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FIELD TEST OF A RATE-OF-FIRE-SPREAD MODEL IN SLASH FUELS

James K. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

The Author

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph. D. from the University of Michigan in 1968, all in forestry. From 1961 to 1965 he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965 he transferred to the Northern Forest Fire Laboratory, Missoula, Montana, where he is responsible for research on the physical properties of fuel.

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U. S. Department of Agriculture
Ogden, Utah 84401
Robert W. Harris, Director

Abstract

Predicted rates of fire spread using a mathematical model were consistently greater but in reasonably close agreement with rates observed on test fires in ponderosa pine and Douglas-fir slash. Fuel loading, bulk density, particle density, particle surface-to-volume ratio, heat content, total plant salt content, silica-free salt, fuel moisture, and wind velocity were determined as input variables for the test on plots containing slash with and without needles, and at two loadings and three depths. Fuel discontinuities and inadequate knowledge of fuel moisture contents that limit ignition are discussed as the primary reasons for the deviations. One-half of the total fuel weight loss in the flame front was accounted for by particles less than 1 cm. in diameter. A multiple regression for predicting flame length is provided.

Contents

INTRODUCTION

Development of a mathematical model for predicting rate of fire spread is part of an effort at the Northern Forest Fire Laboratory to formulate a system for appraising the fire behavior potential of fuel. Desirable features of such a fuel appraisal system are quantitativeness, predictability, and flexibility.

A fuel appraisal system based upon quantitative inputs and outputs is needed for objectively guiding fire management decisions. Appraisal of the fire spread potential of fuel can help with evaluations of silvicultural treatments, prevention and presuppression planning, budgeting of fire control expenditures, fire simulation training, and wildfire suppression.

Earlier and existing systems of fuel appraisal, of which Hornby's (1935) is the best known and most widely used, have been useful, but contain weaknesses that limit their application for current and future resource management. The major weaknesses seem to involve the following:

1. A fixed level of fire-weather severity is required for making the evaluations. "Average bad" conditions are assumed. Usually fuels are considered quite dry and winds rather strong.

2. Seasonal and yearly changes in the amount and arrangement of fuel cannot be accommodated.

3. Prediction of fire behavior using changing fuel and weather conditions is not possible.

4. The systems are qualitative. They require experienced people to assess the fuels providing a precise meaning only to those closely familiar with the fuels.

A quantitative basis for fuel appraisal, such as provided by a mathematical model, facilitates uniform interpretation of appraisals and makes predictability and flexibility possible. Predictability permits assessment of anticipated land management practices upon the vegetation as fuel. For example, the fuel conditions created by harvesting and thinning could be predicted and appraised before cutting, and plans formulated for proper treatment of the expected hazard. Flexibility means that the application of fuel appraisals could be as broad or specific as desired, depending on the fuel characteristics used as modeling input and their representativeness.

A system of fuel appraisal consists of two phases: (1) Measurement and description of fuel properties required as input to the system; and (2) rating the fire behavior potential indicated by the fuel properties. This paper concerns the second phase; specifically, it reports on tests to determine the accuracy of a mathematical rate-of-fire-spread model designed by Rothermel (1972).

THE RATE-OF-SPREAD MODEL

Rothermel's rate-of-spread model is summarized by the following equation:

$$\text{Rate of spread, } R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad (1)$$

where:

I_R = reaction intensity or the rate of energy release in the flame front of a fire B.t.u./ft.^{2}-min.

ξ = propagating flux ratio--the proportion of I_R required for propagation of a no-wind fire, dimensionless

ϕ_w = multiplying factor for the effect of wind, dimensionless

ϕ_s = multiplying factor for the effect of slope, dimensionless

ρ_b = bulk density of fuel, lb./ft.^{3}

ε = effective heating number which expresses the proportion of fuel that is heated to ignition temperature dimensionless

Q_{ig} = heat of preignition, the heat required to bring a unit weight to ignition, B.t.u./lb.

These terms are computed from a set of rather complex equations. This set, which is summarized in equation (1), constitutes the mathematical model. The basic fuel and environmental input variables for the model are shown in table 1.

Table 1.--*Fuel and environmental inputs that determine values for the terms in the rate-of-fire-spread equation*

Input variables	Terms in the spread equation						
	I_R	ξ	ϕ_w	ϕ_s	ρ_b	ε	Q_{ig}
Loading, lb./ft.^{2}	X	X	X	X	X		
Heat content, B.t.u./lb.	X						
Fuel particle density, lb./ft.^{3}	X	X	X	X			
Fuel particle surface-to-volume ratio, ft.^{2}/ft.^{3}	X	X	X			X	
Depth of fuel, ft.	X	X	X	X	X		
Fuel moisture content, fraction of dry wt.	X						X
Total salt content, fraction of dry wt.	X						
Silica-free salt content, fraction of dry wt.	X						
Wind velocity, ft./min.			X				
Angle of slope				X			

The model was developed from data gathered using controlled laboratory combustion facilities, fuel beds comprised of uniformly distributed dead fuel particles of a single size, and quasi-steady-state fire. Conditions were varied to show the effect of fuel depth, loading, particle size, windspeed, and slope. The effect of fuel moisture and mineral content was taken from other work.

Predictions of fire spread and flame front intensity using the model should apply most accurately to surface fires in uniform distributions of such fuels as needle litter, grass, logging slash, and perhaps crowning fires in brush. Less accurate predictions would be expected for patchy distributions of fuel.

The model pertains to fire spread by a flaming fire front. Fire propagation from spotting, fire whirls, and blowup conditions is not a part of the model. The model was designed for fuel appraisal, fire-danger rating, and presuppression planning where relative fuel and fire behavior evaluations are useful. Accurate fire behavior predictions for specific fires will require further refinement of the model and understanding of fuels.

Application of the model to heterogeneous fuels--fuels containing more than one size of fuel--requires recognition of the contribution to fire spread made by each kind and size class of particle. This is accomplished by entering the input variables as mean values weighted by surface area of each kind and size class of fuel particle. A complete explanation of the model and its development is given by Rothermel (1972).

PROCEDURES

Observed and predicted rates of fire spread were compared using test fires on an old bed of the Clark Fork River east of Missoula, Montana (fig. 1).

Plots 8 by 30 feet were prepared using logging slash hauled by truck as the fuel. All other vegetation was cleared from the plots. Slash was used as a test fuel because it (a) often is a hazard and silvicultural problem of considerable concern to land managers, (b) cannot be readily tested in a laboratory, and (c) provides a test of the spread model using heterogeneous fuel for which only theory exists.

Slash of two species, Douglas-fir *(Pseudotsuga menziesii* var. glauca (Beissn.) Franco) without needles and ponderosa pine *(Pinus ponderosa* Laws.) with needles, was used at three depths for each of two loadings. Each combination of species loading and depth was replicated twice, making a total of 24 plots. Two extra plots were constructed for training but were not needed for this purpose so that 13 test fires were burned for each species. The loadings and depths are within a range that is often encountered in slash.

The plots were on a zero slope and were burned under low wind velocities. A test of the spread model at high wind velocities was not possible. Fairly low fuel moisture contents were sought and obtained on all fires.

The plots were loaded uniformly with weighed amounts of slash providing conditions of approximately 15 and 30 tons per acre. Immediately after weighing and loading, the plot moisture content was sampled by ovendrying needles and branches from several diameter size classes. The moisture estimates (with standard errors within 4.9 and 8.6 percent of mean values for Douglas-fir and ponderosa pine, respectively) permitted precise estimation of the actual ovendry weight of fuel. The slash on some plots was buoyed with wire to provide desired fuel depths.

Figure 1.--Plots 8 by 30 feet were constructed on an old bed of the Clark Fork River. Wire strung between steel fenceposts supported the slash at specified depths.

Measurement of Spread Model Inputs

Loading by fuel particle size class.--The amounts of fuel in 0- to 1-, 1- to 3-, and 3- to 5-cm. diameter size classes and the needle class for ponderosa pine were calculated from sample determination of the proportions of total fuel in each size class (fig. 2).

Three branches per plot were randomly collected, dissected into the size classes, and the proportions of total branch weight were determined for each size class. These proportions were used to calculate fuel weights by size class for ponderosa pine because the proportions appeared to be the same on all plots. The amount of fuel in each size was actually sampled on each Douglas-fir plot using the planar intersect technique (Brown 1971) because the amount of 0- to 1-cm. size class material appeared to vary considerably from plot to plot.

Particle surface-area-to-volume ratios.--For the 0- to 1-cm. Douglas-fir, an average particle surface-area-to-volume ratio (σ) was determined by taking random diameter measurements. For a cylinder, σ is 4 divided by the branch diameter. Diameters for the ponderosa pine and the other Douglas-fir size classes were taken at 10-cm. intervals along the three sample branches per plot. Standard errors of the estimate averaged 2.9 percent of the mean diameters for both species and all size classes. The σ for needles was obtained from measurements on needle cross sections (Brown 1970).

Depth.--Twenty-four measurements of depth were systematically taken just prior to ignition of each plot. Standard errors of the estimate ranged from 1 to 5 percent of the mean depths. Depth values were used to compute packing ratios. The packing ratio is the ratio of fuel volume-to-volume occupied by fuel and it indicates compactness of the fuel for internal calculations in the spread model.

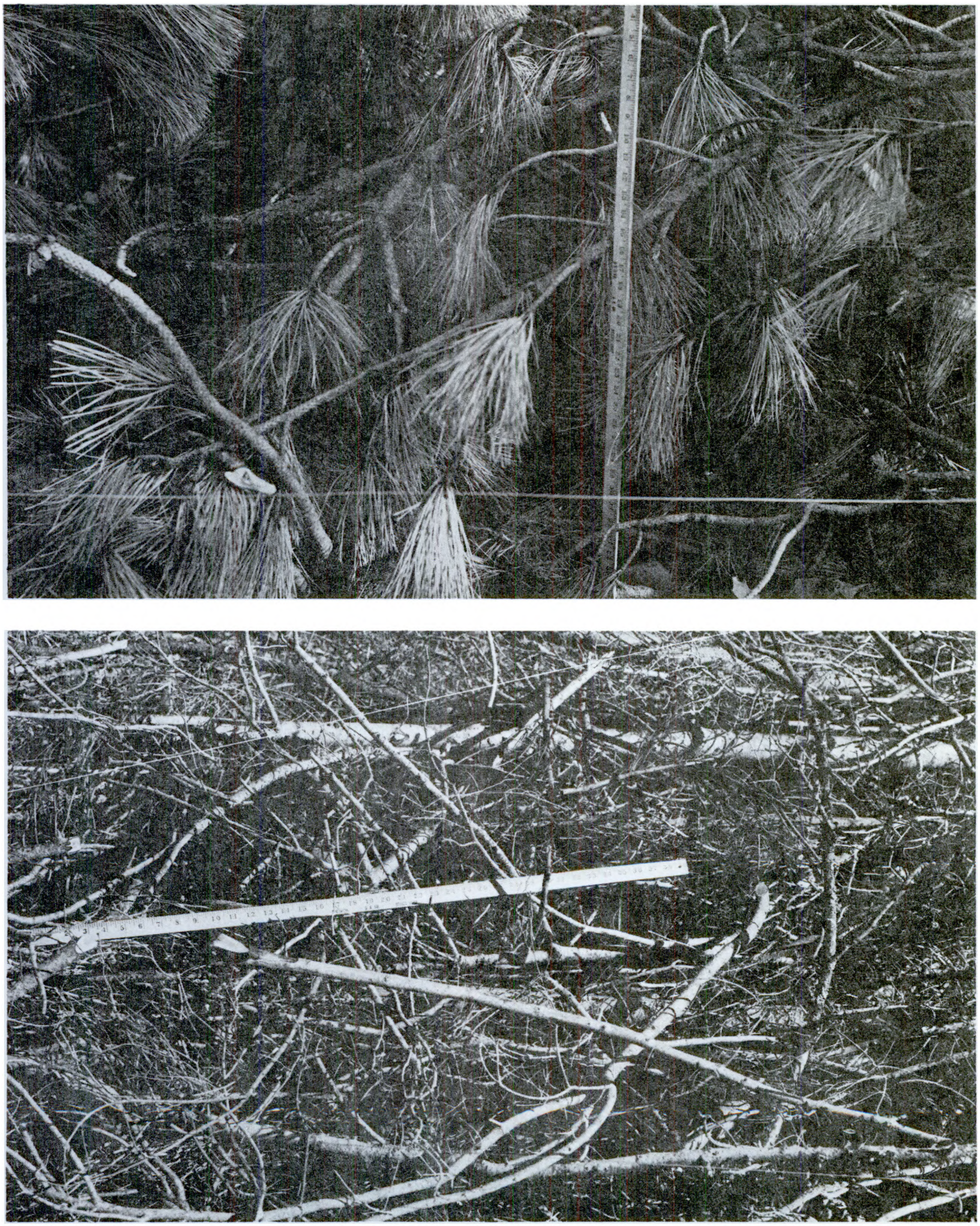

Figure 2.--Variations existed in sizes and arrangements of particles, as shown for ponderosa pine (top) and Douglas-fir (bottom), even though all plots were loaded as uniformly as possible. Clumps of particles exist because of the nature of branching and foliation.

Particle density.--Density values were determined from 12 randomly picked samples from each species and diameter size class. A mercury pycnometer furnished the density values for the needles and 0- to 1-cm. size classes. For the other size classes, volumes for calculating density were determined using average diameters and a length of 15 cm. for the samples. Average diameters were based on two measurements taken perpendicularly at 1-cm. intervals. Weights were on an ovendry basis and volume on an air-dry basis. Standard errors of the estimate were less than 4 percent of the mean density values for each size class.

Low heats of combustion, total ash content, and silica-free ash content.--Duplicate determinations for three samples picked randomly from the slash provided these values for needles and the 0- to 1- and 1- to 5-cm. size classes.

Moisture content.--Six samples for each size class, three near the top and three near the bottom of the slash, were collected just prior to ignition. The branchwood was ovendried and the needles subjected to xylene distillation. Standard errors for each plot ranged from 3-1/2 to 5 percent of the mean moisture contents.

Wind.--Wind velocity was measured at the expected midflame height close to each plot but away from indraft influences of the fires. Anemometers (having a threshold of 0.5 m.p.h.) connected to portable battery-operated recorders furnished the measurements. A wind vane also placed at midflame height recorded wind direction.

Temperature and relative humidity.--Temperature and relative humidity were measured just prior to ignition and continuously. They were recorded for reference but were not required for calculations in the spread rate model.

Measurement of Fire Variables

The plots were ignited across one end and allowed to burn for 5 feet to attain a quasi-steady state before spread rate measurements were begun. Time for the fire to burn between 2-foot intervals was recorded over a 20-foot distance (fig. 3).

Reaction intensity was determined from:

$$I_R = \left(\sum_{i=1}^{n} \eta_i w_i h_i\right)/\tau \qquad (2)$$

$$\tau = D/R \qquad (3)$$

where:

τ = reaction time of flame front (time for propagating flame to pass a fixed point), min.

η = average fractional weight loss of fuel in flame front

w = loading, lb./ft.^{2}

h = low heat yield, B.t.u./lb.

i = index for particle size classes

D = flame depth, ft.

R = rate of fire spread, ft./min.

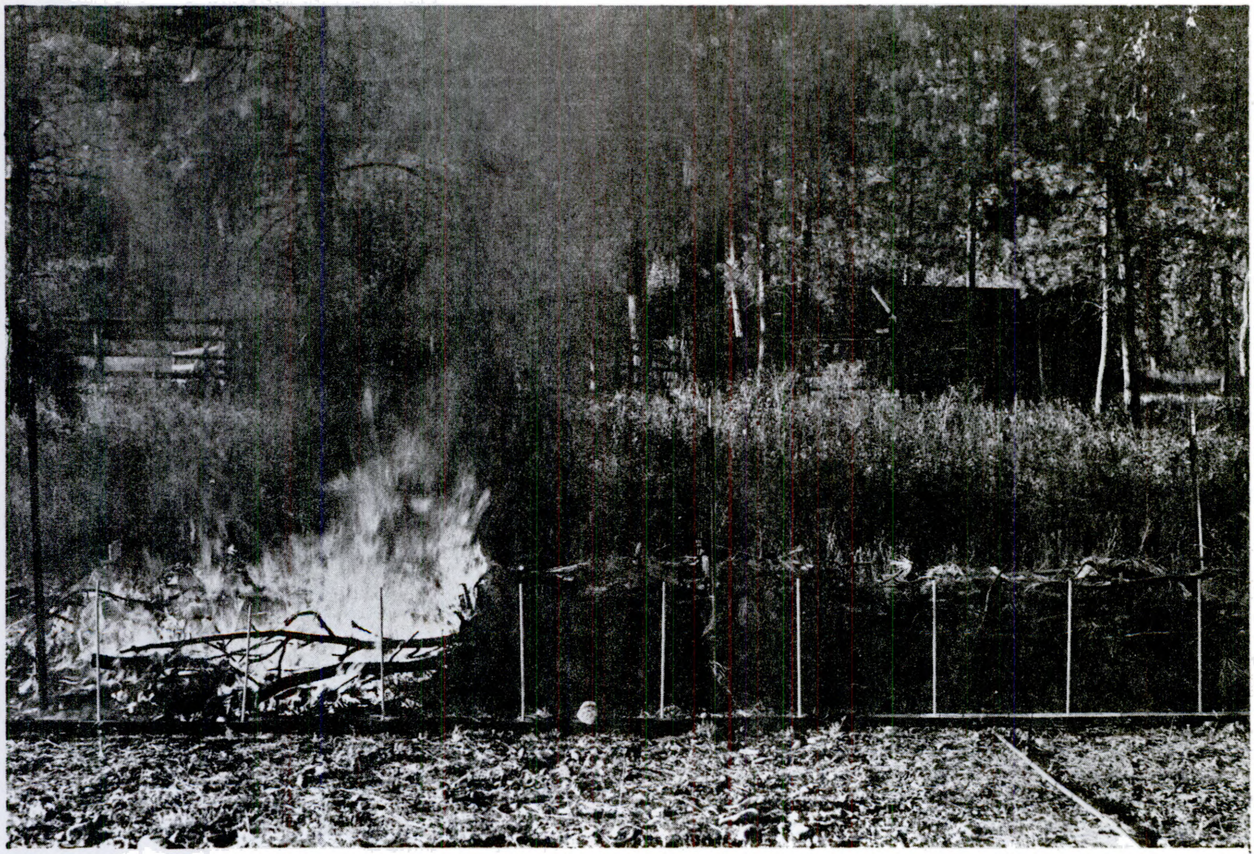

Figure 3.--Rate of spread was recorded as the time taken for the leading edge of the fire to pass each of the markers shown, which were spaced 2 feet apart.

Ovendry weights, which were obtained before and after the burns, permitted calculation of the particle weight loss within the propagating flame front. Weight loss by particle size class (η) was estimated at one location in each plot. Two 15-cm.-long sample branches per size class were tagged and located in a 20- by 100-cm. area 1.5 m. from the end of each plot. The fires were quickly extinguished using a water fog after the rear of the propagating flame passed over the particles.

Flame length and depth were measured on photographs of the fires' profiles taken at 2-foot intervals along the plots. Flame length is the distance from the outermost tip of the unbroken flame to the center of the flame base which lies at the top of the fuel. Flame depth is the horizontal distance through the base of the flame from the leading edge of the flame to a point at the rear where it tapers rapidly into a low and often sporadically flaming region.

RESULTS AND DISCUSSION

Good control over the fuel variables (see tables 2 and 3) was maintained by careful construction of the plots and by obtaining high precision in estimating them.

Rate of Fire Spread

The mathematical model predicted rates of spread that were higher than observed rates on all but three of the plots (fig. 4 and table 4). Deviations (predicted values minus observed values divided by observed values) ranged from -14 to 580 percent. The average overprediction (percent deviation) was 82 for the ponderosa pine plots and 121 for the Douglas-fir plots. These are in reasonably close agreement considering the complexity of the mathematical model and the slash fuels.

Several reasons beyond experimental error probably account for the deviations. The consistent overestimate of the spread rates indicates bias that could be explained by certain aspects of the mathematical model: (1) Assumptions about the fuel; (2) the moisture of extinction chosen for the slash; and (3) the method of weighting input parameters by fuel surface area.

Some bias may have been introduced on the plots having higher intensity fires (some of the 30-ton-per-acre plots) because the 8-foot plot width limited flame development. However, this bias should be small. An analysis of the effects of plot width on flame size and related rate of spread indicates that an 8-foot plot width would retard only slightly the rate of spread for fires having flames greater than 4 feet in length (Anderson 1968). No retardation of spread rate was indicated for fires having flames less than 5 feet in length.

Table 2.--*Average fuel properties of the slash according to species and size class*

Fuel property	Ponderosa pine				Douglas-fir		
	Needles	0-1	1-3	3-5	0-1	1-3	3-5
		cm.	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*
Low heat value[1/] (B.t.u./lb.)	8,826	9,274	8,885	8,885	8,898	8,691	8,691
Silica-free ash[1/] (fraction of dry weight)	.0155	.0123	.0086	.0086	.0145	.0097	.0097
Total ash[1/] (fraction of dry weight)	.0387	.0155	.0096	.0096	.0166	.0108	.0108
Particle density (lb./ft.^{3})	31.8	35.6	33.0	30.8	[2/] 34.8	[2/] 34.8	32.3
σ (ft.^{2}/ft.^{3})	1,756	156	73.5	32.9	393	80.7	29.6
Proportion of total loading (percent)	22	7	43	28	[3/] 27	[3/] 26	[3] 47

[1] Branchwood for the 1-3 and 3-5 cm. size classes was combined for the chemical analyses.

[2] Density values for the 0-1 and 1-3 cm. size classes were not significantly different using a Tukey test at the 0.05 confidence level.

[3] These values were not used to determine loadings for the spread calculations. Instead, loadings by size class were sampled for each plot.

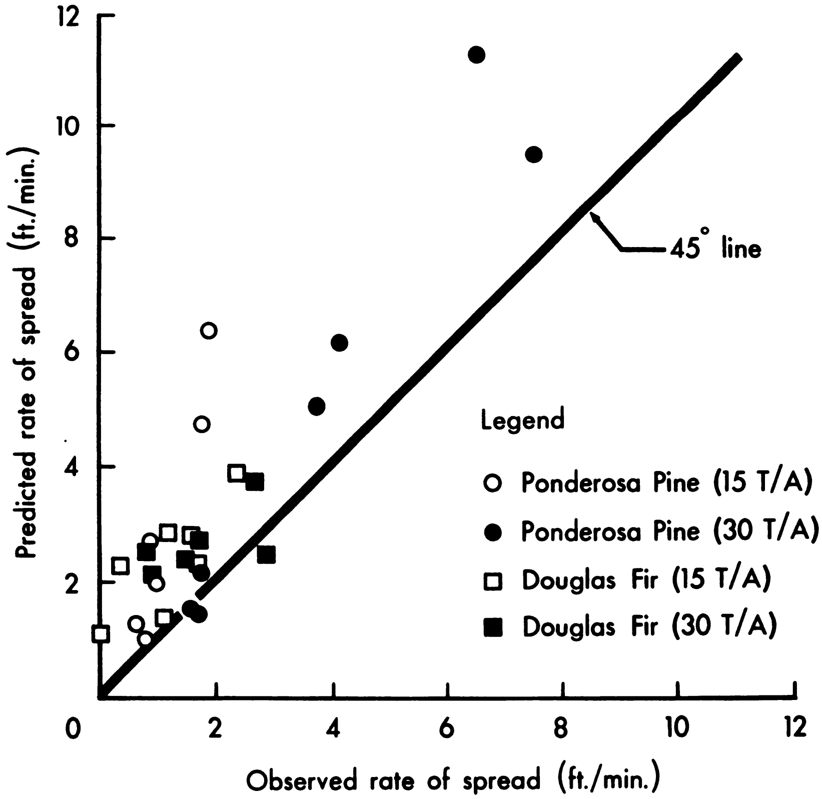

Figure 4.--Comparison between observed and predicted rates of spread for all plots.

Table 3.--*Fuel properties and environmental conditions for each plot at the time of burning*

Species	Plot number	Loading: Needle	Loading: 0-1	Loading: 1-3	Loading: 3-5	Loading: Total	Moisture content[1]: Needle	Moisture content[1]: 0-1	Moisture content[1]: 1-3	Moisture content[1]: 3.5	Fuel depth	Time	Temperature	Relative humidity	Windspeed
		Lb./ft.²					*Percent*				*Ft.*	*Hr.*	*°F.*	*Percent*	*Ft./min.*
Ponderosa pine	1	0.32	0.10	0.61	0.40	1.43	8.0	8.0	8.0	8.0	2.74	0845	56	62	211
	2	.16	.05	.30	.20	.71	7.7	7.7	7.7	7.7	1.55	0745	52	76	150
	3	.32	.10	.61	.40	1.43	6.8	8.4	8.4	8.4	1.67	0800	48	74	185
	4	.16	.05	.30	.20	.71	5.5	7.5	7.5	7.5	1.07	2100	65	38	70
	6	.32	.10	.61	.40	1.43	6.3	6.3	7.6	7.6	1.07	2100	68	50	70
	7	.16	.05	.30	.20	.71	6.0	6.0	7.2	7.2	.65	2000	74	38	106
	8	.32	.10	.61	.40	1.43	7.3	8.8	8.8	8.8	2.92	0700	46	83	97
	9	.16	.05	.30	.20	.71	7.7	7.7	7.7	7.7	1.82	0845	53	60	167
	10	.32	.10	.61	.40	1.43	7.5	7.5	7.5	7.5	1.73	1100	75	36	308
	11	.16	.05	.30	.20	.71	6.5	6.5	6.5	6.5	1.17	2000	78	35	106
	21	.32	.11	.62	.41	1.46	5.8	5.8	5.8	9.4	.93	2100	75	27	176
	23	.18	.06	.36	.24	.84	6.9	9.0	9.0	9.0	.65	0800	51	77	97
	26	.27	.09	.51	.34	1.21	11.0	8.5	8.5	11.0	.87	0800	46	67	154
Douglas-fir	5		.11	.18	.52	.81		9.1	9.1	9.1	.77	1110	73	30	273
	12		.21	.37	1.05	1.63		8.8	8.8	8.8	1.40	1930	82	27	211
	13		.13	.34	.35	.82		9.5	9.5	9.5	.64	1630	69	27	475
	14		.30	.33	1.00	1.63		9.6	9.6	6.0	1.56	1900	87	24	88
	15a		.18	.26	.39	.83		7.6	7.6	7.6	1.29	2000	75	27	220
	15b		.18	.26	.39	.83		7.6	7.6	7.6	1.29	2015	75	27	114
	16		.27	.44	.14	.85		6.4	7.6	7.6	.92	1915	84	21	114
	17		.27	.67	.72	1.66		11.0	8.3	11.0	1.23	0700	44	85	132
	18		.34	.66	.67	1.67		10.6	10.6	10.6	1.28	0830	55	66	141
	20		.35	.39	.90	1.64		7.9	7.9	7.9	1.04	2000	76	28	185
	22		.17	.42	.25	.84		6.2	9.1	9.1	.51	2000	81	16	158
	24		.27	.60	.78	1.65		9.8	9.8	9.8	1.05	1100	73	38	211
	25		.17	.40	.26	.83		8.9	10.9	10.9	.59	1600	81	24	88

[1]Means for each size class that were not significantly different using Tukey's honestly significant difference test at the 0.05 confidence level were combined.

Table 4.--*Rate of spread, flame length, and flame depth for individual plots*

Plot	Rate of spread		Flame length	Flame depth[1]
	Observed	Predicted		
	Ft./min.	*Ft./min.*	*Ft.*	*Ft.*
		PONDEROSA PINE		
1	6.57	11.23	5.3	3.9
2	1.75	4.71	1.9	1.3
3	3.75	5.00	5.4	4.2
4	.91	1.98	2.2	1.7
6	1.67	1.48	7.4	3.9
7	.61	1.30	1.1	1.0
8	4.14	6.13	6.1	3.9
9	1.86	6.34	1.9	1.4
10	7.57	9.47	5.3	3.5
11	.90	2.70	2.8	2.2
21	1.75	2.19	8.5	5.3
23	.78	1.01	2.0	1.5
26	1.54	1.53	3.5	2.1
		DOUGLAS-FIR		
5	.34	2.31	.3	.4
12	2.63	3.79	4.9	3.2
13	1.68	2.34	.5	.5
14	1.68	2.75	4.0	3.2
15a	2.39	3.86	2.4	1.8
15b	1.18	2.83	1.5	1.3
16	1.55	2.84	3.1	1.9
17	.87	2.16	3.4	2.4
18	.84	2.59	1.0	1.0
20	2.88	2.48	7.6	4.4
22	1.12	1.37	2.6	1.9
24	1.52	2.43	3.0	1.4
25	0	1.11	0	0

[1]Depths were determined from measurements on photographs except for plot 24 which was determined by a visual estimate.

Figure 5.--Sporadic flaming typified the 15-ton-per-acre plots; this was probably caused by the relatively small amount of fuel available and the clumpiness of particles.

Discontinuity of fuel and heat flux.--Deviations were highest for the lowest values of packing ratio and fuel loading (table 5). This was especially true for the ponderosa pine plots. A discontinuity in the arrangement of fuel particles and a corresponding decline in the supply of heat for preignition could have existed because of the spacing between fuel particles. The spacing was greater in the least compact fuels: the branching habit and manner of needle growth created various sized gaps between particles, even though the slash was distributed uniformly during construction of the plots (fig. 2). Some gaps were probably so large that a substantial propagating heat flux was required to ignite unburned particles. In contrast, the mathematical spread model was developed primarily using fuel beds having evenly spaced particles without any large gaps between them.

Deviations for the plots having the highest loadings were less, possibly because the higher fire intensities furnished ample heat flux for a nearly uniform rate of particle ignitions. Fires in the low loading plots generally burned more sporadically because particle ignitions were not occurring at a uniform rate (fig. 5).

On one of the low loading Douglas-fir plots (no needles present) fire would not sustain itself; on another similar plot, fire spread was barely sustained. The amount of fuel, particle size, and particle spacing were the dominant limiting factors. The spread model contains mathematically continuous functions that are defined by scant data at the limiting end of the fire scale.

Table 5.--*Percent deviations for the observed and predicted spread rates segregated by species, loading, and packing ratio values*

Loading tons/acre	Packing ratio	Deviation Percent	Deviation Average percent
	PONDEROSA PINE		
15	0.014	169	205
15	.012	241	
15	.021	117	158
15	.019	200	
15	.034	113	72
15	.040	30	
Average		145	
30	.016	71	60
30	.015	48	
30	.027	33	29
30	.026	25	
30	.041	11	12
30	.049	25	
25	.043	1	
Average		34	
	DOUGLAS-FIR		
15	.019	62	
15	.019	140	95
15	.027	83	
15	.038	39	206
15	.032	579	
15	.041	[1]--	
15	.048	22	22
Average		154	
30	.035	44	54
30	.031	64	
30	.040	148	178
30	.039	208	
30	.047	14	37
30	.047	60	
Average		90	

[1]Omitted because no observed rate of spread resulted in an infinite percent deviation.

Moisture of extinction.--Rate of spread is directly proportional to the moisture damping coefficient (η_m), which enters the mathematical model as a multiplier of reaction intensity.

$$\eta_m = 1 - 2.59 \frac{(M_f)}{M_x} + 5.11 \frac{(M_f)^2}{M_x} - 3.52 \frac{(M_f)^3}{M_x} \qquad (4)$$

where:

M_f = moisture content of fuel, fraction of dry weight

M_x = moisture of extinction, fraction of dry weight

The moisture of extinction is the moisture content of fuel at which fire cannot sustain itself. Criteria for choosing M_x are not well established; thus use of this function in the model is rather subjective. We used an M_x of 0.24. Working backwards through the model using fuel inputs and measured rates of spread for each plot, we found that an average M_x of 0.11 for the ponderosa pine and 0.13 for Douglas-fir would have provided perfect agreement between observed and predicted spread rates. M_x values that permitted perfect agreement ranged from 0.065 to 0.45 for all plots. There is good reason to suspect that an M_x of 0.24 is too high for the fuels tested. If so, this would account for much of the deviations between observed and predicted spread rates.

A comparison of M_x with packing ratio and loading values suggests that a relationship exists between M_x and these fuel properties. In this study, plots with higher loadings developed more intense fires. The M_x would be expected to increase at higher intensities because more energy is available for preheating fuel to ignition. Plots having lower packing ratios (more porous) had greater percent deviations between observed and predicted spread rates. Apparently this was in part caused by discontinuities in fuel and heat flux. Discontinuities should tend to lower M_x.

Surface area influence.--Weighting the input variables, especially σ, by the amount of surface area in each particle size class possibly leads to overprediction of spread rate. The thinnest fuel particles in a fuel complex receive heavy weighting for their influence on fire spread rate. This seems appropriate, but perhaps too much weighting is received. Further study should refine the accuracy of this function in the model.

Regression Analysis for Fire Spread

A step wise multiple regression analysis using the combined data for both species of slash resulted in the following equation:

$$Y = 0.109(X_1) + 2.01(X_2) + 0.00827(X_3) - 1.96(X_4) \qquad (5)$$

where:

Y = rate of spread, ft./min.

X_1= surface area of fuel 0 to 1 cm. in diameter per square foot of ground, dimensionless

X_2= total fuel loading, lb./ft.^{2}

X_3= windspeed ft./min.

X_4= bulk density of fuel, lb./ft.^{3}

R^2= 0.71

Standard error of estimate (0.05 confidence level) = 1.04

Surface area of the 0- to 1-cm. fuel accounted for differences between species. Presence of needles on the ponderosa pine branches provided this species with the most surface area. Of the correlation between the X and Y variables, X_1 was closest to Y ($r = 0.57$). Moisture content was nonsignificant in the regression because of the small range in moisture values. X_1 was nonsignificant in regressions in which species were kept separate.

Reaction Intensity

The measured I_R values were mostly less than the predicted ones, as shown in the following tabulation:

	Ponderosa pine	*Douglas-fir*	*Species combined*
Average reaction intensity			
Measured, B.t.u./ft.^{2}-min.	4,621	3,599	4,130
Predicted, B.t.u./ft.^{2}-min.	4,800	3,808	4,324
Average absolute deviation, percent[1]	53.6	52.8	53.2
Overpredictions	10	9	19
Underpredictions	3	4	7

We could not substantiate conclusions about the accuracy of the model to predict I_R because we were unable to measure I_R precisely under field conditions. There was a tendency to overestimate flame depth used to calculate I_R (equation 3) because the widest portion of the flame was outlined on the photographs. The fact that fuel weight loss during passage of the flame front was based on an average value for all plots also contributed to the deviations.

Weight Loss Related to Particle Size

The average percent weight loss during passage of the flame front for sample fuel particles from all plots is tabulated below:

	Ponderosa pine *Percent*	*Douglas-fir* *Percent*
Needles	[2] 96	--
Branches by diameter[3] (cm.)		
0.2	--	[4] 94 ± 2
0.5	--	80 ± 16
1	73 ± 13	71 ± 18
1-3	42 ± 21	36 ± 15
3-5	15 ± 7	11 ± 6

[1] $\frac{\text{Measured } I_R - \text{predicted } I_R}{\text{Measured } I_R} \times 100$ was calculated for each plot and averaged with sign ignored.

[2] The needles were completely consumed; however, needles contain 4 percent ash which theoretically is not a weight loss.

[3] Diameters were chosen to provide sensitivity at the small sizes. Inasmuch as ponderosa pine and Douglas-fir branches have a different size distribution, different diameters for the small sizes were chosen.

[4] The second values are standard deviations. For ponderosa pine particles, n = 26; for Douglas-fir particles, n = 18.

The percent of total fuel weight loss accounted for by needles and branchwood in the different particle size classes is shown in the following tabulation:[5]

	Ponderosa pine	*Douglas-fir*
	Percent	*Percent*
Needles	44	--
Branchwood by diameters (cm.)		
0-0.5	--	19
0.5-1	11	25
1-3	37	43
3-5	8	13

Percentages for individual plots did not vary significantly for different loadings or bulk densities.

When the above percentages were determined, we knew the percent weight loss of individual particles and the proportion of the total fuel contributed by the various size classes. Fuel less than 1 cm. in diameter accounted for half of the total weight loss even though this size material was less than 30 percent of the total loading (table 1). Fuel greater than 3 cm. in diameter provided only about 10 percent of the total weight loss in the flame front (fig. 6). No change in diameter was observed for particles of this size.

For slash and other fuels containing a similar mixture of particle sizes, our findings indicate that only the fine fuel components, essentially particles less than 3 cm. (about 1 inch in diameter) supply the energy that characterizes propagation of the spreading flame front. A generalization of this statement for all fuels likely would be incorrect. Different proportions of fine fuels probably correspond to different diameter limits for the component contributing most of the energy to the propagating flame.

The percent weight loss of particles is compared in figure 7 with the effective heating number of the mathematical model defined in equation 1.[6] The effective heating number is a function of particle size; it expresses the percent of a particle that is heated to ignition ahead of the fire. In figure 7, the percent weight loss curve is drawn through points that represent particle size and the average percent weight loss in the propagating flame front for the sample particles.

The relation between the two curves, each representing a different variable, was expected and supports the concept expressed by the effective heating number. The two curves are close together at the very small particle sizes because the small particles are heated throughout at ignition and their entire organic mass rapidly converted to heat energy. As particle size increases, up to some point, the amount of a particle required for heating to ignition (ε) becomes less than the amount converted to heat in the flame (η). The effective heating number only involves that part of the particle that receives heat during the time when the particle surface rises to ignition temperature. Weight loss in the flame front, which takes place primarily after ignition, is characterized by rapid heat transfer and combustion, and thus involves a larger proportion of the particle. The percent weight loss (on an ash-free basis) should always exceed the effective heating number for the same particle sizes.

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[5]The percentages are averages based on all plots.

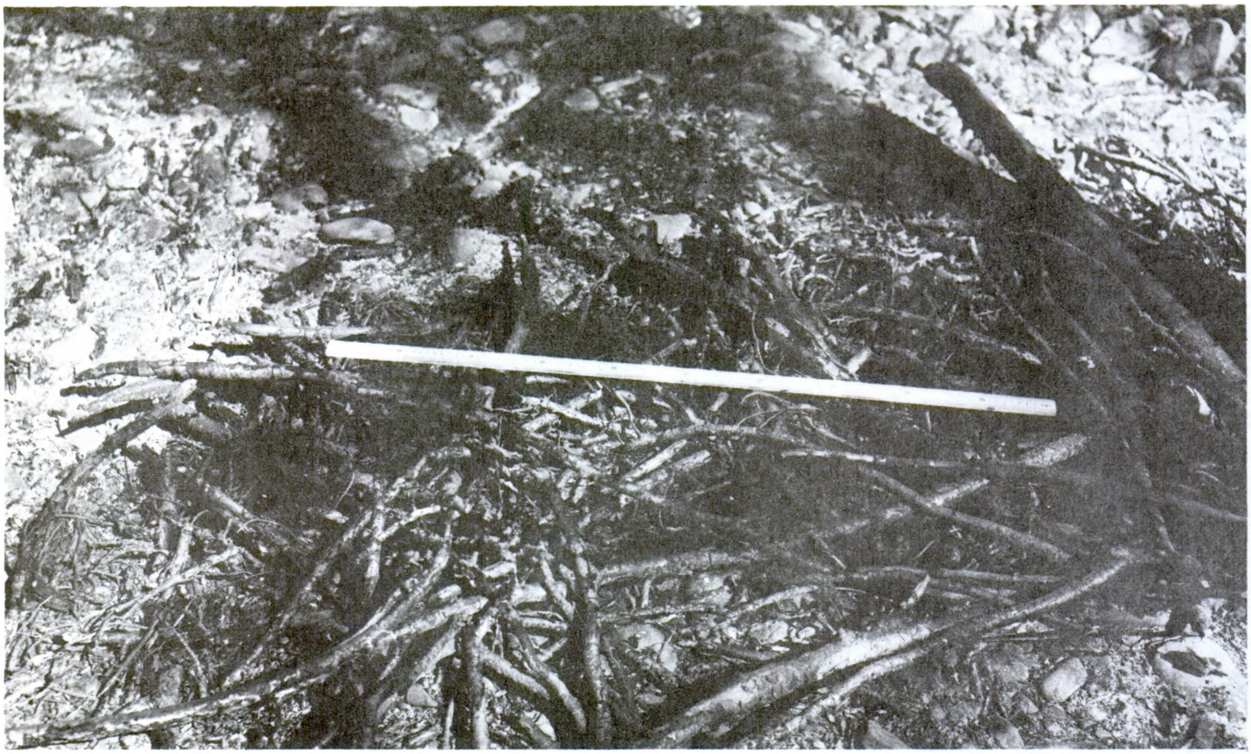

Figure 6.--After the flame front passed here, the fire was extinguished with a fog nozzle. Most of the remaining branchwood was over 1 cm. in diameter. About 80 percent of the branchwood less than 1 cm. in diameter was transformed into heat energy.

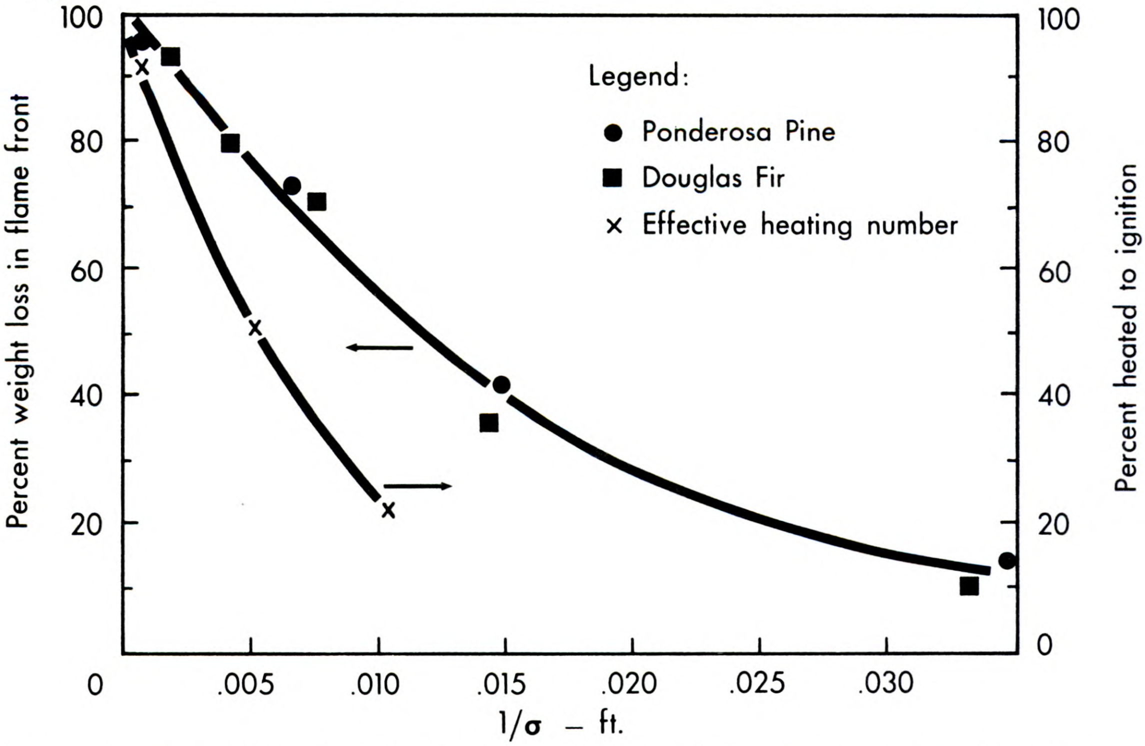

Figure 7.--Percent weight loss in the flame front and percent heated to ignition as a function of the particle surface area-to-volume ratio.

Flame Length

The relationship between flame length and certain fuel properties was examined using a stepwise multiple regression analysis. The fuel properties that varied substantially from plot to plot served as the independent variables. The following equation resulted using data from all plots:

$$Y = 4.28(X_1) + 0.00151(X_2) - 2.92$$

where:

Y = flame length, ft.

X_1 = total loading, lb./ft.^{2}

X_2 = average particle surface area-to-volume ratio weighted by fuel surface area in each size class, ft.$^{-1}$

$R^2 = 0.60$

Standard error of estimate (0.05 confidence level) = 1.52

The packing ratio was nonsignificant as an independent variable. Flame length was expected to correlate with packing ratio because (1) flame length relates closely to rate of energy release (Rothermel and Anderson 1966; Thomas 1963), and (2) packing ratio is quite sensitive to rate of energy release for the smaller size fuels in the spread model. If data covering a greater range of packing ratios had been acquired, it probably would have been significant in the regression analysis. However, loading of fine fuel (certainly particles less than 2 to 3 cm. in diameter) appears to be by far the most important physical property relating to flame length.

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[6] W. H. Frandsen. The effective heating of fuel particles ahead of a spreading fire. USDA Forest Serv., Intermountain Forest and Range Exp. Station, Ogden, Utah. (Manuscript in preparation.)

CONCLUSIONS

The mathematical model's predictions correlated reasonably close to observed rates of spread, although the model tended to overestimate. The study showed that M_x, discontinuities, and possibly the method of weighting by surface area in the mathematical model need additional study. The M_x appears to be a function of particle size, loading, and packing ratio. Its functional relationships in living fuels probably involve other properties as well. Weighting the input parameters by surface area in each size class seems appropriate for heterogeneous fuels. However, the contribution of the very fine fuels to spread rate may be overemphasized.

Although imprecise field methods prevented extensive analysis of I_R and related flame length, refinement of Rothermel's model should improve their prediction. Continued development of mathematical models for fire spread and intensity should be pursued because they will provide a sounder basis for quantitative fuel appraisal.

LITERATURE CITED

Anderson, H. E.
1968. Fire spread and flame shape. Fire Technol. 4: 51-58.

Brown, J. K.
1970. Ratios of surface-area-to-volume for common fine fuels. Forest Sci. 16: 101-105.

Brown, J. K.
1971. A planar intersect method for sampling fuel volume and surface area. Forest Sci. 17(1): 96-102, illus.

Hornby, L. G.
1935. Fuel type mapping in Region One. J. Forest. 33: 67-72.

Rothermel, Richard C.
1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Serv. Res. Pap. INT-115, illus.

Rothermel, R. C., and H. E. Anderson
1966. Fire spread characteristics determined in the laboratory. USDA Forest Serv. Res. Pap. INT-30, 34 p., illus.

Thomas, P. H.
1963. The size of flames from natural fires. Ninth Int. Symp. on Combust. p. 844-859. New York: Academic Press.

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