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Predicting Behavior and Size of Crown Fires in the Northern Rocky Mountains

Richard C. Rothermel



THE AUTHOR

RICHARD C. ROTHERMEL is a research engineer stationed at the Intermountain Fire Sciences Laboratory in Missoula, MT. Rothermel received his B.S. degree in aeronautical engineering at the University of Washington in 1953. He served in the U.S. Air Force as a special weapons aircraft development officer from 1953 to 1955. Upon his discharge he was employed at Douglas Aircraft as a designer and trouble shooter in the armament group. From 1957 to 1961 Rothermel was employed by the General Electric Co. in the aircraft nuclear propulsion department at the National Reactor Testing Station in Idaho. In 1961 Rothermel joined the Intermountain Fire Sciences Laboratory (formerly the Northern Forest Fire Laboratory), where he has been engaged in research on the behavior of fire. He received his master's degree in mechanical engineering at the Colorado State University, Fort Collins, in 1971. He was project leader of the Fire Fundamentals research work unit from 1966 until 1979 and is currently project leader of the Fire Behavior research work unit at the fire laboratory.

RESEARCH SUMMARY

Assessment of crown fire conditions calls for two important judgments: (1) identifying conditions for the onset of severe fires, and (2) predicting the spread rate, intensity, and size of expected crown fires. This paper addresses the second problem and provides methods for making a first approximation of the behavior of a running crown fire in fuels and weather conditions of the Northern Rocky Mountains in the Western United States. Rate of spread is developed from field data correlated to predictions of Rothermel's surface fire spread model. Energy release from surface fuels is obtained from Albini's burnout model. Fireline intensity is estimated from Byram's model. Flame lengths are estimated from Thomas' model. Energy rate, or

power developed by the fire and ambient wind, is developed from Byram's equations and used to ascertain the possibility of a wind-driven or plume-dominated fire. The characteristics of these fires and dangers to fire fighters are discussed. A simple elliptical model is developed for estimating the area and perimeter of a large fire. The paper is oriented for use by well-trained fire behavior analysts to use in the field without the aid of computers to assess the characteristics of running crown fires.

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INTRODUCTION

The increasing number of severe wildfires of the past few years has emphasized the need for methods of assessing quantitatively the probable behavior of crown fires. Two problems must be addressed: (1) identifying conditions under which a crown fire is likely to occur, and (2) predicting the expected size and intensity of anticipated crown fires. Fire behavior prediction methods used in this Nation (Andrews 1986; Rothermel 1983), as well as the National Fire Danger Rating System (Deeming and others 1977) are designed primarily to assess the behavior and risk of surface fires. Progress on the first problem has recently been made with the introduction of the METAFIRE System (Simard 1989), an automated approach for identifying severe fire conditions, and by Haines (1988a), who introduced the Lower Atmospheric Severity Index (LASI), a simple method of evaluating atmospheric conditions conducive to severe fires. This paper is directed at the second problem: estimating the intensity and size of crown fires.

Just as the Richter scale aids interpretation of magnitude and probable effects of earthquakes, quantification of a crown fire's expected size and intensity should greatly aid fire managers to anticipate the problems of suppression, safety, and impacts on both environmental and cultural developments. Unlike an earthquake, however, a severe crown fire may run for several hours and, as the fire spreads, the intensity can rise and fall with variations in weather, topography, and fuels. The rate of spread and intensity of wildfires can vary widely as shown by the Sundance fire (Anderson 1968) and the Mack Lake fire (Simard and others 1983) (fig. 1). This paper considers these problems and presents methods for estimating and displaying the important elements of crown fire behavior.

Predicting the size and intensity of a crown fire is a complex problem, and the methods proposed here must be regarded as approximations; the ever-present variability of fuels, topography, and weather do not permit exact calculations for these intense, fast-moving events. This report is intended to help fire behavior analysts rapidly assess probable behavior from on-site observations without the aid of a computer. The literature review is restricted in the interest of brevity. Although much of the discussion applies to crown fires in general, the methods are designed for use in Northern Rocky Mountain forests where the data are applicable or in other mountainous areas with similar fuel, weather, and timber types.

THE CROWN FIRE PHENOMENON

Compared to other types of fires, crown fires are relatively rare, but their impact is severe. Strauss and others (1989) found that, in the Western United States, 1 percent of the largest fires accounted for 80 to 96 percent of the area burned.

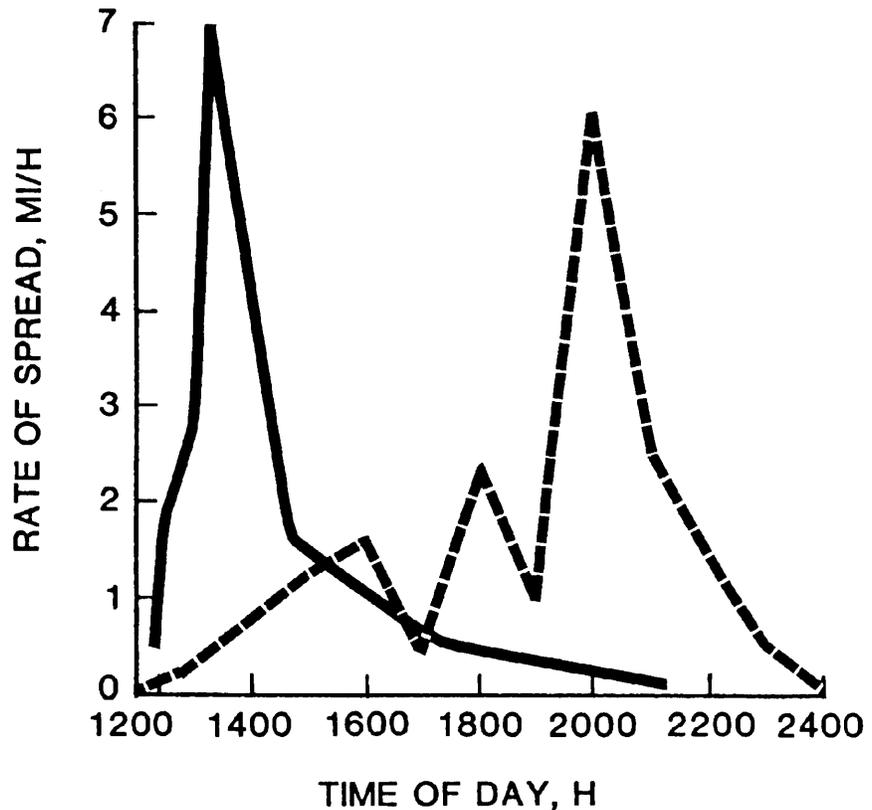


Figure 1—Variation in rate of spread exhibited by running crown fires. The Mack Lake fire, a plume-dominated fire, is shown as a solid line, and the Sundance fire, a wind-driven fire, is shown as a dashed line.

As the name implies, a crown fire is a fire carried through the crowns of living forests. Before reaching this condition, a fire can go through several stages of development. Typically, a fire may spread for some time in surface fuels such as grass, forest litter, or shrubs, without interacting with the overstory. It may even smolder in forest duff for days or weeks until burning conditions improve and the fire becomes active and begins to spread. Beighley and Bishop (1990) provide an excellent description of the transition from surface fire to crown fire in high-elevation forests. Favorable conditions for a crown fire include:

- Dry fuels
- Low humidity and high temperatures
- Heavy accumulations of dead and downed litter
- Conifer reproduction and other ladder fuels
- Steep slope
- Strong winds
- Unstable atmosphere
- Continuous forest of conifer trees

Depending on the degree that some or all of the above conditions are encountered, the intensity of a fire in surface fuels will increase and flames will begin to reach into the crowns or climb ladder fuels into the crowns where the needle foliage will ignite and “torching” of one or more crowns will occur. Torching is the sudden envelopment of an entire tree crown in

flames from the base to the top in a few seconds. The flames may involve a single tree or a small group. If conditions for sustained spread through the crowns are not favorable, the torching trees will quickly burn out, but in the process showers of firebrands can be produced that are lofted and spread by the wind. Most firebrands burn out before they fall and many fall within the fire perimeter, but some are carried ahead of the surface fire where they settle on forest debris and start new fires. These are called spot fires, and the process is referred to as "spotting." Repeated torching produces small islands of burned out trees. Torching can occur at any time of the day, but increases in frequency as conditions become drier and the surface fire becomes more active. As this behavior continues, the stage is set for the development of a sustained crown fire. Again, depending on the degree that the conditions favoring a fire are present, a running crown fire will result, which can have a unique and recognizable behavior pattern. The two most prominent behavior patterns are wind-driven fires and plume-dominated fires.

Wind-driven Fire

A running crown fire can result when winds increase and the flames from torching trees are driven into adjacent trees. Slope can produce the same effect. A wind-driven fire is dominated by strong winds that drive the flames before it. Spread rates can vary from 1 to 7 miles per hour, possibly faster in mountainous terrain. Steep slopes accelerate spread, especially when driven by wind. A running crown fire of any type is accompanied by showers of firebrands, fire whirls, smoke, and the rapid development of a strong convection column.

After running up the side of a mountain, a crown fire often stops at the top of a ridgeline where discontinuous fuels or fuels at high moisture content may be encountered. During drought conditions, however, fuels are ready to burn regardless of topography, and when the wind is strong and sustained, a running crown fire may continue and spread for several hours, burning out entire drainages and crossing mountain ridges that would normally be barriers. A dramatic example of a wind-driven crown fire took place on September 6, 1988, when the Canyon Creek Fire crossed the Continental Divide and burned onto the plains in west-central Montana (Goens 1990). If there is little humidity recovery after sundown, fires will spread well into the night as the Yellowstone fires did in 1988 (Hartford and Rothermel in preparation). This paper is directed toward quantifying the fire behavior during a sustained crown fire run such as those just described.

Plume-dominated Fires

There can be an alternate form of crown fire with a significantly different behavior pattern from the wind-driven crown fire described above. These fires are associated with relatively low windspeeds, usually less than 20 mi/h at the 20-ft level, and the development of a strong convection column, or plume, that towers above the fire rather than leaning over before the wind. To indicate the importance of the convective plume and to differentiate it from wind-driven fires, these will be referred to as plume-dominated fires. Some authors (Byram 1954) have used the term "blow-up fires," but that term has gotten common usage for any sudden increase in fire activity.

There appear to be at least two mechanisms for movement of plume-dominated fires. The first, or conventional type, is caused by momentum feedback from the vertical velocity in the convection column. This feedback increases turbulence in the surface winds and results in increased fire intensity and increased heat transfer to adjacent fuel and hence accelerated fire spread. The process feeds on itself and accelerates as the convection column

grows. This condition is described in Byram's (1954) paper. A reverse wind profile, as described by Byram, may or may not accompany this type of fire. A reverse wind profile means that the windspeed near the surface is faster than winds further aloft. Normally, windspeed increases with altitude; hence the name "reverse wind profile." A reverse wind profile allows a strong vertical convection column to develop directly over the fire without being sheared away by winds aloft. Although important, the reverse wind profile is not a necessity in the development of a plume-dominated fire. Aronovitch (1989) elaborates on Byram's suggestion and ties the phenomena closer to the meteorological aspects. Brotak (1976), in a survey of 62 fires in the United States, found that only 8 percent had reverse wind profiles. In recent years, two plume-dominated fires of this type have been documented: the Butte fire in 1985 in which 73 firefighters were forced into their shelters (Mutch and Rothermel 1986; Rothermel and Gorski 1987; Rothermel and Mutch 1986), and the Mack Lake fire, in which one firefighter was killed (Simard and others 1983). When the Mack Lake fire accelerated, it was spreading in a level jackpine stand with gradient winds of 20 to 25 mi/h. During a 20-minute period, the fire accelerated to a spread rate of approximately 7 mi/h. This rapid spread is comparable to the maximum observed on the wind-driven Sundance fire running before a 40 mi/h wind (Anderson 1968) (fig. 1).

Figures 2 and 3 illustrate the difference in appearance of the convection columns of a plume-dominated and a wind-driven crown fire.

The second type of plume-dominated fire behavior that can be extremely dangerous is one in which a downburst of wind blows outward near the ground from the bottom of a convection cell. For a short period, the fire is driven by wind. These winds can be extremely strong (Haines 1988b), and can greatly accelerate a fire. Such winds occurred on the Dude fire north of Phoenix, AZ, on June 26, 1990, when six fire fighters were killed (USDA FS 1990). Downburst is initiated by evaporative cooling of precipitation that cools surrounding air, causing it to descend rapidly and spread horizontally at the ground level. The author encountered such a phenomenon near the Shoshone fire in Yellowstone National Park on July 23, 1988. Although the fire was not a threat, the wind was strong enough to uproot and break off trees on a 3½ mile front. A helicopter caught in the downburst dropped several thousand feet before recovering. There were no cumulus clouds in the area other than the convective plume above the fire, so the downburst must have come from the fire's convection column. Very light rain was felt approximately ½ hour before the downburst.

Personnel on a fireline should watch for conditions that may indicate the development of a downburst from a plume-dominated fire. The surest indicator is the occurrence of precipitation of any amount, even a light sprinkle, or the appearance of virga (rain evaporating) below a cell. Precipitation cannot always be counted on to reach the surface, especially in the dry western climates.

Another indicator is the rapid development of a strong convection column above the fire, or nearby thunder cells. This is a poor indicator because all crown fires have a convection column located above them in some form, and a person beneath a cell cannot see its vertical development; but observers around the fire periphery could call attention to any large column growing vertically above the fire front.

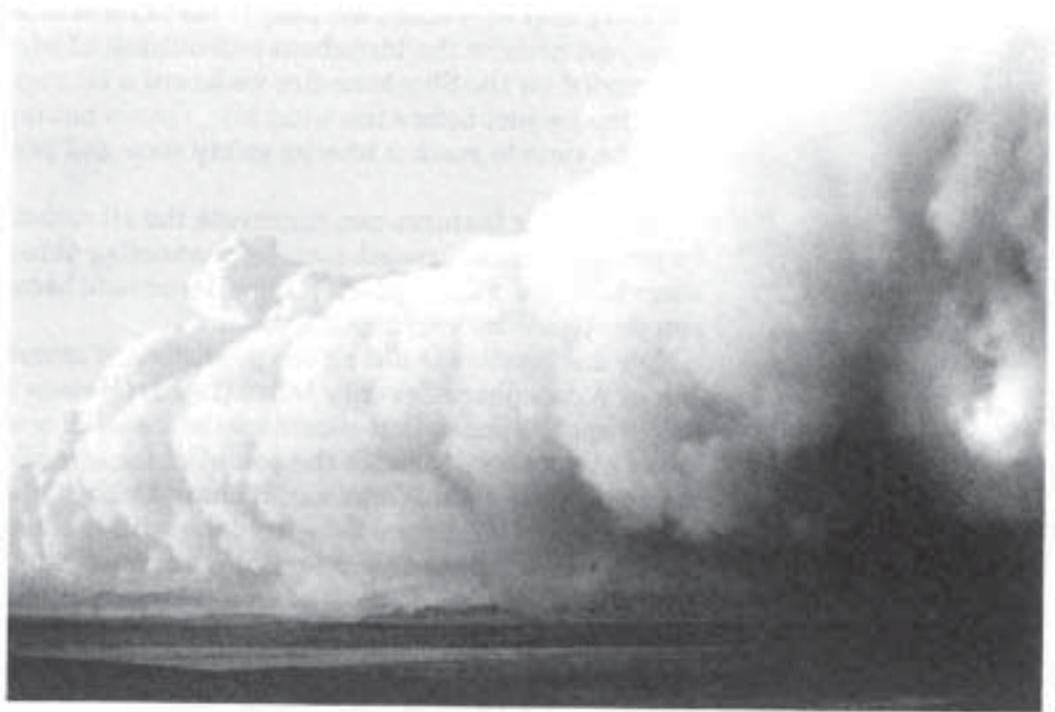


Figure 2—Typical appearance of the convection plume above a wind-driven fire. (Canyon Creek Fire, September 7, 1988; Jim Dolan, Northern Region, USDA Forest Service.)



Figure 3—Typical appearance of the convection column above a plume-dominated fire. (Silver Fire in Southern Oregon, October 1987, Bill Meadows; Northern Region, USDA Forest Service.)

A third and very short warning is the calm that develops when the indraft stops just prior to the turnabout and outflow of wind from the cell. During this period on the Shoshone fire we heard a strange humming sound that grew louder just before the wind hit. This is not much warning, but there could be time to reach a nearby safety zone and prepare to deploy a fire shelter.

Topographic features can aggravate the situation. Downburst winds can be prolonged and strengthened by channeling through canyons. Locations downhill from a fire cannot be considered safe because the downburst winds can drive the fire very rapidly downhill.

New information is aiding the prediction of severe fires. The Haines Lower Atmosphere Severity Index (LASI) (Haines 1988a) is a simple and easily applied index that considers the instability and moisture levels of the lower atmosphere to judge the potential for large fire growth. Fire weather meteorologists Paul Werth and Richard Ochoa (1990) have examined Haines' index on several fires in Idaho with excellent results. These atmospheric observations of wind profiles and instability require data about the atmosphere normally obtained from radiosonde balloons. Werth and Ochoa (1990) extend Haines' work by illustrating the use of water vapor imagery, taken from a satellite, to aid in the delineation of areas of low atmospheric moisture. Radiosonde data can be difficult to apply because of the limited number of locations that release balloons. Satellite data and "gridded data" from the National Weather Service's numerical models should alleviate this problem.

Fires are seldom uniform and well behaved; these descriptions of wind-driven and plume-dominated fire behavior may not be readily apparent and the behavior can be expected to change rapidly as environmental, fuel, and topographic features change. During the course of a running crown fire, one or more of these behavior patterns may be displayed.

MODEL DEVELOPMENT

Andrews and Rothermel (1982) devised a fire behavior characteristics chart that displays four essential features of a fire simultaneously:

- Rate of spread
- Heat per unit area
- Fireline intensity
- Flame length

The objective here is to develop a crown fire characteristics chart for wind-driven fires that includes these characteristics plus information about the energy release rate or power of the fire and the power of the wind. As will be shown, these power values can help determine the behavior pattern of a fire.

Fireline Intensity

Byram (1959) defined fire intensity as the product of the rate of spread and the heat generated from the available fuel.

$$I = Rwh, \text{ Btu/ft}\cdot\text{s} \quad (1)$$

where:

R = rate of spread, ft/s

w = available fuel, lb/ft²

h = heat of combustion, Btu/lb

Fireline intensity is the basic parameter describing the fire intensity needed to calculate flame length and power of the fire. It combines the important fire characteristics, rate of fire spread, and energy release from the fuel. Equation 1 can be evaluated by separating the problem into those two components, evaluation of rate of spread and evaluation of the heat per unit area. Splitting the problem greatly simplifies its solution.

Rate of Spread

In this analysis, rate of spread is established from observations of crown fire behavior. The resulting model is a statistical correlation rather than a deterministic physical model. Careful documentation of crown fire behavior shows that rate of spread can vary dramatically during a run (fig. 1). Often the maximum rate is mentioned in reports, but the maximum may persist only for a short time. To estimate the distance a fire will spread during a run, it is necessary to know the average rate of spread and the length of time conditions are favorable for a run.

Using actual wildfire data offers the best guarantee that the resulting predictive procedures will produce realistic spread rates within the range of observations. To obtain spread rates for this analysis, it was necessary to have data taken periodically during a running crown fire that simultaneously identified the time and location of the fire front plus the associated weather. To estimate the heat per unit area, it was necessary to have data about both the surface and crown fuel loads and the amount consumed. Very few wildfires are documented to that extent. To proceed toward a solution, it was necessary to use data from fires that had at least part of this information. The fires used for determining rate of spread and the environmental data are shown in table 1a. Rates of spread are shown in table 1b.

Table 1a—Environmental conditions during spread of wind-driven crown fires

Fire	Period of crown fire run	Fuel moisture				20-ft wind	Slope
		1-h	10-h	100-h	Live		
		----- Percent -----				Mi/h	Percent
Sundance	2 to 7 p.m.	7	8	9	60	30	0
	7 to 9 p.m.	8	9	9	60	45	10
Red Bench	5 to 7:30 p.m.	5	6	7	70	12	0
Lily Lake	2 to 5 p.m.	5	6	7	100	25	20
Sandpoint	2:30 to 5:30 p.m.	4	5	6	75	12-20	0
Pattee Canyon	4:25 to 5:15 p.m.	4	5	6	100	25-35	15
Mink Creek	1 to 5 p.m.	5	6	7	100	10-20	0
Black Tiger	1 to 3:30 p.m.	3	4	5	90	11	20

Table 1b—Observed crown fire data and model calculations¹

Fire	Period of crown fire run	Distance	Time	R	R_{max}	R_{10}	R/R_{10}	R_{max}/R
		Miles	Hours	-----Mi/h-----				
Sundance	2 to 7 p.m.	7.0	5	1.40	2.5	0.45	3.11	1.78
	7 to 9 p.m.	6.0	2	3.0	6.0	.78	3.85	2.0
Red Bench	4:30 to 8:30 p.m.	2.0	4	.52	.64	.20	2.63	1.23
Lily Lake	2 to 5 p.m.	2.8	3	.92	—	.29	3.2	—
Sandpoint	2:30 to 5:30 p.m.	3.12	3	1.04	1.76	.26	3.97	1.69
Pattee Canyon	4:25 to 5:15 p.m.	1.3	.83	1.56	—	.49	3.21	—
Mink Creek	1 to 5 p.m.	2.2	4	.55	—	.21	2.59	—
Black Tiger	1 to 3:30 p.m.	1.29	2.5	.51	.89	.12	4.1	1.74

¹ R = Average crown fire rate of spread
 R_{max} = Maximum crown fire spread rate observed during run
 R_{10} = Calculated rate of spread for fuel model 10
 — = R_{max} unavailable.

Explanation of data in table 1a:

Fire The fires used here are believed to have been wind-driven during much of their run. Plume-dominated fires, Mack Lake and Butte, did not correlate and were not included in the correlation.

Period The period of crown fire run is that period of time that the fire was known to be running and for which distance, time, and environmental conditions, primarily wind, were known or could be estimated with confidence.

Fuel moisture Fuel moistures were estimated with techniques developed for fire behavior analysts (Rothermel 1983).

20-ft wind Windspeeds were measured or obtained from nearby weather stations.

Slope The most representative slope was estimated according to the methods outlined in the slope section of this paper.

Explanation of data in table 1b:

Distance This is the distance the fire ran during the period of the run obtained from maps documenting the fire growth.

Time Elapsed time of the run.

R Average rate of spread obtained from the distance and time measurements.

R_{max} Maximum rate of spread observed for some known distance and time period within the overall run.

R_{10}	Calculated rate of spread using the firespread model and fuel model 10 with the environmental factors given in table 1a and a wind reduction factor of 0.4.
R/R_{10}	Ratio of the average observed rate of spread divided by the calculated rate of spread for fuel model 10.
R_{max}/R	Ratio of the maximum observed rate of spread divided by the average observed rate of spread.

The spread rate data in table 1b were correlated with predictions of the surface fire spread model developed by Rothermel (1972), adjusted by Albini (1976), and packaged in the BEHAVE fire behavior prediction and fuel modeling system by Andrews (1986). Fuel model 10, timber litter and understory (Anderson 1982), was used to represent the surface fuels in all cases. The correlation is shown in figure 4. The average rate of spread for the crown fires listed in table 1 was 3.34 times faster than predicted for surface fire, with a standard deviation of 0.59. Figure 4 also shows the 75 percent confidence interval for predicting the observed value. Although there are fewer data on maximum spread rate, for five wind-driven fires spread rate was 1.7 times faster than average, with a standard deviation of 0.28.

In the analysis, windspeed measured at 20-ft height, with a wind reduction factor of 0.4 (Rothermel 1983), was used to calculate the spread rate of the surface fire used in the correlation. Although other wind reduction factors may be more suitable in some instances for calculating surface fire spread, 0.4 gave excellent correlation to crown fire observations. Wind often varies considerably; using the upper end of the range of sustained wind speed gave the best results.

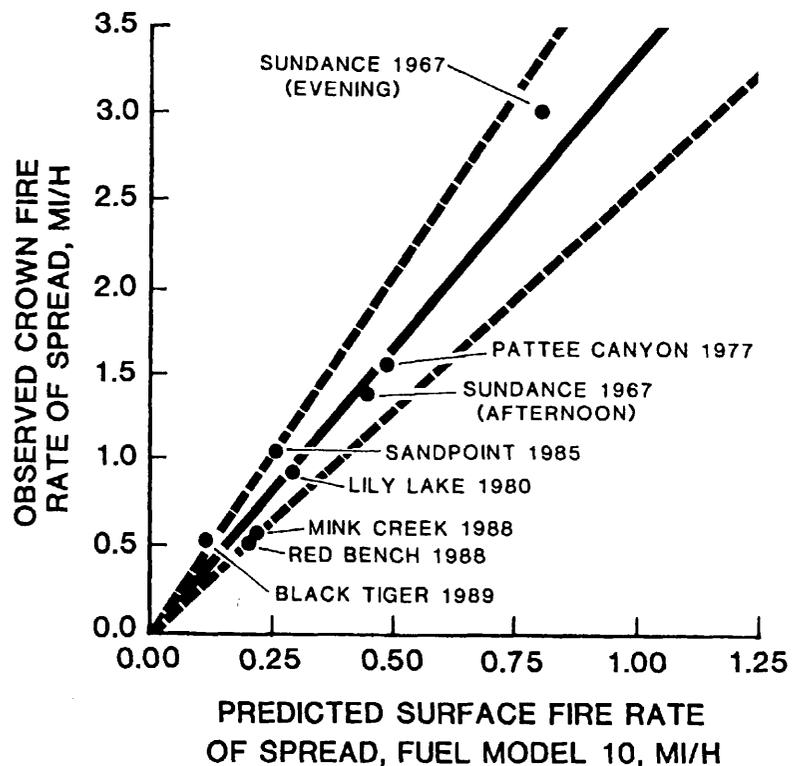


Figure 4—Correlation between observed crown fire spread rates of wind-driven fires and predictions with the fire spread model using fuel model 10.

Available Fuel

Another factor needed to evaluate equation (1) is the proportion of the fuel contributing to the development of the convection column. Because this is a crown fire, we must be able to estimate both the surface fuel and crown fuel loads. This is a difficult problem because we are interested in the energy that produces the convection column, and this is a larger value than the contribution from fine fuels normally assumed to carry the fire at the fire front (Rothermel 1972). Personal observation of severe fires has shown the important contribution made to fire intensity by accumulations of larger sizes of dead and downed fuel.

The amount of energy released by surface fuel can be estimated from Albini's burnout model (Albini 1976). The burnout model accepts fuels of all sizes and produces a continuous estimate of the reaction intensity and the heat per unit area as the fuel is consumed. (Reaction intensity is the energy release rate per unit area per unit time [Rothermel 1972].) Albini's model predicts that, even for situations with heavy accumulations of large fuels, there is a period of major heat release near the fire front. This is followed by a long period of slowly changing heat release as the large fuels burn out. The large heat pulse shown by Albini's model is consistent with development of the strong convection column near the fire front and provides a basis for predicting the energy going into the convection column. This initial pulse terminates when the reaction intensity reaches a minimum after its first peak. Integration of the heat release during this time produces the heat per unit area needed for evaluation of equation (1). The burnout model simultaneously computes the needed energy values.

For areas that do not have an available file of fuel inventory data, there is not time to perform a fuel inventory ahead of a spreading fire; therefore, a few of the 13 fire behavior fuel models (Anderson 1982) are used to expedite the prediction. The unit energy available from the models is shown in table 2. The effect of adding 30 tons/acre of 6-inch fuel to models 9 and 10 is included. Adding the 6-inch fuel increases the energy of the fire front, but not by substantial amounts unless it is decayed. If it is decayed and breaking up, its contribution will be much greater, and an estimate can be made using logging slash fuel model 12 as a guide.

Albini's burnout model can accommodate inventories of dead and downed fuel accumulations as measured by techniques given by Brown (1974). Fuel inventory maps with these data could be used to great advantage in place of the fuel models.

Table 2—Values of unit energy for the fire behavior fuel models used in the analysis

Fuel model	Additional 1,000-h fuel	Unit energy
	<i>Tons/acre</i>	<i>Btu/ft²</i>
8	—	580
2	—	760
9	—	1,050
9	30	1,325
10	—	1,325
10	30	1,570
12	—	3,430

The contribution of crown fuel to the total energy release is assumed to be produced by consumption of the conifer needles. In some fires more than the needles will be consumed; certainly this is true if there is standing dead material. In other cases, the fire can pass through and not consume all of the needles, but such refinements will have to be accommodated later. For this analysis, heat from the crowns is assumed to come from combustion of the needles alone. Assuming heat from the needles is 8,000 Btu per pound of dry needles, the crown fire contribution is added to the surface fuel heat at the rate of 376 Btu/ft² for each ton per acre of needles.

The needle load will be very difficult to estimate with any degree of confidence without prior knowledge of the timber stand characteristics. To help with this estimate, table 3 has been developed from the Region 1 Silvicultural Practices Handbook (USDA Forest Service 1987) stocking guides. These guides provide an estimate of the average maximum density (AMD). The AMD indicates the highest densities that can be found under average forest conditions. Stands at or above this density can generally be expected to stagnate or to suffer stress and significant mortality. Table 3 accepts descriptors of tree type, the diameter at breast height, and the stocking density or tree spacing. Often, all that will be known is the general tree type or mixture. Fortunately, the needle load is not very sensitive to d.b.h. If trees appear to be stocked at less than maximum density, the values can be ratioed down. Hartford (in preparation) is developing a more complete explanation of these data.

Flame Length

Byram also showed how the flame length could be calculated from the fireline intensity with the model:

$$L = 0.45I^{0.46} \text{ flame length, ft} \quad (2)$$

This formula has been used extensively for estimating the flame length of spreading surface fires (Albini 1976; Andrews 1986; Rothermel 1983), but personal observations of flame lengths and discussions with fire behavior analysts have shown that Byram's model seriously underpredicts the flame length of crown fires. Byram (1959) suggests adding one-half of the mean canopy height to L when estimating crown flame lengths. Flame length is an elusive parameter that exists in the eye of the beholder. It is a poor quantity to use in a scientific or engineering sense, but it is so readily apparent to fireline personnel and so readily conveys a sense of fire intensity that it is worth featuring as a primary fire variable.

Alternatively, Thomas (1963) proposed a flame length model based on convection theory:

$$L = 0.2I^{2/3} \text{ ft} \quad (3)$$

Thomas' model will generate flame lengths of 100 to 200 feet for fireline intensities associated with crown fires. Table 4 provides equivalent values for flame length and fireline intensity. Van Wagner (1990) agrees that Thomas' $2/3$ power law model should represent crown fire flame lengths better than Byram's square root model, but suggests that it may underestimate flame lengths for low-intensity crown fires. Thomas' model will be used in this development.

Power of Fire and Wind

Byram (1959) extended his work on plume-dominated fires by examining the power of the fire in relation to the power of the wind. The power of the fire is the rate at which energy is released, ft·lb/s, and is calculated on a unit

Table 3—Crown fuel load for average maximum stocking density, the highest densities that can be found under average forest conditions

	D.b.h. (Inches)		
	4	12	20
	-----Tons/acre-----		
Lodgepole pine			
Average max trees/acre	2,300	400	175
Tree spacing, feet	4	10	16
Crown fuel load, tons/acre	8	9	7
Ponderosa pine			
Average max trees/acre	2,000	340	150
Tree spacing, feet	5	11	17
Crown fuel load, tons/acre	10	12	11
Douglas-fir ¹ (moist habitats)			
Average max trees/acre	1,950	340	150
Tree spacing, feet	5	11	17
Crown fuel load, tons/acre	12	10	9
Douglas-fir ² (other habitats)			
Average max trees/acre	1,700	290	130
Tree spacing, feet	5	12	18
Crown fuel load, tons/acre	10	9	8
Subalpine fir ³ (lower habitats)			
Average max trees/acre	2,400	425	190
Tree spacing, feet	4	10	15
Crown fuel load, tons/acre	17	15	12
Subalpine fir ⁴ (upper habitats and wet lower)			
Average max trees/acre	2,000	330	150
Tree spacing, feet	5	12	17
Crown fuel load, tons/acre	14	11	9
Spruce			
Average max trees/acre	1,900	320	140
Tree spacing, feet	5	12	18
Crown fuel load, tons/acre	14	12	10
Western larch			
Average max trees/acre	2,400	410	190
Tree spacing, feet	4	10	15
Crown fuel load, tons/acre	6	4	3
Grand fir			
Average max trees/acre	2,000	350	160
Tree spacing, feet	5	11	16
Crown fuel load, tons/acre	19	16	14
Western hemlock			
Average max trees/acre	2,100	370	160
Tree spacing, feet	5	11	17
Crown fuel load, tons/acre	12	10	8
Western redcedar ⁵ (wet habitat)			
Average max trees/acre	2,400	400	180
Tree spacing, feet	4	10	16
Crown fuel load, tons/acre	16	14	12
Western redcedar ⁶ (other habitat)			
Average max trees/acre	2,600	460	200
Tree spacing, feet	4	10	15
Crown fuel load, tons/acre	17	15	13
Western white pine			
Average max trees/acre	2,600	460	200
Tree spacing, feet	4	10	15
Crown fuel load, tons/acre	11	8	6

¹Douglas-fir on moist habitat types (PICEA, ABGR, THPL, TSME, TSHE, and moist ABLA).

²Douglas-fir on PSME habitats and most ABLA habitat types.

³Subalpine fir on mesic, lower subalpine habitat types—ABLA/CLUN, LIBO, VACA, VAGL, VASC, CARU, and XETE.

⁴Subalpine fir on timberline, upper subalpine, and wet lower subalpine habitat types.

⁵Redcedar on wet habitat types—THPL/CLUN, THPL/ATFI, THPL/OPHO.

⁶Redcedar on all other habitat types.

Table 4—Fireline intensity equivalents to flame lengths calculated by Thomas' (1963) model

Flame length	Fireline intensity	
	<i>Feet</i>	<i>Btu/ft•s</i>
20	1,000	3,460
30	1,840	6,370
40	2,830	9,790
50	3,950	13,700
75	7,260	25,100
100	11,200	38,800
125	15,600	54,100
150	20,500	70,900
175	25,900	89,500
200	31,600	109,000
225	37,700	131,000
250	44,200	153,000
275	51,000	176,000
300	58,100	201,000

area basis, ft•lb/(s•ft²). This power is the source of energy that produces the convection column. The rate of flow of kinetic energy in the wind field can be expressed in the same units. The heat energy produced by the fire gives rise to the convection column by virtue of the temperature rise of the air, which lowers the density and produces the buoyant vertical force. As the rising air is subjected to the force of the wind, the column is tipped in the direction the wind is traveling (fig. 2). Byram suggested that if the power of the fire is greater than the power of the wind, the fire-wind system is dominated by the energy of the fire. Such fires are plume-dominated and stand almost vertically (fig. 3).

The expected spread rate of a plume-dominated fire is not yet predictable, but methods are given for estimating power levels of crown fires to help assess whether a plume-dominated fire can be expected. Byram (1959) provides the following equations for calculating the power of the fire, P_f , and the power of the wind, P_w .

$$P_f = I/(C_p(T_o + 459)) \quad (4)$$

$$P_w = \rho(V - R)^3/2g \quad (5)$$

where

- I = fireline intensity, Btu/ft•s
- C_p = specific heat of air, Btu/lb•°F
- T_o = ambient temperature, °F
- ρ = density of air, lb/ft³
- V = windspeed, ft/s
- R = rate of spread, ft/s
- g = acceleration of gravity, ft/s²

To simplify evaluation, typical conditions will be assumed:

- C_p = 0.24 Btu/lb °F
- T_o = 80 °F
- ρ = 0.0679 lb/ft³
- g = 32.2 ft/s²

Equations (4) and (5) become:

$$P_f = I/129 \quad \text{ft}\cdot\text{lb}/\text{s}\cdot\text{ft}^2 \quad (6)$$

$$P_w = 0.00106 (V - R)^3 \quad \text{ft}\cdot\text{lb}/\text{s}\cdot\text{ft}^2 \quad (7)$$

If R is small compared to V , it can be ignored; however, this can produce errors and should not always be assumed. Charts and procedures are provided later in the paper for estimating P_f and P_w .

Crown Fire Characteristics Chart

Equations (1), (3), and (6) are evaluated from rate of spread and unit energy to produce the crown fire characteristics chart (fig. 5). The curved lines in figure 5 are hyperbolas that can be interpreted as fireline intensity, flame length, or the power of the fire. Values for flame length and power of the fire are shown to simplify field use of the chart. The fireline intensity equivalent to any flame length can be obtained from table 4. The flame lengths computed from the Thomas model, equation 3, appear to be reasonable except at low intensity; no exact values for such a phenomena can be fixed, but the numbers serve as useful field guides to the intensity of the fire.

Fire characteristics charts used for surface fires (Andrews and Rothermel 1982) have a much lower range of intensity. The surface fire chart depicts the limits of fire control as well as the danger of torching and crown fire development. These limits are all exceeded by running crown fires. Because of the difference in fire characteristics and the flame length models, a fireline intensity of 1,000 Btu/ft·s produced by a surface fire gives a flame length of approximately 11 feet, whereas the same intensity of a crown fire produces a flame length of approximately 20 feet. Even this value may be low because of the vertical orientation of the crown fuel. Fires exceeding 1,000 Btu/ft·s should still be considered uncontrollable by direct attack at the head of the fire.

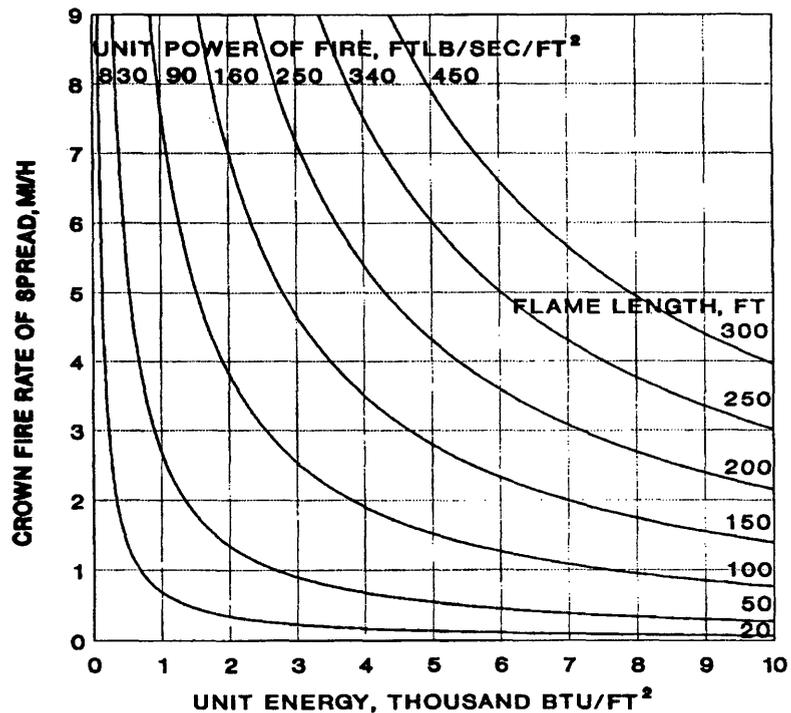


Figure 5—Crown fire characteristics chart.

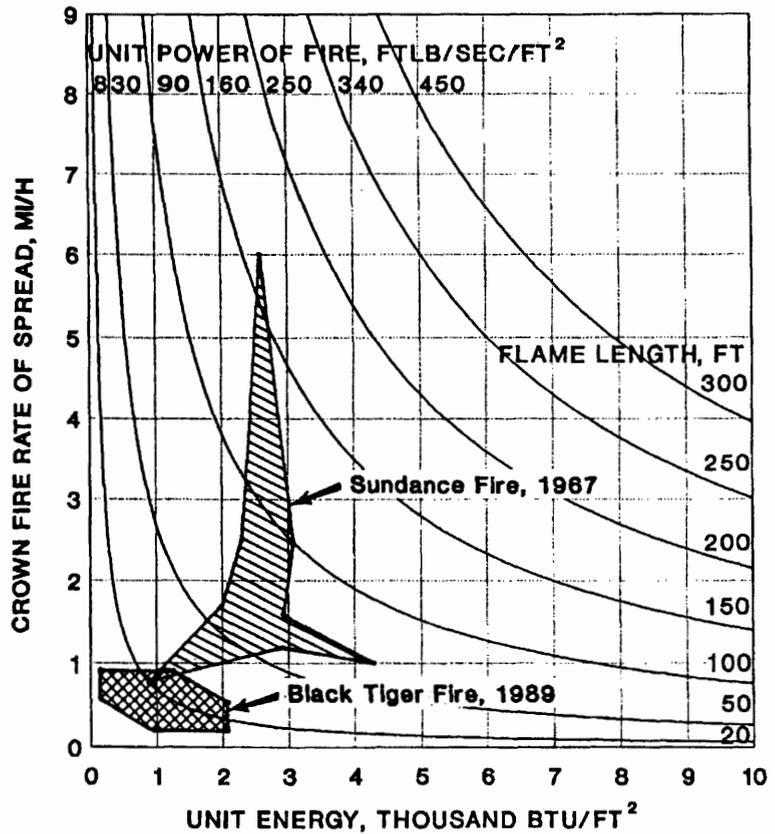


Figure 6—Comparison of the fire behavior characteristics of the Sundance and Black Tiger fires.

To illustrate the use of the fire characteristics chart, the Sundance fire that burned across northern Idaho on September 1, 1967 (Anderson 1968) is shown in comparison to the Black Tiger fire that destroyed 44 homes in the mountains just outside of Boulder, CO, on July 9, 1989 (National Fire Protective Association 1990) (fig. 6). The Sundance fire, burning in mixed conifers, was driven by winds up to 45 mi/h and reached spread rates of 6 mi/h. Two firefighters lost their lives when it burned over them near the start of its run. Anderson's data in figure 6 indicate the flame lengths would have been on the order of 150 feet for unit energy values ranging from 1,000 to 3,000 Btu/ft².

The Black Tiger fire in Colorado, by contrast, was burning primarily through sparse east-slope ponderosa pine and pockets of mixed conifers. Its maximum spread rate was less than 1 mi/h and maximum unit energy reached 2,000 Btu/ft² when pockets of mixed conifers were encountered. Plotting these data in figure 6, the Black Tiger fire straddles the 20-ft flame length line, indicating that some areas of the fire were controllable and some were not. That was indeed the case; firefighters were able to save many homes where they had access on roads located in meadows and open areas. Nevertheless, this fire, which was much less intense than the Sundance fire, destroyed 44 homes.

Fire Size

Anderson (1983) and Van Wagner (1969) have shown that fires tend to produce an elliptical burn pattern. Anderson shows that this representation

is altered by a fluctuating wind direction or distorted by topography or multiple runs. Anderson (1983) reviewed the literature of fire shape and, working with wind tunnel data taken by Fons (1946), developed a double elliptical model to represent fire shape. Anderson suggested the length-to-width ratio as a function of wind to be:

$$d/b = 1.873 \exp(0.1147U) \quad (8)$$

where

d = fire spread distance from origin, ignoring backing distance

b = half width of ellipse

U = midflame windspeed, set at half the average 20-ft windspeed

Unfortunately, this model does not reduce to a circle at zero windspeed and produces extremely elongated fires at high windspeeds.

Andrews (1986) examined Anderson's model and simplified it for use with the BEHAVE system by using a linear function for the length-to-width ratio:

$$\text{length/width} = 1 + 0.25U \quad (9)$$

To further simplify the model so that the same 20-ft windspeed used in calculating rate of spread can be used, the model becomes

$$\text{length/width} = D/W = 1 + 0.125V \quad (10)$$

where

D = approximate forward spread distance (the backing spread is ignored)

W = maximum width of ellipse

V = 20-ft windspeed

Using equation 10, and assuming an elliptical fire shape, the area of the fire can be expressed as:

$$A = (\pi D^2)/(4(1 + 0.125V)), \text{ mi}^2 \quad (11)$$

converting to acres:

$$A = (160 \pi D^2)/(1 + 0.125V), \text{ acres} \quad (12)$$

An estimate for the shortest perimeter to match the area ellipse becomes:

$$P = (\pi D/2)(1 + 1/(1 + 0.125V)), \text{ miles} \quad (13)$$

For field use, the equations for length/width, area, and perimeter have been tabulated in tables 5, 6, and 7. The actual perimeter can be substantially larger due to irregularities in the fire shape.

Table 5—Length-to-width ratio for maximum sustained 20-foot windspeed

Windspeed	Length/ width	Windspeed	Length/ width
<i>Mi/h</i>		<i>Mi/h</i>	
10	2.2	40	6.0
15	2.9	45	6.6
20	3.5	50	7.3
25	4.1	55	7.9
30	4.8	60	8.5
35	5.4	65	9.1

Table 6—Fire area, acres

Forward spread distance	Maximum sustained 20-foot windspeed, mi/h										
	10	15	20	25	30	35	40	45	50	55	60
<i>Miles</i>											
0.25	14	11	9.0	7.6	6.6	5.8	5.2	4.7	4.3	4.0	3.7
.5	56	44	36	30	26	23	21	19	17	16	15
1	220	180	140	120	110	94	84	76	69	64	59
1.5	500	390	320	270	240	210	190	170	160	140	130
2	890	700	570	500	420	370	340	300	280	260	240
2.5	1,400	1,093	900	760	660	580	520	470	430	400	370
3	2,000	1,600	1,300	1,100	950	840	760	680	620	570	530
3.5	2,700	2,100	1,800	1,500	1,300	1,100	1,000	930	850	780	720
4	3,600	2,800	2,300	2,000	1,700	1,500	1,300	1,200	1,100	1,000	950
4.5	4,500	3,500	2,900	2,500	2,100	1,900	1,700	1,500	1,400	1,300	1,200
5	5,600	4,400	3,600	3,000	2,600	2,300	2,100	1,900	1,700	1,600	1,500
5.5	6,800	5,300	4,300	3,700	3,200	2,800	2,500	2,300	2,100	1,900	1,800
6	8,000	6,300	5,200	4,400	3,800	3,400	3,000	2,700	2,500	2,300	2,100
8	14,000	11,000	9,200	7,800	6,800	6,000	5,400	4,900	4,400	4,100	3,800
10	22,000	17,000	1,400	12,000	11,000	9,300	8,400	7,600	6,900	6,400	5,900
12	32,000	25,000	21,000	18,000	15,000	13,000	12,000	11,000	10,000	9,200	8,500
14	44,000	34,000	28,000	24,000	21,000	18,000	16,000	15,000	14,000	13,000	12,000
16	57,000	45,000	37,000	31,000	27,000	24,000	21,000	19,000	18,000	16,000	15,000
18	72,000	57,000	47,000	39,000	34,000	30,000	27,000	25,000	22,000	21,000	19,000
20	89,000	70,000	57,000	49,000	42,000	37,000	34,000	30,000	28,000	26,000	24,000
22	110,000	85,000	70,000	59,000	51,000	45,000	41,000	37,000	34,000	31,000	29,000
24	130,000	100,000	83,000	70,000	61,000	54,000	48,000	44,000	40,000	37,000	34,000
30	200,000	160,000	130,000	110,000	95,000	84,000	75,000	68,000	62,000	57,000	53,000
35	270,000	210,000	180,000	150,000	130,000	110,000	103,000	93,000	85,000	78,000	72,000
40	360,000	280,000	230,000	190,000	170,000	150,000	130,000	120,000	110,000	100,000	95,000

Table 7—Fire perimeter, miles

Forward spread distance	Maximum sustained 20-foot windspeed, mi/h										
	10	15	20	25	30	35	40	45	50	55	60
<i>Miles</i>											
0.25	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
.5	1.1	1.1	1.0	1.0	1.0	.9	.9	.9	.9	.9	.9
1	2.3	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.8	1.8
1.5	3.4	3.2	3.0	2.9	2.9	2.8	2.7	2.7	2.7	2.7	2.6
2	4.5	4.2	4.0	3.9	3.8	3.7	3.7	3.6	3.6	3.5	3.5
2.5	5.7	5.3	5.0	4.9	4.8	4.7	4.6	4.5	4.5	4.4	4.4
3	6.8	6.4	6.1	5.9	5.7	5.6	5.5	5.4	5.4	5.3	5.3
3.5	8.0	7.4	7.1	6.8	6.7	6.5	6.4	6.3	6.3	6.2	6.1
4	9.1	8.5	8.1	7.8	7.6	7.5	7.3	7.2	7.1	7.1	7.0
4.5	10	9.5	9.1	8.8	8.6	8.4	8.2	8.1	8.0	8.0	7.9
5	11	11	10	9.8	9.5	9.3	9.2	9.0	8.9	8.9	8.8
5.5	12	12	11	11	10	10	10	9.9	9.8	9.7	9.7
6	14	13	12	12	11	11	11	11	11	11	11
8	18	17	16	16	15	15	15	14	14	14	14
10	23	21	20	20	19	19	18	18	18	18	18
12	27	25	24	23	23	22	22	22	21	21	21
14	32	30	28	27	27	26	26	25	25	25	25
16	36	34	32	31	30	30	29	29	29	28	28
18	41	38	36	35	34	34	33	33	32	32	32
20	45	42	40	39	38	37	37	36	36	35	35
22	50	47	44	43	42	41	40	40	39	39	39
24	54	51	48	47	46	45	44	43	43	42	42
30	68	64	61	59	57	56	55	54	54	53	53
35	79	74	71	68	67	65	64	63	63	62	61
40	91	85	81	78	76	75	73	72	71	71	70

APPLICATION

Determination of Fire Characteristics

Nomograms that incorporate the analytical methods described above and the crown fire characteristics chart have been developed for predicting the behavior of crown fires in the Northern Rocky Mountains. It is expected that they will be useful in other areas where similar tree types and weather exist in mountainous terrain. It was mentioned earlier that there can be two types of crown fires: wind-driven fires and plume-dominated fires; the nomograms presented here are designed to depict the behavior of wind-driven crown fires, and to aid assessments for the possible occurrence of plume-dominated fires.

To simplify their use, nomograms have been developed for five representative moisture conditions:

- (1) Early spring before greenup (fig. 7).
- (2) Late spring or early summer after greenup (fig. 8). Conditions are fairly wet, but crown fires can be driven by strong winds.
- (3) A normal dry summer (fig. 9).
- (4) Summer drought (fig. 10).
- (5) Late summer severe drought (fig. 11).

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

EARLY SPRING BEFORE GREENUP

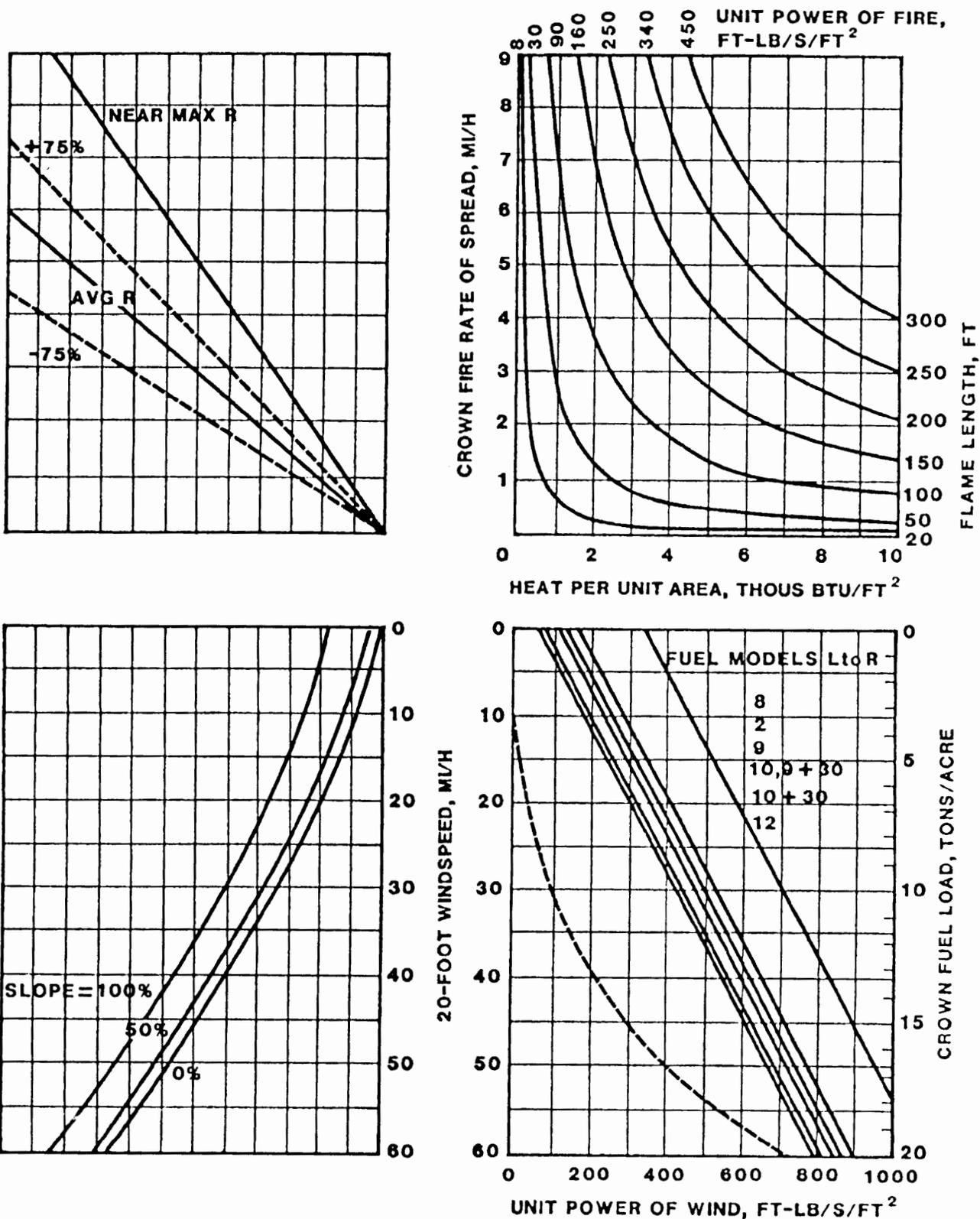


Figure 7—Crown fire nomogram for early spring before greenup.

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

LATE SPRING AFTER GREENUP

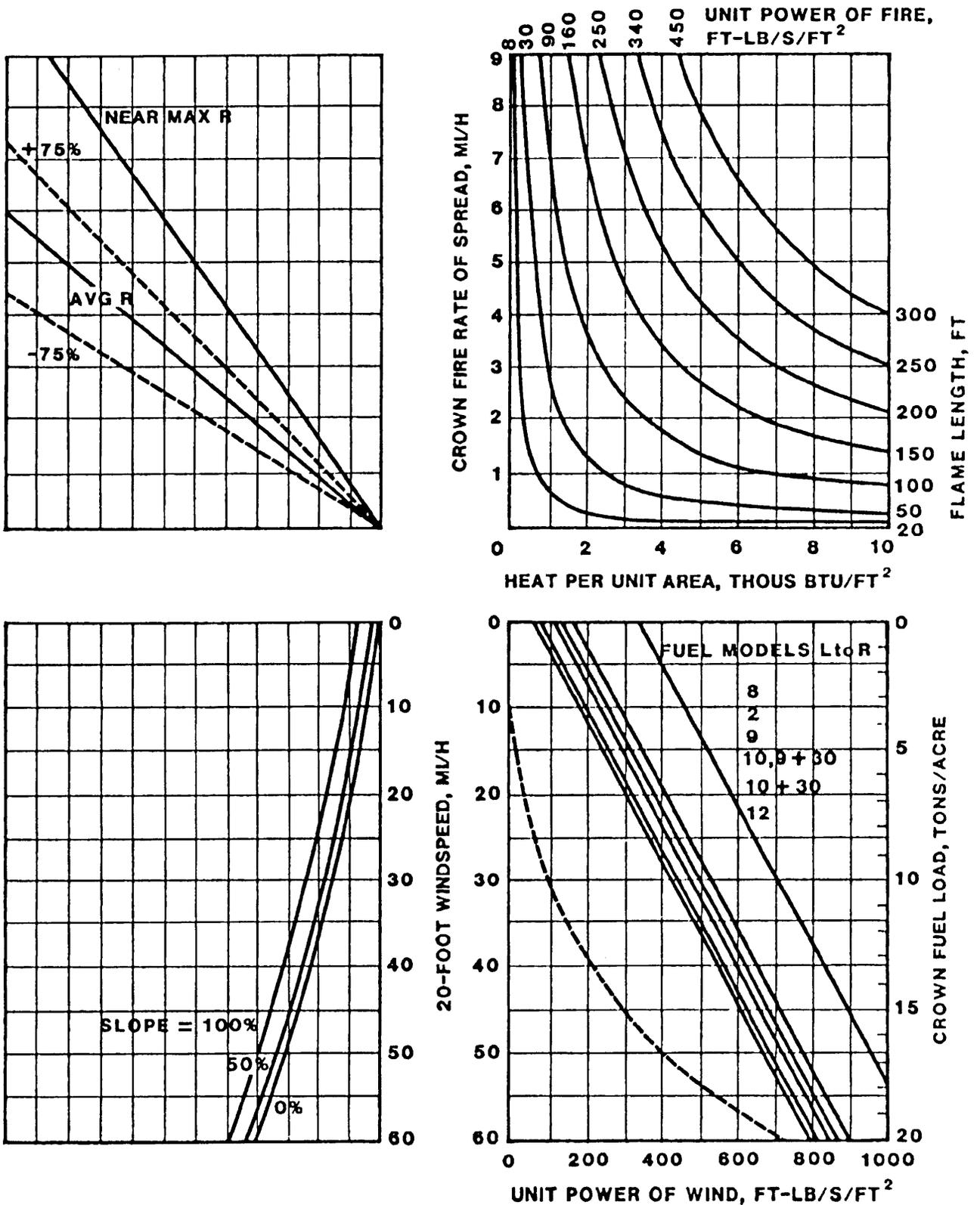


Figure 8—Crown fire nomogram for late spring.

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

NORMAL SUMMER

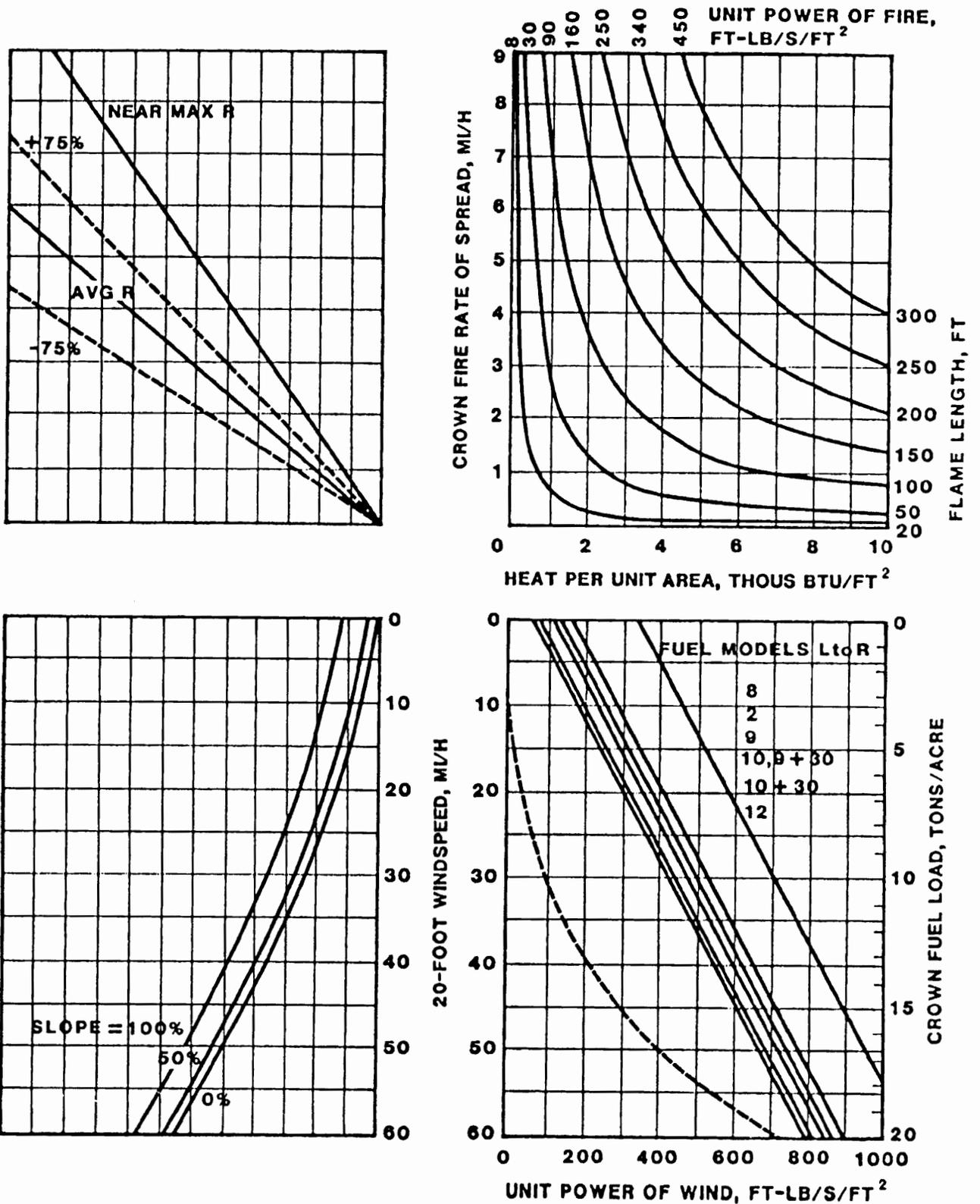


Figure 9—Crown fire nomogram for normal summer.

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

DROUGHT SUMMER

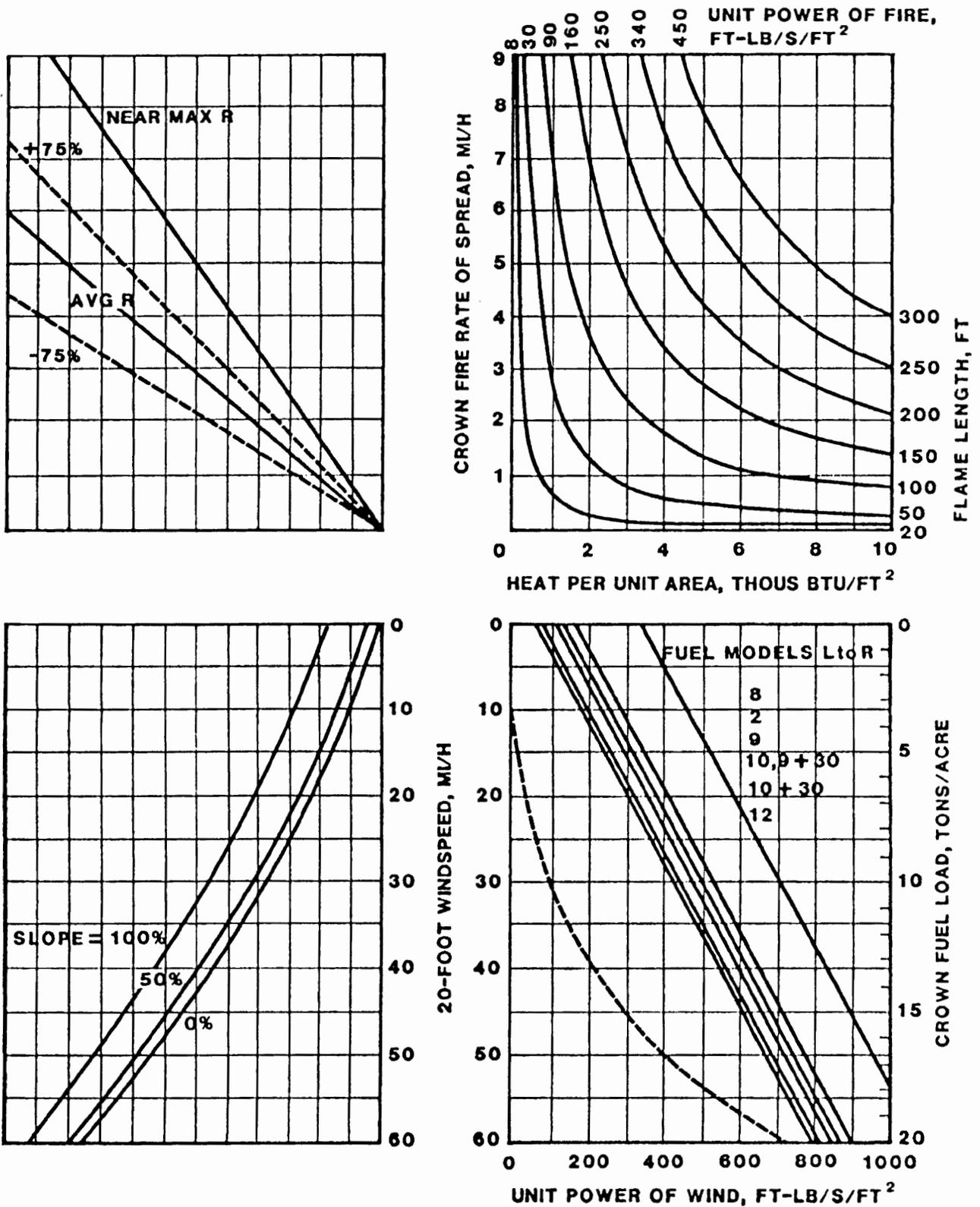


Figure 10—Crown fire nomogram for summer with drought.

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

SEVERE DROUGHT LATE SUMMER

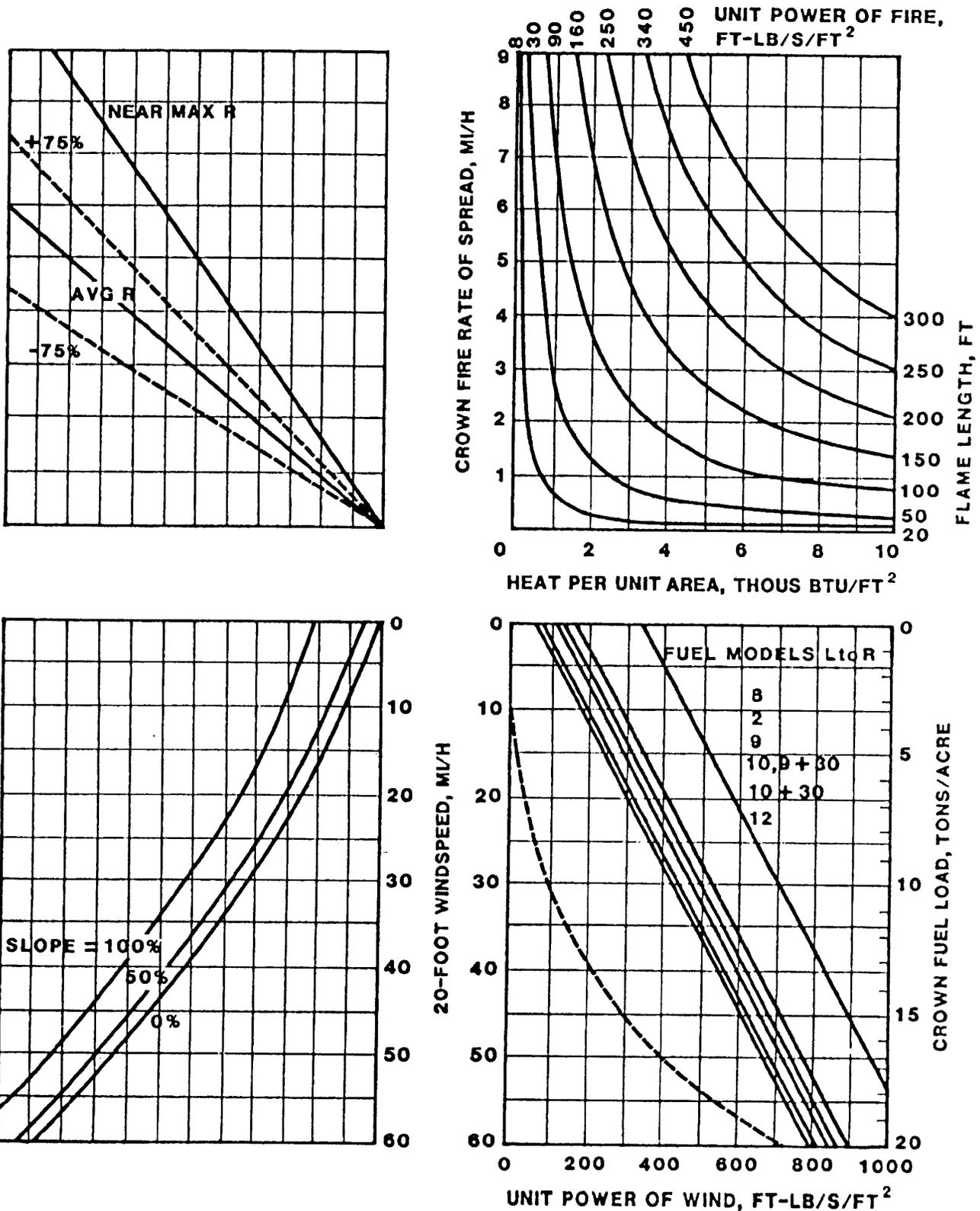


Figure 11—Crown fire nomogram for late summer with severe drought.

Table 8—Fuel moisture values used for the five seasonal moisture conditions

Condition	Early spring	Late spring	Normal summer	Drought summer	Late summer severe drought
1-h	8	9	6	4	3
10-h	14	11	8	5	4
100-h	18	15	10	7	6
1,000-h	25	19	13	9	8
Live	65	195	117	78	70

The fuel moisture values used to represent these five conditions are shown in table 8.

The nomograms have been structured so that rate of spread is determined on the left-hand side and energy of the fires on the right-hand side. These determinations are made independently and then combined within the fire characteristics chart in the upper right-hand quadrant.

Note that the curves in the lower left-hand quadrant shift significantly from season to season. This is produced by the variation in fuel moisture in different seasons and the effect of moisture on the rate of spread calculated for fuel model 10. There are not enough data in table 1a and 1b to verify whether this shift is correct in all situations. Reliance is based on the correlation between observed crown fire rate of spread and the prediction of rate of spread from model 10 shown in figure 4 to give reasonable results. It is readily apparent that more research is needed to strengthen this analysis, and it is emphasized once again that these are first-order approximations of crown fire behavior.

The nomograms should be selected according to the time of year and prevailing moisture conditions of the threatened area. Consultation with local fire management officers, dispatchers, and fire weather meteorologists familiar with local fire danger indices and other indicators can provide information about the state of fire season development and drought conditions.

Rate of Spread

After choosing the appropriate nomogram, the only other inputs needed to determine rate of spread are the windspeed and slope. For predictions, the usual source of wind information would be from a fire weather meteorologist. The free-stream surface winds normally measured at 20 feet are used. Windspeed information is usually received as a range, such as SW at 25 to 30 mi/h with gusts to 40 mi/h. For input, use the upper end of the sustained range, in this case 30 mi/h. If the gusts are expected to be sustained as the day progresses, they may be considered; in this case, 35 mi/h would be a reasonable choice. Measurements can also be used, but the location of the anemometer and interpretation of sustained winds and gusts are critical. Do not expect good agreement between observed fire spread and predictions if the wind data are not representative of the free-stream sustained winds driving the fire.

Slope selection is more difficult. The problem is that the fire may move up and down several slopes in the course of a run. As stated earlier, fires can spread much faster up the side of a mountain, and even though the stated purpose of this paper is to estimate the average rate of spread of a sustained fire run wherein the fire may climb and descend several ridges, it is still necessary to identify the slope to be used on the nomogram.

It is also desirable to have an estimate of the maximum spread rate during a run which, in all likelihood, will occur on a slope. The following rules are suggested:

1. To estimate the average rate of spread wherein the fire may travel across uneven terrain, use zero slope.
2. To estimate the average rate of spread wherein the fire is expected to spread through an area that is consistently increasing in slope such as a large drainage, even though there is some variation in terrain, use an estimate of the representative slope. Large valleys usually have gentle slopes of less than 10 percent, which will produce little difference compared to zero slope.
3. To estimate the near-maximum rate of spread for short bursts of the fire, which can generally be expected to run upslope, use the maximum slope the fire is expected to encounter and the near-maximum-spread rate line in the upper left-hand quadrant of the nomogram.

Spotting is not addressed separately on the nomograms. Because spotting was involved in the spread of the observed fires, nominal spotting is accounted for in the correlation factor. Long-range spotting responsible for new and independent fires is not addressed in these procedures. The spotting distance models (Albini 1981, 1983) are applicable to surface fires and torching tree crowns (Albini 1979), but no model is known for predicting the spotting distance for running crown fires. The probability of ignition due to spotting is given in table IV-4 in Rothermel (1983). These calculations are automated in BEHAVE (Andrews 1986) or for the HP-71B (Susott and Burgan 1986).

To begin the determination of rate of spread on a nomogram, start with the 20-ft windspeed on the lower center vertical axis. An example of rate of spread determination is shown in figure 12 for a windspeed of 37 mi/h and a maximum slope of 50 percent. From the windspeed, draw a straight line to the left, intersecting the zero and 50 percent slope lines. Interpolate between the slope values if necessary for other values. From the intersection with the zero and 50 percent slope lines, draw a vertical line into the upper left-hand quadrant. There are four straight lines in this quadrant for depicting the average and near-maximum spread rates. The middle solid line is the turning line for the average spread rate. The two dashed lines on either side are for determining 75 percent confidence limits of the average spread rate, and the upper line provides an estimate of the near maximum spread rate. From the intersections with these lines, draw horizontal lines to the right into the fire characteristics chart depicted in the upper right-hand quadrant. On the left-hand edge of the fire characteristics chart, read the spread rates in miles per hour. The example, figure 12, has an average rate of spread of 2 mi/h and a near maximum of 4 mi/h.

Energy Release

A combined heat per unit area for both surface fuels and crown fuels is determined in the lower right-hand quadrant of the nomogram. The heat from combustion of the needles in the crowns is determined from the needle load in tons per acre along the right-hand side. This value is obtained from table 3 for Northern Rocky Mountain conifers. If there is an understory of reproduction such as subalpine fir beneath a decadent lodgepole stand, an estimate of the amount of needles on the reproduction in proportion to the overstory should be included. For instance, if the overstory is considered to

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

EARLY SPRING BEFORE GREENUP

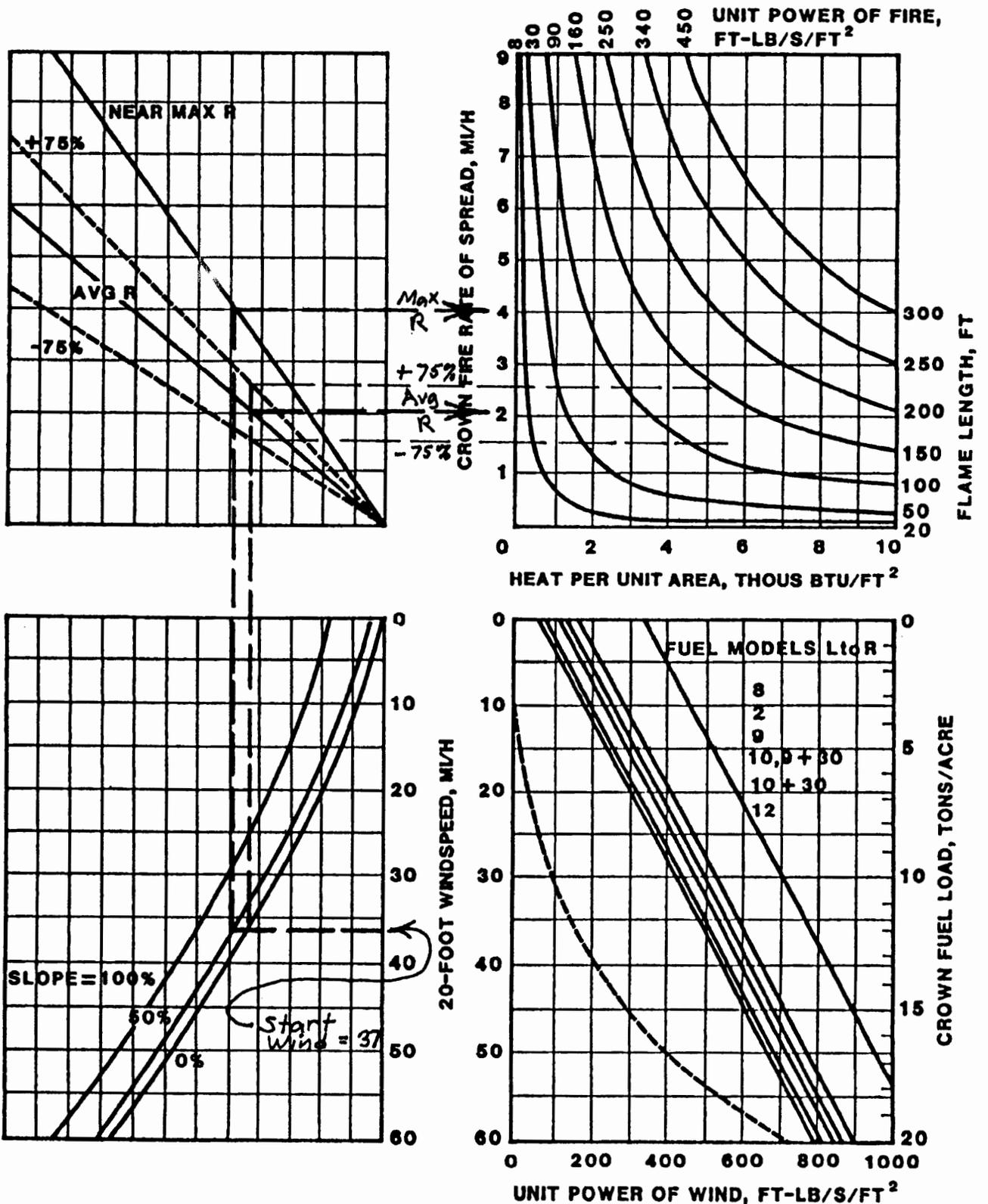


Figure 12—Example of determining rate of spread on a nomogram.

carry 8 tons/acre of crown fuel, and the reproduction is estimated to be 25 percent of that, or 2 tons/acre, enter 10 tons/acre as the crown fuel load.

The contribution of heat from the surface fuel is obtained by choosing one of the fire behavior fuel models depicted as straight lines slanting down to the right. If the fuels are mixed, two models can be selected that represent a lower and upper range of fuels on the ground. Standard fuel models 9 and 10 are provided with the addition of 30 tons/acre of 1,000-h fuels. The legend identifies the lines with the fuel models starting from left to right. Note that some lines represent more than one model. Model 12 is included to show an extreme case. If the trees were cut or fell in a windstorm to produce the amount of fuel in model 12, there would not be enough standing to carry a crown fire. Alternatively, the previous stand of trees on the site may have fallen years before due to bug kill or fire, and the tree boles remaining could be decayed. If these are dry, they will add substantially to the fire intensity at the head of the fire. In such cases, the surface fuel load should be interpreted toward fuel model 12.

An example of unit energy determination is shown in figure 13 for a crown load of 7 tons/acre and surface fuels represented by models 8 and 10 plus 30 tons of large fuel. From the right-hand side at the appropriate needle load, draw a horizontal line to the left, intersecting the slanted straight lines for the selected fuel model(s). If a range of crown needle loads is expected, two lines can be used to represent the range in crown fuel. At the intersection with the surface fuel model(s), draw a vertical line(s) toward the top, extending into the fire characteristics chart until the previously drawn rate of spread lines at the 75 percent confidence level are intersected. These lines identify an envelope of fire behavior. Draw an oval within the envelope on the fire characteristics chart that represents the range of fire behavior that may be expected for this fire. If you wish to know the fireline intensity, table 4 gives corresponding values of fireline intensity for the flame lengths shown on this chart. The combined heat per unit area produced by the crown fire and surface fire is read off the bottom axis; for this example it is between 3,000 and 4,000 Btu/ft². The range of expected flame lengths is found by following the curved lines nearest the oval, down and to the right. For the 75 percent confidence range of this example, the flame lengths are expected to be between 80 and 120 feet.

After proficiency is developed at using and interpreting the nomograms, the near-maximum spread rate can be combined with the heat per unit area to estimate maximum flame lengths and fire intensity values that may occur for short periods. It must be emphasized again that fires will surge and stall as they spread, producing a large range of behavior.

Power of Fire and Wind

The power of the fire can be determined by following the curved lines nearest the oval up to their intersection at the top of the chart. The power of the fire is given here in ft·lb/s·ft². For this example, the power of the fire would lie between 40 and 100 ft·lb/s·ft². The power of the fire should be compared with the power of the wind to determine which is larger. The power of the wind can be determined from the 20-ft windspeed indicated on the lower vertical axis in the center of the nomogram. To determine the power of the wind, from the wind axis, draw a horizontal line to the right to where it intersects the sharply curved line in the lower right-hand quadrant. At this intersection draw a vertical line downward to the bottom of the quadrant where the power of the wind is displayed. For the example in figure 13,

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

EARLY SPRING BEFORE GREENUP

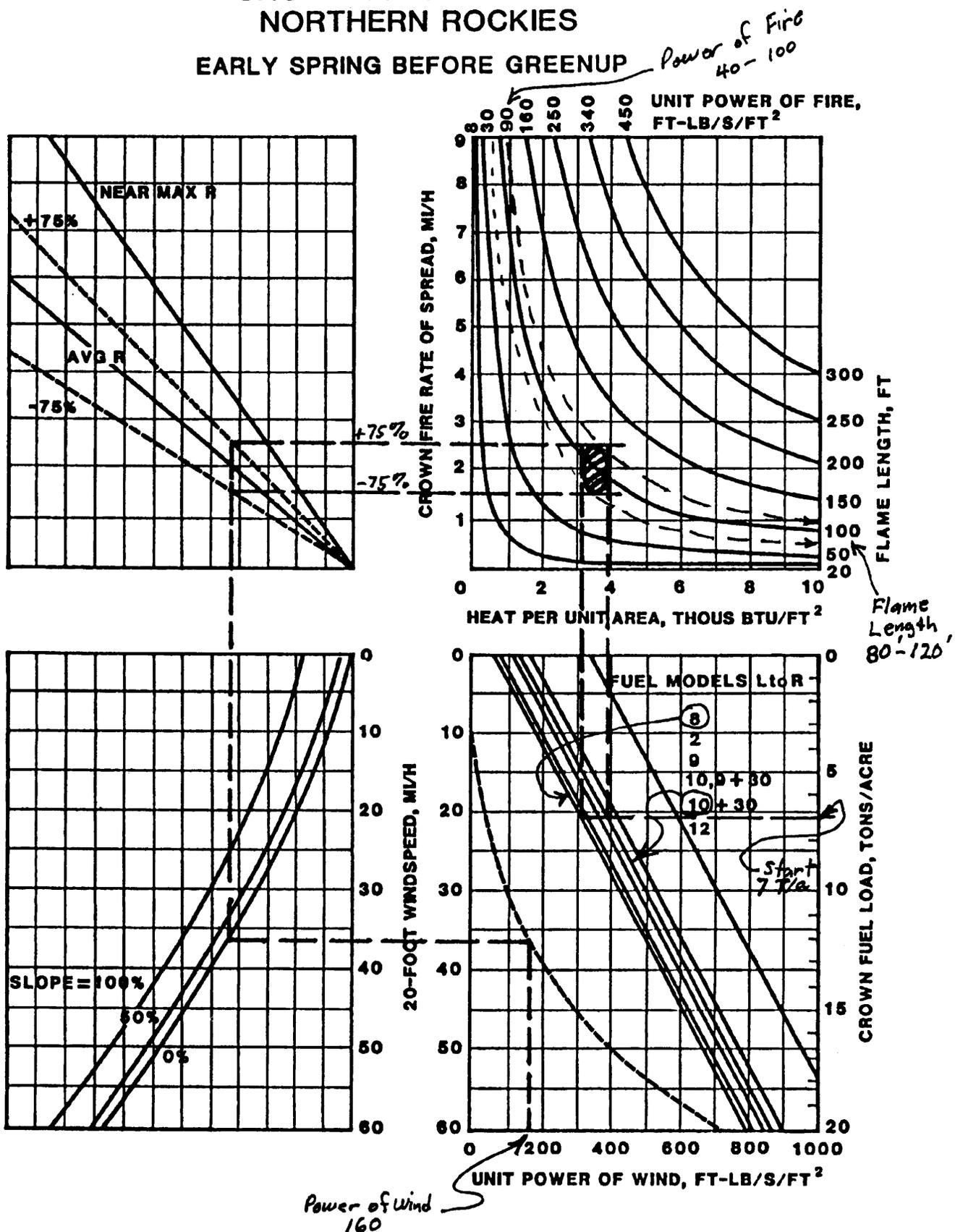


Figure 13—Example of determining unit energy, flame length, power of the fire, and power of the wind; overall characterization of fire behavior.

the power of the wind is $160 \text{ ft}\cdot\text{lb/s}\cdot\text{ft}^2$. This is much greater than the expected power of the fire, and a wind-driven fire can be expected. If the power of the fire is close to or greater than the power of the wind, be aware that a plume-dominated fire is possible that may produce a sudden fire acceleration and spread rates faster than predicted. Additional information about the atmospheric conditions should be obtained from a fire weather meteorologist when the possibility of a plume-dominated fire is indicated.

Depicting previous fires of known behavior on the fire characteristics chart illustrates the range of fire behavior that can be expected and serves as a guide to prediction of new fires. A set of contrasting fires occurred in Yellowstone Park in 1988. The Shoshone fire that threatened Grant Village in late July was often burning on nearly level ground with winds on the order of 10 to 15 mi/h, gusting to 20 mi/h through lodgepole pine. Some of the lodgepole pine in the area was fallen and decayed; there was also subalpine fir reproduction with a needle load about 20 percent of the overstory. The Hellroaring fire, spreading through lodgepole pine, was assumed to have surface fuel represented by fuel models 8 and 10. It made a major run on August 20 that produced extreme fire behavior. Twenty-foot winds of 50 mi/h were measured that day on Mount Holmes, with gusts estimated at 80 mi/h. The Hellroaring fire was driven up a shallow slope in a confined canyon with a maximum slope of 30 percent at the head. The contrasting behavior of these two fires is readily shown in figure 14.

Even though the Shoshone fire appears less severe on the nomogram, its intensity was too great to be controlled or stopped as it approached Grant Village, but with advanced preparation to reduce fuels and reduce fire hazard within the village, coupled with a burnout around Grant Village just before the fire arrived, the village was saved. The only course of action for the much more extreme behavior of the wind-driven Hellroaring fire was to evacuate ahead of the fire; nothing could be done to deter a fire of that magnitude. Note that the Hellroaring fire had flame lengths that ranged between 125 and 180 feet at the 75 percent confidence level, with maximum lengths perhaps as much as 300 feet. The power of the fire over the 75 percent range was about 130 to 200 $\text{ft}\cdot\text{lb/s}\cdot\text{ft}^2$. The average rate of spread was about 3.5 mi/h. The maximum rate could have been 6 to 7 mi/h. For a windspeed of 50 mi/h after subtracting the average rate of spread, the power of the wind was about $320 \text{ ft}\cdot\text{lb/s}\cdot\text{ft}^2$, which is well above the power of this very intense wind-driven fire. By contrast, the Shoshone fire had a power of 30 to 70, but the wind was so low as to be only about $20 \text{ ft}\cdot\text{lb/s}\cdot\text{ft}^2$. Thus, the Shoshone fire was plume-dominated under these conditions, which is consistent with the downburst experienced on July 23, 1988. Because the fire appears to have been plume-dominated, the rate of spread and flame lengths may be underpredicted.

Spread Distance

An estimate of fire spread distance can be used to estimate the size of a fire resulting from a crown fire run, and to project the expected fire position on a map. Attention should be directed to assessment of one burning period at a time, even though the fire may pick up and run again on another day. Spread distance can be limited by either a change in environmental conditions such as a significant decrease in windspeed, or a rise in moisture conditions as a result of rising humidity, or the occurrence of rain or snow. Alternatively, the fire may spread to the limits of fuel suitable for sustaining a run. In nondrought years, north slopes and high elevations can have

CROWN FIRE BEHAVIOR NORTHERN ROCKIES DROUGHT SUMMER

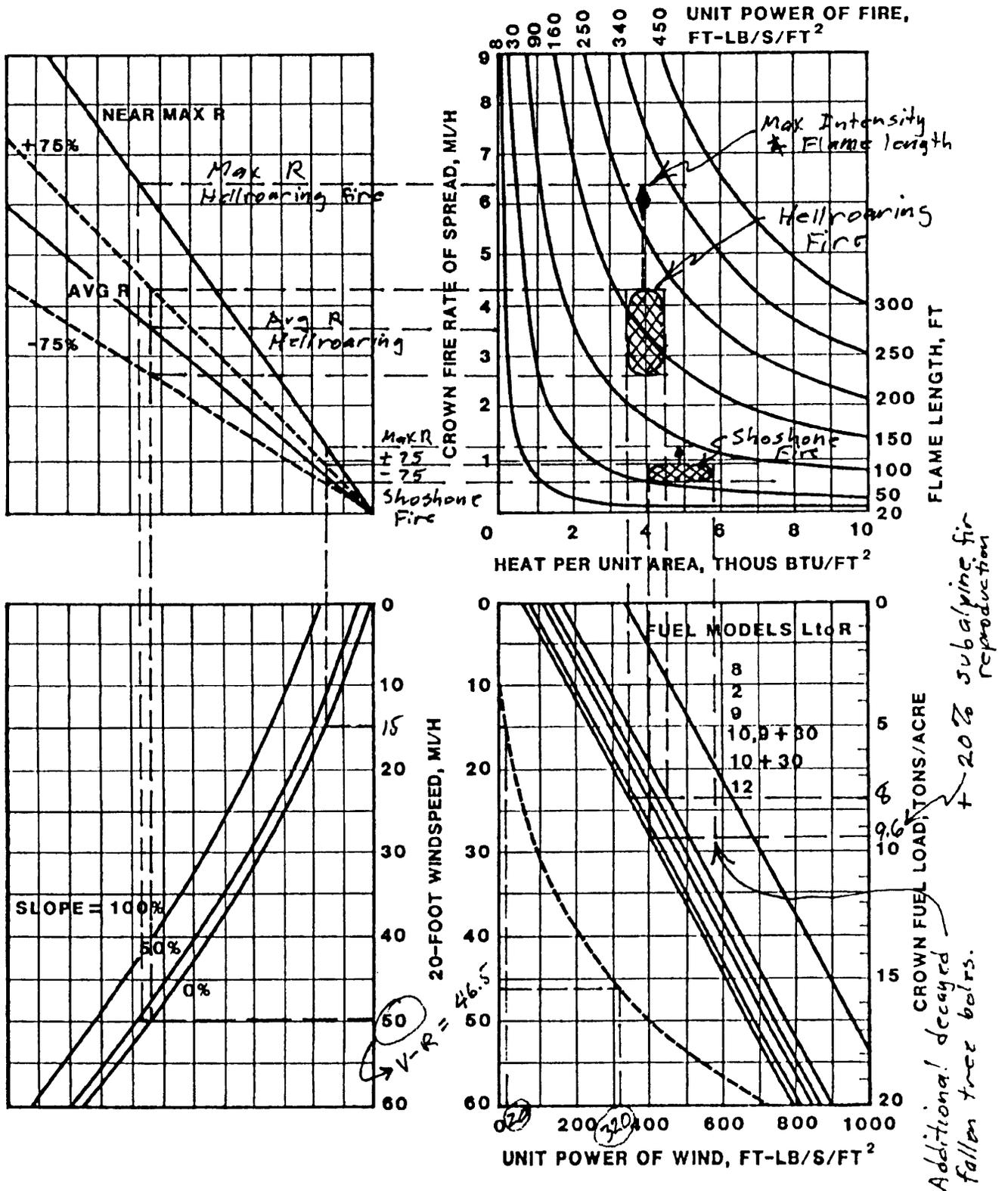


Figure 14—Contrast in predicted behavior between two fires in the Greater Yellowstone Area in 1988. The Shoshone fire was plume-dominated and the Hellroaring fire was wind-driven.

enough moisture to slow or stop a fire. Similarly, nighttime humidity recovery can raise fuel moistures enough to produce the same result. Late in the summer and during periods of drought, nighttime moisture recovery and high elevation moisture are reduced and cannot be depended upon. High mountain ridges devoid of a tree canopy can prevent a crown fire from continuing, but the ever-present danger of airborne firebrands starting spot fires beyond the ridge must be considered.

If the fire is expected to run out of crown fuel, the situation should be noted on a map and the expected spread distance can be scaled from the map. The time it takes to travel that distance can be estimated by dividing the distance by the average spread rate determined from the nomogram. If the fire is not expected to run out of fuel nor encounter a barrier, the expected spread distance can be estimated by multiplying the average rate of spread by the expected time period of the run.

$$D = Rt \quad \text{miles} \quad (14)$$

where R is in miles per hour and time (t) is in hours or fractions of hours.

The expected time period of the run will be difficult to estimate. Weather conditions and behavior of the fire on previous days can serve as guides for determining the beginning and ending times. The onset of crowning is exceedingly complex; wind, slope, humidity, fuel moisture, atmospheric stability, inversions, surface fire intensity, ladder fuels, time of year, amount of exposed fireline, and frontal passage can all play a role. This problem is not addressed here. The termination of a crown fire run, even though continuous fuels are available, will usually be the result of a significant weather change, namely decreased windspeed or increased moisture. In the Northern Rocky Mountains, 30 percent humidity has been used as a rule of thumb to indicate when fires' spread would become marginal. This was not the case in the 1988 Yellowstone fires; a relative humidity of near 50 percent was needed to slow the fires in late summer (Hartford and Rothermel in preparation). This was not occurring until after midnight. It appears that, because of the extreme drought, there was no soil moisture to augment the rising humidity at night. Beighley and Bishop (1990) provide guides for indicating the onset of fire spread in high-altitude fires. Work with the fire weather meteorologist to estimate when conditions will no longer sustain a crown fire run. The spread distance can then be estimated with equation 14.

Crown fires can run for several miles. The procedures described herein were designed to estimate on that order of magnitude, not the shorter intervals as described by Rothermel (1983).

A plot of the expected fire position on a map is probably its most useful form. This plot will have only a few hours of useful lifetime for predicting fire behavior, but is an important record. It is important that the work be done in a timely manner to be useful in strategy sessions and for planning operations. The map distance equivalent to the firespread distance can be calculated if the map scale is known. But maps in fire camp are often copies or portions of other maps, and the scale is not shown. The scale can be quickly determined by measuring section line spacing and, since these are set at 1-mile intervals (some are foreshortened), the mile equivalent in inches can be determined. Calculate the firespread distance for the map scale, D_m , as follows:

$$D_m = DS \text{ inches} \tag{15}$$

where

- D = spread distance, mi
- S = scale of map, in/mi

The spread distance should be laid out on the map in the dominant wind direction, taking into account the effect of large valleys on wind direction. An examination of the drainage structure, ridge lines, large lakes, etc., will set some limits on fire growth and possible boundaries.

Using drainage shapes and natural fire barriers, sketch the expected position of the fire in a roughly elliptical shape with the length-to-width ratio determined by the windspeed and table 5.

A change in wind direction can alter the course of a fire. The passage of a cold front can turn a fire flank into a fire head, with disastrous results, as experienced on Ash Wednesday in Victoria, Australia, in 1983 (Country Fire Authority of Victoria 1983). To the extent possible, weather forecasts should be used to anticipate these alterations.

Report Information

Worksheets (fig. 15) should be used to summarize data from the nomograms, estimate the size of the fires, and plot the expected fire position on a map. The position of the fire on the nomogram in relation to other known fires should serve as a useful guide to expected fire behavior.

Provide an estimate of fire behavior to the fire overhead team by methods suggested in S-590, Fire Behavior Analyst training.

Save worksheets, nomograms, maps, and weather records for fire reviews and to assist research to expand and improve fire behavior predictions.

Work Sheet Instructions

Line 1: Record the name of the fire, the name of the analyst predicting fire behavior, and the date the projection is made.

Line 2: Enter the area threatened, either by geographic area or a section of the control line. Also enter the date for which the projection of fire behavior is being made.

Line 3: Enter the expected time period for the length of the run, beginning time to ending time, and the elapsed time from beginning to end in hours.

Line 4: Identify the most applicable moisture condition. These five conditions correspond to the five nomograms. If you believe you are between conditions—for instance, between early spring and late spring—calculations can be made for each case and differences reconciled.

Lines 5 to 11 are to aid in the use of table 3 to estimate the crown fuel load. If there is more than one overstory species on a site, the fuel loads in table 3 are not additive; but the range in fuel load determined for each species can indicate the range in expected energy.

Line 5: Indicate the name of the dominant overstory species. Use separate species if the species are in separated and distinct areas. If they are intermixed, a value for the mix will have to be estimated from table 3.

Line 6: Indicate diameter at breast height. Notice that this is not a very sensitive parameter for many species in table 3.

Line 7: Tree spacing and average maximum trees per acre in table 3 are guides for the upper limit of crown needle load. For more open sites, values should be scaled down.

Crown Fire Worksheet

1. Name of Fire _____ Analyst _____ Date _____
2. Area threatened _____ Projection date _____
3. Expected time period of run _____ to _____. Elapsed time t _____ hrs.
4. Moisture condition: Early spring Late spring
 Normal summer Drought summer Extreme drought
5. Overstory species _____
6. DBH _____ inches
7. tree spacing _____ feet
8. crown fuel load _____ tons/acre
9. Reproduction % _____ % of overstory needles
10. Reproduction amount _____ tons/acre
11. Total crown load _____ tons/acre
12. Surface fuel model _____
13. Additional 1000-hr fuel _____ tons/acre, sound or decayed?
14. Forecast windspeed and direction _____
15. Upper value of sustained windspeed _____ mi/h Knots x 1.15 = mi/h
16. Slope: representative _____ % Maximum _____ %

Outputs

17. Average rate of spread, R _____ mi/h
18. Average spread distance, $D = R \times t$ _____ miles
19. Elliptical area _____ acres
20. Elliptical perimeter _____ miles
21. 75% range in flame length, L_f _____ to _____ feet
22. Near maximum rate of spread R_{max} _____ mi/h
23. 75% range in power of fire, P_f _____ to _____ $ft \cdot lb/s \cdot ft^2$
24. Power of wind, P_w _____ $ft \cdot lb/s \cdot ft^2$
25. Range in power ratio, $P_f/P_w =$ _____ to _____ If greater than one,
 consider possibility of plume-dominated fire. Contact Fire Weather Meteorologist for information on
 Atmospheric stability,
 Atmospheric moisture,
 LASI index,
 Wind profile.

Figure 15—Crown fire worksheet.

Map Projection

26. Map scale, S _____ inches/mile
27. Spread distance, D _____ miles, from line 18
28. Map spread distance, D_{map} _____ inches. $D_{map} = S \times D$
29. Length/width ratio _____
30. Fire width, W_f _____ miles $W_f = D / (\text{length/width})$
31. Map width of fire, W_{map} _____ inches $W_{map} = W_f \times S$
32. 75% range in rate of spread _____ to _____ mi/h
33. 75% range in spread distance _____ to _____ miles
34. 75% range in map spread distance _____ to _____ inches

Notes

Line 8: Indicate the best estimate of crown needle fuel load.

Line 9: If an understory of reproduction is present, estimate the amount of needles as a percentage of the overstory.

Line 10: Calculate the amount of needle load of the reproduction from the percent in line 9 and the overstory load on line 8.

Line 11: Sum the overstory crown load and the reproduction crown load to obtain the total crown load.

Line 12: Identify the surface fuel model that best represents the dead and downed fuel on the site.

Line 13: Indicate additional 1,000-h fuel that may be on the site and indicate whether it is sound or decayed.

Line 14: Record the forecasted windspeed and direction. A range of windspeeds that indicates the upper value of expected windspeed should be obtained rather than the average windspeed.

Line 15: Record the upper value of the sustained windspeed in miles per hour. If it is received in knots, multiply by 1.15 to obtain miles per hour.

Line 16: Record the approximate or representative slope for the area according to instructions in text; also record the maximum slope if an estimate of maximum spread rate is desired.

OUTPUTS

Line 17: Enter the average rate of spread determined from the nomograms in miles per hour.

Line 18: Record the spread distance obtained by multiplying average rate of spread by the expected run time obtained from line 3. Be sure that run time is expressed in hours and fractions of hours, not hours and minutes.

Example: 4 hours and 30 minutes is 4½ or 4.5 hours.

Line 19: The expected area can be found from table 6. To compute area, you need the forward spread distance and the maximum sustained 20-ft windspeeds.

Line 20: The minimum or elliptical-shape perimeter is obtained from table 7.

Line 21: The 75 percent range in flame length is obtained from the nomogram and is the expected range in flame length as delineated by the average fire behavior between the plus 75 percent and minus 75 percent rate of spread lines.

Line 22: The near-maximum rate of spread obtained from the nomogram.

Line 23: The 75 percent range in power of the fire obtained by following the curved lines bracketing the fire envelope to the upper left corner of the fire characteristics chart.

Line 24: Subtract the average rate of spread from the windspeed; then record the upper value of sustained power of the wind obtained from the lower right-hand quadrant of the nomogram. If the average rate of spread is small, 1 or 2 mi/h, the correction to windspeed can be ignored.

Line 25: Divide the power of the fire at the upper and lower 75 percent range by the power of the wind and record these ratios. Note that if these ratios are greater than 1, there is a possibility of a plume-dominated fire.

Exact interpretation of these values cannot be given without further experience. Additional information should be sought from a fire weather meteorologist.

Items that can be discussed with the fire weather meteorologist are atmospheric stability, atmospheric moisture, and the Haines LASI Index. Unstable atmosphere and very low moisture levels of the atmosphere can promote severe fire behavior without strong wind. Fire weather meteorologists can help you calculate the lower atmosphere severity index and interpret it for you. If a reverse wind profile is measured in the lower atmosphere, this can also indicate the possibility of a plume-dominated fire. The expected spread rates and intensity of plume-dominated fires can be greater than indicated by the nomogram. Precautionary measures such as warning of crews and evacuation should be considered if severe fire behavior is expected. The danger of these fires is the surprise of a high-intensity, fast-spreading fire at low windspeeds.

MAP PROJECTION

Line 26: Indicate the map scale in inches per mile.

Line 27: Record the average spread distance from line 18.

Line 28: Determine the map distance in inches, which is the product of the map scale times the average spread distance.

Line 29: Record the length-to-width ratio obtained from table 5.

Line 30: Record the width of the fire ellipse determined by dividing the spread distance by the length-to-width ratio.

Line 31: Record the map width of the fire, which is determined by multiplying the fire width by the map scale. Lay out the spread distance and fire width on a map to indicate the bounds of the fire and sketch the fire boundary in an approximate elliptical shape.

Line 32: Record the 75 percent range in rate of spread obtained from nomogram.

Line 33: Multiply the 75 percent range in rate of spread by the expected spread time to obtain the range in spread distance.

Line 34: Multiply the spread distance by the map scale to obtain the 75 percent range in map spread distance. This range in spread can also be indicated on the map, to indicate uncertainty in the expected fire size.

Notes: Record pertinent information that could affect fire behavior such as spotting or unusual fuel conditions or weather. If available, any weather forecast information used in this analysis should be attached.

Summary of Major Assumptions

- These methods are designed to provide a first approximation of the expected behavior of a running crown fire.
- Applicable to the Northern Rocky Mountains or mountainous areas with similar fuels and climate.
- The methods are designed to predict the rate of spread and other behavior features of a wind-driven crown fire and help identify the onset of a plume-dominated fire.

- Rate of spread predictions were derived from a small number (8) of fires; prediction relies on the correlation of these fires to predictions of rate of spread using the firespread model (Rothermel 1972) and fuel model 10 (Anderson 1982).
- The heat pulse associated with the development of the convection column can be interpreted from the short-term surge of energy predicted by Albini's burnout model.
- Thomas' flame length model represents crown fire flames.
- The wind can be represented by using the upper end of the forecast windspeed at the 20-ft level.
- The moisture of fuels, live and dead, can be represented by five seasonal groups.
- The period of a crown fire run can be estimated.
- The area and perimeter of a fire can be represented by a simple ellipse.
- The effect of firebrands on spreading the fire is accounted for in the correlation of spread to actual fires.
- The surging and stalling of a fire as it climbs and descends slopes can be averaged by assuming zero slope.
- The maximum spread rate can be estimated by using the maximum slope and correlation to maximum observed spread rates during the run of actual fires.
- The range in fire behavior can be reasonably represented by 75 percent confidence limits about the average rate-of-spread estimate.
- Standard fuel models, with addition of large fuels in some cases, can adequately describe the energy release of the surface fuels.
- The energy available from the overstory can be estimated by the crown needle load.
- The effect of additional heat from an understory of reproduction can be assumed to be some fraction of the overstory.
- The burning of decayed logs will increase the heat per unit area significantly, and this additional heat will have an upper limit approximated by fuel model 12.

Example 1

On August 9, 1988, the Canyon Creek fire in west-central Montana made a 5.5-mile crown fire run through the Tobacco Valley to the Continental Divide. This example illustrates application of these methods to that run of the fire.

By the first part of August, the area was in a summer drought condition with the National Fire Danger Rating System Energy Release component in the surrounding stations indicating values at the 80th to 90th percentile levels. The fire was located at a high elevation on the west side of the Continental Divide. It was burning in subalpine fir and lodgepole pine with surface fuels represented by fuel models 9 and 10. Free-air windspeeds were 20 to 25 knots, with a reported 35-knot wind being created by the fire (Bushey in preparation).

Fire activity started to pick up at approximately 2:30 p.m.; by 2:50 p.m., convection columns were evident. The run up Tobacco Valley was estimated to start at 3:30 p.m. and end at 7:00 p.m. when it reached the Continental Divide, a distance of 5½ miles. The average rate of spread during the run was 1.57 mi/h, and during the day a total increase in fire size of 7,743 acres was made in the vicinity of Tobacco Valley (Bushey in preparation).

Use of the crown fire nomogram, worksheet, and map is demonstrated in figures 16, 17, and 18.

Example 2

On August 29, 1985, the Butte fire on the Salmon National Forest suddenly increased in intensity and spread rate, and was subsequently characterized as a blowup fire (Rothermel and Gorski 1987).

The following description of the fire environment and fire behavior is taken from Rothermel and Mutch (1986):

Severe drought characterized weather in the Butte Fire area throughout the summer of 1985, contributing to critically low fuel moisture levels. The fire weather station at nearby Indianola along the Salmon River measured only 0.31 inch of precipitation in June and 0.23 inch in July. Although more than half an inch of precipitation fell on two different days in early August, some of this as snow, only 0.12 inch fell between August 13 and 31. At a remote automatic weather station near the fire, 1,000-hour fuel moisture readings from the National Fire Danger Rating System were rated at 8 percent prior to the run up Wallace Creek.

Weather on the day of the blowup, August 29, was not unusual. In the afternoon the temperature reached the mid-70's, and minimum relative humidity was in the upper teens. At base camp, low-level winds were out of the south at 8 to 12 miles per hour in the afternoon, with occasional gusts of 17 to 20 miles per hour. District personnel reported that fuel loadings ranged from 80 to 100 tons per acre in spruce-fir stands in drainage bottoms, to 25 to 40 tons per acre in higher elevation lodgepole pine-fir stands. Fuel models 8 and 10 characterized most of the Wallace Creek drainage.

On August 29 wind velocities were not especially high. In the early afternoon, eye level winds were measured at 7 to 8 miles per hour at the confluence of Owl Creek and Wallace Creek. At the higher elevation near the head of Wallace Creek, the local winds were stronger. Division Supervisor Jim Steele estimated winds to be 10 to 15 miles per hour, with gusts to 20 miles per hour across the ridges. Measurements nearby confirmed this estimate, but with gusts of 25 to 30 miles per hour.

It appears that up until about 1530, although crowning and developing strong convection columns, the fire behavior was similar to the behavior observed on the two preceding days. The spread rate was low, about ½ mile per hour. After 1530 the fire spread much faster, with an average rate of about 2 miles per hour and a maximum of about 3½ miles per hour. This period was described as a firestorm by observers.

The analysis shows that the power of the fire could have been twice as great as the power of the wind, with all conditions favoring a plume-dominated fire. Consequently, the spread rates and intensities would be greater than indicated on the nomogram. We cannot yet estimate the spread rate and intensity of such fires, except that they can be expected to be worse than indicated on the fire characteristics chart. Use of the crown fire behavior nomogram and worksheet is shown in figures 19 and 20.

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

DROUGHT SUMMER

*Canyon Crk Fire
Tobacco Valley Run 8/9/88*

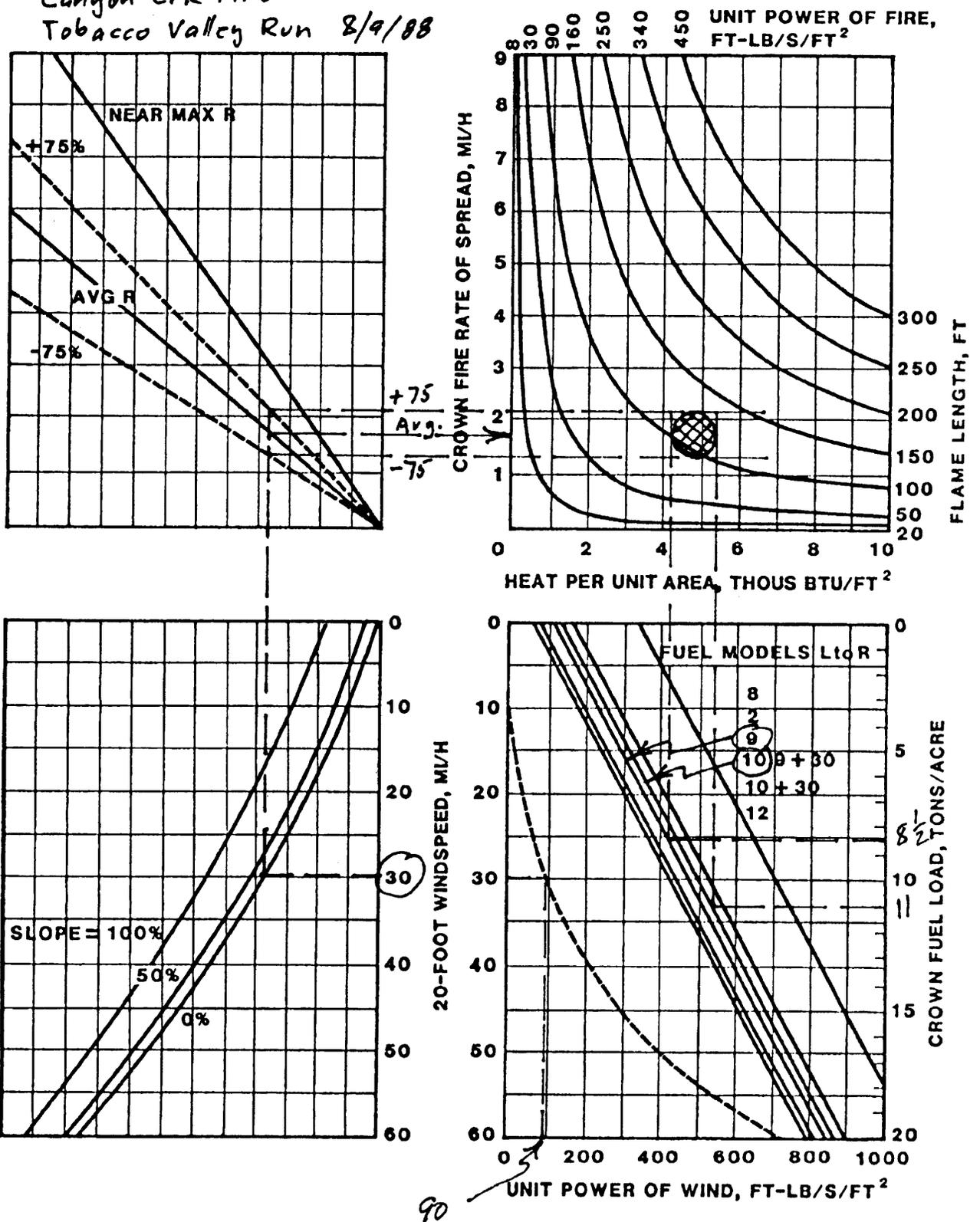


Figure 16—Example 1, crown fire nomogram.

Crown Fire Worksheet

1. Name of Fire Canyon Creek Analyst Rothermel Date _____
2. Area threatened Tobacco Valley Projection date 8/9/88
3. Expected time period of run 1530 to 1900. Elapsed time t 2 1/2 hrs.
4. Moisture condition: Early spring Late spring
 Normal summer Drought summer Extreme drought
5. Overstory species LP Pine Subalp Fir
6. DBH _____ inches
7. tree spacing _____ feet
8. crown fuel load 8.5 11 tons/acre
9. Reproduction % _____ % of overstory needles
10. Reproduction amount _____ tons/acre
11. Total crown load _____ tons/acre
12. Surface fuel model 9 and 10 9 and 10
13. Additional 1000-hr fuel _____ tons/acre, sound or decayed?
14. Forecast windspeed and direction W 10-20 knots
15. Upper value of sustained windspeed 30 mi/h Knots x 1.15 = mi/h
16. Slope: representative >10 % Maximum 30 %

Outputs

17. Average rate of spread, R 1.75 mi/h
18. Average spread distance, $D = R \times t$ 6 miles
19. Elliptical area 3,800 acres
20. Elliptical perimeter 11 miles
21. 75% range in flame length, L_f 90 to 130 feet
22. Near maximum rate of spread R_{max} _____ mi/h
23. 75% range in power of fire, P_f 80 to 140 ft•lb/s•ft²
24. Power of wind, P_w 90 ft•lb/s•ft²
25. Range in power ratio, $P_f/P_w =$.89 to 1.6 If greater than one, consider possibility of plume-dominated fire. Contact Fire Weather Meteorologist for information on

Atmospheric stability,
 Atmospheric moisture,
 LASI index,
 Wind profile.

Although strong winds were on this fire, it was probably plume-dominated when heavy fuels were encountered or when spreading upslope.

Figure 17—Example 1, worksheet.

Map Projection

26. Map scale, S 1.27 inches/mile
27. Spread distance, D 6 miles, from line 18
28. Map spread distance, D_{map} 7.6 inches. $D_{map} = S \times D$
29. Length/width ratio 4.8
30. Fire width, W_f 1.6 miles $W_f = D / (\text{length/width})$
31. Map width of fire, W_{map} 2 inches $W_{map} = W_f \times S$
32. 75% range in rate of spread 1.3 to 2.2 mi/h
33. 75% range in spread distance 4.5 to 7.7 miles
34. 75% range in map spread distance 5.7 to 9.8 inches

Notes

Figure 17—(Con.)

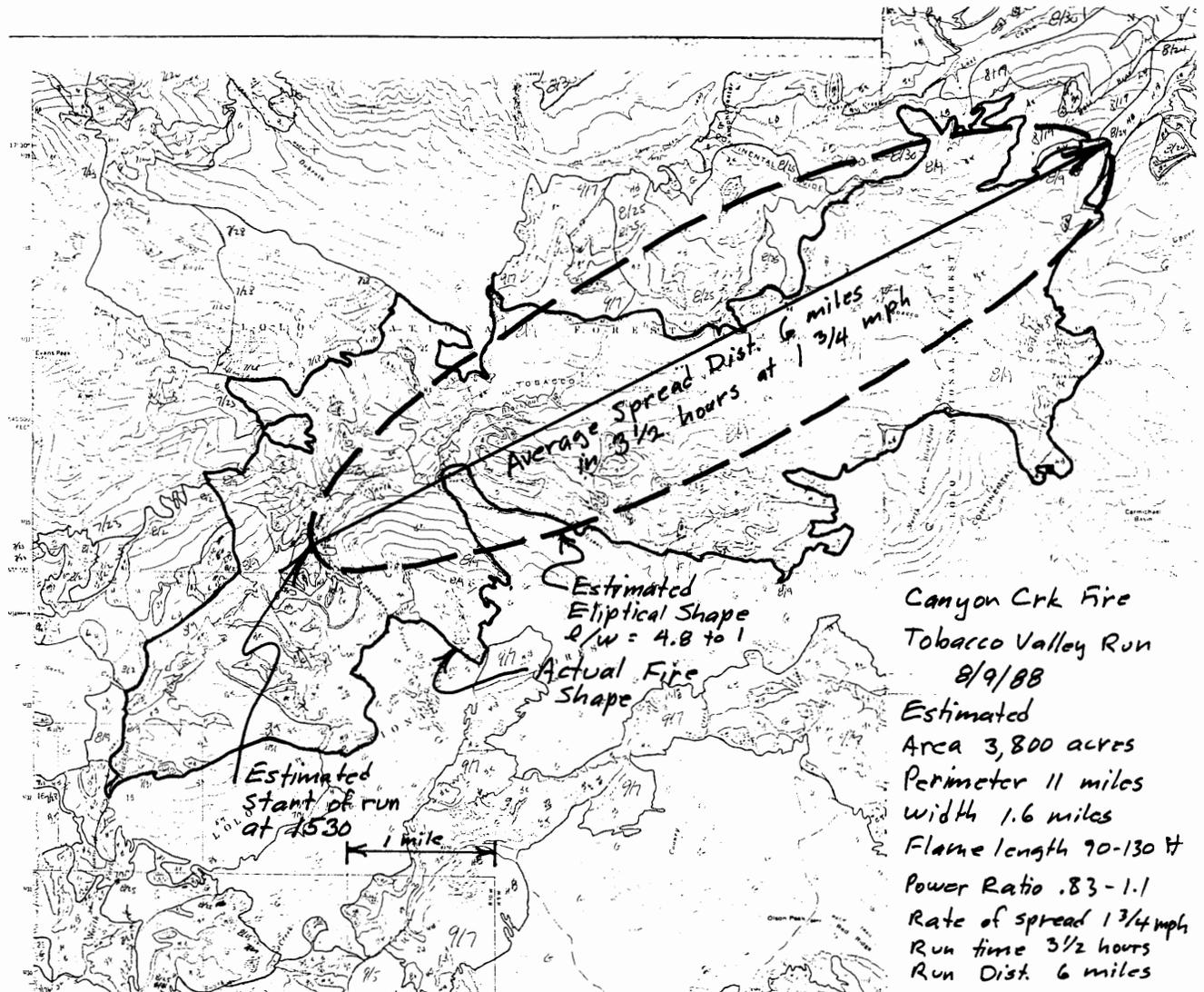


Figure 18—Example 1, fire map.

CROWN FIRE BEHAVIOR NORTHERN ROCKIES

SEVERE DROUGHT LATE SUMMER

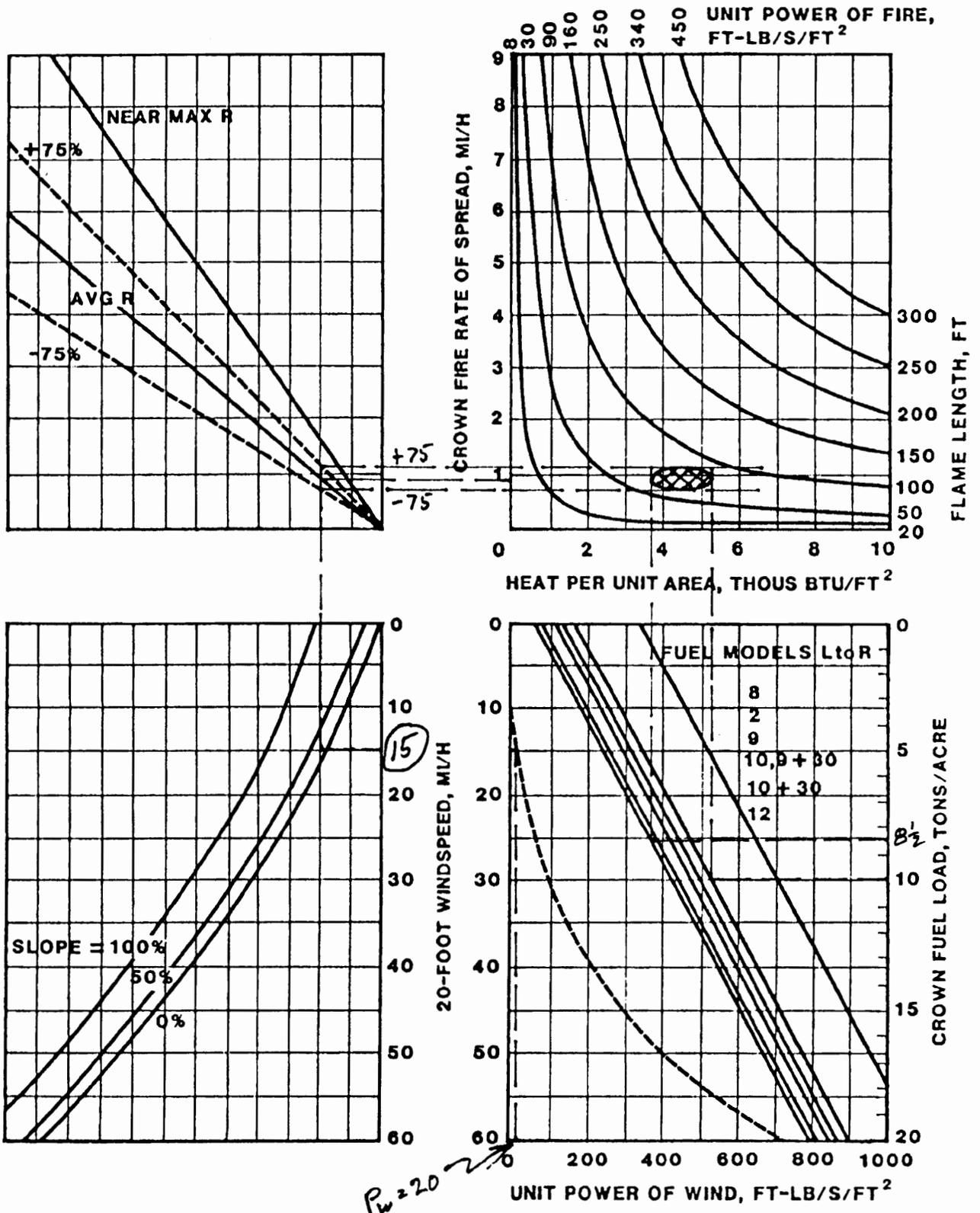


Figure 19—Example 2, crown fire nomogram.

Crown Fire Worksheet

1. Name of Fire Butte Analyst Rothermel Date _____
2. Area threatened Wallace Crk Projection date 8/29/85
3. Expected time period of run 1530 to 1610. Elapsed time t 0.6 hrs.
4. Moisture condition:

Early spring <input type="checkbox"/>	Late spring <input type="checkbox"/>
Normal summer <input type="checkbox"/>	Drought summer <input type="checkbox"/>
	Extreme drought <input checked="" type="checkbox"/>
5. Overstory species Spruce LP Pine
6. DBH _____ inches
7. tree spacing _____ feet
8. crown fuel load 12 8 1/2 tons/acre
9. Reproduction % _____ % of overstory needles
10. Reproduction amount _____ tons/acre
11. Total crown load _____ tons/acre
12. Surface fuel model 10 8
13. Additional 1000-hr fuel 30 tons/acre, sound or decayed?
14. Forecast windspeed and direction S 10-15, Gusts 20-30
15. Upper value of sustained windspeed 15 mi/h Knots x 1.15 = mi/h
16. Slope: representative 10 % Maximum _____ %

Outputs

17. Average rate of spread, R 1 mi/h
18. Average spread distance, $D = R \times t$ 0.6 miles
19. Elliptical area _____ acres
20. Elliptical perimeter _____ miles
21. 75% range in flame length, L_f 60 to 90 feet
22. Near maximum rate of spread R_{max} _____ mi/h
23. 75% range in power of fire, P_f 40 to 80 ft·lb/s·ft²
24. Power of wind, P_w _____ ft·lb/s·ft²
25. Range in power ratio, $P_f/P_w =$ 2 to 4 If greater than one,

consider possibility of plume-dominated fire. Contact Fire Weather Meteorologist for information on

Atmospheric stability,
 Atmospheric moisture,
 LASI index,
 Wind profile.

Post fire analysis found that the LASI Index was almost 6, the maximum for severe fires. Analysis showed that a reverse wind profile was probably over this and several fires in the area.

Figure 20—Example 2, worksheet.

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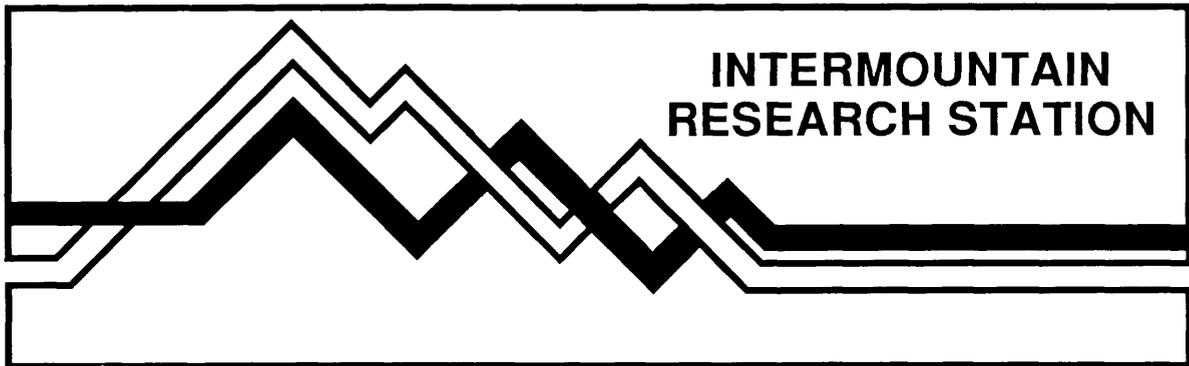
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Rothermel, Richard C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Res. Pap. INT-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 46 p.

Describes methods for approximating behavior and size of a wind-driven crown fire in mountainous terrain. Covers estimation of average rate of spread, energy release from tree crowns and surface fuel, fireline intensity, flame length, and unit area power of the fire and ambient wind. Plume-dominated fires, which may produce unexpectedly fast spread rates even with low ambient windspeeds, are covered and supplemental methods suggested for estimating their occurrence. The spread information can be used to estimate and map fire area and perimeter.

KEYWORDS: rate of spread, fireline intensity, flame length, energy release, power, fire model, crown fire, fire size



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