons of relative-humidity readings in the open and under timber cover, 1925*

Date	In the open		In the woods		Date	In the open		In the woods	
	Amount	Change	Amount	Change		Amount	Change	Amount	Change
	Per cent	*Per cent*	*Per cent*	*Per cen*		*Per cent*	*Per cent*	*Per cent*	*Per cent*
July 3	72		60		Aug. 7	51		70	
4	29	−43	63	+3	8	74	+23	67	−3
5	45	+16	53	−10	11	67		74	
7	56		59		12	62	−5	79	+5
8	53	−3	67	+8	18	48		49	
11	47		69		19	44	−4	69	+20
12	56	+9	64	−5	24	72		73	
15	44		61		25	53	−19	76	+3
16	52	+8	58	−3					
27	37		63						
28	44	+7	59	−4					

From numerous tests, some of them listed in Table 4, it is apparent that measurements of relative humidity at a certain spot or station may not be truly indicative of near-by changes in humidity under different exposures to the weather. The humidity changes shown by the measurements in the open fail materially to indicate the changes occurring in the near-by forest. In one such series of early morning observations made by an experienced operator during a period of two months, the measurements in the open were never dependable when applied to the forest, and similarly the measurements in the forest would too often have been misleading if used as criteria of humidity or fuel moisture content in the near-by old burns or open areas. It is only when these probable errors are recognized and the degree of exposure is taken into consideration that humidity measurements may safely be used alone.

The statistical study by Saari (*31*) previously mentioned gives the correlation coefficients found to exist between relative humidity and forest fires in Finland as follows:

Correlations	Correlation coefficient	Probable error
Relative humidity and number of fires	−0.36	±0.23
Relative humidity and area burned	−0.48	±0.21

As will be noted, the correlation coefficients are smaller and the probable errors larger than when rainfall and fires were compared. They are also less indicative of good correlation than the coefficients that will be shown between air temperature and forest fires. The reader should remember, however, that these coefficients apply to the particular weather and timber types of Finland, and that area burned depends very greatly upon the efficiency of the fire protective organization as well as upon the dryness of the fuels. The true measure of effect of each of the weather elements must be made independently of organization efficiency, because the very purpose of the study is to determine how, when, and where the fire protective organization must be strengthened.

Eventually the relation between relative humidity and the moisture content must be studied for each of the important fuels if humidity measurements are to be used for estimating prevailing fuel dryness or for predicting dryness of fuels. The fact of most immediate use brought out by the present study is that for the top layer of duff in northern Idaho, and regardless of the other weather elements, measurements of relative humidity alone may be classified as indicating generally safe, slightly dangerous, dangerous, and extremely dangerous conditions of inflammability.

EFFECTS OF TEMPERATURE

Although the temperature of the air is not a measure of the amount of moisture in either the atmosphere or the fuels, it is an important control of both atmospheric and fuel-moisture content. High temperatures of the air also affect inflammability by raising the temperature of fuels and creating a condition in which less additional heat is required both to start and to maintain combustion. Futher-

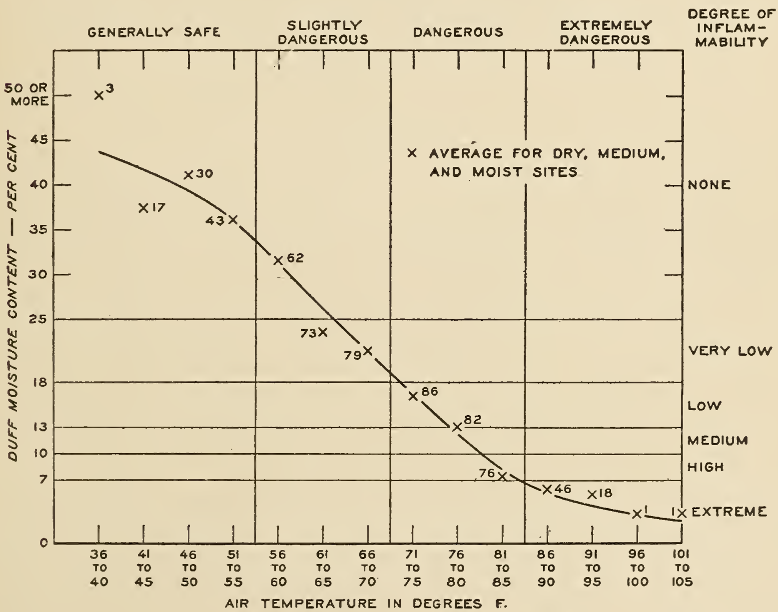

FIG. 8.—Composite curve of simultaneous air temperatures and duff moisture content on three sites. Basis—617 simultaneous measurements of both duff moisture content and air temperature. Numerals indicate number of measurements used as basis

more, the differences between temperatures at separate stations in any region are important because the more pronounced these differences are, the greater is the resultant flow of air and consequently the greater the wind velocity. Most textbooks on meteorology emphasize the importance of air temperature in affecting humidity, precipitation, wind direction, wind velocity, and nearly everything else that contributes to the sum total of both weather and climate (*18*).

In the preceding discussion of relative humidity many temperature effects were also described. It was shown that temperature alone is not an important control of the moisture contents of fuels in equilibrium with relative humidity, but that it is a very important factor in determining the length of time that must elapse before fuel moisture content reaches equilibrium with atmospheric humidity when these two conditions have been thrown out of balance by some other weather element, such as rain. It has further been shown that low relative humidities on hot days or nights are much more dangerous than similar humidities with lower temperatures.

In the present investigation measurements of air temperature have been compared with coincident measurements of duff moisture content, in the same way that relative humidity was compared with duff moisture. Figure 8 shows the results of 617 simultaneous measurements and permits a tentative determination of the various degrees of duff inflammability according to measurements of prevailing air temperature. As is shown by the composite curve, when the air is over 85° F. conditions are usually extremely dangerous, from 71° to 85° they are dangerous, from 56° to 70° slightly dangerous, and at less than 56° generally safe. The degree of dependability of these classifications, however, varies considerably.

By the combined use of the classifications of relative humidity and air temperature, it should be possible to estimate more accurately the degree of existing duff inflammability. For example, a relative humidity of 40 per cent would indicate, if used alone, a dangerous condition, but if the air temperature at that time was found to be 53° F., a generally safe condition, and if equal weight were given to the two measurements, a compromise estimate of slightly dangerous conditions might be obtained.

The question of how much weight to give to measurements of each of the weather elements when they indicate different degrees of danger still remains to be determined. At first glance relative humidity might be estimated as most important, but the effect of temperature or the effect of rain on the fuel moisture content may prevent the accurate use of humidity. The amount of moisture in the fuels affects the relative importance of each of the weather elements. Until further work shows the comparative importance of each component of the weather, the accurate use of measurements of single weather elements will be greatly hindered. In the meantime each of the elements may be measured separately and when, for instance, both humidity and temperature agree in indicating a certain degree of danger, that indication may be accepted as more likely to be trustworthy than a compromise indication based upon a disagreement between humidity and temperature.

In using the classification of danger based on measurements of air temperature, the fact should be considered that the fuel was responding to all the weather elements, including rain, humidity, and wind, and that the correlation shown by Figure 8 includes all these factors. although it distinguishes air temperature as the ostensible independent variable. The degree of correlation is, therefore, not the effect of temperature alone on duff moisture content, but is explained by the fact that as a rule low temperatures accompany rain and high humidity and high temperatures are coincident with fair weather and low humidities. By selecting and measuring one of these significant variables, the usual trend of the others is indicated and the sum-total effect thereby approximated. In this way it appears that, for northern Idaho at least, air temperature may be used alone nearly as well as humidity. After a sufficient number of comparable measurements are obtained, perhaps 1,000 or more, a statistical study will be made to determine the degree of correlation existent between measurements of each of the weather elements and the moisture content of each of the important fuels.

The study made in Finland determined the following correlation coefficients between temperature and forest fires:

Correlation	Correlation coefficient	Probable error
Mean temperature and number of fires	+0.57	±0.15
Mean temperature and area burned	+0.65	±0.13

A negative correlation exists, however, between rainfall and temperature, and when the partial correlation coefficients were computed to distinguish between these two controlling factors, a coefficient of −0.66 was obtained between rainfall and number of fires, and a coefficient of +0.31 was found between mean temperature and number of fires. Saari (*31*) concludes, therefore, that the rains have a greater effect than the temperature.

EFFECTS OF WIND

The flow of air from one region to another is a very important factor in the occurrence of forest fires, their rate of spread, and the damage done. If the incoming air has passed over a desert region, losing much of its moisture and gaining heat, that wind is much more drying than one coming from a moist and cool forested area. The higher velocities of the dry wind also accelerate the rate of drying of the fuels and fan the flames of existing fires so that they are harder to control and do more damage.

At nearly all official meteorological stations in northern Idaho the prevailing wind during the summer months is from the southwest, coming across the eastern Oregon and Washington semidesert region before it strikes the forests of Idaho. This dry wind contributes greatly to the difficulty of forest protection, whereas in western Oregon and Washington the moister westerly wind from the ocean is much more favorable to protection. As an example, the Weather Bureau records for August, 1923, show a prevailing southwest wind with an average 5 p. m. relative humidity of 28 per cent at Spokane, Wash. At Portland, Oreg., during the same month the prevailing wind direction was from the northwest, and the average relative humidity 43 per cent at 5 p. m. According to the composite curve in Figure 6 this means an average duff moisture content of about 17 per cent or low inflammability near Portland, and an average of only 10 per cent, or medium to high inflammability, near Spokane.

Departures from the common wind direction naturally may be expected to cause departures from the average degree of fire danger. In western Washington, a wind from the east, coming from the dry eastern Washington region instead of from the ocean, brings lower humidities and higher temperatures and thereby produces drier fuels and greater danger. An east wind in northern Idaho, however, coming across the forests of western Montana instead of across the arid region of Washington, is usually more humid and cooler than the common wind, and brings much less than average fire danger. In estimating the degree of fire danger, the wind direction should receive critical attention by the forest protective organization. The significance of departures from the average direction as affecting humidity should be recognized and acted upon.

Wind is one of the few weather elements which influence fire danger in other ways than by affecting the amount of moisture in the fuels. Show's (*32*) determination of the fact that, other conditions being similar, the rate of spread of fire varies about as the square of the wind velocity indicates that small increases in the wind are much more dangerous than one might believe. Show and Kotok (*35*) have more recently concluded that wind velocity is equally important with relative humidity in controlling the rate at which fires spread in California.

Common experience has shown that local topography exerts an important effect on both direction and velocity of wind, and that forest fires also affect both direction and velocity. A few measurements obtained during the 1925 fire season in northern Idaho indicate that a fire of sufficient size may produce local winds out of all proportion to the regional condition and may, therefore, cause entirely unexpected behavior of the fire. Further measurements must be obtained, however, before any general conclusions can be drawn. These additional measurements should be sufficiently comprehensive to show the effect of the forest fire on the surrounding humidity and temperature, as well as on the wind. The preliminary results indicate that a fire may be of such size and location as to offset entirely improved weather conditions, and to nullify the benefits of careful forecasting.

No studies have been made to determine the effect of increased oxygen supply caused by increased wind velocity or the minimum volume of air required for combustion of forest materials in situ.

One of the most important effects of wind is the springing up, ahead of the main conflagration, of spot fires caused by wind-borne glowing embers (see illustration on the cover of this publication). According to reliable observers in this region, spot fires a mile or more in advance are not at all uncommon. The winds that cause such jumps may be either region-wide, local to the fire and caused by it, or a combination of both. The most usable information concerning this effect of wind appears to be a knowledge of whether or not the forest materials will be ignited by these glowing embers.

EFFECTS OF EVAPORATION

Evaporation results from a complex of at least three and perhaps four separate weather elements. Humidity, temperature, and wind are the recognized major controls. Students of evaporation admit also the effect of sunlight, and instruments for the measurement of evaporation have been designed, some with black surfaces to respond more to sunlight, some with white surfaces to respond less. All of these factors combined—humidity, temperature, wind, and sunlight—act to remove moisture from the forest fuels; none of them except humidity supplies moisture to the fuels, and the moistening effect of humidity is limited. Consequently, measurements of evaporation obtained by the use of rain-correcting atmometers or evaporimeters always express a loss of water; never if they are properly constructed do they show a gain. Such instrumental measurements can therefore be used only for estimating the probable rate of drying of the forest materials. They can not indicate the probable and frequent absorption of water by the fuels.

Measurements by instruments employing saturated surfaces, furthermore, are not dependable indicators of the rate of drying of forest materials whose surfaces are not saturated. Livingston (*23*), Humphreys (*18*), and others have emphasized the fact that evaporation rate determined with one type of instrument can not even be translated accurately into evaporation rate by another type of atmometer, even though both reveal the amount of evaporation from a saturated surface. The size, shape, and physical structure of the evaporating surface all affect the rate of evaporation from any object. The degree of saturation of the object also influences the final result. As the forest materials vary through such a range of size, shape, and physical and chemical structure, and as the degree of moisture in the different materials varies through a great range, instrumental measurements can not properly express the amount of water lost by the fuels. The most accurate measurements either of the rate of drying of the fuels or of their absorption of moisture, can probably be obtained from samples of the fuels themselves.

The principal use of instrumental measurements of evaporation rate has been found in the present investigation to be the integration of the effects of humidity, temperature, wind, and sunshine into one figure. Such measurements fill a distinct void which exists when the four weather elements are measured separately. Even though these four conditions are measured and recorded automatically with satisfactory precision, there is no known formula which can be used to compute their combined effect on the removal of water even from a saturated surface. An instrumental measurement of water loss can be made once or twice each day which will show for the preceding period whether the combined effect of humidity, temperature, wind, and sunshine has been greater or less than during other similar periods, and the amount of the difference. In the present work, the Bates or Forest Service type of evaporimeter has been used to good advantage for obtaining such comparisons from day to day at any particular station, and to obtain a comparison of the evaporation rates at different stations.

A comparison of the evaporation rate with duff moisture content (fig. 9) shows that the evaporation rate may be classified on that basis as generally safe, slightly dangerous, dangerous, and extremely dangerous, as were relative humidity and temperature. The results indicate that even though this measurement of evaporation rate covers a period of hours, whereas the duff moisture measurement represents the condition at a certain moment, the relationship between the two conditions is usable as an approximate criterion of duff inflammability. The same main objection applies to this method as to humidity and temperature measurements used alone that, although the usual relationships are fairly dependable, the frequent exceptions may lead to erroneous conclusions.

The average duff moisture contents shown in Figure 9 for evaporation rates of 20.1 to 22 grams per day are out of line with adjacent points because of one such exception to the average which was even more marked than usual. In this case, for June 17, 1925, all fuels were still rather wet from recent rains so that, although June 17 was very hot and drying, with a total evaporation of 21 grams, the duff layer failed to dry out to the indicated low point.

One interesting feature is brought out by study of each of the three curves used as a basis for Figure 9. This feature is shown in Figure 6 and is also true of the basic data for Figure 8. At the lowest temperatures, highest humidities, and lowest evaporation rates the duff in the open area or dry site is the wettest, and on the timbered or moist area the driest, with the medium site in between these

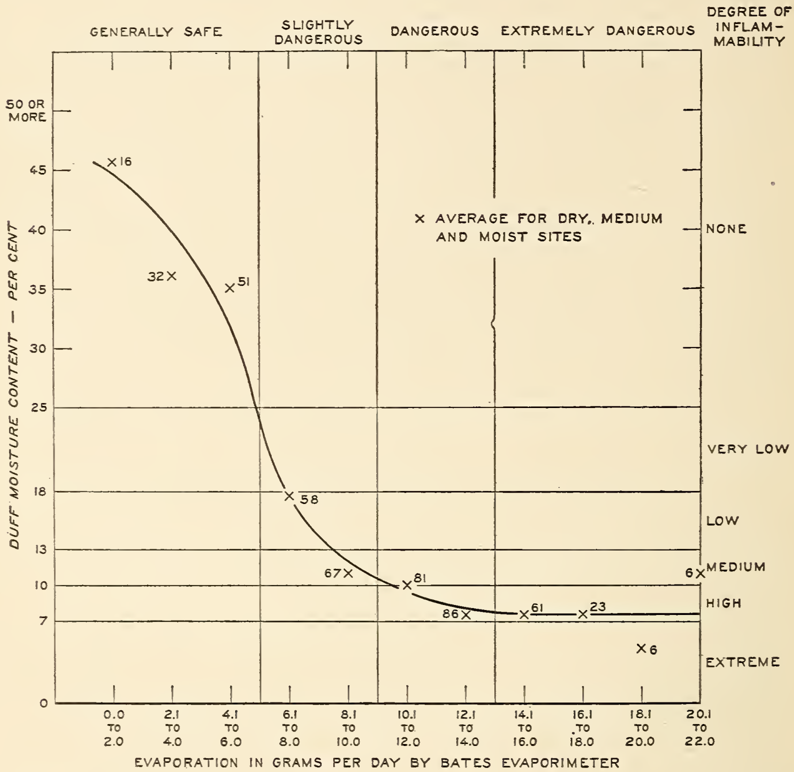

FIG. 9.—Composite curve of evaporation in the open and duff moisture content on three sites. Basis—487 measurements of duff moisture on 176 days. Evaporation measured once each day. Numerals indicate number of measurements used as basis

two. As the evaporation rate per day increases, the curves cross until the order of dryness is reversed. Such a change merely tends to prove again the stabilizing or moderating effect of forest cover. When atmospheric conditions are such as to produce wet materials, the forest cover on a full-timbered area keeps the materials less wet. When the atmospheric conditions tend to produce dry materials, the fullest forest cover keeps the materials wetter than on the partially cut-over or medium site with only half-timber cover. This half-timber cover by the same process kept the duff on its area neither so wet nor so dry as the extremes experienced on the open area.

Raphael Zon has frequently urged for the Lake States the retention of some timber cover on areas being logged, merely to help retain more moisture during the driest weather and so to retard the development of a great fire danger. Frank H. Lamb, president of the Wynooche Timber Co., of Hoquiam, Wash., also has recognized such a possibility even in very young stands of timber. In an article (*20*) Lamb maintains that a dense growth of reproduction quickly obtained after logging is the best possible means of reducing fire menace to the slash on a logged-off area, because of the higher moisture content and lower inflammability of the slash under reproduction as compared with its condition when fully exposed to the weather. The numerous measurements made on the three sites mentioned demonstrate the fundamental truth in the statements of both Zon and Lamb, and indicate the reasons for such a condition.

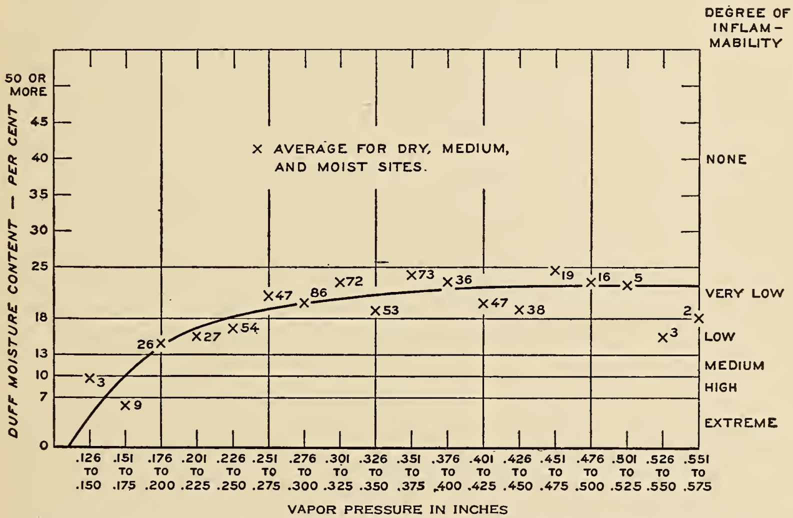

FIG. 10.—Composite curve of simultaneous vapor pressures and duff moisture content on three sites. Basis—616 simultaneous measurements of both vapor pressure and duff moisture. Numerals indicate number of measurements used as basis

EFFECTS OF VAPOR PRESSURE

By his investigations of forest-fire conditions in the southern Appalachians, McCarthy has shown (*24*) that in that region more forest fires occur in periods of low vapor pressure than in periods of high vapor pressure.

No attempt has been made in the present study to compare number of fires per day, or for a short period, with any of the weather elements, because the number of fires is a result not only of dryness of fuels but also of activity of fire-starting agencies, human as well as natural. Periods of two or three weeks may elapse with few or no fires starting, yet the weather may be hot and dry and the fuels may be extremely inflammable. At such times the number of fires is not at all an accurate criterion of fire danger.

An attempt to compare duff moisture content with simultaneous vapor pressures is shown in Figure 10. From the chart it is evident that no pronounced or usable relationship existed between duff moisture content and vapor pressure in the 616 simultaneous measurements made of these two conditions. The average duff moisture content was always low enough to indicate at least some inflammability, regardless of coexistent vapor pressures. Local vapor-pressure measurements fail entirely to indicate no inflammability, and the relationship is also too uncertain in the other zones of inflammability to permit vapor pressure alone to be used as an indicator.

Such a lack of apparent correlation does not imply, however, that vapor pressure can be disregarded in forest-fire protection. As high vapor pressure indicates a large amount of absolute moisture per unit volume of atmospheric space, it also implies that less cooling will be required to condense or precipitate that moisture than if the vapor pressure was low. For instance, if the vapor pressure is found to be 0.499 inch and the air temperature is 80° F., then a cooling to only 59° will produce saturation of space, and any cooling below 59° will cause precipitation. When the vapor pressure is 0.203 inch, however, and the air temperature 80°, then a cooling to 35° F. is required to produce saturation. In the summer time a nightly cooling to less than 59° can generally be anticipated, whereas a cooling to 35° can not be expected in this region. Hence if a vapor pressure of 0.499 inch is found in the afternoon when the air temperature is 80°, the normal cooling at night can be expected to produce at least a very high relative humidity and probably precipitation. A vapor pressure of 0.203 inch, however, would indicate a much lower humidity and practically no chance of rain resulting from nightly cooling alone. Such information is more in the nature of a forecast than a measure of existing fire danger.

EFFECTS OF OTHER WEATHER ELEMENTS

At least three other weather conditions that have not been investigated intensively as yet in the present work deserve study. These are winter snowfall, barometric pressure, and sunlight.

There seems to be no general agreement among foresters as to whether or not the amount of winter snowfall, or the snow depth at any particular date early in the spring, has an appreciable effect upon the fire danger two or three months later. A comparison of records of snow depth at seven stations well distributed in northern Idaho with the fire reports of the same region fail to show any usable relationship. The depth of snow was compiled as of February 28, March 15, and March 31, and the number of fires for May, June, and July during eight successive years. An indication of relationship was found in the fact that the year having the greatest surplus of snow on the ground on March 31 had the fewest fires in May and June. The year having next to the greatest deficiency of snow on March 31 also had the greatest number of fires in May and June. Between these two extremes, however, no consistent relationship appeared. Records covering a longer period, giving snow depths at later dates and at higher elevations, may show more positive correlation with number of fires in May and June, but such records are not at present available and consequently no positive conclusions can be drawn.

During the summer months in northern Idaho high barometers are nearly always indicative of high temperatures and low relative humidities, consequently of a high rate of evaporation. As high temperature, low humidity, and high evaporation have been shown to indicate low duff moisture content as a rule, it would seem reasonable to believe that a study of barometric pressure and duff inflammability would indicate very close correlation between the two. Barometric pressure also is one of the weather elements which can be forecast by the Weather Bureau most accurately, and therefore should serve as the basis of general forecasts of duff inflammability according to the degree of correlation shown. Before the present study is completed in this region barometric pressure in relation to the fire problem should be investigated.

Sunlight alone also appears to be an important factor influencing fuel moisture content. Both Livingston and Bates recognized the importance of direct sunlight when they constructed their atmometers or evaporimeters, by blackening the exposed surface of the evaporating portion of the instrument so that the heat of the sun would be absorbed and converted into kinetic energy. Livingston also provides white-surfaced evaporating cups which reflect the sunlight instead of absorbing it.

On most areas containing a large quantity of slash or dead timber there is a contrast of black with almost white surfaces that may have an important bearing on the rate of evaporation from these surfaces and hence on the moisture content and inflammability of such fuels. When branch wood or entire trees are killed, by fire for instance, the bark usually separates from the wood, leaving a smooth surface exposed to the weather. The bleaching action of the sun and weather soon produces a dull gray to almost white color in this surface. Such a color merely means that most of the light striking that surface is being reflected, rather than absorbed. Let fire run over this area again, however, and the color is changed to black, which indicates almost full absorption of all light rays. It would be interesting to know how much warmer the blackened materials become as a result of this change in color, and how much more rapidly they lose moisture because of the resultant increase in heat absorption from sunlight.

It might be of value to determine also whether any common fuel, following rains, loses moisture content faster in sunlight than in shade, other conditions such as air temperature, humidity, and wind being similar. If it were found that the shaded materials retained their moisture appreciably more than those exposed to the sun, then the desirability would be shown of retaining every possible source of shade on logged-off areas. If compulsory broadcast burning of slash areas blackens the surfaces of the materials left and also destroys much of the previously existing shade, then it might be demonstrated exactly how such a practice lowers the moisture content and increases the inflammability of the large volume of material which always remains after a single burn. Opinions on this subject are easily obtainable; actual measurements, however, would be of much more value in arriving at dependable conclusions.

LIMITATIONS OF APPLICATION OF WEATHER MEASUREMENTS

In preceding sections of this circular the usual fuel moistures to be expected in accordance with prevailing temperature, humidity, etc, have been so defined that by simple measurements of the weather it may be possible to estimate with some accuracy the amount of moisture in the fuels, hence their inflammability. None of these relationships, are entirely dependable when used alone, or even when all are used together, because the fuel moisture content does not respond immediately to changes in the weather elements and the materials may therefore be either wetter or drier than indicated, depending upon the preceding weather as well as upon the rate of response of the respective fuels.

If the weather as measured at any instant continues without change long enough to allow the fuels to come to equilibrium with it, the fuel moisture content indicated might be accepted as a forecast; but the weather is not constant and the changes are so rapid and of such magnitude that before the fuels can come into equilibrium with existing weather a marked change will have taken place and the tendency of the fuel moistures will be radically different. Hence, although measurements of existing weather may indicate the fuel moisture content at any moment, forecasts of the weather must be obtainable before forecasts of fuel moisture can be made.

It is all too common in forest protection to plan action for to-morrow purely on a measurement or observation of conditions to-day. Such procedure will be dependable in direct proportion as the weather of to-morrow is the same as that of to-day. No thorough comparisons have been compiled for this region to show how often this is so, but if changes of 5° in maximum or minimum temperature, 5 per cent in humidity, and 2 or 3 miles per hour in the velocity of the wind are significant, then the weather in northern Idaho is seldom the same two days in succession during the fire season. Hence action planned for to-morrow on the sole basis of to-day's weather will lead either to insufficient or too great preparation in the majority of cases.

The most accurate basis for determining desirable action one or more days ahead is a measurement of existing inflammability together with a weather forecast which will indicate the most probable weather. This weather forecast applied to the measurement of existing inflammability will then produce a forecast of inflammability. A weather forecast alone is not a forecast of inflammability, and should not be used as such, any more than a prediction of to-morrow's duff inflammability is a forecast of to-morrow's weather. The two conditions are distinct; the weather is a cause and the degree of inflammability is an effect, but to-morrow's weather is not the sole control of the effect. The weather of several preceding days also is effective to-morrow.

One striking illustration of this hang-over influence of previous weather has been mentioned before under the subject of effects of evaporation. During the period of June 9 to 11, 1925, on the Priest River experimental forest, a total rainfall of 0.6 inch was well absorbed by the fuels, the duff moisture content rising to 50 per cent or over. On June 15, four days later, the maximum temperature was 80° F., the 5 p. m. relative humidity was 25 per cent, the average wind velocity 1.4 miles per hour, and the total evaporation was 11.7 grams. This caused rapid drying of the fuels, but the effects of the previous rains were still so much in evidence that the duff moisture dropped to only 47 per cent on the timbered northwest slope. Thus did the effects of previous weather prevent the danger which an exact forecast of the temperature, humidity, and evaporation for June 15 would have indicated.

Numerous other examples could be mentioned to illustrate the fact that the effects of present or future weather are controlled by the immediate condition of the fuel as determined by previous

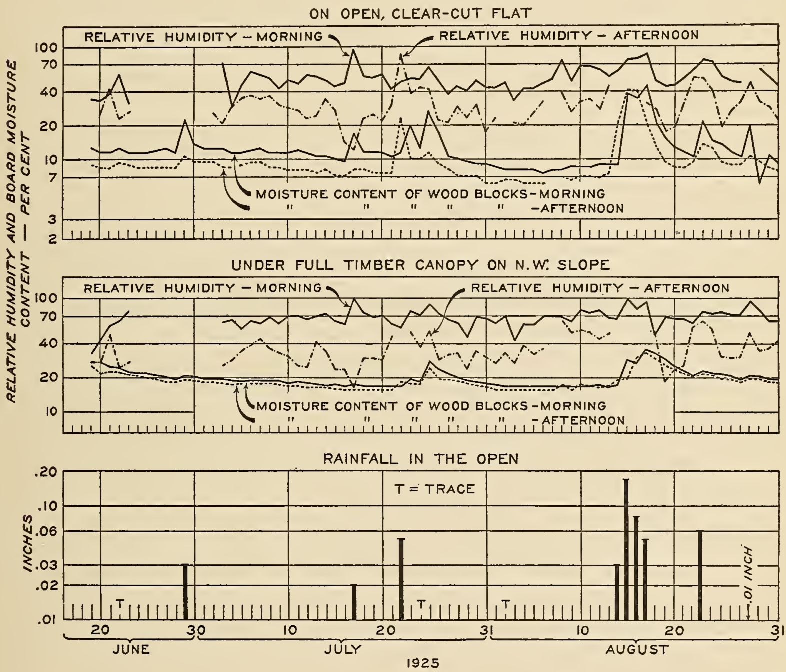

FIG. 11.—Rainfall, relative humidity, and moisture content of wood. Season 1925. Wood samples consisted of boards 1 by 5 to 10 inches lying on the duff or ground. Moisture contents are averages for two boards on each site

weather conditions. It is for this reason that the present investigations are being focused rather upon direct measurements of moisture content of forest fuels than upon weather conditions alone as criteria of fire danger. Figure 11 gives for one fire season the effects of the various weather elements upon wood blocks. The results shown in this figure represent only a beginning of the study of forest fuels other than duff, but it is interesting to note that they appear to substantiate the relationships already discussed as existing between the weather and the moisture content of duff. As these measurements are extended to all the forest fuels and the data for successive fire seasons are compiled, the resultant compilations should serve not only as an accurate statement of prevailing inflammability, but also as a basis for the application of weather forecasts to current measurements of moisture content of forest fuels.

FORECASTING FIRE DANGER

Accurate forecasts of fire danger undoubtedly can be used to good advantage in reducing the loss and expense caused by forest fires. It is the consensus of opinion of the best fire fighters in northern Idaho and western Montana that if accurate statements of probable danger several days ahead could be supplied, the men in charge of forest protection would know how to act most efficiently to meet the situation. Although the exceptionally bad fire years are known to be the cause of by far the greater proportion of our present high average annual loss, forecasts of bad years can be built up only by predicting bad months, weeks, or days. Show and Kotok (*35*) have shown that the harder fire seasons differ from the easier ones only in the relative number of short periods of greatest danger. The short-period prediction of great fire danger, therefore, is the logical beginning of forecasts of bad years, and the weather forecast is, of course, a vital factor in the forecast of fire danger.

The organizations in northern Idaho engaged in hiring fire fighters from the large labor centers, furnishing food, blankets, and tools for these men, and supplying transportation to the fires remote in the mountains already operate smoothly, quickly, and efficiently. The forecasts of probable weather or fire danger must cover a period of time greater than that required by the service of supply, if they are to be used with maximum efficiency. It is the rule, rather than the exception, that failures of the fire-fighting organization to meet most efficiently the varying degrees of fire danger result more from lack of forecasts or from incorrect forecasts than from errors in judgment based on correct forecasts. If the men in charge of forest protection know how long it will take to get men and supplies to a fire, and if they can then learn what weather to expect after these reinforcements arrive at the fire, they are not apt to send too many or too few fire fighters. If they do not know what weather to expect following the period required to dispatch fire fighters, they must guess, and either play overly safe by sending too many men, or take a chance and, in an attempt to cut down expenses, perhaps lose considerable acreage and value by sending too few men. Accurate weather forecasts for two or three days ahead, translated into terms of inflammability of fuels, constitute the information most needed.

The United States Weather Bureau is the agency which assembles the basic information and frames the weather forecasts in most common use in this country. Measurements of existing weather are made at least twice each day (8 a. m. and 8 p. m., seventy-fifth meridian time) at hundreds of official weather stations, and the reports are telegraphed to sectional centers for assembly, study, and the production of forecasts. By observing what kind of weather is present at these stations, how the weather is changing, which way the centers of certain kinds of weather are moving, and how fast they are moving, the meteorologists of the Weather Bureau are able to predict with satisfactory accuracy the weather to be expected in this region up to 36 hours ahead of its arrival.

Such weather forecasts have been received and studied in the present investigation for four successive fire seasons. The effects of the weather on fuel moisture content have been noted, and the weather forecasts have been applied to measurements of prevailing inflammability so that predictions of fire danger could be framed. Inflammability forecasts were not attempted, however, until two years of research had provided the basic information on how the weather affects the fuels. Forecasts were prepared during the third season, but not given out to the forest protective organization until the degree of dependability could be ascertained. The results of this trial were sufficiently satisfactory, being rated by the Forest Service fire chief in this region as 80 to 85 per cent dependable. Therefore, the fourth year the forecasts were supplied to the Kaniksu and Pend Oreille National Forests as a practical test. Unfortunately, the terms used in the forecasts were not the best to permit a statistical study of their accuracy. In the future the fuel moisture content will be predicted in terms of percentage instead of zones of inflammability, and the results can then be rated more accurately. The predictions of the 1925 fire season were sufficiently satisfactory to the field officers, however, to be continued, weather forecasts and measurements of prevailing fuel moisture contents being used as a basis.

There are three main classes of weather forecasts according to their use in forest protection. Forecasts of wet weather are the most important in the reduction of expense caused by forest fires, because if wet weather can be predicted accurately, it is often possible to stop with safety the shipment of men and supplies to large fires and, therefore, to hold down the cost of suppressing such fires. Forecasts of hotter, drier, and windier weather, on the other hand, indicate greater fire danger and the necessity of spending more money in order that the loss caused by the fire may be reduced. Forecasts of weather continuing without marked changes are the most common type, and are principally important in showing that no marked departures are necessary in the handling of fires that are being controlled satisfactorily.

Since rain is the only weather element that has been found to eliminate fire danger completely during the summer months in northern Idaho, forecasts of rain are of the greatest value in reducing the expense of fighting fires. Forecasts that rain will occur have been found to be generally dependable, but the amount of rain and its distribution in time and place are not yet being predicted. Meteorological research undoubtedly can be depended upon to supply this information at some future date, and the sooner it is supplied the sooner large savings can be made in the cost of suppressing forest fires. Until the local duration and amount of rain can be predicted dependably, the potential damage from any going forest fire is so great that men and supplies must be maintained on going fires regardless of the rainfall forecast.

Air temperature is now being predicted for northern Idaho with very satisfactory accuracy, if the user of the forecast carefully observes the words used and their significance for his particular region. For instance, the official forecast for northern Idaho received the morning of June 19, 1925, and applying to the period from 5 p. m. June 19, to 5 p. m. June 20, read as follows: "Fair and continued warmer to-night and Saturday, low humidity, light northwesterly winds." The user of such a forecast should note first that the statement is for "to-night and Saturday", not for "to-day". The distinction should be kept clearly in mind. All too often field men are inclined to rate the forecasts as inaccurate because they judge a forecast for to-night and to-morrow according to existing weather. The second point of interest is the statement "warmer with low humidity." This is a relative statement which can easily be translated into absolute terms. On June 19 the maximum temperature was 86° F. and the 5 p. m. relative humidity 25 per cent which is recognized as low. The forecast stated "warmer with low humidity," and on June 20 the maximum temperature was 92° and the 5 p. m. relative humidity 24 per cent. Such a degree of accuracy is very hopeful, and this is an example of the results commonly obtained in northern Idaho.

The prediction of fire danger that was based on this same forecast also will serve as an example of the application of weather predictions to duff-moisture measurements in order to obtain duff-inflammability forecasts. On the morning of June 19, the measurements of duff-moisture content made at 5 p. m. on the 18th were available. These duff measurements showed a condition of very low inflammability on the moist site, and high inflammability on the dry site. (See fig. 1.) On the morning of the 19th the observer at the Priest River experimental forest considered this information and predicted low inflammability for the moist site, and extreme inflammability as the most probable condition which would be found on the dry site at 5 p. m. June 20, 36 hours later. As is shown by Figure 1 the actual conditions at 5 p. m. on the 20th were low to medium inflammability on the moist site, and extreme inflammability on the dry site.

In making these forecasts the observer considered (1) the existing moisture content on the two sites as shown by the duff hygrometer measurements of June 18, and (2) the fact that on the 20th the maximum temperature could be expected to be well above 78°, the maximum for the 18th, and the humidity about 25 per cent or lower. As is shown by Figures 6 and 8 such weather conditions indicate, as an average, extreme inflammability according to humidity, and medium or high inflammability according to temperature. The hang-over effects of previous weather were known to the observer, however, by reason of the duff hygrometer measurements, and the inflammability forecasts were therefore framed to distinguish between the clear-cut and the timbered areas in a way that could not have been done if weather measurements had been used alone.

Relative humidity forecasts are now being supplied for northern Idaho as a result of a special study in which the lumber interests of the Pacific Northwest and the Weather Bureau have cooperated closely. These forecasts are frequently dependable, even though this special service is barely 2 years old.

Another possible method of predicting fire danger a few hours in advance has been advocated by Hofman and Osborne (*17*), who state that "the possible conditions for the day are generally indicated by the humidity record as early as 8 o'clock in the morning and extreme periods are often indicated earlier." This possibility of using morning measurements of relative humidity to indicate late-afternoon conditions has been investigated at the Priest River experimental forest, with the results shown by Figure 12. Sling psychrometer measurements were made at 8.30 a. m. and 5 p. m. on 189 days during two successive fire seasons. On 93 per cent of the days the afternoon humidity was as low as that of the morning, or lower, indicating that atmospheric moisture is normally higher in the morning than in the afternoon.

The question of most importance is: How much lower can the humidity be expected to be in the afternoon? If the morning humidity is between 76 and 80 and the afternoon humidity is 71 per cent, very little, if any, fire danger need be expected; whereas if the morning humidity is between 76 and 80 and the afternoon humidity is only 9 per cent, an entirely different degree of fire danger must be anticipated. Actual measurements show the possibility of considerable error, at least for the region under discussion, if morning humidity is used as a criterion of afternoon conditions.

A large number of other examples go to show, however, that low humidities in the morning usually indicate very low humidities in the afternoon. In fact, when the average relations are computed and plotted as in Figure 12, it is obvious that as a general rule the lower the humidity in the morning the lower it will be in the afternoon.

The value of this information lies in the average relationships only, since neither the chance of error nor the probable degree of error is indicated. After more records have been obtained, this relationship will be investigated by the use of accurate statistical methods and the degree of correlation and probable error between morning and afternoon humidities will be determined. It is sufficient at present to point out the existence of a general relationship together with the possibility of occasional serious errors.

The main disadvantage of this method of forecasting relative humidity lies in its complete failure to predict afternoon humidities of over 60 per cent. As shown by Figure 12, the highest humidity to be expected at 5 p. m., according to any humidity at 8.30 a. m., is only 60 per cent. Yet actually in 21 days out of the 189, or in 11 per cent of the observations, the 5 p. m. humidities were over 60 per cent.

If the degrees of danger shown by Figure 12 for the 5 p. m. humidities be used in classifying the probable degree of danger inherent in morning humidities, it is possible to distinguish morning measurements of 40 or less as extremely dangerous, those between 41 and 75 as dangerous, and those of over 75 per cent as slightly dangerous. The detailed data substantiate this differentiation 82 per cent of the time for the extremely dangerous class of humidities, 45 per cent of the time for the dangerous class, and 34 per cent of the time for the slightly dangerous class. Such a method of forecasting different degrees of danger in the afternoon consequently is not recommended for use in northern Idaho, except that morning humidities of less than 40 per cent may be regarded with assurance as being indicative of extremely dangerous afternoon humidity. It is advisable to remember that this conclusion is based on northern Idaho conditions and may not hold at all true for other regions having different climate and weather.

Forecasts of wind velocity and direction for large regions such as northern Idaho are now being supplied by the Weather Bureau with reasonable accuracy for the region as a whole. In fire suppression, however, the wind velocity and direction on small areas are often of vital importance and frequently differ from the velocity and direction of the prevailing winds. Although practically no research has been conducted in this region dealing with this phase of the fire problem, observations by forest rangers and others who by long experience and familiarity with local topography have become acquainted with local peculiarities have led to a knowledge of the differences to be expected in certain valleys and drainages according to the regional wind velocity and direction. The conscious observation of such differences probably will provide reliable information on local winds, which can be used to very good advantage in fire suppression. At present such observations are not made purposely and consciously in very many localities; if they were, the practice might increase the efficiency of the protection supplied. At some future date intensive research should be devoted to this phase of the problem.

In using the forecasts of wind velocity supplied by the Weather Bureau the fact is frequently overlooked that the words "light, gentle, moderate," etc., as used by the meteorologists, have specific meanings. The following tabulation (Beaufort) shows the range of wind velocities in miles per hour indicated by each of the more general words used in forecasting:

Terms used in forecasts	Wind velocity in miles per hour	Descriptive terms
Light	7 or less	Smoke drift slight; wind felt on face; leaves rustle.
Gentle	8 to 12	Leaves and small twigs in constant motion; wind extends light flag.
Moderate	13 to 18	Raises dust and loose paper; small branches are moved.
Fresh	19 to 24	Small trees in leaf sway.
Strong	25 to 38	Large branches and small trees in motion; whistling in telegraph wires; inconvenience felt in walking against wind.
Gales	39 to 54	Twigs broken off trees; progress impeded.

The importance of knowing the different wind velocities implied by these terms is obvious. All too frequently wind forecasts have been rated as useless by field men, not because the forecasts were incorrect, but merely because the field men did not know the facts in the above tabulation. In forest protection, a subdivision of winds of less than 7 miles per hour into very light (less than 4 miles per hour) and light winds (4 to 7 miles per hour) can be used to advantage when such differences can be predicted.

Evaporation forecasts are not yet being made available for general use, partly because of the lack of a formula based on temperature, humidity, and wind, and partly because of the variety of methods used in measuring evaporation. The gradual accumulation of records of evaporation may, however, provide the basic information for future study of the posibility of predicting evaporation. As the average relations between evaporation rate and fuel moisture content are already known, such forecasts could be used to good advantage in forest protection.

After three seasons' use of weather forecasts in northern Idaho and western Montana, the Forest Service still fails to obtain full value from this information. There are several reasons for this failure, all of which are gradually being eliminated. Probably the most important is the shortness of the period covered. Weather forecasts prepared on the basis of the 5 a. m., Pacific time, measurements, must be dispatched from San Francisco and Denver to northern Idaho and western Montana, respectively. These forecasts are generally received by the forest supervisors about 9 or 10 a. m. They must then be relayed to the district rangers and again to the fires

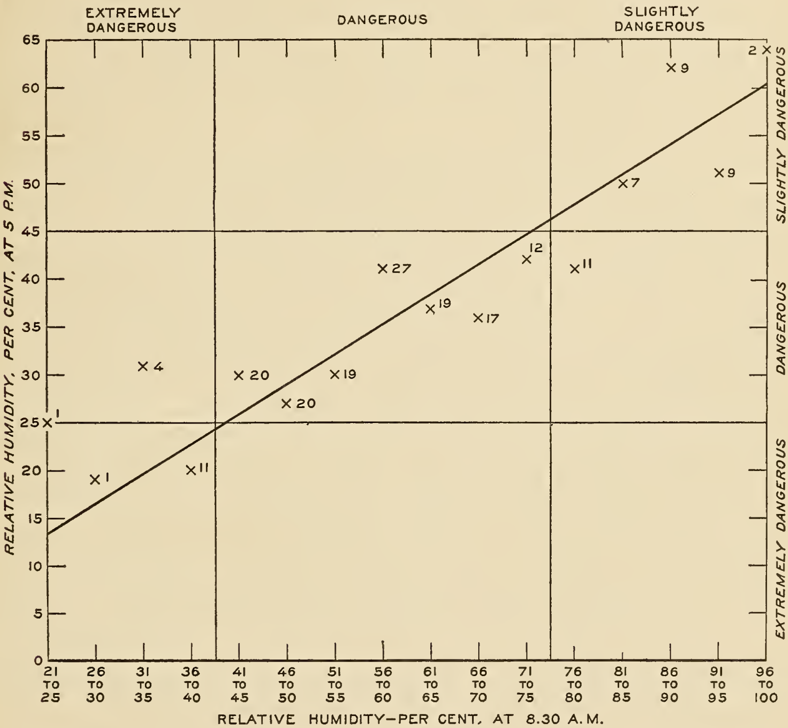

Fig. 12.—Relation between morning and evening relative humidities. Basis—measurements made morning and evening on 189 days. Numerals indicate number of days on which the averages of measurements for dry, medium, and moist sites coincide with the point plotted

being fought. With an all-too-scanty network of telephone lines, or in many cases a total lack of lines between the ranger station and the fire, there is a great delay in getting the weather forecast to the man in charge of a fire so that he can determine what action should be taken. By the time the forecast is received it may be too late to send word back contermanding an order for more men and supplies or ordering additional help to meet emergency conditions on the morrow.

A second reason for some past failures to use the available weather forecasts has been a lack of accurate information as to the exact effects of various kinds of weather on the behavior of forest fires. As has been stated, in the past it was generally recognized that high temperatures and wind and low humidity meant great danger, whereas low temperatures and wind and high humidity meant less danger. It had not been shown, however, what temperatures, wind velocities, and humidities were high and what were low. The lines of accurate distinction had not been drawn; different effects had not been distinguished; and the recipient of weather forecasts had no guide except his experience in determining the most probable effects of these forecasted weather conditions. Although accurate information is not yet available on all these particulars, it may be possible, with the information on the relation of the weather to duff moisture and inflammability gained from the present investigation, to estimate the effects of the weather in this region and to distinguish the importance of small changes in the weather elements more accurately than was possible in the past.

Other causes, also, prevent the full use of available weather forecasts in forest protection, not the least important being the common lack of inclination to use new information and methods. Actually, the man in charge of a forest fire predicts the weather whenever he makes his plans for fire suppression on the morrow. If such a man can show a higher percentage of accuracy than the accepted weather forecasts, then he should rely on his own predictions. It is not believed, however, that any man can forecast accurately on the basis of noninstrumental observations of immediate local conditions.

All reliable forecasts of weather or degree of inflammability available to-day are distinctly short-period notices. They fail entirely to indicate months in advance the probability of an extremely bad fire year; yet these worst fire years, though of rare occurrence, are largely to blame for the greatest proportion of the present high average annual loss and expense caused by forest fires. Eliminate the two driest and most dangerous of the past 18 fire seasons in Montana and northern Idaho, and the average annual area burned over is decreased from 251,751 acres to only 37,913 acres. In other words, approximately 85 per cent of the national forest area burned over in the last 18 years was lost during the two seasons which are recognized as "bad years." Forecasts of the approach of such years obviously are the most needed of all information.

The efficiency of any forest-protection organization depends upon its ability to meet easy, average, and extremely bad years alike with a minimum of cost plus damage. A permanent organization of constant strength designed to meet the average year with maximum efficiency will spend too much money during the easy years and will permit too much loss during the extremely dangerous years. The ultimate organization must be sufficiently flexible to contract and save expenses during easy years, and to expand to prevent undue loss during the most dangerous seasons. Such an organization can be built if, and only if, forecasts are available to dictate when to expand or contract. Show and Kotok (*35*), after a careful study of the forest-fire problem in California, conclude that weather forecasts "offer a major opportunity for improving systematic fire protection in the pine region of California."

When weather forecasts are available for periods of satisfactory length, when these can be adapted into highly accurate predictions for relatively small areas, when the effects of all the weather elements are known accurately, when the information can be transmitted with the least possible delay, and when the men who should use the information are convinced of its value and understand its use, then action can be taken to reduce the loss and expense caused by forest fires to that minimum which is the goal of forest protection.

SUMMARY

It is only by modifying the action of the forest protective organization in accordance with variations of fire danger caused by natural controls that the most efficient protection can be given the forest.

In northern Idaho and western Montana the most important of all the natural variables appears to be the amount of moisture in the fuels, since this controls the ease of ignition and the rate of combustion and hence the degree of inflammability of the forest. Tests have shown that the various degrees of inflammability of forest duff may be distinguished according to the moisture content of the duff, as measured by the duff hygrometer.

A comparison of several hundred measurements of duff moisture content with the existing weather elements indicates that precipitation alone, of all the weather elements, makes fuels noninflammable during the fire season. Rains of 0.6 of an inch or more evenly distributed throughout 48 hours are necessary to saturate the duff and eliminate inflammability. Rains of 0.2 inch or more in 24 hours are generally sufficient to eliminate fire danger temporarily. The beneficial effects of a downpour often are less than the effects of a lesser volume of rain well distributed over a longer period. As a general rule about 2 inches of rain per month are necessary to allay fire danger in this region, but the exact amount varies with duration of fall and the evaporating power of the atmosphere between storms.

Relative humidity has also been proved to be a very important factor in controlling fuel moisture content and inflammability. Although rain raises the fuel moisture content to extremely high points and produces the most lasting relief from fire danger, a high relative humidity is capable of causing relief for shorter periods. Low relative humidities, on the other hand, result in dry fuels and high fire danger.

The general relationship found between relative humidity and duff inflammability is as follows: Over 70 per cent relative humidity, generally safe; 46 to 70 per cent, slightly dangerous; 26 to 45 per cent, dangerous; 25 per cent or less, extremely dangerous.

To obtain reasonably accurate results with relative-humidity measurements as an index of inflammability, it is necessary to consider also the character of the fuel, its present moisture content, its exposure, the depression of the wet-bulb thermometer, the prevailing temperature, and the wind velocity.

The temperature of the air has been found to be important, and the agreement between simultaneous measurements of duff moisture

and air temperature is sufficiently close so that temperature may be rated as generally safe when it is 55° F. or less, slightly dangerous at 56° to 70°, dangerous at 71° to 85°, and extremely dangerous when over 85°. In using temperature measurements as a criterion of prevailing inflammability, the same factors must be considered as for humidity measurements.

Wind velocity influences duff moisture content by affecting the rate of evaporation of water from the fuels. It also affects the rate of spread of fire. No classification of wind velocities has been made to express the most probable degrees of danger. Show's conclusion that the rate of spread of fire varies about as the square of the wind velocity is the most usable information available at present concerning the effect of wind.

The evaporation rate agrees very closely with duff moisture content, and may be classified as generally safe when the total evaporation in the open (by Bates evaporimeter) is 6 grams or less for a 24-hour period, slightly dangerous when between 6.1 grams and 10 grams, dangerous at 10.1 grams to 14 grams, and extremely dangerous when over 14 grams. Evaporation measurements serve best to integrate the total effects of temperature, humidity, wind, and sunshine for any desired time interval. Rainfall, the exposure of the fuels to the weather, and the existing fuel moisture content are the other principal factors which must be observed when evaporation measurements are used as a criterion of fire danger.

Vapor-pressure measurements have been found to be of no marked value in rating fuel moisture content in this region. They are useful, however, in predicting the most probable changes of relative humidity.

The exposure of the fuels to the weather elements exerts an extremely important effect on moisture content and inflammability. Within a small area one class of fuel, such as the top layer of duff, may show extremely different degrees of inflammability and important differences in the duration of fire danger in direct accordance with the degree of exposure. The value of preserving all possible green shelter on cut-over areas to help conserve the moisture in the dead materials is emphasized by these measurements. Light cuttings instead of clear cutting, as well as the rapid production of a full timber canopy on clear-cut areas, may greatly increase the length of the period of noninflammability and may reduce very appreciably the period of extreme inflammability.

The cumulative effect of the weather on fuel moisture content and inflammability has been found to be very important. Although the smaller fuels respond very readily to a few days of extremely hot, dry weather at any time, the heavier materials, such as logs and windfallen trees, are most affected by a gradual drying, which generally produces greatest fire danger in August or early September.

Forecasts of degree of inflammability at least 24 hours in advance are of much more value in reducing the loss and expense caused by forest fires than are the measurements of existing inflammability upon which predictions are based. Three classes of information are necessary if danger is to be predicted accurately. The present degree of inflammability of each of the important fuels must be known, the future weather elements must be predicted in detail, and the effects of each predicted weather element on existing moisture contents must be ascertainable. The present work has shown how the existing danger in one fuel may be measured; the Weather Bureau supplies the weather forecasts; the most probable effect on this one fuel can be determined by applying the general relations between weather and duff found in the present study to the measurements of existing conditions. Future investigation must determine the best methods of measuring existing inflammability for each of the important fuels; it must assist the Weather Bureau in improving the weather forecasts by obtaining records for study; and it must determine the effects of each of the weather elements on each of the fuels.

No one condition has been found that can be used as a thoroughly dependable criterion of fire danger. Instead it appears that numerous factors control numerous conditions, all of which affect forest-fire danger. Dependable measurements or forecasts of fire danger demand that proper consideration be given to each of these several factors.

In actual application the results of the present investigation may serve as a preliminary method of measuring, instead of estimating, changes of the natural factors influencing fire danger which demand changes in the fire-protective organization if adequate protection is to be supplied at minimum expense. Until the factors controlling the inflammability of all the fuels have been isolated, and their effects determined, the results presented must be used with caution. The policy of relying most upon their accuracy when they indicate increasing or great danger, and relying least upon them when they indicate decreasing or little danger, may help in reducing the fire loss, but not the expense of protection. Later, as higher accuracy and dependability are attained, it may be possible to employ measurements so accurate that protection expenses can be safely reduced.

APPENDIX

THE DUFF HYGROMETER

The sampling method for determining the moisture content of a certain class of fuel at frequent intervals is unsuitable for use in forest protection, where results must be obtainable immediately at small expense. Errors of sampling and variations in environment demand that the fuel measured be constantly exposed in situ and under natural conditions.

After a careful study of the various methods of measuring moisture content, such as changes in weight, shape, size, and electrical conductivity, it was decided that in order that measurements might be made as often as desired of the moisture content of a representative sample of duff under fully natural conditions, it would be necessary to perfect some registering instrument that could be inserted in the duff layer and could be read easily in that position. A short section of rattan was finally chosen as the best medium for registering moisture changes when exposed within the duff layer.

Rattan responds to changes in atmospheric moisture surrounding it in the same manner as the hair used in a common hygrograph. As the atmosphere becomes more moist the rattan becomes longer; as the atmosphere becomes drier the rattan shortens. A section of the rattan about 12 inches long held in a suitable frame will reveal changes in its length on a sensitive gauge properly attached. It is necessary only that the section of the instrument containing the rattan be inserted horizontally in the duff so that it will be exposed to the atmosphere in the interstices of the duff. Then as the duff becomes wet from any cause it supplies a corresponding amount of moisture to its interstitial spaces and the rattan absorbs this moisture until it is in equilibrium. As the duff dries, the spaces within it also dry out and the rattan loses moisture and changes length accordingly.

The limiting factor in the changing length of the rattan is its fiber-saturation point, above which there is no change in length. This point has been found to correspond to a duff moisture content of about 50 per cent. Hence, when there is 50 pounds or more of water for every 100 pounds of duff, the rattan is at its maximum length, and further additions of moisture to the duff will not produce any change in the length of the rattan exposed within the duff.

As the duff dries below 50 per cent moisture content, however, the rattan shrinks proportionately and the amount of the shortening is shown on the gauge to which one end of the rattan is attached.

Rattans of various diameters were tried in perfecting this duff hygrometer. As a rule the smaller the diameter of the rattan the faster it responded to changes in duff moisture content. Rattans of about 0.1 inch diameter have been found most suitable for this work because they are stronger than the smaller pieces and yet are capable of changing from saturation to extreme dryness in less than 15 minutes. As the duff never dries out thus rapidly, such a sensitivity is entirely satisfactory. The duff does increase in moisture content at times with greater rapidity than a 0.1 inch diameter rattan, and on such occasions the hygrometer fails to be as accurate as might be desired.

All users of hair hygrographs are familiar with the fact that these instruments must be checked by sling-psychrometer measurements at frequent intervals, if reasonable accuracy is desired. This is due to the fact that small quantities of oil or dirt on the hair interfere with its consistent behavior in relation to changes of atmospheric moisture. Rattan has been found to be better than hair in this respect, especially when inserted in the duff, and a determination of the various rattan lengths corresponding to various moisture contents may be expected to remain reliable for at least one month, and perhaps for three or four months of continuous use, if the other parts of the duff hygrometer function perfectly.

The process of determining the length of the rattan according to the moisture content of the duff is called calibration. Without it the gauge readings merely show the changes in length of the rattan and are meaningless in forest protection. The accuracy of the process of calibration determines the accuracy of the hygrometer and the value of comparisons of readings of one hygrometer against readings from another at a different station. Each rattan has its own characteristic curve of correlation between its length and duff moisture content, consequently each instrument has to be calibrated individually. The process used at present is rather slow, requires special equipment, and must be done at least once every fire season.

In this calibration process each hygrometer is exposed in duff of known moisture content and the gauge readings determined for each of a sufficient number of moisture contents so that a smooth curve can be drawn to show all gauge readings below 50 per cent. Zinc or galvanized-iron tubes with friction covers are used, of sufficient size to hold about 100 grams of oven-dry duff. The duff in one tube is held at about 2 per cent moisture content, in another at about 10, in others at 20, 30, 40, and 50 per cent, respectively. A hygrometer is inserted in a tube and left there until the gauge readings show that the rattan has reached a condition of equilibrium with the moisture content of the surrounding duff. The instrument is then removed, the tube and its duff contents accurately weighed, and the exact duff moisture content computed. These coincident conditions, gauge reading, and duff moisture content, are then plotted on a calibration chart and the hygrometer inserted in another tube to repeat the process. After the instrument has passed through all tubes, a chart similar to that shown in Figure 13 is obtained. By running two hygrometers simultaneously in each tube more instruments can be calibrated with less equipment and each instrument serves as a check on the other. Usually a period of from 6 to 12 hours is required for the hygrometer to reach equilibrium with the duff when a change of 10 per cent or more is involved.

As is shown in Figure 13, even rattan changes its characteristic curve of correlation between length and duff moisture content after a period of continued use. In this instance, after three months' use of one instrument during the 1924 fire season, the readings were about 1 per cent too high for duff moisture content of less than 10 per cent, and were as much as 12 per cent too low for duff moisture content of 50 per cent. The measurements between 10 and 35 per cent were correct throughout the entire period.

In the processes of original calibration and of recalibration or check at a later date, there is one important condition which should be recognized and measured with great care. This is the oven-dry weight of the duff used in the calibration tubes. If all the duff samples are dried in one oven and moved at the same time, they will all be of the same absolute dryness, regardless of the temperature and humidity within the oven. Further use of that duff, though it be

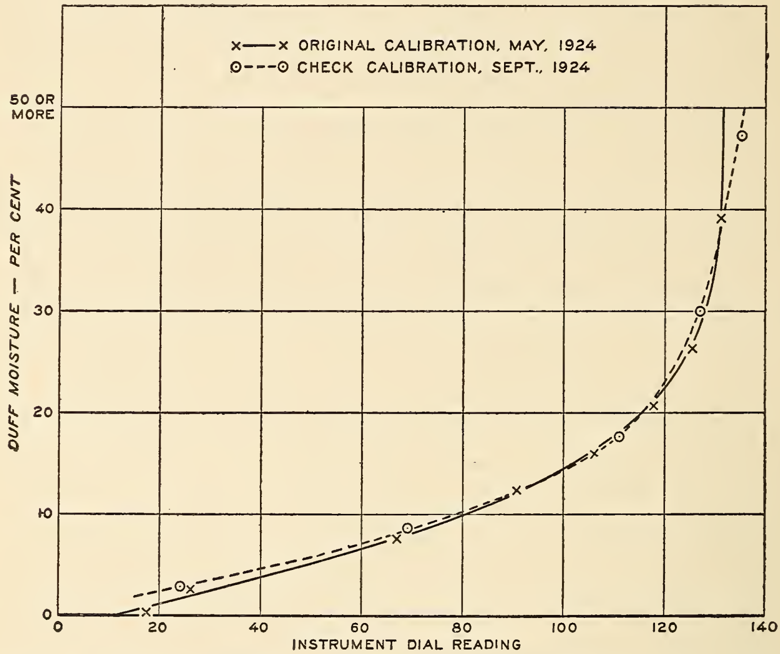

FIG. 13.—Change of duff-hygrometer accuracy. Showing the calibration curves before and after three months use of one instrument

divided and put in separate tubes, will give comparable results. If, however, several batches of duff are dried separately, each batch should be left in the oven until it ceases to lose moisture at a certain temperature and humidity, which are the same for the finishing of all batches. Unless this procedure is followed, the duff samples will go into the tubes with slight differences in moisture content, and further measurements based on these approximately equal oven-dry weights will not be truly comparable or exact.

It is easy enough to measure the exact temperature in a small drying oven, but it is more difficult to measure the humidity inside such a small space. In order that the humidity may be measured, and that numerous batches of duff may be dried to a constant and known condition, G. D. Shallenberger, head of the physics department of the University of Montana, has developed a formula for this purpose.

In using this formula it is assumed that there is sufficient circulation of air through the oven so that a gas such as water vapor will circulate freely through the oven, merely changing its temperature and volume. Under such conditions the measurement of relative humidity in the room containing the oven, and of temperature in the room and temperature in the oven, will permit the computation of the relative humidity in the oven. The formula, as derived by Dr. Shallenberger, follows:

$$r_o = r_r \times \frac{\text{Pressure of saturated vapor at room temperature}}{\text{Pressure of saturated vapor at oven temperature}}$$

where r_o = relative humidity in the oven
r_r = relative humidity in the room

Saturated vapor pressures are determined for both the room and the oven in smilar units. The tables in Weather Bureau publication No. 235 (*26*) contain vapor pressures which serve this purpose.

As an example of the variation of oven dryness to be expected, the two following examples are of interest:

1. $r_o = 40 \text{ per cent of } \frac{1.022 \text{ (room temperature } 80^\circ \text{F.)}}{15.279 \text{ (oven temperature } 180^\circ \text{ F.)}}$

$r_o = 0.4 \times 0.067 = 0.0268 = 2.7$ per cent humidity.

2. $r_o = 10 \text{ per cent of } \frac{0.616 \text{ (room temperature } 65^\circ \text{ F.)}}{28.75 \text{ (oven temperature of } 210^\circ \text{ F.)}}$

$r_o = 0.1 \times 0.0214 = 0.0021 = 0.2$ per cent humidity.

From this comparison it is evident that if one batch of duff be withdrawn from the drying oven when its temperature is 180° F. and when the relative humidity in the room is 40 per cent, then the sample will be in equilibrium with a humidity of 2.7 per cent, whereas, in the second example, the sample will be in equilibrium with an oven humidity of only 0.2 per cent. As no precise measurements have been made of the relation of duff moisture content to such low humidities, no statement can be made of the exact differences between oven dryness in these two cases. The difference is easy to eliminate, however, when the proper methods are used. In the present investigations, temperature and humidity in the oven are controlled so that when a sample of any fuel is stated as oven-dry, it is meant that the moisture content of that sample is in equilibrium with an oven temperature of 200° to 210° and an oven humidity of less than 0.5 per cent.

Although this degree of control of the calibration process may appear to be an overrefinement in contrast with subsequent use of the duff hygrometers, it is evident that such control is easily obtained and acts to eliminate one of the errors which might affect results. It may, therefore, be better to practice overrefinement than to countenance known errors.

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