FOREST-FIRE BEHAVIOR STUDIES

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GENERAL principles of forest management were established over 200 years ago in Central Europe and the task of the American forester has been largely to adapt these principles to the management of the vast, rough, and inaccessible natural forests of this country. A series of essentially new problems has arisen, however. In the humid climate where forestry originated, forest fires are relatively rare and unimportant, while in the New World, fire protection is the most serious of all problems facing American foresters. This has necessitated the development of methods of investigation for which there is little precedent.

ORGANIZATION OF FOREST PROTECTION

A brief description of the protection problem in the national forests of California will serve to exemplify the problem in the nation as a whole. The national forests comprise about 19,000,000 acres, approximately 20 per cent of the State of California. Each year these forests are subjected to a period of drought lasting from 4 to 6 months, during which the natural debris and dead undergrowth become tinder dry. Atmospheric lightning accounts for about 40 per cent of the annual total of 1500 fires, while man and the works of man account for the remainder.

Efficiency in forest-protection organization has increased steadily since its inception in 1905. It is now the practice in all forested areas to post guards in lookout towers throughout the summer season for the purpose of detecting and reporting the smokes of forest fires. Communication lines lead to centers where fire dispatchers locate fires accurately by triangulation. Forest guards, tank trucks, and suppression crews are strategically located to provide a minimum travel time to fires. Costs must be kept to a minimum, as only approximately 3 cents per acre per annum is provided for direct expenditure on forest protection. Over 95 per cent of all fires are controlled in their incipient stage, but a few, because of rapid initial spread, attain a size in excess of the strength of the initial crew, and become large, damaging, and expensive. Occasional fires reach 10, 20, or even, in rare instances, 200,000 acres. The elimination of these large fires is the present principal problem of all forest-protection agencies. The total average yearly cost of forest fires in California, $1,500,000, could be reduced to one third or less, if all fires were confined to a maximum of 300 acres.

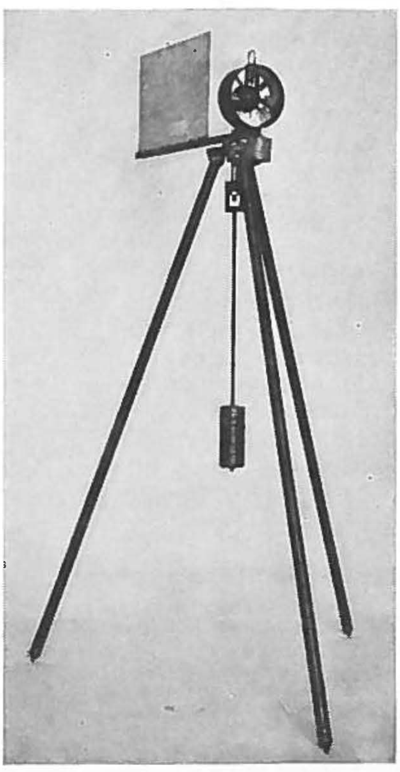

FIG. 1 VANE ANEMOMETER MOUNTED ON SPECIAL TRIPOD AND FITTED WITH DIRECTION VANE

Many forest-protection problems remain unsolved after 35 years of work. A few general principles have been developed, but little fundamental information is available to guide planning and management in fire control. In this respect, it is far behind such older branches of forestry as silviculture, forest utilization, and protection of forests from insects and tree diseases.

Fire behavior is a general term covering all natural forest-fire phenomena of importance from the standpoint of fire protection. These include ignition of forest fires, their spread, crowning, and spotting. Of prime importance to forest protection are the first problems, fire ignition and fire spread; ignition because it largely controls the occurrence of fires, and spread because it governs size which fires may attain during any time interval.

Other investigators, notably Gisborne (1),[1] Stickel (2), and Wright (3), have studied ignition and its influence on fire danger. Show (4) made a preliminary study of fire spread 20 years ago and, in the last 6 years, his work has been continued and extended by the California Forest and Range Experiment Station.

The study of fire spread consists in the recognition of the variables controlling this phenomenon, in developing methods and techniques of measurement, and finally in evaluating the influence of all relevant variables, both individually and jointly, on the rate of spread. The goal of this study is a precise method of estimating the size to which a fire would grow under any natural conditions within a given time. Solution of this problem would have immediate application in establishing the necessary speed and strength of attack for successful suppression.

General experience in forest-fire control, the early work of Show (4), and theoretical studies by Hawley (5) and Gray (6) demonstrate at least four independent primary variables affecting rate of spread: (*a*) Fuel, its composition, size, and arrangement; (*b*) fuel moisture; (*c*) air movement or wind velocity; and (*d*) topographic slope. In addition to these, there are several secondary factors such as air and fuel temperatures, atmospheric humidity, air oxygen content, and, possibly, others still unrecognized. The theoretical analyses indicate, however, that the major fluctuations in rate of

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[1] Numbers in parentheses refer to the Bibliography at the end of the paper.

FIG. 2 TEST FIRE IN EVEN-AGED STAND OF PONDEROSA PINE; 8 MIN AFTER IGNITION

spread of fires under natural conditions may be largely explained by fluctuations of the four major factors listed, namely, fuel, fuel moisture, wind, and slope.

TEST FIRES UNDER FIELD CONDITIONS

Preliminary studies (7) consisted of observations of fire spread under natural conditions of fuel, weather, and topography. It appeared desirable to attempt to investigate rate of spread first by means of test fires set in one simple uniform fuel type where measurements of all other variables could be made.

The ponderosa-pine type was chosen for these early experiments because this type grows occasionally in dense stands with quite uniform needle litter. Fires in this type spread as surface fires comparatively easy to control. During two summers of field experimentation in pine litter, 300 fires were studied, 250 on surfaces of less than 5 per cent slope.

Six primary measurements were made on all test fires, viz., (*a*) fuel depth, (*b*) moisture content of fuel, (*c*) wind movement, (*d*) slope of the ground, (*e*) elapsed time from start, (*f*) perimeter at elapsed time intervals. Fuel moisture was determined by gathering a sample of top needles, selected at random over the entire surface of the plot, weighing the sample immediately, and later drying to a constant weight in an oven held at a temperature of 90 C. Wind velocities were measured at a height of 2.5 ft from the ground by means of the vane anemometer shown in Fig. 1. Perimeters of the fire were plotted every 2 min on polar-coordinate paper by reference to steel stakes set at regular intervals on lines radiating from the point of ignition. Fig. 2 illustrates a fire 8 min after ignition on a typical test plot.

Fig. 3 illustrates the type of fire chart obtained in this study, for zero wind, and Fig. 4 for a wind of constant direction. Moisture content varied from 3 to 13 per cent, the normal range during the seasonal drought period. The range of wind velocity was from zero to a maximum of 5 mph. Winds higher than 5 mph are rarely experienced near the ground floor in closed pine-forest stands, although concurrent velocities above the trees or in the open would attain as much as 30 mph.

The data were analyzed by combining for each 2-min interval the measurements of perimeter increase, fuel moisture, wind velocity, elapsed time, and, where important, slope. The maximum time period considered was 22 min, as observations over a longer time were meager. The data were plotted and smoothed on each variable, utilizing the method of successive approximations and finally, as an empirical expression for the functions, were obtained equations of the type

$$\left(\frac{dP}{dt}\right)_t = a + bM + cV \qquad [1]$$

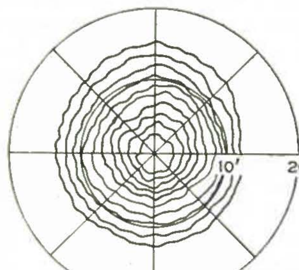

FIG. 3 TYPE OF FIRE CHART OBTAINED FOR ZERO WIND
(Diagram of slowly spreading fire; wind velocity, zero; fuel moisture content, 7 per cent; perimeters shown at each 2-min interval.)

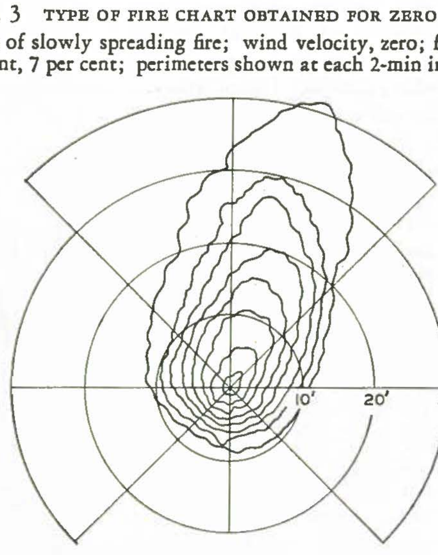

FIG. 4 TYPE OF FIRE CHART OBTAINED FOR WIND OF CONSTANT DIRECTION
(Diagram of rapidly spreading fire; wind velocity, 2 mph; fuel moisture content, 4.3 per cent; perimeters shown at each 2-min interval.)

in which $(dP/dt)_t$ = rate of increase of perimeter fpm at time t

V = average wind velocity during interval, mph
M = moisture content of fuel, per cent
a = 6.35 for all time intervals
b and c = quantities which are constant during any particular time interval.

Equation [1] describes the influence of both wind velocity and fuel moisture as linear, a relation which appears well established within the limits of moisture content and wind velocity investigated.

It is apparent that, for any values of wind and moisture within the range of the data, it is possible to calculate the total perimeter for any time up to 22 min from the relationships expressed in Equation [1]. This may be accomplished by summing up the rate equations for each consecutive interval to get

$$P_t = at + BM + CV \qquad [2]$$

where, P_t = total perimeter at time t
B = Σb, the sum of all values of b up to time t
C = Σc, the sum of all values of c up to time t

The values of B and C are given in Table 1. Fig. 5 illustrates the manner in which total perimeter increases with time.

TABLE 1 *B* AND *C* VALUES FOR CALCULATING TOTAL PERIMETER BY EQUATION [2]

Time, min	*B*	*C*	Time, min	*B*	*C*
2	0.69	0.52	13	4.85	16.44
3	1.04	1.26	14	5.26	18.33
4	1.40	2.26	15	5.68	20.27
5	1.76	3.46	16	6.10	22.25
6	2.13	4.79	17	6.53	24.27
7	2.50	6.23	18	6.96	26.32
8	2.88	7.76	19	7.40	28.40
9	3.26	9.37	20	7.85	30.51
10	3.65	11.05	21	8.30	32.65
11	4.05	12.79	22	8.75	34.81
12	4.45	14.59	..	...	...

To test the accuracy of the linear expression of perimeter increase as a function of moisture content and wind velocity for this pine-needle fuel, the perimeters of 118 fires were calculated by use of Equation [1] and compared with the observed values for all 2-min intervals. The results of these calculations are given in Table 2, in which the accuracy of the calculated values is expressed as a standard error in both feet and per cent.

TABLE 2 SUMMARY OF ACTUAL AND CALCULATED TOTAL PERIMETERS OF TEST FIRES

Time, min	Cases, no.	Average perimeter: Actual, ft	Average perimeter: Calculated, ft	Standard error of estimate: Ft	Standard error of estimate: Per cent
2	118	7.5	7.6	2.1	28.0
4	118	17.7	17.7	4.5	25.4
6	118	28.9	26.8	6.2	21.5
8	118	40.0	40.0	9.4	23.5
10	118	51.2	51.6	11.1	21.7
12	117	63.5	63.0	13.7	21.6
14	114	75.4	74.7	16.0	21.2
16	109	87.0	86.1	16.5	19.0
18	96	97.7	96.5	19.2	19.7
20	71	102.3	102.8	17.2	16.8
22	56	112.6	112.6	19.7	17.5

This analysis showed that with the methods used, the total perimeter of small fires could be estimated with a standard error of about 17 per cent. This error is attributable to (*a*) variations of the fuel, which were not measured; (*b*) variations in fuel moisture not fully accounted for; (*c*) methods of measuring wind not wholly satisfactory; and (*d*) secondary variables not considered.

DETAILED STUDY OF VARIABLES

Fuel moisture was known to vary from place to place on the plots, and these variations were not evaluated in the sampling technique used; furthermore, the method of determining fuel moisture was unreliable for the degree of refinement required. Wind values, although reliably accurate, were not readily applicable to fire-control practice because the relation between measurements inside the stand and customary measurements in the open were not available. Consequently, it was decided to study all important elements individually prior to any attempt to extend the field studies to other more complex fuel types. Pursuant to this plan, the following studies are now being made:

1 Methods of sampling fuels for moisture content and of analyzing for fuel moisture.

2 Wind movement in forest stands and its correlation with movement in the open.

3 Influence of fuel variables, including size, arrangement, and composition, on rate of spread.

Fuel Moisture. Because of the large influence on rate of burning of small changes in moisture content, it was essential to develop a more accurate method of measuring fuel moisture.

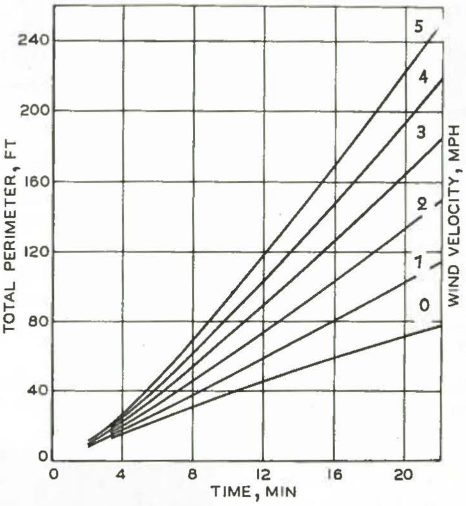

FIG. 5 TOTAL PERIMETER WITH TIME; VARIOUS WIND VELOCITIES; MOISTURE CONTENT, 7 PER CENT

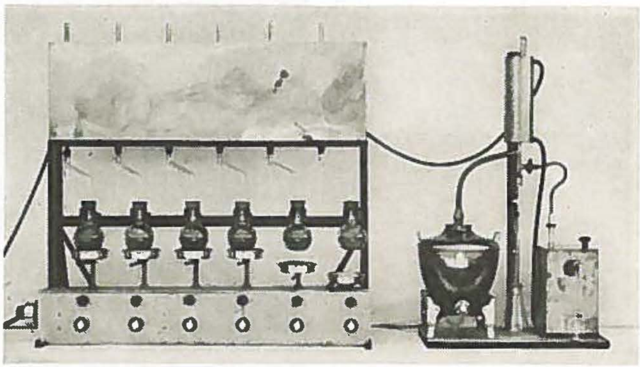

FIG. 6 MOISTURE DETERMINATION AND XYLENE-RECOVERY APPARATUS USED IN FIRE-BEHAVIOR STUDIES

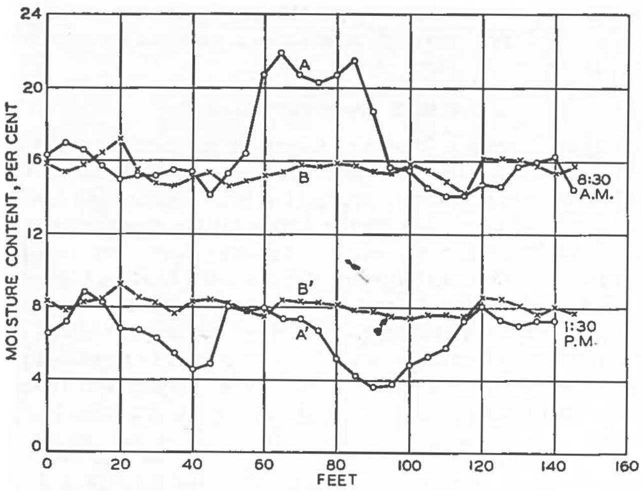

FIG. 7 TYPICAL FUEL-MOISTURE VARIATIONS AS FOUND IN OPEN AND CLOSED STANDS

(Variation in moisture content of pine litter at 8:30 a.m. and 1:30 p.m. on a 150-ft strip 5 ft wide; samples taken at 5-ft intervals. *A-A'*, open stand; *B-B'*, closed stand.)

Erratic behavior of fuel samples in well-designed drying ovens demonstrated that this method could not be relied upon for determining moisture content more closely than to the nearest 2 per cent. Recent investigations by Buck and Hughes (8) resulted in the development of the xylene-distillation apparatus, Fig. 6, by which results could be duplicated within a consistent range of approximately 0.2 per cent. This precise method has been a boon to the detailed investigations of other variables.

During the fire season, variations in the moisture content of typical forest fuels are influenced mainly by fluctuations in atmospheric humidity, and also by dew and soil moisture. By sampling transects in pine stands of varying densities, principles basic to the selection of test plots of uniform fuel moisture, and to the sampling of test plots for reliable mean moisture estimates, were developed. Typical variations as found in open and closed stands are illustrated in Fig. 7.

Currently this study is being extended to obtain data for the correlation of fuel moisture with precipitation, relative humidity, wind velocity, temperature, and soil moisture. Also an investigation is being included of seasonal and diurnal variations in moisture content of the green foliage of certain common brush species in which rate-of-spread studies are contemplated.

Wind in Forest Stands. Studies of wind movement are a necessary part of rate-of-spread investigations to permit determination of the proper location of anemometers on test fires and correlation of wind velocities within the forest stand with measurements made by standard anemometers in the open. Such studies have produced new and valuable information on the relation of wind velocities to height in forest stands and in open grassland. Fig. 8 shows wind intensity in relation to

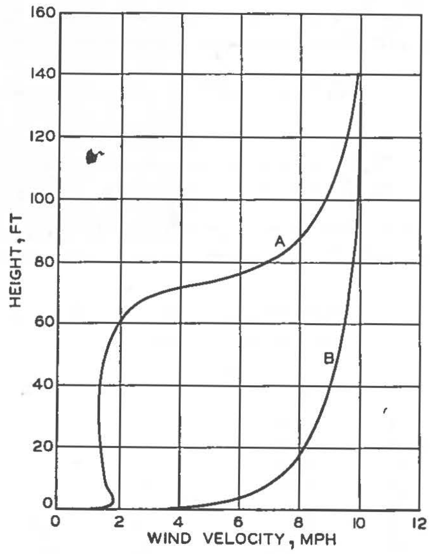

FIG. 8 WIND VELOCITY IN RELATION TO HEIGHT

(*A*, Even-aged coniferous forest, 70 ft high; *B*, open grassland.)

height in a moderately dense coniferous forest as compared to an open grassland. It may be noted from curve *A* that the wind intensity is decreased enormously at the tops of the trees at 70 ft and is nearly constant in the canopy. These experiments have provided a basis for converting stand wind intensities to

FIG. 9 TYPICAL NORTHERN CALIFORNIA BRUSH FUEL

intensities in the open and have shown the arbitrary height of $2^1/_2$ ft originally adopted for anemometer exposure in closed stands to be satisfactory for future work.

Fuel Study. Determination of the effect of fuel is of major importance to the rate-of-spread problem. The immediate aim of these fuel studies is to ascertain the pertinent variables and to develop methods for their measurement.

Forest fuels may vary from a uniform needle litter in pure coniferous stands, Fig. 2, through dense uniform brushfields, Fig. 9, to uneven-aged mixed stands where little or no physical uniformity in fuel is apparent. Fuels thus exhibit great differences in such physical characteristics as size, shape, and surface texture.

In considering a simple fuel condition such as that presented by pine needles or dead grass, two types of fuel variables may be distinguished, those of the fuel particle and those of the fuel bed. The fuel in these cases is a thin elongated particle the dimensions of which are amenable to measurement and expression, and these dimensions are in part responsible for the speed of propagation of the fire. On the other hand, fuels in the forest naturally occur as beds of particles compacted to various degrees by rain, snow, and weathering. This compactness is characteristic not of the fuel particle but of the fuel bed, and exerts, independently of the particles, its influence on fire propagation. Accordingly, fuels of this simple sort may be studied from two standpoints, first, as individual particles of different dimensions, and second, as beds of different compactness.

TABLE 3 DENSITY AND SURFACE AREA FOR SEVERAL TYPES OF FUELS

Fuel type	s Sq in. per g	γ G per cu in.	σ In.$^{-1}$
Ponderosa-pine needles	15.4	8.3	128
Lodgepole-pine needles	15.1	9.3	140
Sugar-pine needles	18.7	8.8	165
Ponderosa pine, 0.036-in-sq stick	15.7	7.0	111
Ponderosa pine, 0.044-in-sq stick	12.8	7.0	90
Ponderosa pine, 0.062-in-sq stick	9.1	7.0	64
Ponderosa pine, 0.101-in-sq stick	5.6	7.0	39
Ponderosa pine, 0.245-in-sq stick	2.3	7.0	16
Poplar excelsior	40.0	6.2	248

Fuel-Bed Experiments. It is common knowledge that, for rapid burning, fuel must be piled loosely. This increases the proportion of air spaces or voids which influence the oxygen supply and the distribution of radiant energy. The exposed fuel surface affects the rate at which heat is absorbed and, hence, the rate at which progressive ignition takes place. The ratio of voids to fuel-surface area has been hypothesized as the fuel-bed variable controlling the rate of flame pro-

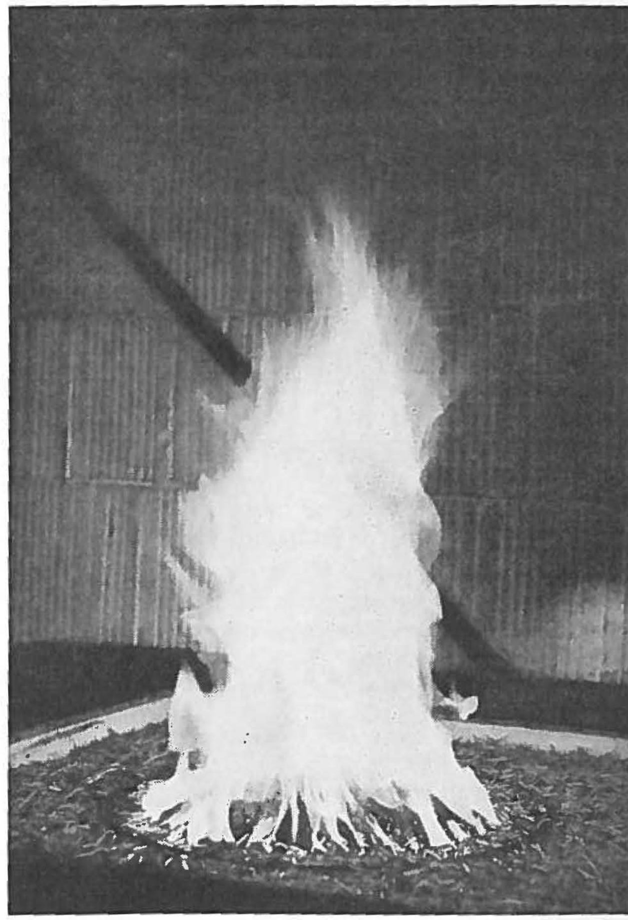

FIG. 11 MINIATURE EXPERIMENTAL FIRE IN PINE-NEEDLE BED

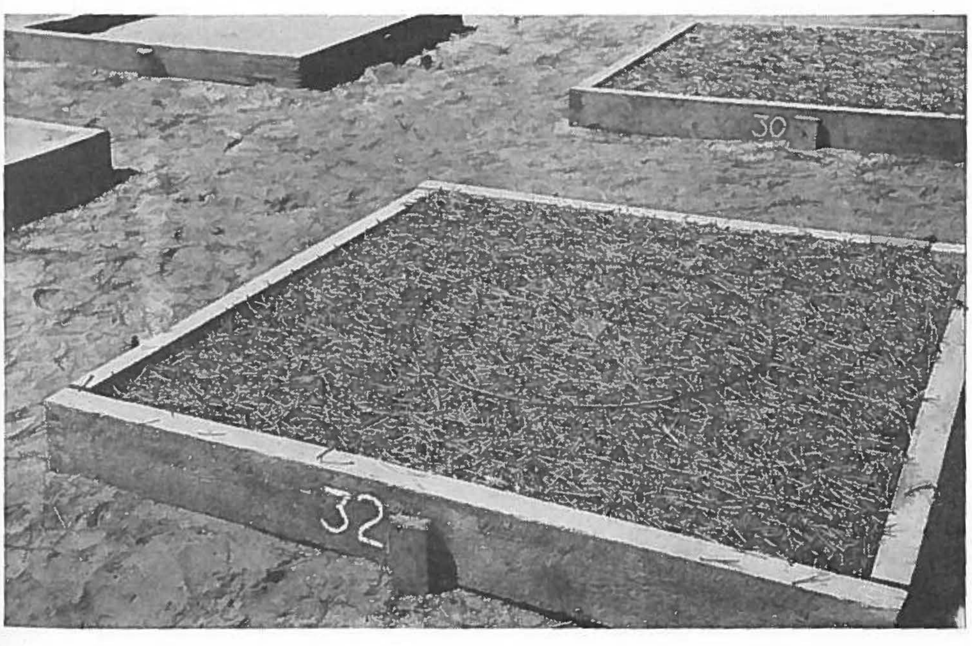

FIG. 10 PINE-NEEDLE BED PREPARED FOR MINIATURE-FIRE EXPERIMENT

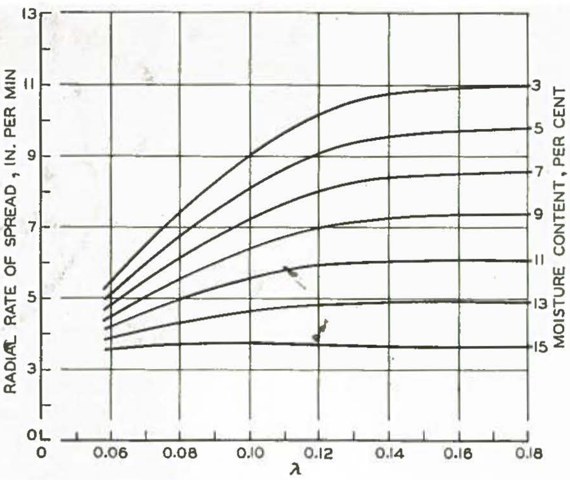

FIG. 12 RADIAL RATE OF SPREAD AS A FUNCTION OF λ FOR VARIOUS MOISTURE CONTENTS IN PONDEROSA-PINE NEEDLES; $\sigma = 111$

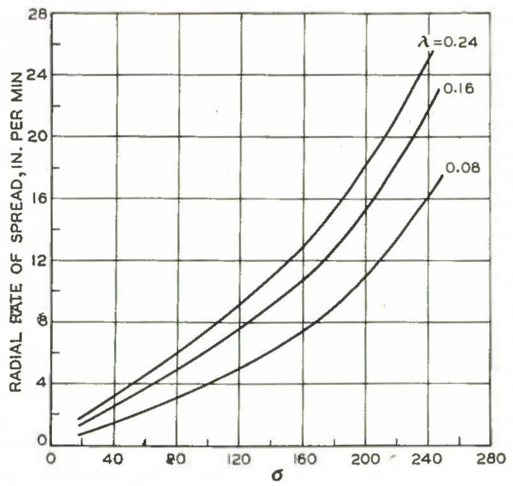

FIG. 14 RADIAL RATE OF SPREAD AS A FUNCTION OF σ, FOR THREE VALUES OF λ

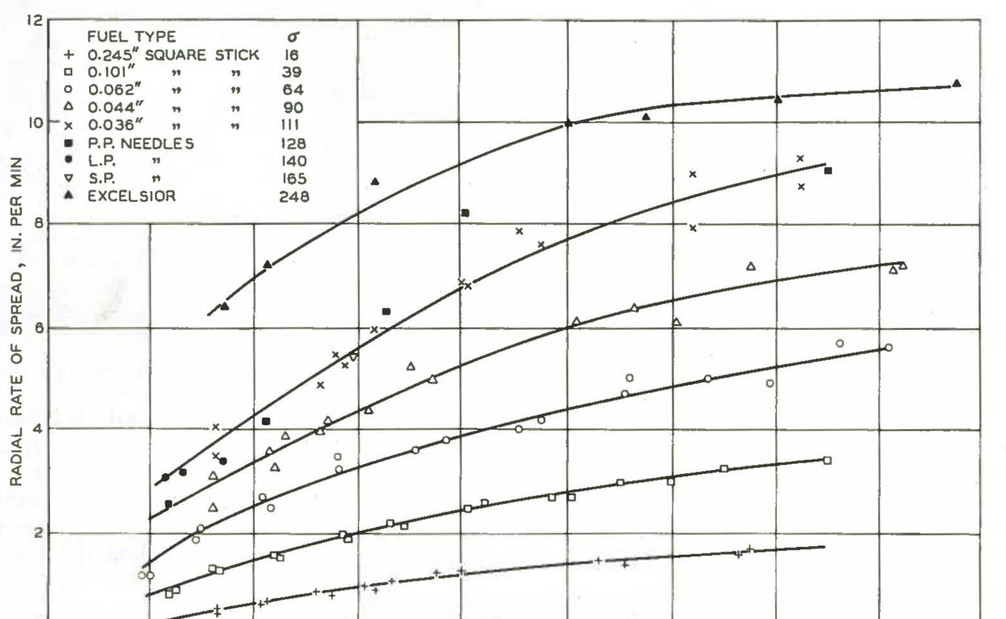

FIG. 13 RADIAL RATE OF SPREAD AS A FUNCTION OF λ FOR SEVERAL FUELS

(Moisture content 8.8 ± 1 per cent. Radial spread for excelsior divided by 2.5.)

pagation. This ratio may be expressed in terms of known quantities as follows:

$$\lambda = \frac{1}{Ws} - \frac{1}{\gamma s}$$

where for unit volume of the fuel bed

- λ = volume of voids per fuel-surface area
- W = dry weight of fuel
- s = surface area per unit weight of fuel
- γ = density of fuel.

To utilize this equation, it is necessary to determine s and γ for the individual particles comprising the fuel bed. This has been done for several types of needles and artificial fuels as shown in Table 3.

To test the hypothesis that rate of spread is a function of λ miniature fires were set in prepared beds of ponderosa-pine needles, Fig. 10, holding the fuel particle constant but varying λ and moisture content. Each fire was allowed to burn to 18 in. diam, and the radial rate of burning in inches per minute was computed. A typical fire is shown in Fig. 11. The combined effect of λ, moisture content, and rate of spread, which were obtained from 450 miniature fires, is presented in Fig. 12. It may be noted that the rate of spread varies regularly with λ but that, at high moisture value, its effect becomes unimportant.

Fuel Particle Experiments.[2] It is a matter of common observation that fineness in fuels promotes rapid combustion. Physically, the essential difference between fine and coarse fuel is the surface area per unit volume, hereafter designated by the

[2] Experiments were conducted by R. K. Blanchard, California Forest and Range Experiment Station.

symbol σ, and this has been tested as the fuel-particle variable governing rate of spread. This was done in a second series of miniature-fire experiments in which λ and σ were varied but with moisture content held constant within 1 per cent. The following fuels were used: (*a*) Ponderosa-pine sticks of square cross section; (*b*) hardwood excelsior; and (*c*) pine needles. The values of σ for these fuels are given in Table 3.

Fig. 13 shows rate of spread of individual fires plotted as a function of λ for these several fuels. The curves of Fig. 14 were obtained by cross-plotting curves of Fig. 13. They indicate that, in so far as these relatively simple fuels are concerned, the attribute of the fuel pertinent to the rate of spread of surface fires is simply and adequately expressed by considering as independent variables, surface area per unit volume σ, and voids per unit area λ.

All experimental fires to date have been conducted with zero wind. To extend these tests over the normal range of forest wind velocity, a wind tunnel, Fig. 15, has been constructed, capable of producing wind velocities up to 15 mph. Future research is also contemplated in the more complicated fuels of brushfields and mixed stands.

CONCLUSION

Although this field of study is new and progress has not been great, the results are already being utilized in the solution of fire-control problems. A systematic method of rating fire danger on all California national forests has been developed in part from these studies. Under this method, fuel moisture, wind velocity, relative humidity, and other important fire-behavior variables are currently measured and integrated into a series of indexes expressing, relative to normal summer conditions, the chance of fires starting, their rapidity of spread, and, finally, the type of organization required to cope with current fire danger. Under this system, guards and other fire-suppression forces may be increased to 5 times normal for extreme conditions. The system developed has an advantage over most other fire-danger rating systems in being based partially upon studies in fire behavior.

Progress in rate-of-spread studies will undoubtedly be slow. The program can be advanced best by research in other localities and by new suggestions in approach. Of particular importance is the solution of the problem of describing and measuring the fuel variable. Upon the solution of this problem rests the possibility of broad generalization in regard to rate of spread of forest fires.

BIBLIOGRAPHY

1 "Measuring Forest-Fire Danger in Northern Idaho," by H. T. Gisborne, Misc. Pub., No. 29, U. S. Dept. of Agriculture, 1928, p. 64.

2 "The Measurement and Interpretation of Forest-Fire Weather in the Western Adirondacks," by P. W. Stickel, Tech. Pub., No. 34, New York State College of Forestry, Syracuse University, 1931, p. 115.

3 "Forest-Fire-Hazard Research as Developed at the Petawawa Forest Experiment Station," by J. G. Wright, Forest-Fire-Hazard Paper No. 2, Dept. Interior, Forestry Branch, Canada, 1932, p. 58.

4 "Climate and Forest Fires in Northern California," by S. B. Show, *Journal of Forestry*, vol. 17, no. 8, 1919, pp. 965–979.

5 "Theoretical Considerations Regarding Factors Which Influence Forest Fires," by L. F. Hawley, *Journal of Forestry*, vol. 24, no. 7, 1926, pp. 756–763.

6 "Preliminary Report on Fire-Hazard-Rating Study" (mimeographed), by L. G. Gray, U. S. Weather Bureau, San Francisco, Calif., 1933, p. 54.

7 "Rate of Spread of Surface Fires in the Ponderosa-Pine Type of California," by J. R. Curry and W. L. Fons, *Journal of Agricultural Research*, vol. 57, no. 4, pp. 239–267.

8 "The Solvent Distillation Method for Determining the Moisture Content of Forest Litter," by Charles C. Buck and John E. Hughes, *Journal of Forestry*, vol. 37, no. 8, 1939, pp. 645–651.

FIG. 15 WIND TUNNEL FOR FIRE-BEHAVIOR STUDIES

(Since this photograph was taken the test section of the wind tunnel has been lengthened by twelve feet to eliminate entrance disturbances.)