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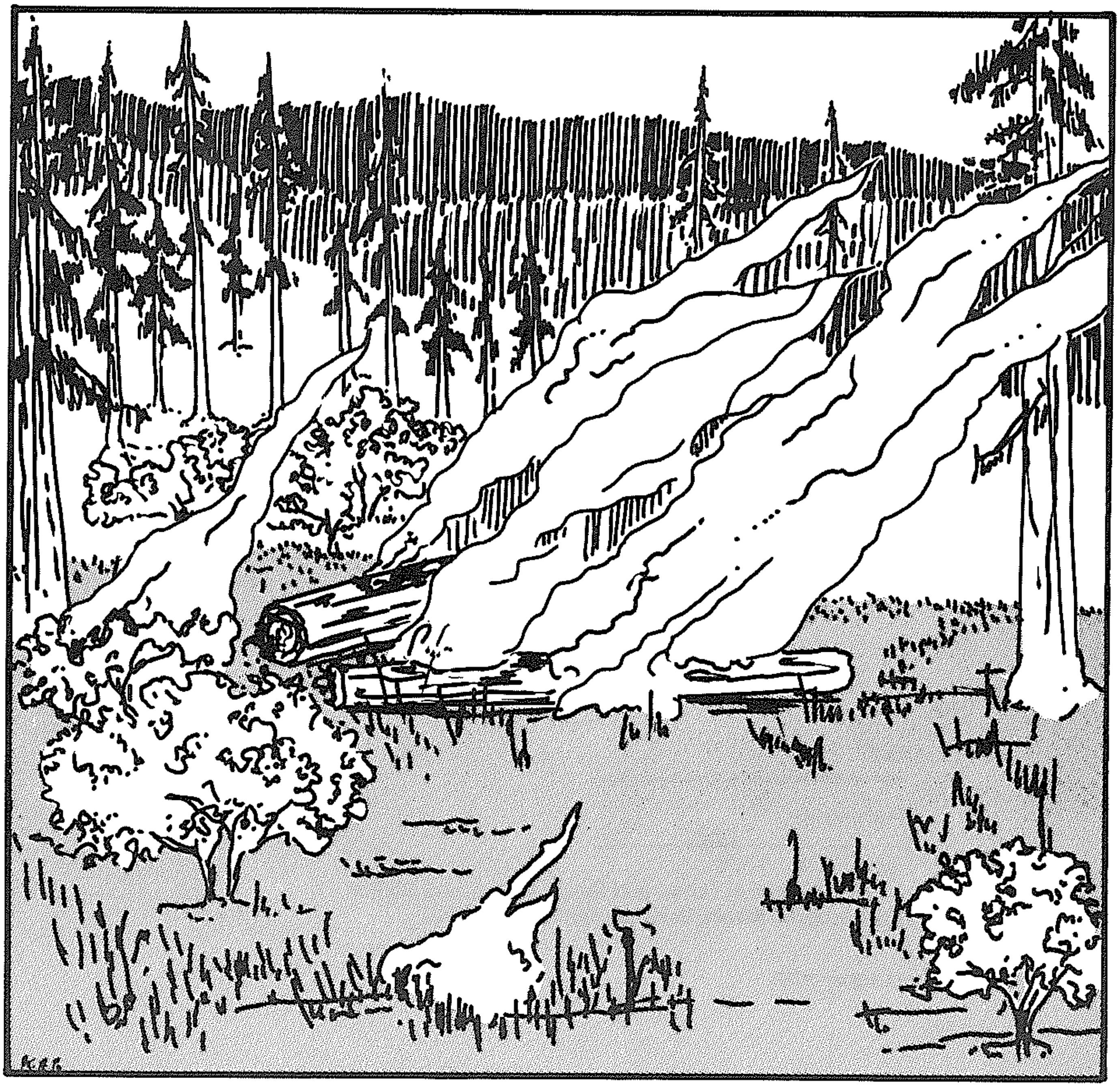
Sensitivity of Fire Behavior Simulations to Fuel Model Variations

Lucy A. Salazar



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CONTENTS

IN BRIEF...

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Retrieval Terms: fire behavior, fuel models, probabilistic fire modeling, wildfire

Stylized fuel models, or numerical descriptions of fuel arrays, are used as inputs to fire behavior simulation models. These fuel models are often chosen on the basis of generalized fuel descriptions, which are related to field observations. Site-specific observations of fuels or fire behavior in the field are not readily available or necessary for most fire management planning situations. Fuels are thought of in general terms and a single fuel model is often assigned to represent large areas of land. Variations in weather, which can substantially affect fire behavior, are not reflected in the available aids for selecting fuel models. The sensitivity of simulated fire behavior variables to the 13 fire behavior fuel models and two-fuel-model alternatives was analyzed. The two-fuel-model concept demonstrated the effect of combining fuel models on simulated fire behavior results.

Weather data from 20 fire weather stations within the Northern Rockies and Intermountain Zone were processed by a computer program that produced joint distributions of live and dead fuel moistures and windspeeds. These joint weather-related distributions, along with definitions of fuel model, slope, aspect, time of year, and time of day were used as inputs to a fire behavior simulation model. Model output was joint distributions of rate-of-spread and fireline intensity. The fire behavior distributions for the set of 13 fuel models and their two-fuel-model alternatives were displayed on the fire behavior characteristics chart, which allows comparisons of ranges and frequencies of occurrence.

The results showed the sensitivity of the simulated fire behavior to the 13 fuel models at 100 percent area coverage, and the wide range of outcomes that this set of fuel models represents. The two-fuel-model simulations also showed a broad range of results, indicating that this alternative use of fuel models could add substantially to a fire manager's planning capabilities. Interpretations of the fire behavior characteristics chart indicated how often certain fuel conditions could present suppression problems, and that variations of the area coverages in the two-fuel-model alternatives could dramatically affect initial attack effectiveness. Other factors, including arrival times, production rates, and multiple fire events would also have to be evaluated in an actual situation.

The set of 13 fire behavior fuel models may not be adequate for simulations in some site-specific, high resolution wildland situations. Alternative methods, such as creating custom fuel models, may be more appropriate.

INTRODUCTION

Fire managers must be aware of the effect that selection of a fuel model will have on predictions of fire behavior and suppression effectiveness. A set of 13 stylized fuel models used extensively in fire behavior modeling was developed on the assumption that fuel array parameters are inherent to a model (Albini 1976). That is, once characteristics such as fuel loading, moisture of extinction, and surface-area-to-volume ratios are defined, they need not be remeasured. A commonly used wildfire spread model, which uses fuel models as inputs, assumes that fire progresses in a quasi-steady state through continuous fuel beds that are contiguous to the ground (Rothermel 1972). For fire management planning purposes, fuels are thought of in general terms, and a single fuel model is often assigned to represent large areas of land.

A fuel model must be assigned not only on the basis of the generalized physical description of the fuel bed, but also on the fire behavior characteristics it is known to produce (Rothermel 1983). Site-specific observations of fuels or fire behavior in the field are not readily available or necessary for most fire management planning situations. Therefore, visual and descriptional aids to the selection of the appropriate fuel models based on field observations have been developed (Anderson 1982, Main and Haines 1983). Adjustment procedures have also been developed to match a fuel model to observed fire behavior once a fuel model has been selected (Rothermel and Rinehart 1983). A guide to fuel model selection included a description of the expected fire behavior and a single rate-of-spread and flame length value for each of the 13 fire behavior fuel models, calculated with one windspeed and fuel moisture value input (Anderson 1982). However, variations in weather and topographic conditions will produce different fire behavior results from these calculated values.

An alternative procedure available to fire managers is applying the two-fuel-model concept (Rothermel 1983). Two fuel models are used in the fire spread model to represent fuel arrays that are not uniform enough to be described with a single fuel model. In this procedure, rates-of-spread are weighted by the proportional area coverage assigned to each of the two selected fuel models.

This paper documents the sensitivity of distributions of selected fire behavior variables (rate-of-spread, fireline intensity, and heat per unit area) to the 13 fuel models and to changes in the percent area coverage assigned to the two-fuel-model combinations. These results are discussed in a fire management planning context, but implications for real-time fire modeling are also apparent.

METHODS

Data from National Fire Weather Data Library weather stations were processed, by a computer program that produced joint distributions of fuel moistures and windspeeds. These weather-related inputs, in addition to fuel model, slope, aspect, time-of-day, and time-of-year, were used to produce joint probabilities of rate-of-spread and fireline intensity (Salazar and Bradshaw in preparation).

The 20 weather stations that provided the information were all located above 4500 ft (1372 m) in the Northern Rockies and Intermountain Zone, which encompasses eastern Oregon and Washington, Idaho, western Montana, and southwestern Wyoming (Schroeder and others 1964). All recorded weather data from July to September 1954 to 1981 were processed, representing a total of 30,899 days of weather (Salazar and Bradshaw 1984). This elevation band and time-of-year class were chosen because the majority of fires in the northern Rocky Mountains occur in those situations.

Only fires starting during the day were simulated. To allow for diurnal adjustments of temperature and relative humidity, which affect fuel moistures, daytime was split into four time periods: 0500 to 0759, 0800 to 1159, 1200 to 1559, and 1600 to 1959 local standard time. The midpoints of each of these periods were used in the computation of diurnal temperatures and relative humidities (Salazar and Bradshaw 1984). The National Fire Danger Rating System curing routines were used to represent seasonal changes in fuel moisture (Bradshaw and others 1984). The standard recorded 20-ft (6-m) windspeed was used for all time-of-day classes and was reduced to midflame windspeed (Baughman and Albini 1980).

Fire behavior was calculated for each time-of-day class, and the resulting set of four joint frequency distributions aggregated into one by the use of weighting factors. Weights for each time-of-day class were derived from the frequency that detection times

Table 1—*Inherent characteristics of 13 fire behavior fuel models*

Fuel model description	Fuel loading[1] 1 hr	10 hr	100 hr	Live	Fuel bed depth[2]	Moisture of extinction dead fuels	Wind reduction factor
	tons/acre				*ft*	*percent*	
1 Short grass (1 ft)	0.74	0.00	0.00	0.00	1.0	12	36
2 Timber (grass and understory)	2.00	1.00	.50	.50	1.0	15	25
3 Tall grass (2.5 ft)	3.01	.00	.00	.00	2.5	25	44
4 Chaparral (6 ft)	5.01	4.01	2.00	5.01	6.0	20	55
5 Shrubs (2 ft)	1.00	.50	.00	2.00	2.0	20	42
6 Dormant shrubs, hardwood slash	1.50	2.50	2.00	.00	2.5	25	44
7 Southern rough	1.13	1.87	1.50	.37	2.5	40	25
8 Closed timber litter	1.50	1.00	2.50	.00	.2	30	17
9 Long needle pine, hardwood litter	2.92	.41	.15	.00	.2	25	17
10 Timber (litter and understory)	3.01	2.00	5.01	2.00	1.0	25	12
11 Light logging slash	1.50	4.51	5.51	.00	1.0	15	36
12 Medium logging slash	4.01	14.03	16.53	.00	2.3	20	43
13 Heavy logging slash	7.01	23.04	28.05	.00	3.0	25	46

Source: Anderson (1982), Baughman and Albini (1980)

[1] tons/acre × .2241 = kg/m²

[2] ft × .3048 = m

on Forest Service fire reports (Form FSH 5100.29) appeared in each class (Salazar and Bradshaw in preparation). This weighting procedure emphasized the weather conditions at the times fires were detected. Fires were assumed to be in a steady state at the time of detection.

The large number of joint occurrences of rate-of-spread and fireline intensity precluded the storage and use of each unique combination that was generated. The outputs for these two fire behavior parameters were instead split into four classes, with the class boundaries subjectively chosen to represent low, medium, high, and extreme severity:

Class	Fire severity	Rate-of-spread	Fireline intensity
		ft/min (m/min)	*BTU/ft/s (kW/m)*
1	Low	0 – 2.5 (0.762)	0 – 100 (346)
2	Medium	2.51 – 12.5 (3.810)	100.1 – 500 (1730)
3	High	12.51 – 25.0 (7.620)	500.1 – 1000 (3459)
4	Extreme	25.01 +	1000.1 +

Frequencies and expected values were generated for each unique combination of these fire classes and were graphically displayed. The fire behavior computer processor also produces two other fire behavior variables—length-to-width ratio and scorch height (Salazar and Bradshaw in preparation). The results for each of these variables were also separated into four classes. Even though these two extra variables were not used in this study, the unique combinations that they produced were kept intact. Therefore, a unique combination of rate-of-spread and fireline intensity sometimes had several expected values.

Each of the 13 fire behavior fuel models (*table 1*) was input to the fire behavior processor. Other necessary inputs and their designated standards for this study were 20 percent slope and south aspect. Again, these inputs where chosen because a large number of fires in the northern Rocky Mountains occur under these circumstances.

The two-fuel-model weighting procedure was applied by combining each of the 13 fuel models with another one of the set under two different area coverage percentages (*table 2*). The second fuel model was subjectively chosen to represent a feasible combination. The processor calculated fire behavior for both fuel models. The rate-of-spread values were weighted together by the proportion of area coverage assigned to each fuel model. In the examples, the area proportions were subjectively chosen at either 40 or 60 percent to get an indication of the effect that the dominating fuel model (i.e., the one with the greatest area coverage) had on the weighted results. The wind reduction factors (Baughman and Albini 1980), which affect rate-of-spread and fireline intensity calculations, were those of the fuel model with the higher proportion. The computed fireline intensities were not weighted together. The largest calculated fireline intensity of the two fuel models was stored as the output because it was assumed to be the most useful for planning situations.

The fire behavior characteristics chart incorporates the fire behavior variables of rate-of-spread, fireline intensity, and heat per unit area into one graph. It has been known to be useful in many fire management situations (Andrews and Rothermel 1982, Main and Haines 1983, Rothermel 1983). This chart was used to display the fire behavior distributions of the 13 fuel models and their two-fuel-model alternatives. Because only rate-of-spread and fireline intensity were calculated by the processor, the following formula was used to calculate heat per unit area from the expected values of rate-of-spread and fireline intensity:

$$\text{Heat per unit area (BTU/ft}^2\text{)} = \frac{\text{fireline intensity (BTU/ft/s)} \times 60 \text{ (s/min)}}{\text{rate-of-spread (ft/min)}}$$

Suppression capabilities can also be predicted directly from interpretations of the fireline intensity bands, which were also graphed on the chart (Andrews and Rothermel 1982):

Fireline intensity, BTU/ft/s (kW/m)	Interpretation
<100 (346)	Fire generally can be attacked at the head or flanks by persons using hand tools. Handline should hold the fire.
100–500 (1730)	Fires are too intense for direct attack at the head by persons using hand tools. Handline cannot be relied on to hold fire. Equipment such as plows, bulldozers, pumpers, and retardant aircraft can be effective.
500–1000 (3459)	Fires may present serious control problems—torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
>1000	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective.

RESULTS OF SENSITIVITY ANALYSIS

Equilibrium, steady-state burning conditions were assumed for this analysis (Rothermel 1972). Therefore, the results do not account for situations that include:

• Smoldering fires in tightly packed litter, duff, snags, or rotten wood

• Extreme fire behavior exhibited by crowning, spotting, or fire whirls

• More fuel nonuniformity than that assumed for the two-fuel-model procedure.

The potential for severe fire behavior, however, is indicated by the interpretations of fireline intensity above (Andrews and Rothermel 1982). For example, fires with fireline intensities greater than 1000 BTU/ft/s (3459 kW/m) will probably result in crowning and spotting conditions, making direct attack at the fire head virtually ineffective.

The differences in fire behavior potential of the 13 fuel models and their selected two-fuel-model alternatives are displayed by their frequency distributions on fire behavior characteristics charts (*figs. 1-13 in appendix*). The maximum expected values varied substantially between fuel models. Therefore, the scales may differ between fuel models, but the scales are the same among the three alternatives for each fuel model. A weighted average of the fire behavior variables was displayed for points that were too close to be legible. Some frequency distributions do not add up to 1.0 due to rounding.

Often the recorded weather was such that a simulated fire could not spread. These "nonfire" events and their frequency of occurrence are also displayed for comparison purposes in the position for zero rate-of-spread and zero heat per unit area. The variability in the occurrence frequency of these nonfire events is mainly due to differences in the fuel-model-specific moisture of extinction (i.e., the fuel moisture content above which the fire will not spread) of the dead fuels (*table 1*).

The fire behavior characteristics charts show (1) the sensitivity of the fire behavior outputs to the 13 fuel models, at 100 percent area coverage, and (2) the wide range of outcomes that this set of fuel models represents. Two of the fuel models dominated by short grass (*figs. 1 and 2*) exhibited some potential for high rates-of-spread, with predominantly low to moderate intensity levels. A fire in the tall grass fuel model (*fig. 3*) would almost always be difficult to suppress if it occurred under the weather conditions modeled here. A fire in the chaparral fuel model (*fig. 4*) would present suppression difficulties to hand crews approximately 93 percent of the time, but nonfire days occurred 3 percent of the time. The other three shrub fuel models (*figs. 5–7*) exhibited much less severe fire behavior potential. Fires in the timber-dominated fuel models (*figs. 8–10*) would rarely present suppression problems except in situations where they exceeded the surface fire conditions assumed in this study. The slash fuel models (*figs. 11–13*) varied dramatically in their fire behavior potential, due to inherent differences in loading, moistures of extinction, wind reduction factors, and fuel depths. Fuel models of different general categories often showed similar fire behavior results. For example, simulation results for fuel models 2 and 7 (*figs. 2 and 7*) overlapped in the 400 to 500 BTU/ft^2 (4540–5674 kJ/m^2) heat per unit area and the 0 to 10 ft/min (3.048 m/min) rate-of-spread bands. This overlap could prompt a fire manager to select a fuel

Table 2—*Two-fuel-model alternatives for each of the 13 fire behavior fuel models*

Fuel model	Fuel models (percent area coverage)	
	Alternative 1	Alternative 2
1	1(40)/9(60)	1(60)/9(40)
2	2(40)/9(60)	2(60)/9(40)
3	3(40)/2(60)	3(60)/2(40)
4	4(40)/7(60)	4(60)/7(40)
5	5(40)/8(60)	5(60)/8(40)
6	6(40)/9(60)	6(60)/9(40)
7	7(40)/8(60)	7(60)/8(40)
8	8(40)/10(60)	8(60)/10(40)
9	9(40)/8(60)	9(60)/8(40)
10	10(40)/8(60)	10(60)/8(40)
11	11(40)/8(60)	11(60)/8(40)
12	12(40)/11(60)	12(60)/11(40)
13	13(40)/11(60)	13(60)/11(40)

model typically used for southern rough to describe an open pine modeling situation.

In some cases the second fuel model substantially affected the resulting fire behavior distributions and in other cases a second fuel model had little effect on the resulting fire behavior. For example, the rate-of-spread values representing the combination of 40 percent fuel model 1 and 60 percent fuel model 9 are lower than those for 100 percent fuel model 1 (*fig. 1*). But at the same time, heat per unit area increased substantially. Conversely, the two alternative combinations for fuel models 8, 9, and 10 (*figs. 8–10*) had little rate-of-spread variation, but the heat per unit area was more markedly affected.

DISCUSSION AND CONCLUSIONS

The use of fire behavior class boundaries and expected values within these classes aggregated the resulting data, making it much more manageable for planning purposes. At the same time, by generalizing the data into discrete points, some of the actual data, which might be necessary for high resolution applications, were eliminated. The consequences of this elimination would have to be evaluated case by case.

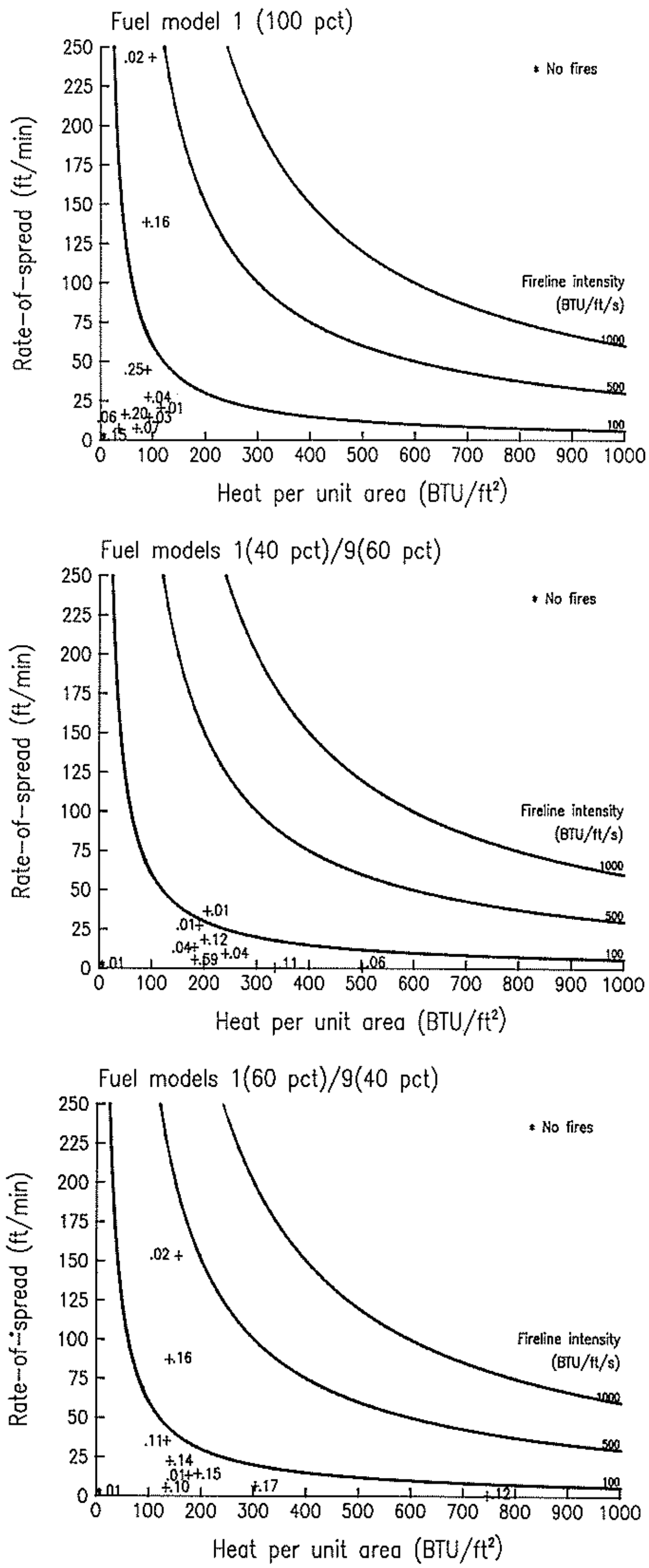
The fire behavior characteristics chart provided a useful and easily interpretable medium for displaying the fire behavior potential for the 13 fuel models used in this study. The results showed that fire behavior simulations that use the fire behavior fuel models usually produced a wide range of possible outcomes. An awareness of this range would be especially useful in real-time wildfire and prescribed fire situations. Also, in actual fire situations some fuel models evidently could be used interchangeably under specific weather and fuel conditions.

The use of the two-fuel-model concept keeps the integrity of the fire behavior simulations and simultaneously accounts for some of the spatial heterogeneity of forest fuel beds. The two-fuel-model concept offers virtually innumerable combinations for fire behavior simulations. Both the fuel model selection and the percent area coverage are potential options available to the fire manager in evaluating the effect of changes in fuel profiles on fire behavior. For example, windthrow within a closed timber stand could be represented by a combination of fuel models 10 and 13. The encroachment of pines on open grasslands could be displayed by a combination of fuel models 1 and 2. For site-specific, high resolution modeling the set of 13 fuel models may not be adequate under some situations. Alternative methods, such as those used in creating custom fuel models for the BEHAVE computer fire modeling system (Burgan and Rothermel 1984), might be more appropriate.

Interpretations of the fire behavior characteristics chart indicate how often certain fuel conditions could present suppression problems. Other factors that affect suppression effectiveness would also have to be considered, including arrival times, production rates, and multiple fire events. From these simulated results and the generalized interpretations of the fire behavior characteristics chart, variations in fuel model area coverages apparently could dramatically affect initial attack effectiveness. Further research is necessary to determine if this effect is as substantial in actual wildfire situations.

APPENDIX

Fire behavior characteristics charts for 13 fuel models each with two two-fuel-model alternatives (*figs. 1-13*) show differences in their fire behavior potential by frequency distributions. The fuel model percentages correspond to those in *table 2.* (ft/min × .3048 = m/min, BTU/ft/s × 3.4592 = kW/m, BTU/ft² × 11.349 = kJ/m²)



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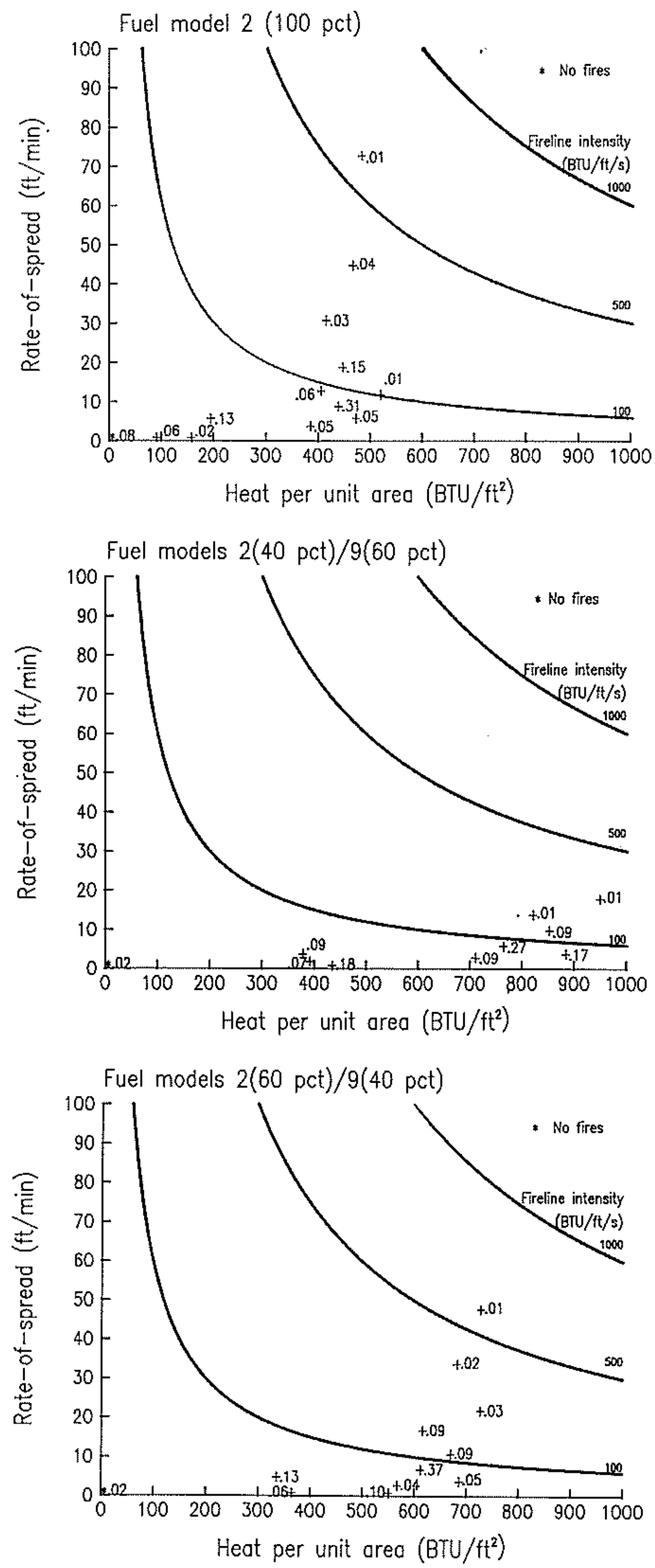

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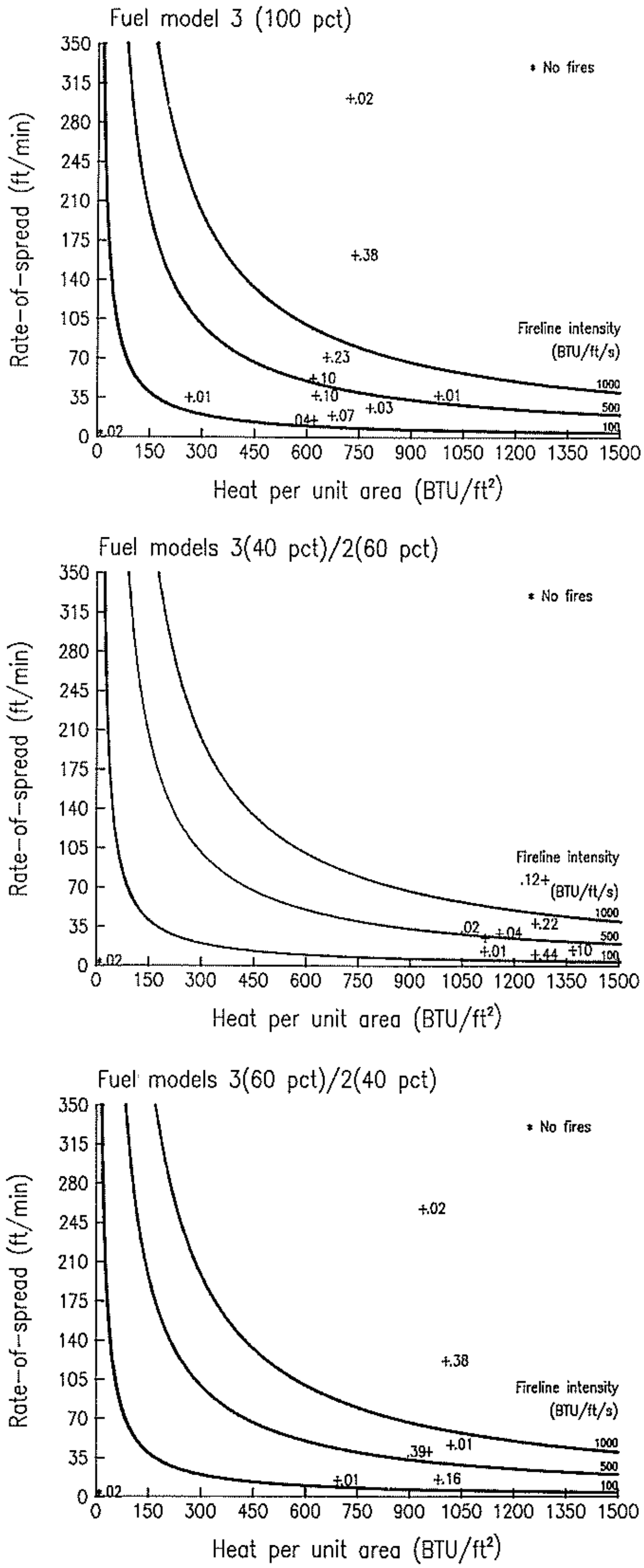

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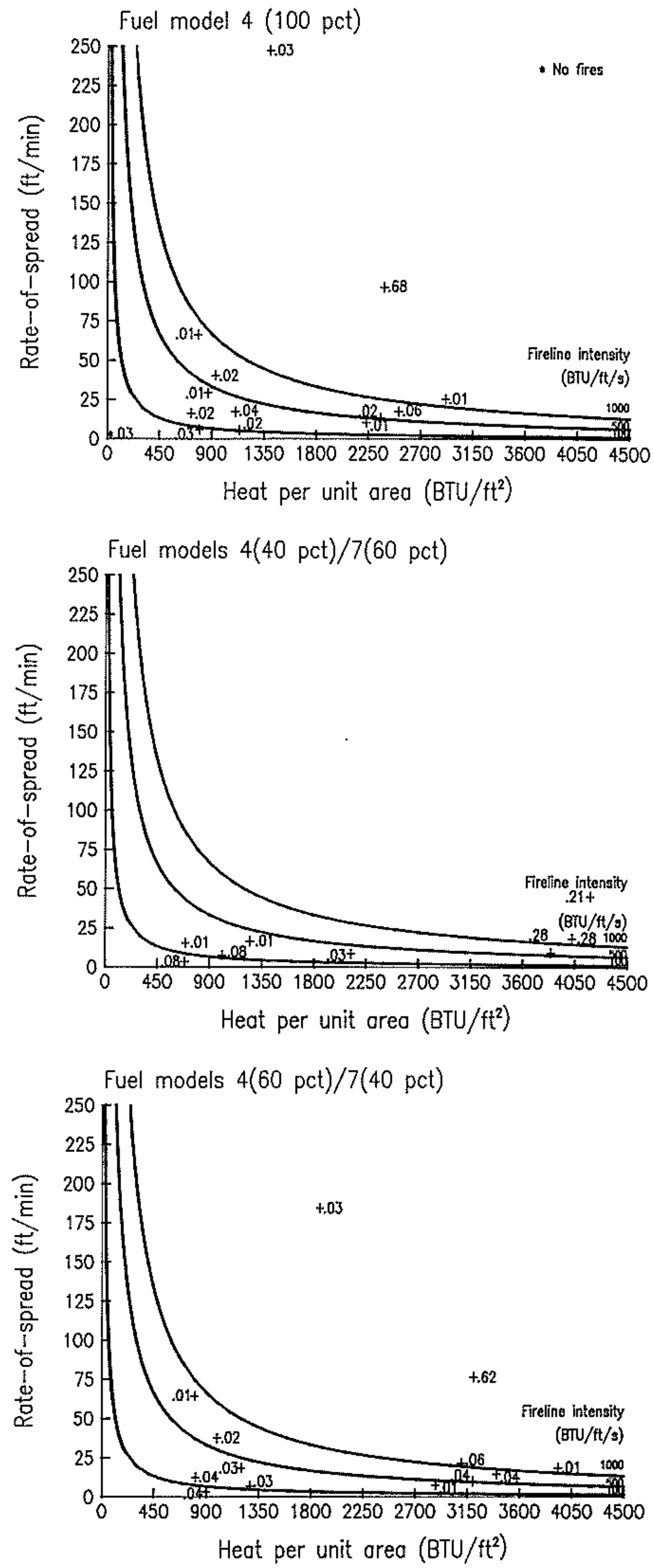

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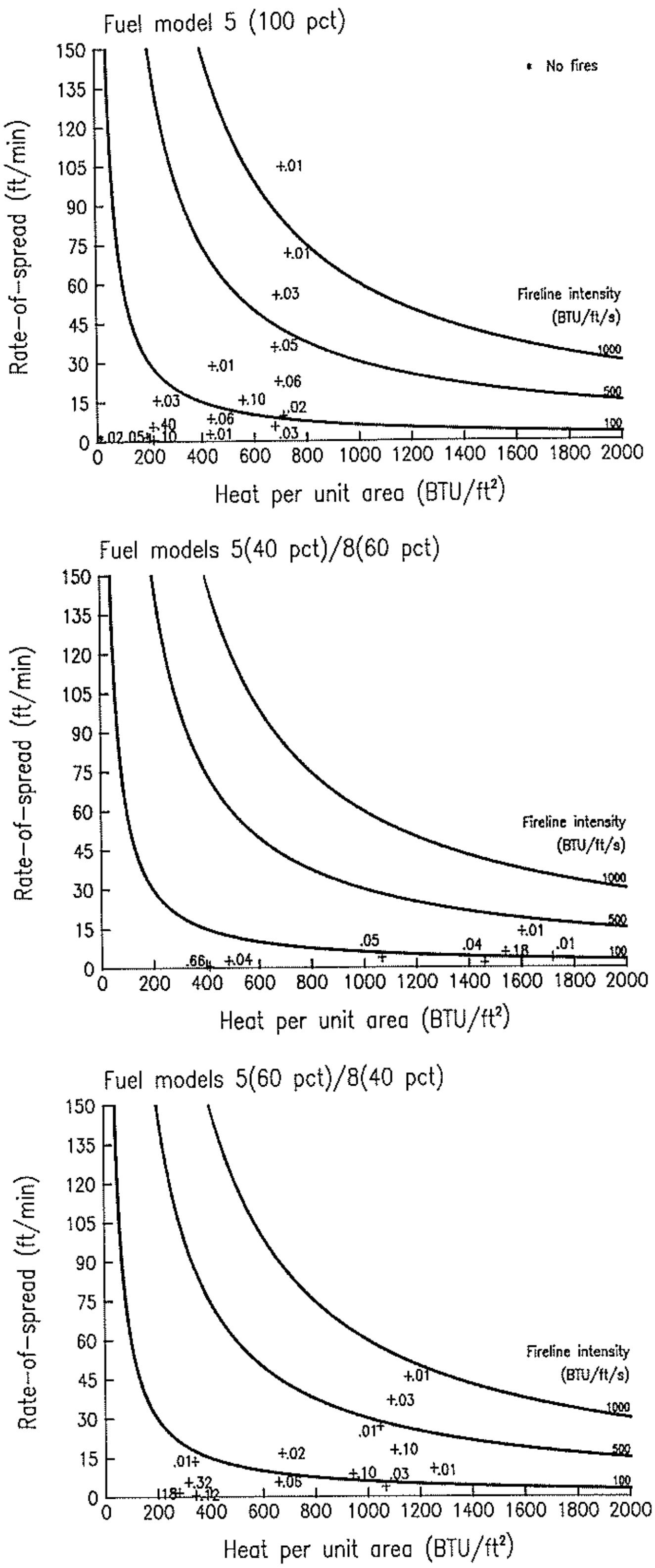

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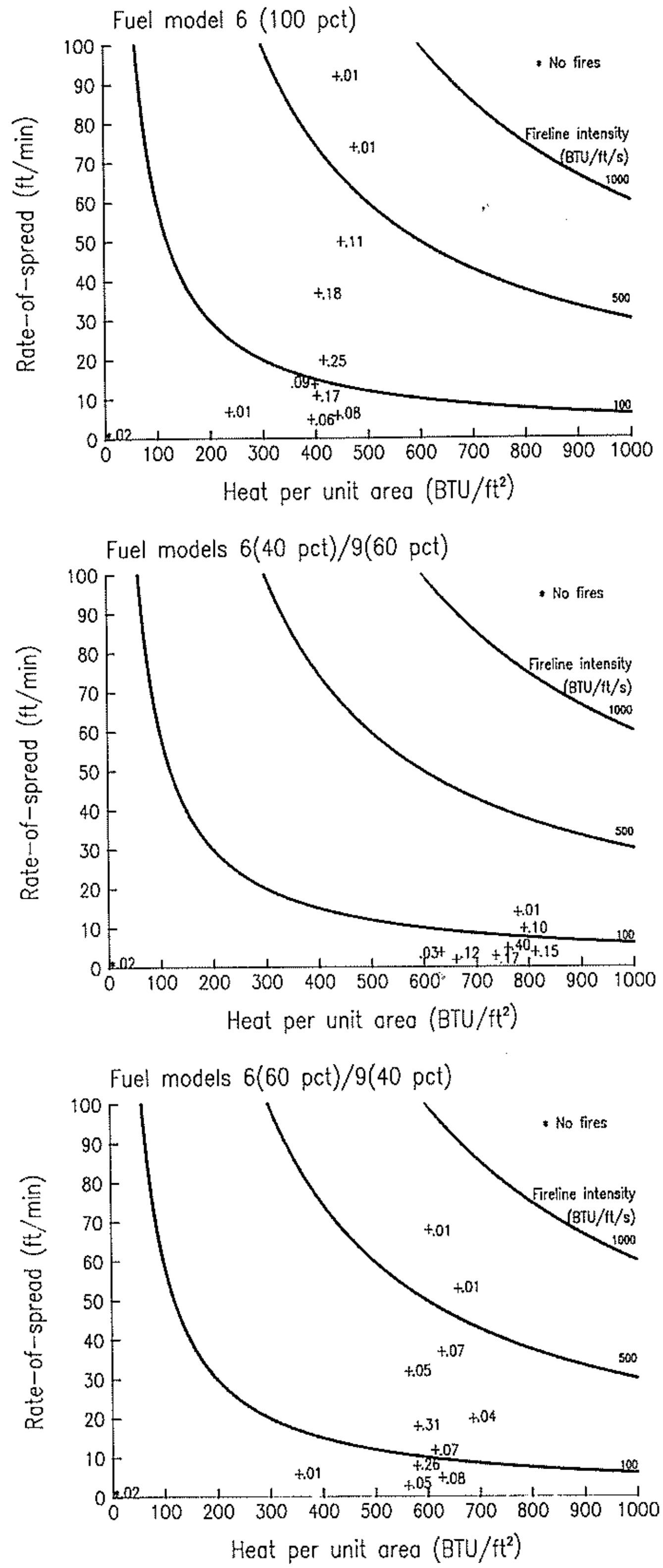

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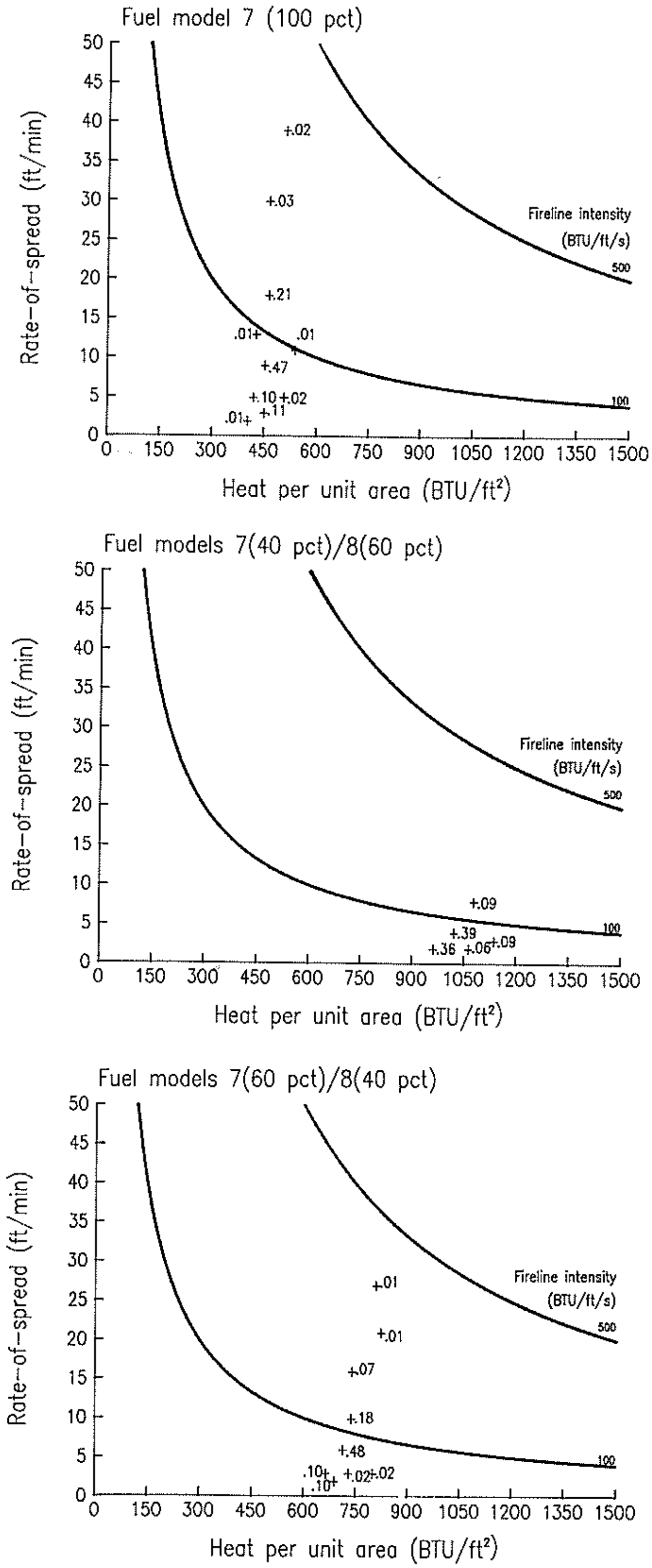

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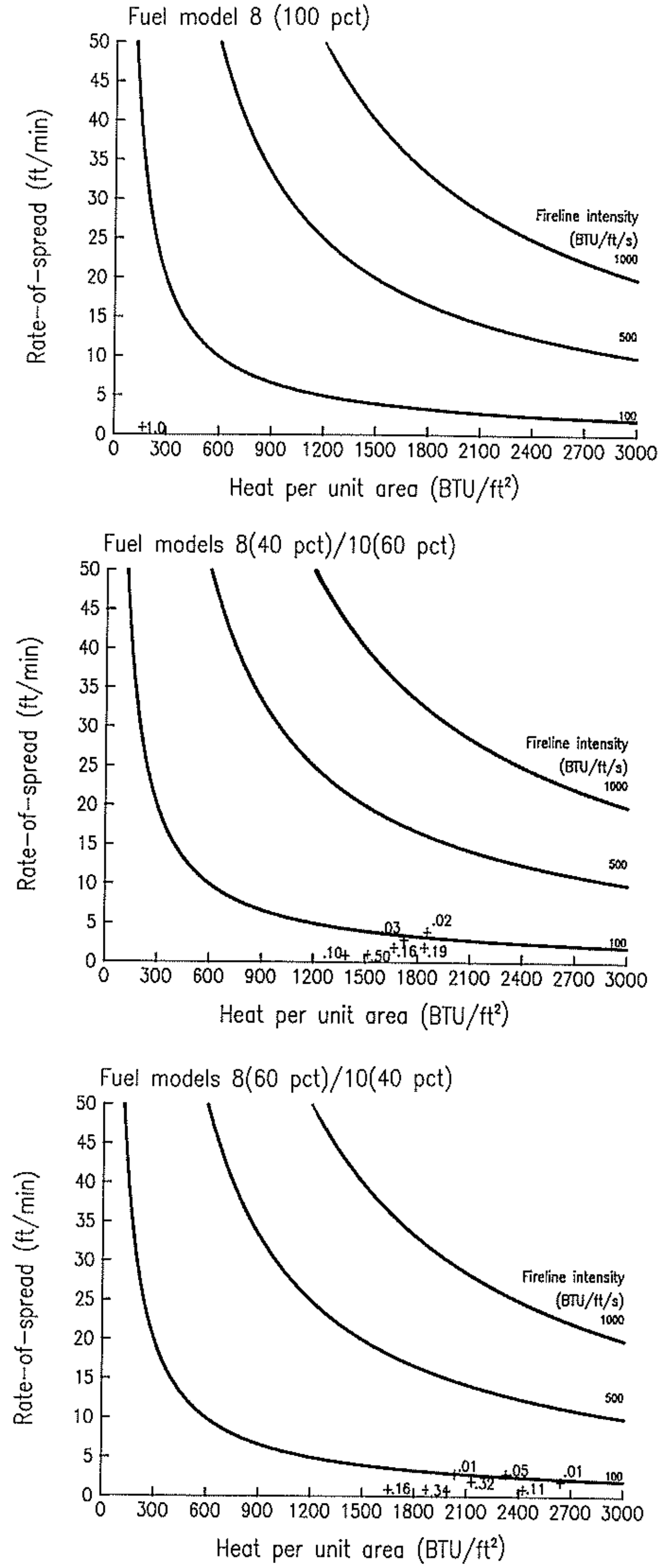

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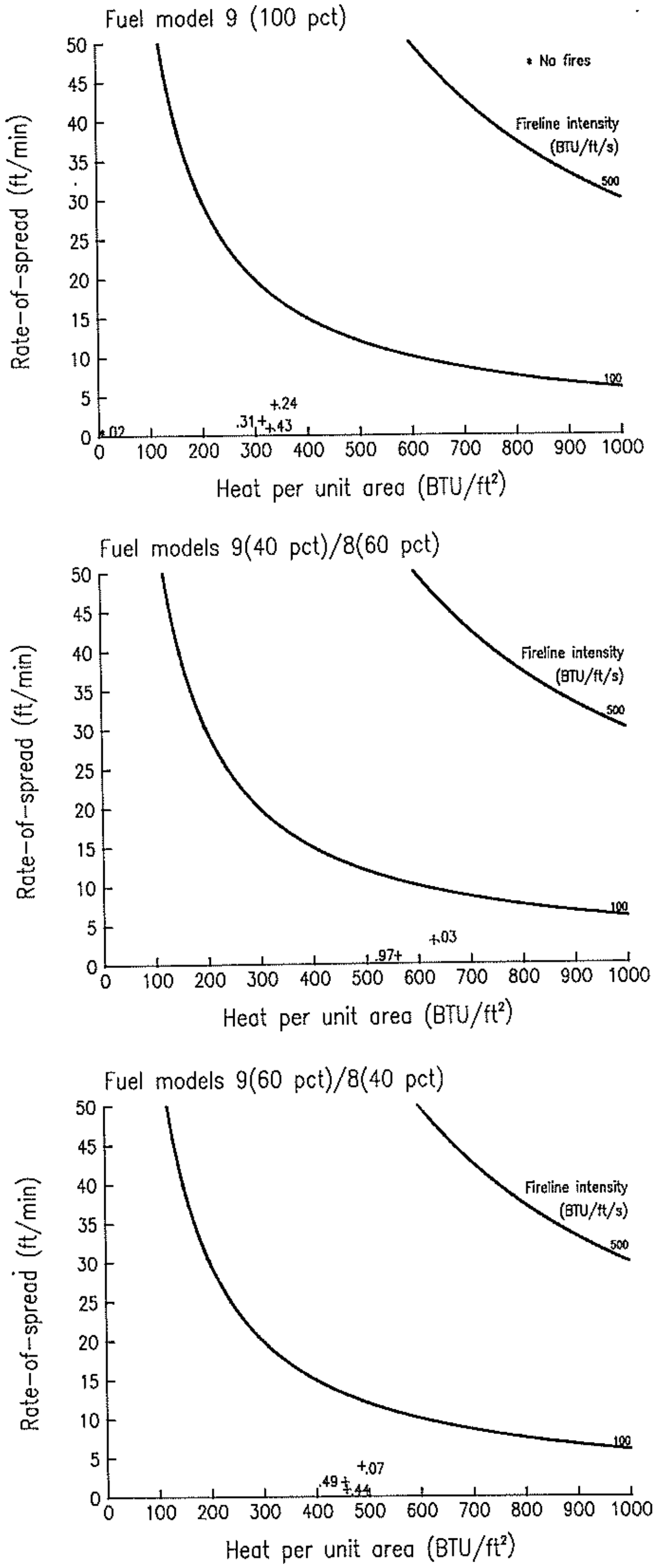

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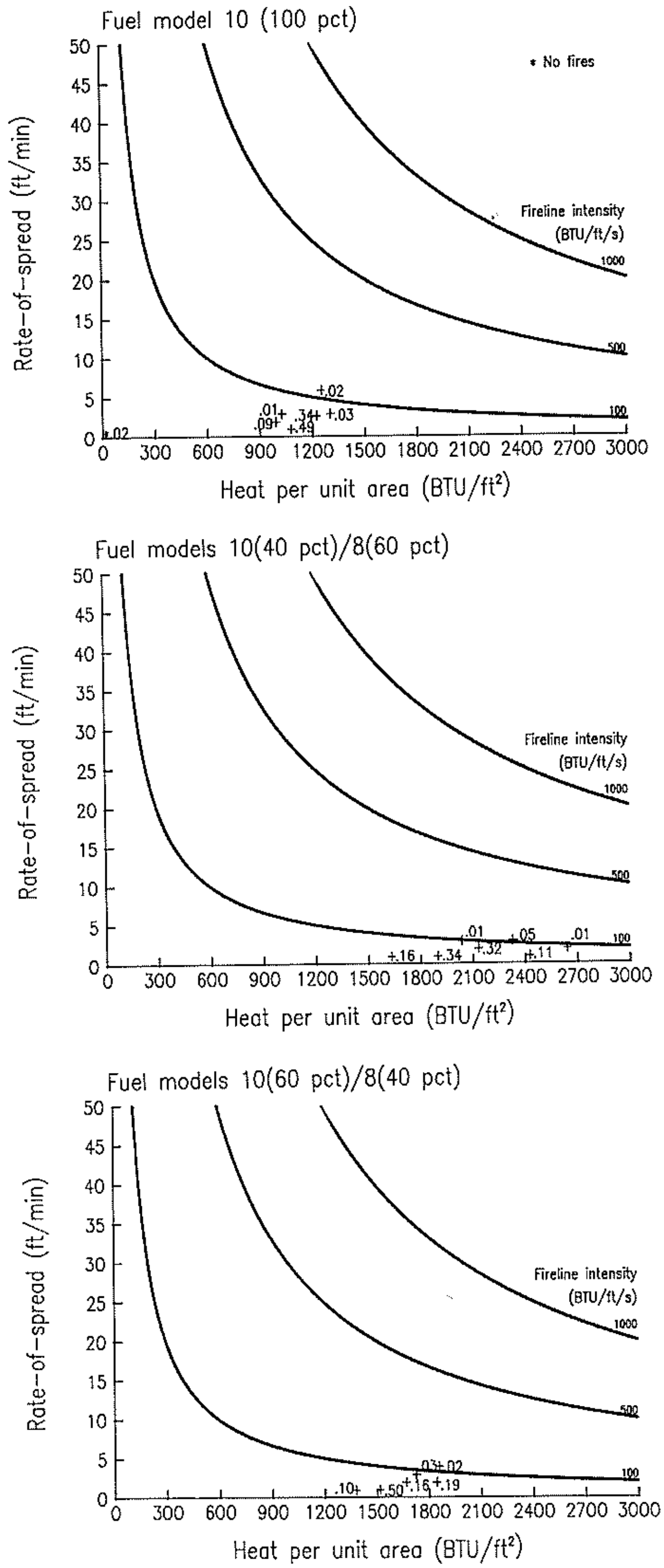

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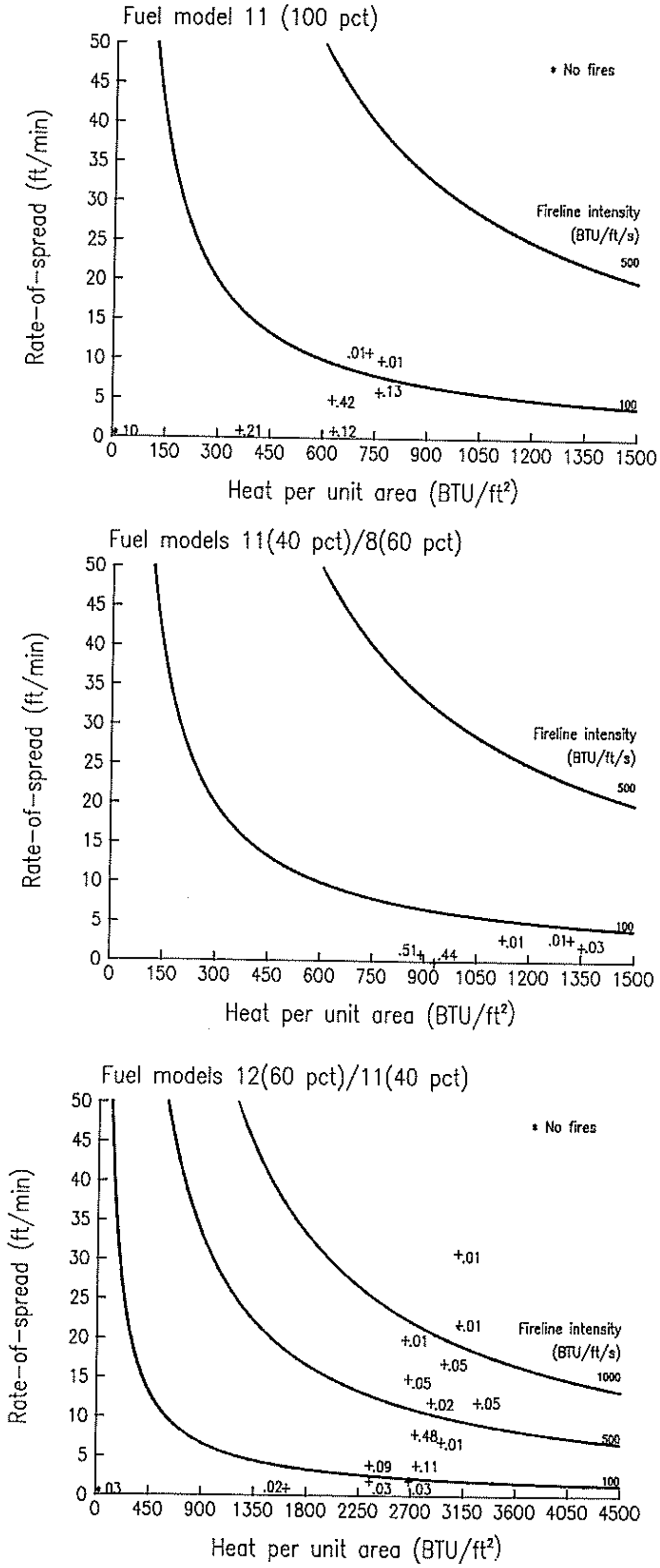

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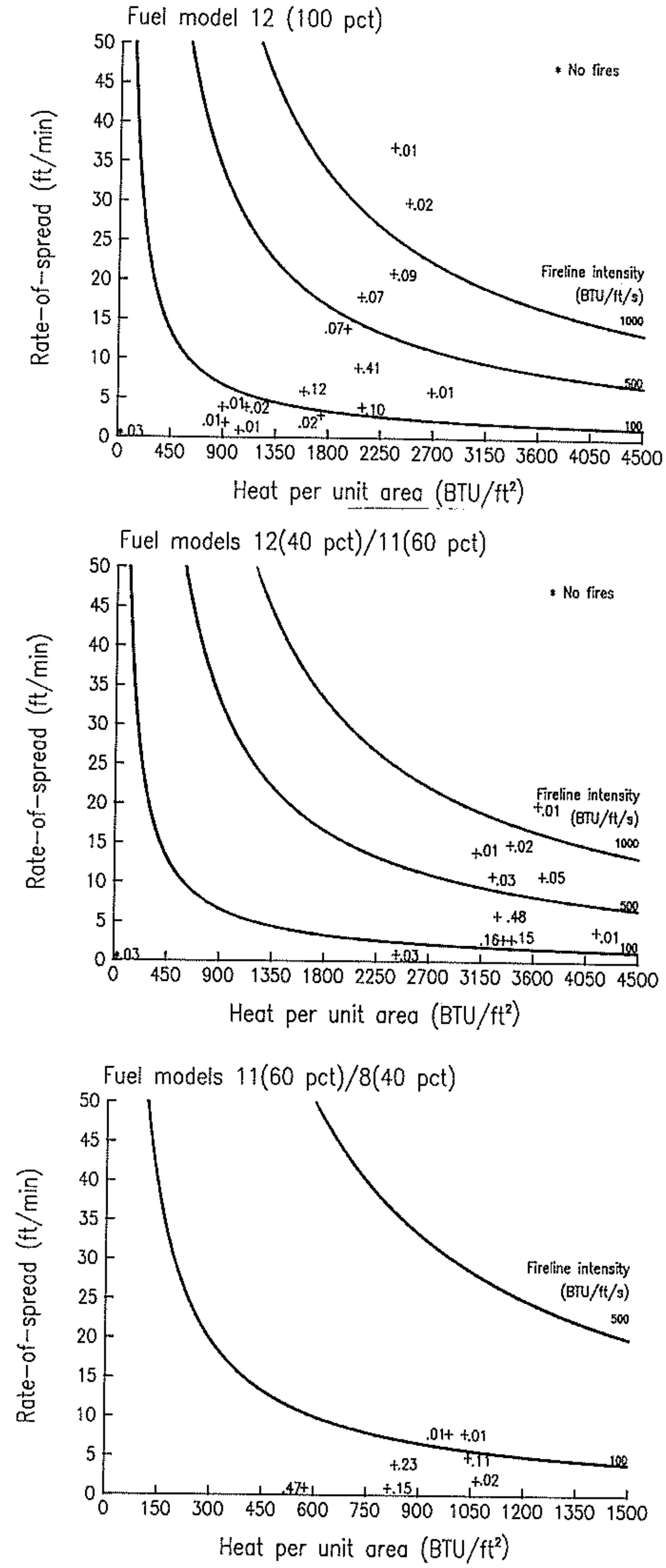

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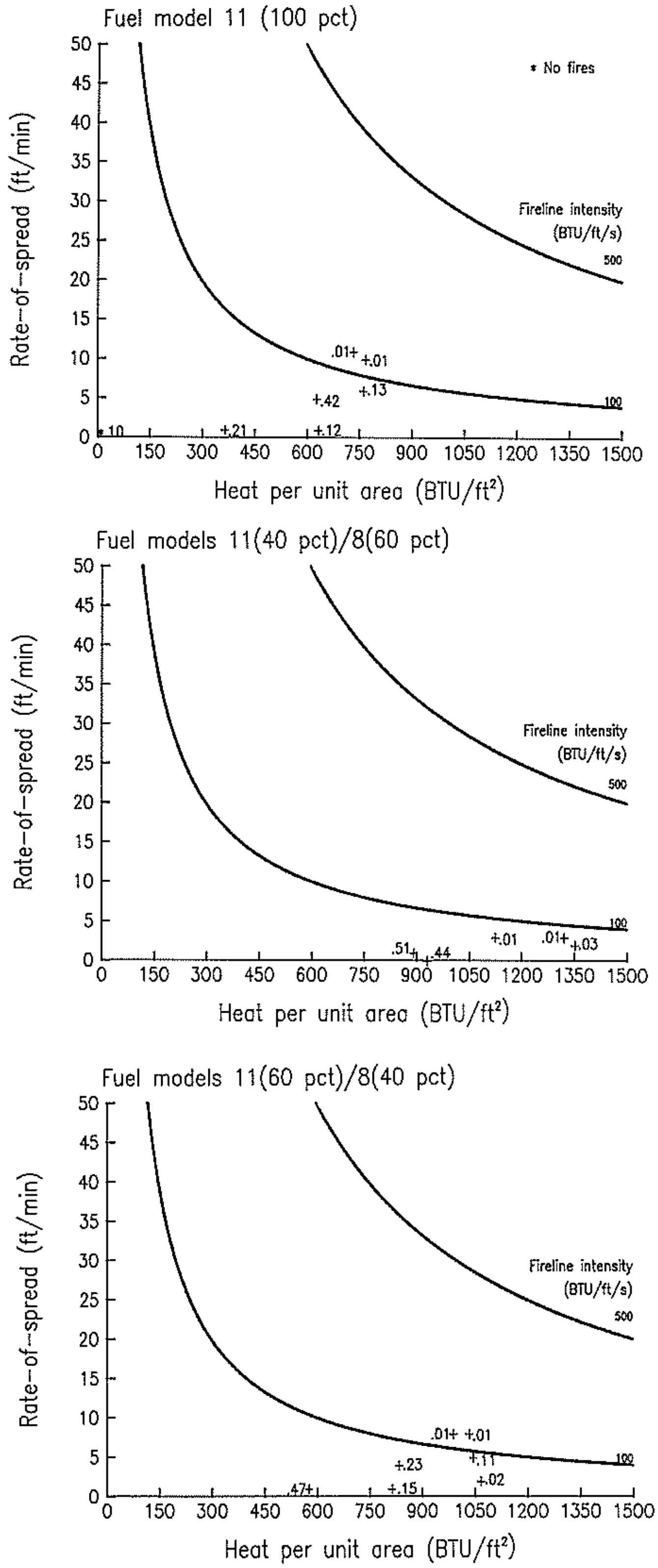

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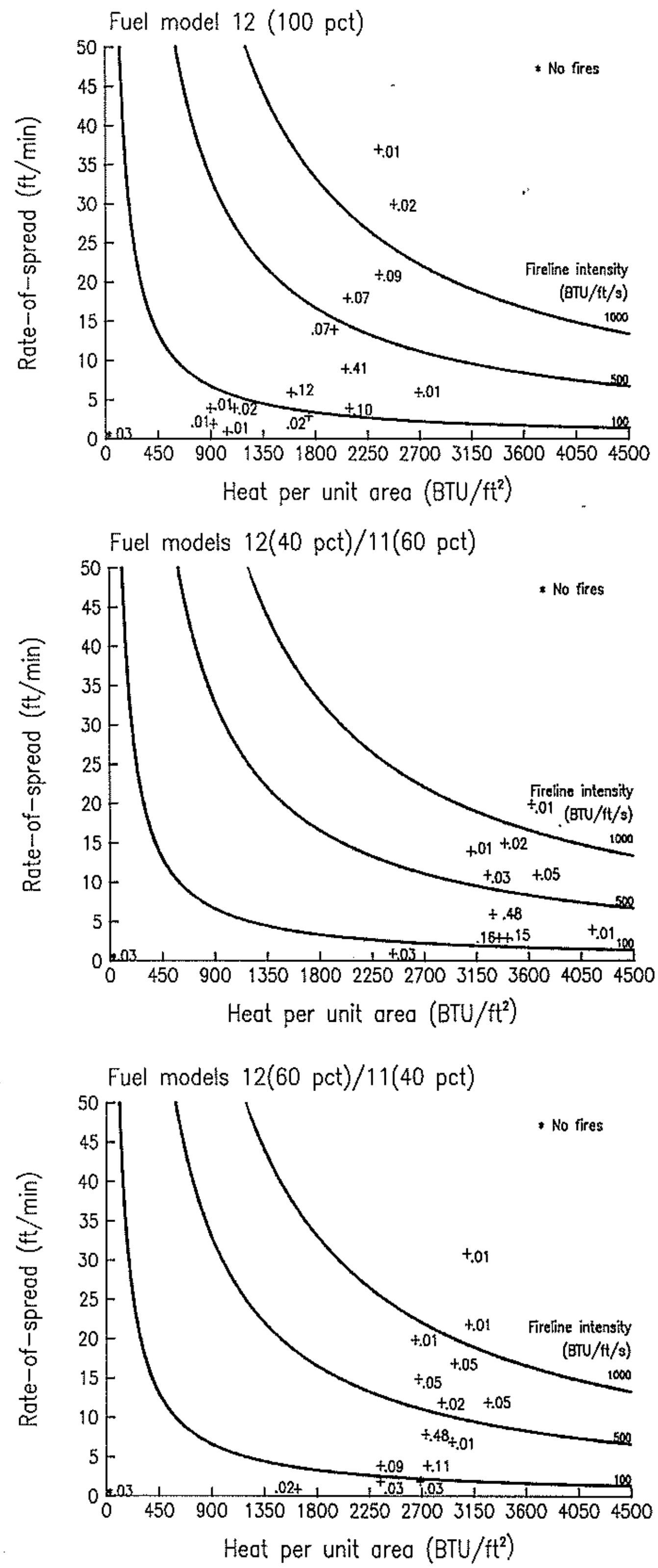

Figure 12

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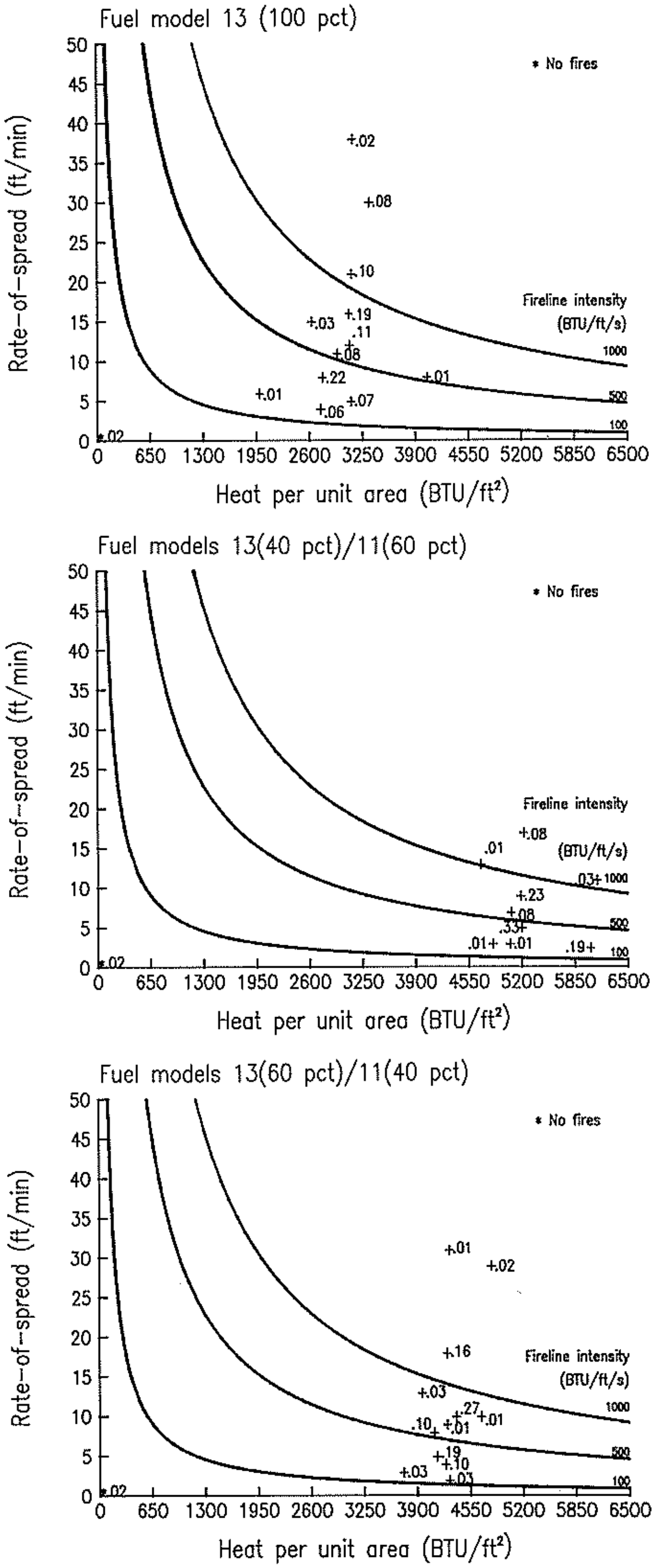

Figure 13

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Fire behavior is often simulated with stylized fuel models as input information. These fuel models are often selected on the basis of their assigned typical fuel bed description, but their variability under different weather conditions may not be sufficiently considered. In a fire management planning context, the sensitivity of simulated fire behavior variables to 13 fuel models and two-fuel-model alternatives was analyzed under specific weather, topographic, and temporal conditions. Distributions of these variables were graphically displayed on the fire behavior characteristics chart, allowing for easy comparisons. For most of the fuel models tested, the fire behavior simulations produced a wide range of outcomes. The two-fuel-model concept demonstrated the effect of combining models on simulated fire behavior. Variations in fuel area coverages apparently can dramatically influence the effectiveness of a simulated initial attack.

Retrieval Terms: fire behavior, fuel models, probabilistic fire modeling, wildfire