2

Fire Behavior

As we move from the discussion of *fire fundamentals* in Chapter 1 to *fire behavior* in this chapter, we adjust our point of view as illustrated in Figure 1.1. In Chapter 1 we examined the physical and chemical properties of fuel. Now we look at the whole complex, including such factors as the arrangement and mixture of size classes. We move from an examination of the effect of slope angle on heat transfer to the effect of the lay of the land on fire behavior. And we examine the effects of weather elements, not just the availability of oxygen to the combustion process. Because of the many variable forces influencing fire behavior, no two fires are alike. But much is known about influencing factors and their probable effect on the fire. Some relationships can be described and recognized, others can also be scientifically analyzed and modeled.

The beginning firefighter quickly becomes aware that a fire burning upslope behaves differently from one burning downslope under the same weather and fuel conditions, that windspeed and direction can quickly affect the rate and direction fire spread, and that a fire in logging debris differs from a grass fire. But many variations in the fire environment and their effects on fire are not so obvious, and skill in recognizing them comes from training and experience.

Wildland fire exhibits a tremendous range of fire behavior—from quiet smoldering in duff under a snow bank, to slow moving flames through litter and grass under a pine stand, to a blazing conflagration moving through the tops of trees. The three basic types of fire behavior are named according to the vegetation layer in which the fire is burning: ground, surface, and crown fire (Figure 2.1).

Surface fires spread by flaming combustion through fuels at or near the surface—grass, shrubs, dead and down limbs, forest needle and leaf litter, or

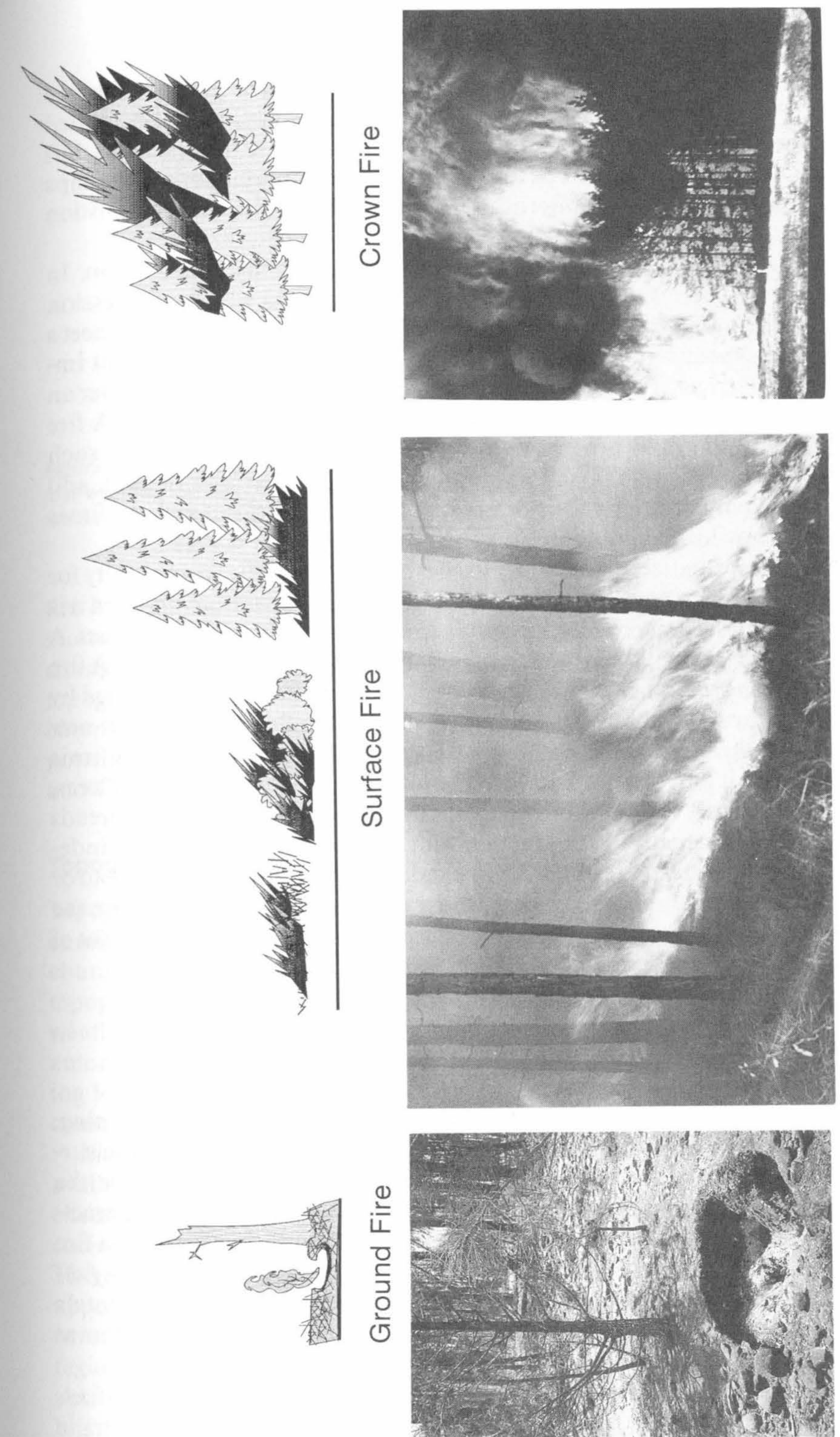


Figure 2.1. The three basic types of fire behavior are named according to the vegetation layer in which they are burning-- ground, surface and crown fire. Ground fire photograph from Dude Fire, Arizona, 1990. Photos courtesy of USDA Forest Service.

debris from harvesting or land clearing. *Crown fires* burn through the tree crowns. They are often dependent on surface fires and are invariably ignited by surface fires. *Ground fires* are fires in subsurface organic fuels, such as duff layers under forest stands, Arctic tundra or taiga, and organic soils of swamps or bogs. Ground fires burn underneath the surface by smoldering combustion and are most often ignited by surface fires.

Fires are also categorized according to human management action. In current United States terminology, *wildfires* are those on which suppression action is taken. *Management ignited prescribed fires* are ignited in order to meet a land management objective such as debris removal or wildlife habitat improvement. *Prescribed natural fires* are those that are allowed to burn under an approved plan to preserve the natural role of fire in the ecosystem. A fire management plan and prescription define acceptable conditions for such elements as time of year, location, drought condition, weather pattern, and other fire activity. If criteria for a prescribed natural fire are not met, the fire is designated a wildfire and appropriate suppression action is taken.

There is a specialized vocabulary used by the wildland fire community for describing different types of fire behavior. A fire is said to be *running* when it is spreading rapidly. It is *creeping* when it is spreading slowly with low flames. A fire is *smoldering* when it burns without a flame and is barely spreading. A fire is said to be *spotting* when it is producing sparks or embers that are carried by the wind or by the combustion column caused by the fire and that start new fires beyond the main fire. The new ignition points are called *spot fires*. A fire is *torching* when it moves from a surface fire into the crowns of individual trees, but not necessarily from one crown to another. It is *crowning* when it spreads from tree to tree, usually in conjunction with, but sometimes completely independent of, the surface fire. A *flareup* is a sudden acceleration of fire spread or intensity, of relatively short duration for a portion of the fire. A *blowup*, on the other hand, is a dramatic change in the behavior of the whole fire, the point of rapid transition to a severe fire.

2.1 THE FIRE ENVIRONMENT

Fire behavior is a product of the environment in which the fire is burning. Countryman (1972) presented the concept of the fire environment—the surrounding conditions, influences, and modifying forces that determine the behavior of a fire. Topography, fuel, weather, and the fire itself are the interacting influences that make up the fire environment. This is illustrated as a fire environment triangle with the fire in the center (Figure 2.2). While the *fire fundamentals triangle* in Chapter 1 shows the major factors in fire fundamentals (fuel, oxygen, and heat), the *fire environment triangle* shows the major factors at the fire behavior scale of our examination of fire.

The changing states of each of the environmental components—fuel, topography, and weather—and their interaction with each other and with the

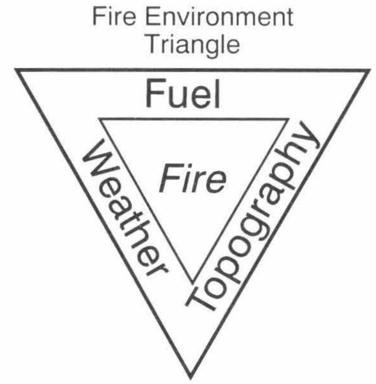


Figure 2.2. *The fire environment triangle illustrates the influencing forces on fire behavior: fuel, weather, and topography. The fire in the center signifies that the fire itself can influence the fire environment.* Based on Countryman (1972).

fire itself determine the characteristics and behavior of a fire at any given moment. Changes in fire behavior in space and time occur in relation to changes in the environmental components. From a wildland fire standpoint, topography does not vary with time, but can vary greatly in space. The fuel component varies in both space and time. Weather is the most variable component, changing rapidly in both space and time. Chapter 3 is devoted to fuel and Chapter 4 to weather.

Topography

Topography includes the elements of slope steepness, aspect, elevation, and configuration of the land. Variations in topography can cause dramatic changes in fire behavior as a fire progresses over the terrain. Although topography may not change in time, it affects the way in which fuel and weather change. The fire environment triangle symbolizes this interaction among the elements. Topography modifies general weather patterns, producing localized weather conditions that in turn affect fuel type and moisture content.

Elevation above sea level influences general climate and thereby affects fuel availability. Length of fire season and fuel vary with elevation due to differences in amount of precipitation received, snow melt dates, and greenup and curing dates. Temperature and relative humidity vary with *position on the slope*. There can be significant difference between valley bottoms, midslope, and upper slopes. The *thermal belt* is a relatively warm area at midslope where the inversion layer contacts the mountain slopes. At night, the temperature of this region can be warmer than that on the slopes above or below. The thermal belt area typically experiences the least variation in daily temperature, has the highest average temperature, and has the lowest average relative humidity.

This is significant because while areas above or below may be relatively quiet, there may be active burning in the thermal belt during the night.

Aspect is the direction a slope is facing. Aspect affects fire behavior through variations in the amount of solar radiation and wind that different aspects receive. In general, in the northern hemisphere, south and southwest aspects are most favorable for fire start and spread. These aspects receive more sunshine and therefore have lower humidities and higher fuel temperatures.

Solar radiation intensity is greatest when the slope is perpendicular to the sun angle (Figure 2.3). In the northern hemisphere, fuels on slopes with an easterly aspect will dry out earlier in the day, but not become as dry as those on slopes with a westerly aspect. Slope steepness also affects the radiation intensity and fuel moisture. The slopes where the fuel will be the driest vary with time of year, time of day, and latitude. Thus, as a fire moves over the landscape its behavior can be expected to change with time of day and topographic characteristics because of the variations brought about by the different amounts and intensity of the solar radiation received.

During the day, sunlight moves across different aspects, and air temperature, relative humidity, fuel moisture, and fuel temperature all change. An inactive surface fire on a southwest aspect in the early morning may become an active crown fire that afternoon. After the sun sets, the same fire may again become a surface fire with fire intensities that allow successful suppression action.

Slope reversal refers to fire crossing onto a slope of opposite aspect, as when a fire runs to the top of a ridge and begins to back down on the opposite slope, or when a fire backs down a slope, crosses a drainage, and begins to run up the next ridge.

Slope reversal affects rate of spread and intensity as well as airflow. Commonly, as a fire runs to the ridgetop, it encounters an opposing upslope airflow from the other side of the ridge. This effect can slow the fire spread and limit

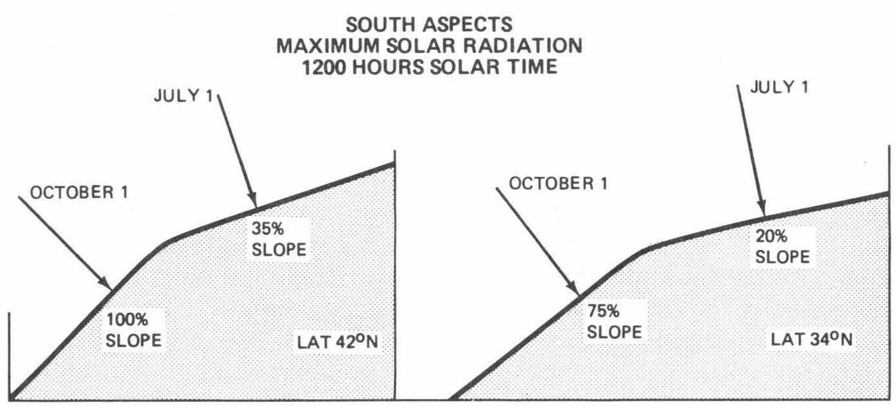


Figure 2.3. *Solar radiation is affected by aspect, slope steepness, and date. Maximum solar radiation for 1 October and 1 July for two latitudes.* From Countryman (1978).

the spotting problem on the opposite slope. Conversely, the effect of erratic winds converging at the ridgetop can contribute to spotting. A wildland fire burning near the top of the windward slope can spot across the ridgetop and onto the other slope.

Narrow canyons or ravines can affect fire behavior in several ways. A fire burning on one slope radiates a great deal of energy toward the opposite slope. This radiation can dry the fuel and preheat it enough to make it highly susceptible to ignition from sparks and embers. Occasionally, the whole slope, or a large part of it, will ignite in a matter of a few minutes. Such crossings can occur progressively, at multiple points, creating a hazardous situation for crews.

When a fire is burning in a canyon under an inversion or stable air conditions, the fire is slowly drying out fuels. When the inversion breaks, winds will increase into the canyon, and likewise fire activity will increase.

Barriers, both natural or artificial, are important terrain features. Barriers to fire spread include rocks or bare soil; lakes, streams, and moist soil situations; roads, trails, and other improvements; changes in fuel type and fuel moisture conditions; and previously burned areas. Suppression action often creates barriers by removing fuel, by line construction or by burnout. Sometimes a narrow line scratched in the litter is enough to stop fire spread; other times highways, rivers, and even lakes are not enough.

The "*chimney effect*" has claimed the lives of firefighters. A chimney, as the name suggests, depicts the topographic features of a steep narrow chute with three walls, similar to a box canyon. Normal upslope air flow is rapid and funneled to the chimney's shape. Because of upslope preheating and cross-canyon radiation, these chimneys draft a fire, much like an actual stove chimney. The chimney effect occurs when unstable air conditions at the surface create a convection current through the canyon, drawing air in at the base of the canyon and exhausting it at the top (Figure 2.4).

Slope steepness has a direct effect on flame length and rate of spread of a surface fire. Whether the wind or slope has the greatest effect depends on their relative force. A strong wind can push a fire downslope.

When a fire burns up a steep slope the convection column sometimes becomes "trapped," flowing upward along the slope for a considerable distance (Figure 2.5). At other times, the column separates from the slope at or very near the fire edge. Attachment of the flame to the slope will reduce the scorch height in trees from what would be expected on level ground where the flames stand vertically. But further up the slope at a ridge line where the convection column breaks from the surface and rises, the concentration of hot gases will result in higher scorch than expected on the flat.

Fuel

The influence of fuel on fire behavior is so important that Chapter 3 is devoted to the subject. In Chapter 1 we examined intrinsic fuel parameters and their role in the combustion process. When looking at the behavior of wildland fire, we examine other features of the fuel: the mixture of live and dead fuel, the

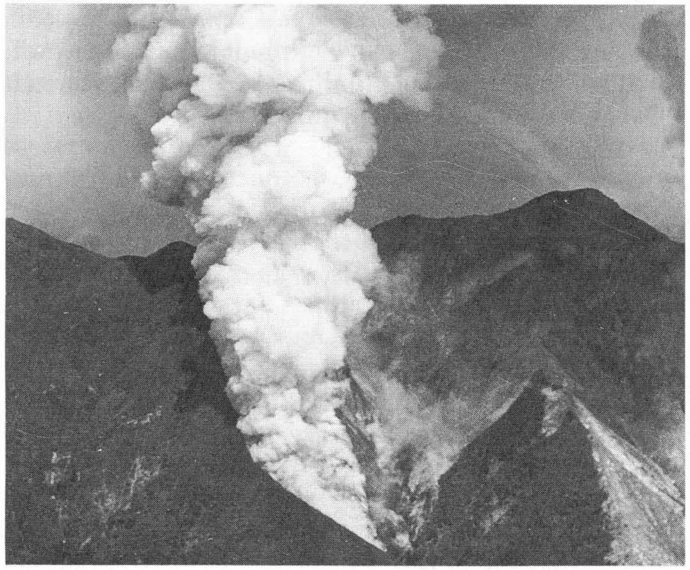


Figure 2.4. *Chimney effect on a fire in Southern California.* Courtesy of USDA Forest Service.

arrangement and size of fuel particles, and fuel moisture. As we move from fire fundamentals to the fire behavior scale we look at the whole fuel complex, which includes ground, surface, and crown fuels.

Fuel can be described in terms of both fuel state and fuel type. Fuel state refers to the moisture content of the fuel and whether it is live or dead. A description of fuel type includes horizontal and vertical continuity of the fuel, size and shape of components, compactness, and so on.

Weather

Weather influences are discussed throughout this chapter and as a separate topic in Chapter 4. Temperature, relative humidity, and precipitation affect fuel moisture. Wind is a dominant influence on fire behavior. It is also one of the hardest elements to predict due to variability of windspeed and direction and the influences of topography, vegetation, and local heating and cooling.

Wind is measured and forecasted at 20 ft above the vegetation in the United States (10 m in most of the rest of the world). The wind on a surface fire can be considerably less, as shown by the wind profile in Figure 2.6. A table of wind adjustment factors has been prepared to adjust 20-ft wind to the wind that influences a surface fire, called midflame wind. The adjustment factors account for the decrease in windspeed according to the wind profile as well as the effect of topography and sheltering by the overstory.

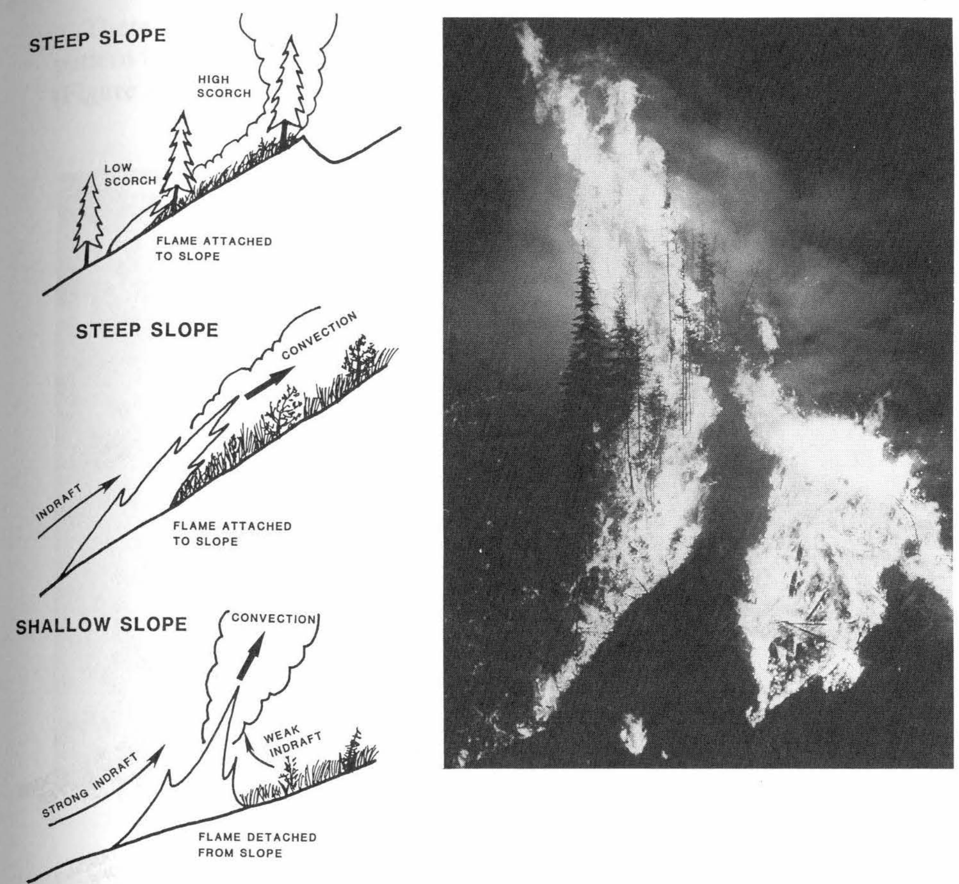


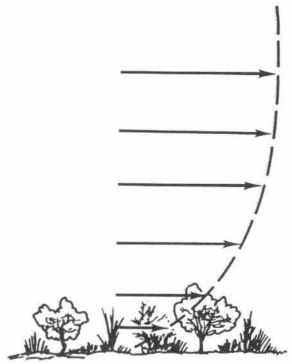
Figure 2.5. *Slope steepness affects fire behavior. Flames detached from a shallow slope and attached to a steep slope. Scorching conditions can be higher at the top of a steep slope.* From Rothermel (1985). Photo by Roberta A. Hartford, USDA Forest Service.

Fire Interaction With the Environment

The fire in the center of the fire environment triangle (Figure 2.2) symbolizes the interaction between the fire and the environment. Fire behavior is generally determined by the fuel, weather, and topography. But in some cases the fire itself influences the environment and thus the fire behavior, a feedback loop. Heating from the fire can modify or produce local winds, contribute to atmospheric instability, and cause cumulus cloud development. At the extreme, a combustion column can build to the point where it can generate lightning, rain, and dangerous downbursts.

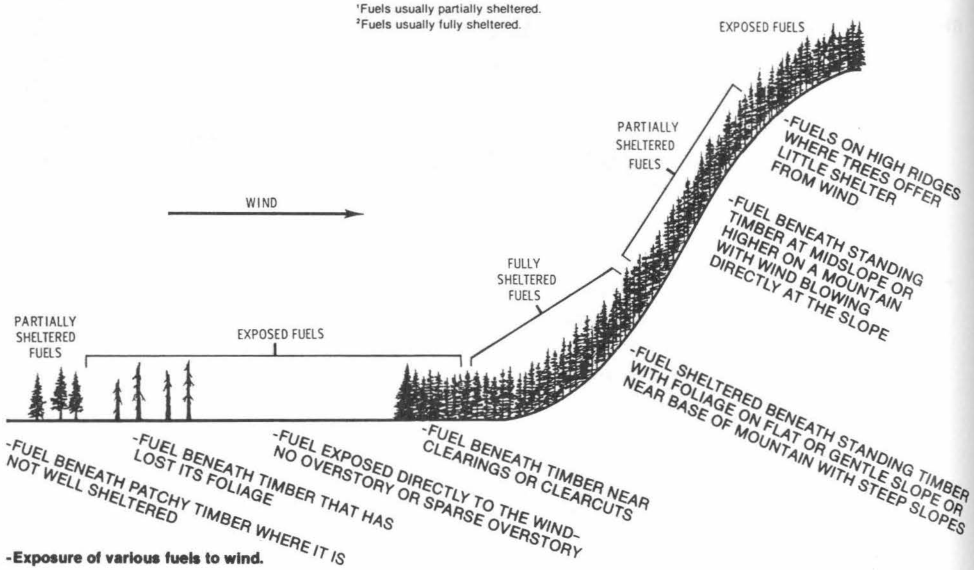
Water vapor is formed in the combustion process and from the moisture in the burning fuel. This vapor is carried aloft in the smoke or convection column

Wind adjustment table. Find the appropriate adjustment factor and multiply it by the 20-ft windspeed. Use the result as the midflame windspeed



Fuel exposure	Fuel model	Adjustment factor
EXPOSED FUELS		
Fuel exposed directly to the wind— no overstory or sparse overstory; fuel beneath timber that has lost its foliage; fuel beneath timber near clearings or clearcuts; fuel on high ridges where trees offer little shelter from wind	4	0.6
	13	0.5
	1,3,5,6,11,12 (2,7)[1] (8,9,10)[2]	0.4
PARTIALLY SHELTERED FUELS		
Fuel beneath patchy timber where it is not well sheltered; fuel beneath standing timber at midslope or higher on a mountain with wind blowing directly at the slop	All fuel models	0.3
FULLY SHELTERED FUELS		
Fuel sheltered beneath standing timber on flat or gentle slope or near base of mountain with steep slopes	All fuel models Open stands	0.2
	Dense stands	0.1

[1]Fuels usually partially sheltered.
[2]Fuels usually fully sheltered.



-Exposure of various fuels to wind.

Figure 2.6. *Windspeed must be adjusted from the 20-ft height to midflame level. Diagram shows the general wind profile near the surface. Table and diagram give adjustment factors based on fuel types, canopy cover, and topography.* From Rothermel (1983).

and can contribute to the formation of a white "cap." The heat released when the vapor condenses can add significant amounts of energy to the convection column, increasing its strength and adding to the fire activity. A fire is said to create its own wind when the column builds to the point where air rushes into the fire to replace air evacuated by the combustion column.

There is an interaction between fire and its environment when the ignition pattern is used by expert burners to modify the behavior of a prescribed fire (Figure 2.7). One strip or line of fire may be ignited, then additional parallel

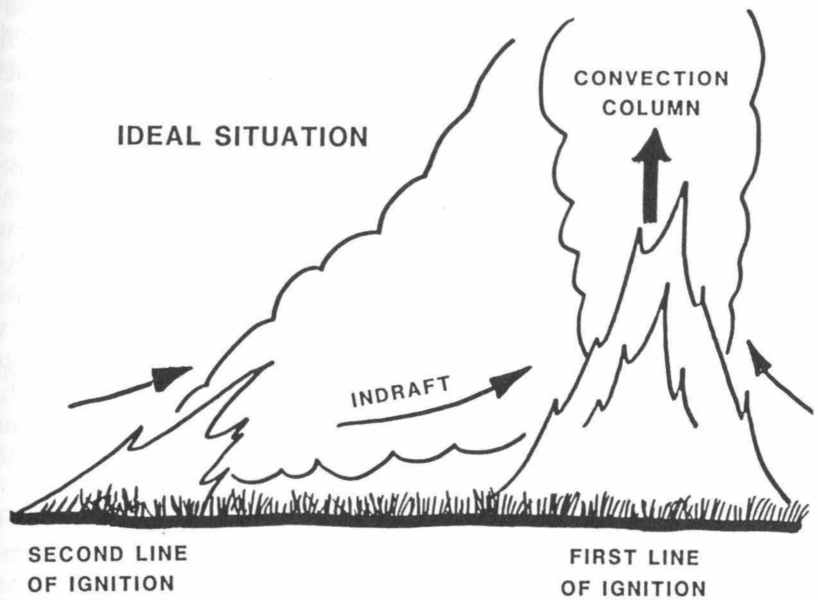


Figure 2.7. *The pattern of ignition can affect the behavior of the fire.* Strip fire photograph from Kilgore and Curtis (1987). Diagram from Rothermel (1985).

strips timed and spaced so that each portion of the fire generates enough heat to create an indraft and draw in the next. Similarily, ignition may begin with a substantial central area followed by ignitions around the premimeter that are drawn to the center.

These principles are also used as suppression techniques on a wildfire. A *backfire* lit in front of the main fire draws into the main fire, eliminating fuel for further fire spread. This differs from a *burnout* operation on a wildfire where a fire is lit for the purpose of eliminating fuel along prepared firelines or in an area the fire has not yet reached. The backfire directly affects the behavior of the main fire while a burnout affects the main fire when it reaches the barrier of an area of no fuel.

2.2 FIRE GROWTH

A wildland fire goes through several stages: ignition, transition to a spreading fire, acceleration or buildup of spread rate, and spread at a steady-state rate; sometimes a fire continues to increase in intensity, exhibiting elements of extreme fire behavior.

Ignition

Wildfires start from lightning strikes and from a variety of human causes including discarded cigarettes, sparks from equipment, and arched power-lines. Prescribed natural fires, by definition, start by lightning. Management ignited prescribed fires are started by techniques and equipment designed for that purpose. Ignition is determined by the relationship between the heat available from the ignition source and the heat required to bring the fuel to ignition, as described in Chapter 1. Schroeder (1969/unpublished, described by Bradshaw 1983) developed an estimate for probability of ignition based on the heat of preignition, the net amount of heat necessary to raise the temperature of a fuel particle from its initial temperature to its ignition temperature. The model is also based on the results of a study by Blackmarr (1972), who measured the influence of moisture content on the ignitability of slash pine litter by dropping lighted matches onto fuel beds conditioned to different levels of moisture content. Probability of ignition is the chance that an ignition will result if a firebrand lands on flammable material. Schroeder defined probability of ignition as a function of fuel moisture and of fuel temperature, which is estimated from ambient temperature and shading. Figure 2.8 shows example calculations of probability of ignition for a range of fine dead fuel moistures and ambient temperatures when fuel shading is 40%.

Lightning is an important source of ignition in some parts of the world. It is especially important when it occurs without rain. An extraordinary lightning episode on 30 August 1987 started 1600 fires in Southwest Oregon and Northwest California. Emissions from the Silver Fire, the largest of the fires that started that day, was discussed as an example in Chapter 1.


```
IGNITE
 1--DRY BULB TEMPERATURE, F      40.0  60.0  80.0 100.0 120.0
 2--1-HR FUEL MOISTURE, %         2.0   4.0   6.0   8.0  10.0  12.0  14.0
 3--FUEL SHADING, %              40.0
```

PROBABILITY OF IGNITION, % (V4.0)

DRY BULB TEMP (F)	1-HR FUEL MOISTURE, % 2.	4.	6.	8.	10.	12.	14.
40.0	90.	70.	50.	40.	30.	20.	10.
60.0	90.	70.	50.	40.	30.	20.	20.
80.0	100.	80.	60.	40.	30.	20.	20.
100.0	100.	80.	60.	50.	40.	30.	20.
120.0	100.	90.	70.	50.	40.	30.	20.

Figure 2.8. *Example calculations for probability of ignition for a range of dead fuel moistures and ambient temperatures when fuel shading is 40%. Calculations from the BEHAVE fire behavior prediction system.* From Andrews (1986).

Lightning, or course, is a unique ignition source, supplying more energy to a fuel than most other sources, and the probability of ignition relationship described above does not apply. Latham and Schlieter (1989) developed equations for probability of ignition for lightning continuing currents. The relationships were based on laboratory experiments where the effect of several variables was examined. The most important of the variables associated with the discharge was its duration. They also found that moisture content (for moistures less than 40%) played a very small role in the ignition of duff from short-needled species; fuel depth was more influential. In the case of litter and duff from long-needled species, ignition probabilities depended mostly on the fuel moisture.

Point Source Fire

Wildfires generally start at a single point. In some cases there is a significant delay from ignition until the fire begins to spread. These fires are sometimes referred to as *holdover* fires. A lightning strike may cause the heart of a standing dead tree, or snag, to smolder for weeks before weather conditions change and fuels dry to the point where flaming spread is possible. An ignition may even smolder in ground fuels over the winter.

There is a period of time, referred to as *buildup* or *acceleration time*, from the time spread begins until the fire reaches an *equilibrium* or *quasi-steady-state* *spread rate.* The "quasi" is added because there is no actual steady-state in wildland fire. The relationship used in the Canadian Forest Fire Prediction System (Forestry Canada Fire Danger Group 1992) is shown in Figure 2.9. The relationship is based on experimental data from both laboratory and field for open canopy fuel types. The time required to reach equilibrium rate of spread from a point source ignition was found to be constant, regardless of weather conditions.

Fire spreads most rapidly in the direction of local wind and in the direction of upslope in uneven terrain. The fastest-spreading part of the perimeter is called the *front* or *head*; the slowest-spreading part is called the *back*. The lateral portions, or *flanks*, spread at intermediate rates. Growing from a point of ignition, a fire in uniform fuel on smooth terrain achieves an elongated shape under the influence of wind. As pointed out by Albini (1992), "it is a remarkable fact that the general shape is the same for a savanna fire, a shrub fire, or a timber crown fire."

An ellipse is often used to quantify the shape of a point source fire (Figure 2.10). The length-to-width ratio is greater with increasing windspeed. The more uniform the conditions, the closer to the elliptical shape. Given an estimate for the head fire rate of spread, the ellipse equation can be used to calculate the flanking and backing spread rates. Variation in fire shape is a result of fuel type changes, barriers, effect of slope and wind, and spotting.

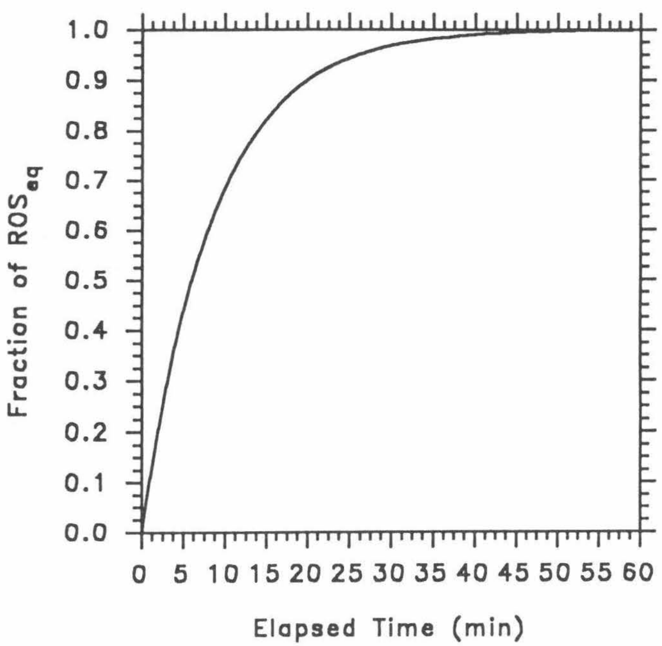


Figure 2.9. *Fire acceleration model for open canopy fuel types used in the Canadian Fire Behavior Prediction System.* From Forestry Canada Fire Danger Group (1992).

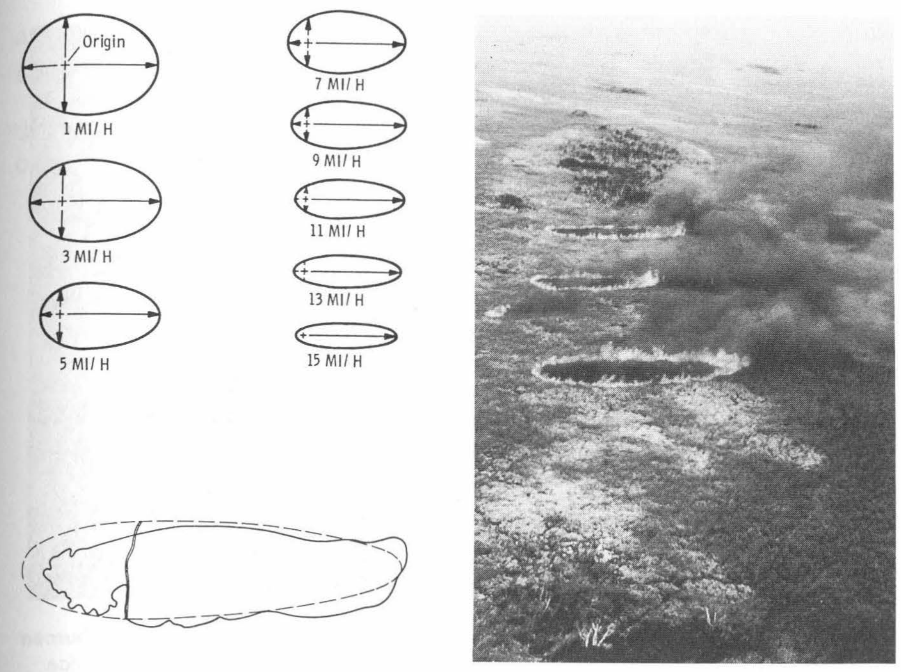


Figure 2.10. *Many fires have been shown to be approximately elliptically shaped. Length-to-width ratio of fire shape is a function of windspeed.* From Rothermel (1983). *Wandilo Fire in South Australia 1958.* From Anderson (1983). *Everglades NP photo courtesy of USDI National Park Service.*

Large Fires

A fire *spreads* by igniting new fuel along its outer perimeter. It may *grow* through ignition of fuel that is remote from its edge by producing burning embers or sparks that are transported by wind and the fire's convection column. All of the area inside the fire perimeter may not be burned. Figure 2.11 shows a burn mosaic resulting from a fast-moving fire in Yellowstone National Park in 1988.

Kerr and others (1971) characterized eight types of large fires, as summarized in Figure 2.12 and shown in Figure 2.13. The types are concerned with relationships between the convection column and the wind. They related the types to characteristics of spread, spotting potential, and smoke drift.

A Type I fire occurs with low surface windspeeds and low to moderate speeds aloft. Instability is usually present near the ground. A towering convection column, which may reach to 25,000 to 50,000 ft, remains vertical. The convection column may cause the fire to spread faster than would be predicted by surface wind observations. Virtually all combustion products are carried aloft in the rapidly rising convection column so smoke is negligible near the ground. For the same reason, spotting is minimal because potential firebrands

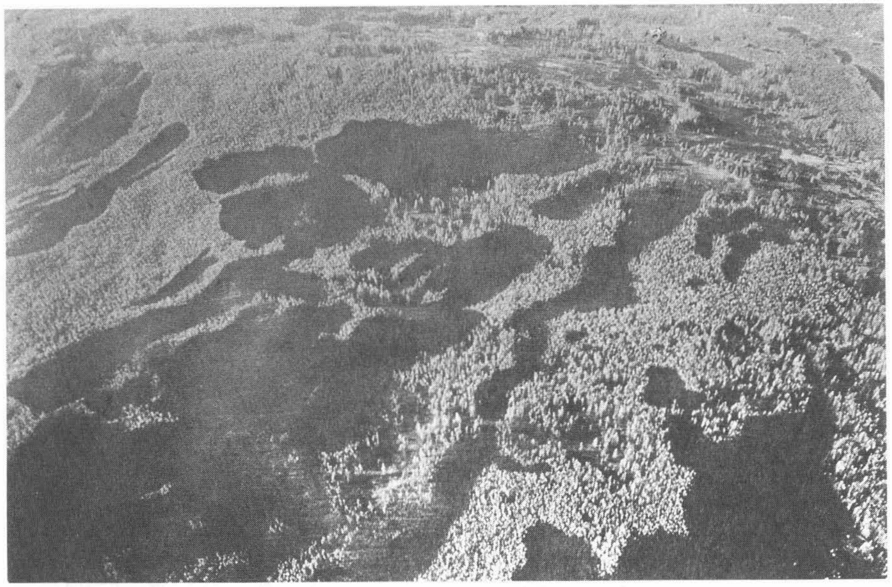


Figure 2.11. *Rapidly spreading crown fires generally leave a mosaic of burned and unburned fuel, Yellowstone National Park, 1988.* Photo by Robert A. Hartford, USDA Forest Service.

No	Type	Dominant Features
I	Towering convection column with light surface winds	Moderate to rapid fire spread persistent until changes in the atmosphere or fuel
II	Towering convection column over a slope	Rapid short-term spread with convection cutoff at ridge crests
III	Strong convection column with strong surface winds	Fast, shifting spread with short-range spotting
IV	Strong vertical convection cutoff by wind shear	Steady or shifting spread with occasional long-range spotting
V	Leaning convection column with moderate surface winds	Rapid, shifting spread with both short- and long-range spotting
VI	No rising convection column under strong surface winds	Very rapid spread driven by combined fire and wind energy; frequent close spotting
VII	Strong surface winds in mountainous topography	Rapid spread both up- and down-slope with frequent spotting and area ignition
VIII	Multiple head fires (mostly types I through V)	Broad fire front with two or more independent convection columns

Figure 2.12. *Summary of large fire types.* Based on Kerr and others (1971).

are carried so far aloft that they burn out before dropping back to the ground.

Type II fires burn in mountainous terrain under wind and stability conditions similar to those of Type I fires. The driving force for fire spread is not only the convection column but also the tilt of the slope, resulting in an

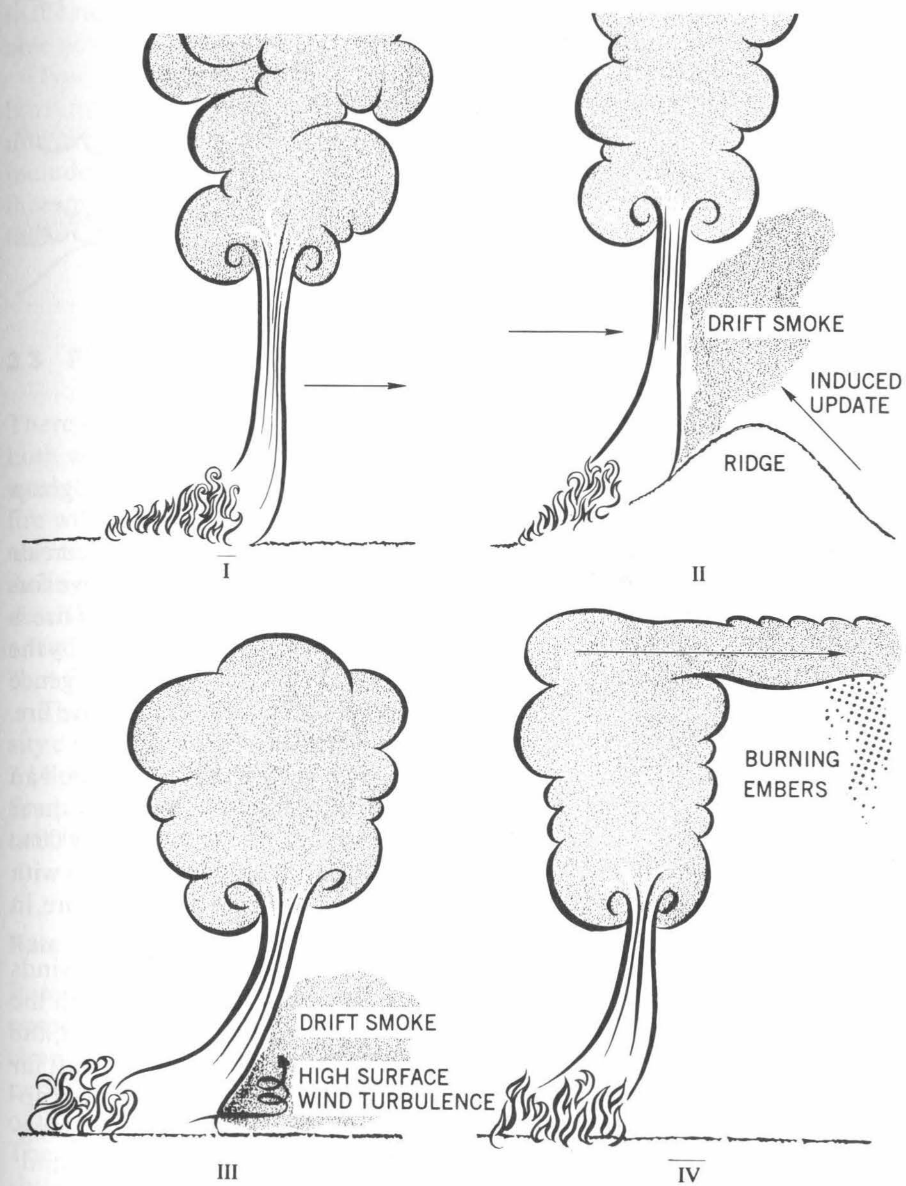


Figure 2.13. *Large fire types.* From Kerr and others (1971).

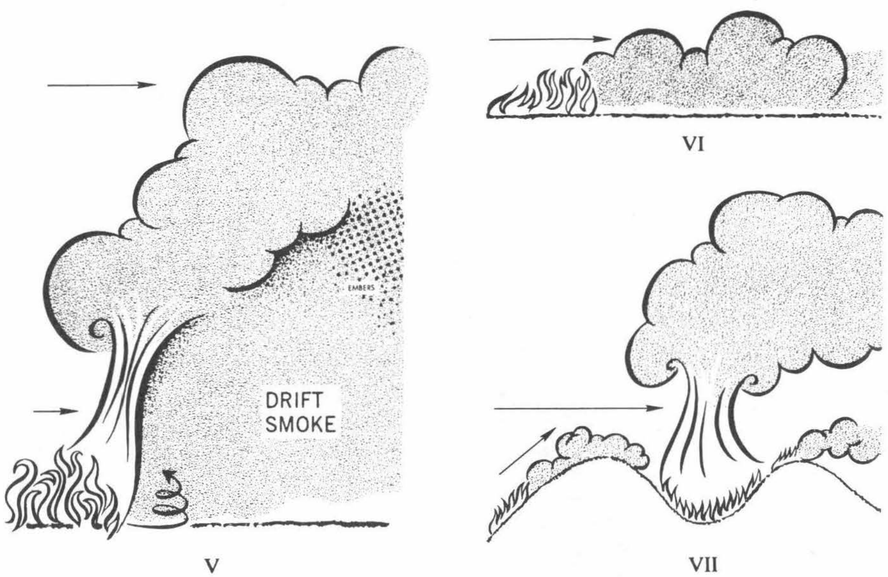


Figure 2.13. (Continued)

increased rate of spread. Smoke is plentiful along the slope to the ridgetop where it moves off into the upper air.

Type III fires burn under the influence of strong surface winds with decreasing winds aloft. They develop a towering convection column and move forward more rapidly than Type I fires. The driving energy for this type of fire is derived from the force of the convective activity strongly supplemented by the force generated by the strong surface winds. These winds form a convergence zone ahead of the fire with resulting strong vorticity at the head of the fire. There is usually considerable smoke for some distance downwind.

Large fires often occur under conditions typical of Types I or III, but with an otherwise towering convection column sharply cut off by a strong wind shear aloft, called a Type IV fire. This discontinuity in windspeed is common 5000 to 10,000 ft above the surface. This represents a highly dangerous situation with respect to long-distance spotting. Spot fires may occur 6 to 10 miles, or more, in advance of the fire front.

Type V fires occur when winds aloft increase with altitude. The strong winds aloft are usually accompanied by at least moderate surface winds. With the increased mixing of the convection column with the ambient air aloft, the column becomes quite disorganized or diffused with smoke carried aloft far downwind. Under these conditions there is also considerable smoke for appreciable distances in advance of the fire front. There is both short- and long-range spotting, becoming less frequent with increasing distance downwind.

Type VI fires are essentially wind-driven, occurring in neutrally stable to stable atmosphere. Strong surface winds prevent the convection column from

rising more than a short distance above the surface. Smoke is often carried forward in a narrow ribbon for perhaps a hundred miles or more with slight dissipation. Spotting is confined to short distances ahead of the fire front.

Type VII fires burn under the conditions described for Type VI fires, but in mountainous topography they spread up the windward slopes with extreme rapidity, while showering great numbers of firebrands ahead of the fire. This area ignition, coupled with the highly turbulent winds in lee areas, can result in the rapid development of mass fire with extreme heat outputs and considerable convection activity causing very complex fire behavior patterns.

Type VIII fires, multiple-headed fires, are included because any intensely burning fire such as those described in Types I through VII tend to break up into two or more separate head fires when the fire front becomes long. Causes include variation in fuel and terrain, barriers, and separate convective cells in the atmosphere. These multiple heads may result in unburned islands of fuel.

2.3 FIRE SPREAD AND INTENSITY

There is a need to characterize rate of spread and intensity of wildland fire, both wildfire and prescribed fire. In the planning stages, this information is used to define the conditions under which a management ignited prescribed fire will be conducted, both to achieve the stated objectives of the burn and also to retain control of the fire. Predicted spread rate and intensity are used during a wildfire in determining suppression tactics. And it is important to describe the character of the fire for an evaluation of fire effects; it is less than adequate to do an analysis of vegetation response to "fire" versus "no fire" or to "hot fire" versus "cool fire."

The range of fire characteristics is tremendous, with spread rate and intensity covering ranges of values that can span three orders of magnitude. Figure 2.14 gives example values for rate of spread and total heat load related to nonfire physical phenomena. Flame length and fireline intensity values are related to fire suppression activities.

Rate of Spread

Rate of spread is measured from any point on the fire perimeter in a direction perpendicular to the perimeter. Rate of spread can vary considerably due to changing conditions, and is generally taken to be an average value over a period of time. The fastest rate of spread (ROS) is the forward ROS at the head of the fire. The backing ROS is much less, the flanking ROS is intermediate. The behavior of a backing or flanking fire can, however, change quickly with a shift in the wind. A 90° wind shift can change a long, slow-spreading flanking fire into a fast-spreading head fire.

RATE OF SPREAD

RATE OF SPREAD ft/min	TYPICAL FIRE SITUATION	EQUIVALENT TO
1	Litter fire, no wind, no slope	Line building rate for one person in heavy fuel
25	Aged medium slash, 100% slope	Backpacker going up 100% slope
250	Low sagebrush, Santa Ana wind	Brisk walk on level ground
800	Chaparral, Santa Ana wind	Good pace for a marathon run
1200	Dry, short grass high wind	4-minute mile

TOTAL HEAT LOAD

HEAT LOAD Btu/ft^2	FUEL CONSUMED tons/acre	ENERGY RELEASED ON 1 FT^2 WOULD
300	0.75 (grass)	Warm up 2 quarts of stew
1200	3 (tall grass)	Boil away 1 pint of water
4000	10 (1 in. pine duff)	Open car thermostat (5 gal. system)
12,000	30 (thinning slash)	Heat 10 Pulaski heads to full cherry red
48,000	120 (heavy logging debris)	Melt down an aluminum engine block (115 lb)

FLAME LENGTH AND FIRELINE INTENSITY

FLAME LENGTH feet	FIRELINE INTENSITY Btu/ft/sec	FIRE SUPPRESSION INTERPRETATION
< 4	<100	Fire can generally be attacked at the head or flanks by persons using handtools. Hand line should hold the fire.
4-8	100-500	Fires are too intense for direct attack on the head by persons using handtools. Handline cannot be relied on to hold fire. Equipment sucn as plows, dozers, pumpers, and retardant aircraft can be effective.
8-11	500-1,000	Fires may present serious control problems--torching, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
>11	>1,000	Crowning, spotting, and major fire runs are probable. Control efforts at the head of the fire are ineffective.

Figure 2.14. *Examples of rate of spread and total heat load related to nonfire physical phenomena. Flame length and fireline intensity related to fire suppression activities.* Based on unpublished training notes, F. A. Albini.

Slope and wind affect the spread rate similarly because of the effect of tipping the flames toward or away from the fuels ahead of the fire. Interaction between wind and slope depends on magnitude and direction of influence of each (Figure 2.15). If wind is blowing upslope there is a cumulative effect and the head fire moves upslope, a common occurrence. It is also possible, however, for a fast-spreading fire to move downslope, as a chaparral fire under Santa Ana wind conditions.

The fuel element that has the greatest effect on the spread rate of a surface fire is the fine dead fuel—small twigs, grasses, and leaf and needle litter. Burnout of heavy fuels and duff continue after the flaming front has passed.

Intensity and Flame Length

Intensity is heat release per unit time. There are several ways of characterizing intensity. Reference is sometimes made to the intensity of the whole fire, but quantification of intensity for a specific area of the perimeter is appropriate for most applications. General principles of intensity and heat release were discussed in Chapter 1. Here we describe the intensity calculations as used in the United States fire behavior prediction system, BEHAVE. The equations are summarized in Figure 2.16. *Reaction intensity* is a heat release rate and is part of

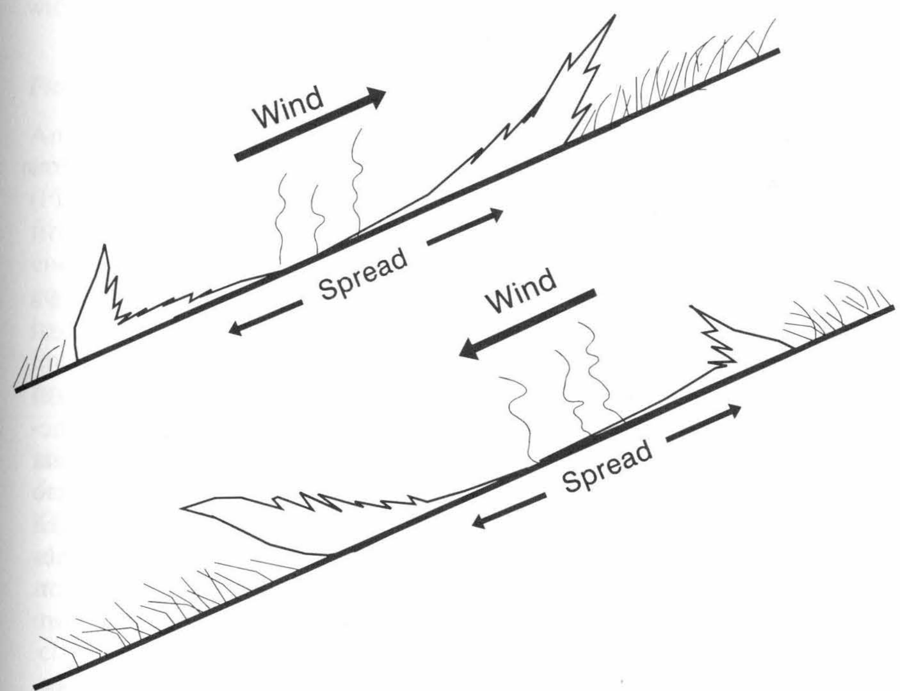


Figure 2.15. *The influence of wind and slope depends on the magnitude of each. The head fire may burn either up- or downslope.* Based on Rothermel and Rinehart (1983).

$$t_r = 384/\sigma$$

$$D = Rt_r$$

$$H_A = I_R t_r$$

$$I_B = I_R D/60 = I_R R t_r/60 = H_A R/60$$

$$F_L = 0.45 I_B^{0.46}$$

where

σ = characteristic surface-area-to-volume ratio of the fuel array, ft^2/ft^3
t_r = flame residence time, min
R = rate of spread, ft/min
D = flame depth, ft
I_R = reaction intensity, $Btu/ft^2/min$
H_A = heat per unit area, Btu/ft^2
I_B = Byram's fireline intensity, Btu/ft/s
F_L = flame length, ft

Figure 2.16. *Intensity equations used in the BEHAVE fire behavior prediction system.* From Andrews (1986).

Rothermel's fire spread model (1972). It is the heat released per minute from a square foot of fuel while in the flaming zone. *Heat per unit area* is the heat released from that square foot of fuel for the whole time the flaming zone is in that area. Heat per unit area is calculated from reaction intensity times *residence time.* Flame residence time was found by Anderson (1969) to be a function of the diameter of the fuel. *Byram's fireline intensity* (1959) is the heat released per second from a foot wide section of fuel extending from the front to the rear of the flaming zone, the *flame depth.* Fireline intensity is calculated from the reaction intensity times the flame depth, or heat per unit area times rate of spread. *Flame length* is a function of fireline intensity. Fire suppression interpretations of flame length and fireline intensity were given in Figure 2.14.

Example calculations of fire behavior from the BEHAVE fire behavior prediction system are given in Figure 2.17. This shows a comparison of calculated rate of spread, heat per unit area, and flame length for two sets of fuel moisture conditions for five fuel types. This illustrates the fire model's ability to reflect a wide range of behavior.

ENVIRONMENTAL CONDITIONS:						
Dead fuel moisture, %	4			10		
Live fuel moisture, %	70			200		
Midflame windspeed, mi/h	4			4		
Terrain slope, %	30			30		
FUEL MODEL	RATE OF SPREAD ch/h	HEAT PER UNIT AREA Btu/ft^2	FLAME LENGTH ft	RATE OF SPREAD ch/h	HEAT PER UNIT AREA Btu/ft^2	FLAME LENGTH ft
1--Short dead grass	87	96	4.5	43	59	2.6
4--Chaparral	95	2972	23	24	1570	9.1
5--Brush, 2 ft.	31	736	7.3	4	226	1.7
9--Hardwood litter	9	416	3.1	6	330	2.3
12--Heavy logging slash	19	3701	12.1	12	2933	8.9

Figure 2.17. *Calculations from the BEHAVE fire behavior prediction system for five fuel types and two sets of moisture conditions.* Based on Andrews (1986).

Fire Characteristics Chart

Andrews and Rothermel (1982) presented the concept of the fire characteristics chart as a way to display several fire behavior values as a single point (Figure 2.18). The fire characteristics chart for surface fires can display four fire characteristics simultaneously: rate of spread, heat per unit area or unit energy, fireline intensity, and flame length. The relationships are given in the equations in Figure 2.16. The chart lends itself well to classifying fire intensity by adjective ratings and color codes. Lines of equal fireline intensity and flame length on the fire characteristics chart correspond to the suppression interpretations in Figure 2.14.

The values for the low moisture conditions from Figure 2.17 are plotted on the fire characteristics chart in Figure 2.18. The range of behavior in different fuel types under the same moisture, wind, and slope conditions is evident. Grass fuels spread very fast, but with a low heat per unit area. Heavy logging slash spreads slower, but with a very high heat per unit area. Chaparral burns with both a high rate of spread and a high heat per unit area. It is possible for two fires to have the same calculated flame length, but to have very different character—high rate of spread and low heat per unit area, or low rate of spread and high heat per unit area.

Rothermel (1991c) expanded the surface fire characteristics chart to make it applicable for crown fires. That chart uses an alternate flame length model

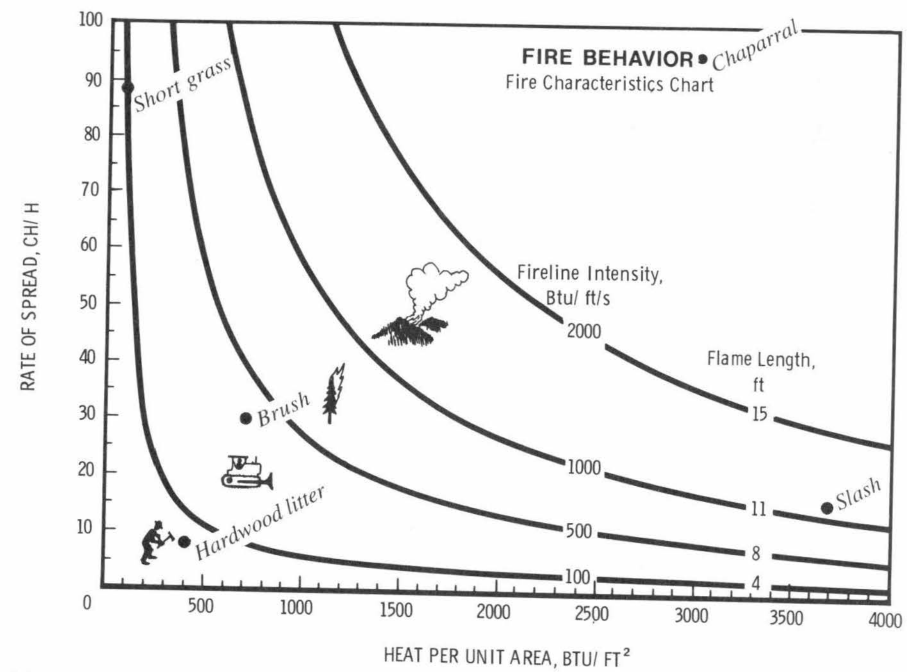


Figure 2.18. *Low moisture fire behavior values from Figure 2.17 plotted on a fire characteristics chart.* Based on Andrews and Rothermel (1982).

developed by Thomas (1962) and the large fuel burnout model developed by Albini (1976a). The crown fire characteristics chart includes methods for estimating the energy generated by the fire and a means of estimating whether crown fires will be wind-driven or dominated by the convection column (plume-dominated). Figure 2.19 is a plot of the fire behavior of two fires that are described as selected examples at the end of the chapter.

The crown fire characteristics chart shows the difference between surface fire and crown fire intensity, and the potential change in behavior as a fire moves from surface to crown. The chart also indicates the small range of behavior wherein control of fires can be expected to be successful (see Figure 2.14).

2.4 EXTREME FIRE BEHAVIOR

Several fire-dependent aspects of fire behavior are grouped for discussion here under the label "extreme fire behavior." They are characteristics that go beyond those exhibited by the majority of fires. Aspects of fire behavior that are included here as "extreme" include crowning, torching, horizontal roll vortices, spotting, and fire whirls. Although relatively few fires exhibit extreme fire behavior characteristics, the fires that do are very important. They can cause problems with safety, control, and suppression effectiveness.

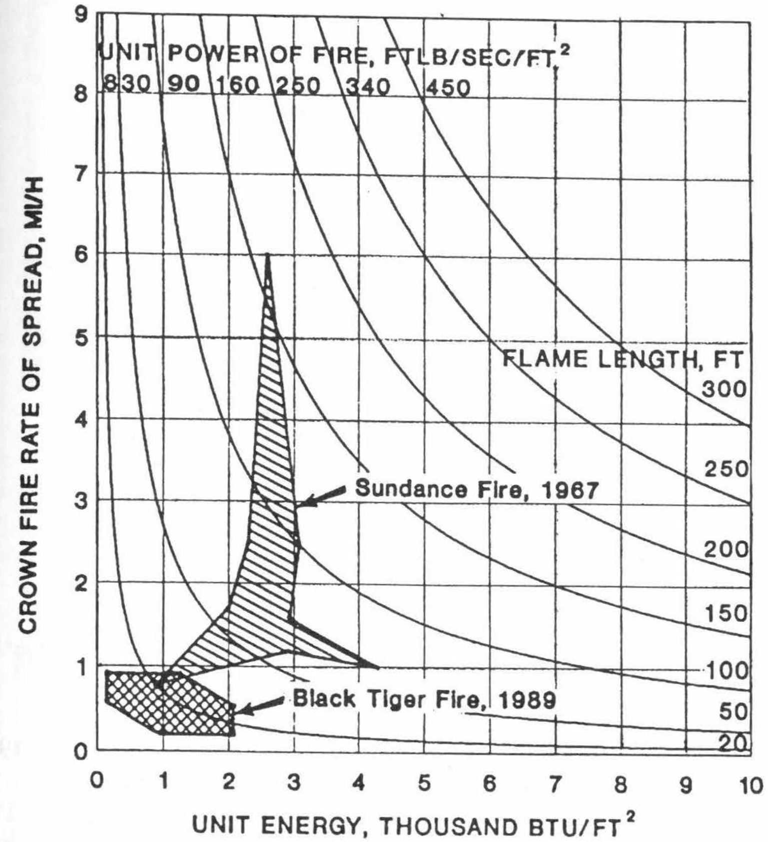


Figure 2.19. *Crown fire characteristics chart. Observed spread rate and intensity for the Sundance fire and Black Tiger fire, which are included as examples at the end of the chapter.* From Rothermel (1991c).

Crown Fire

A crown fire is one that spreads through the overstory. Crowning is one of the most spectacular fire behavior phenomenon that wildland fires exhibit. Crown fires are fast spreading and release a tremendous amount of heat energy in a relatively short period of time. Spread rates exceeding 7 mi/h and flame lengths over 150 ft have been recorded. When 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. Rate of spread of running crown fires can vary widely as shown by the Sundance fire and the Mack Lake fire (Figure 2.20). Both of those fires are included with the examples at the end of this chapter.

Van Wagner (1977) describes three types of crown fires: dependent, active, and independent, according to whether fire in the tree crowns is dependent upon heat from the surface fire, spreading simultaneously with the surface

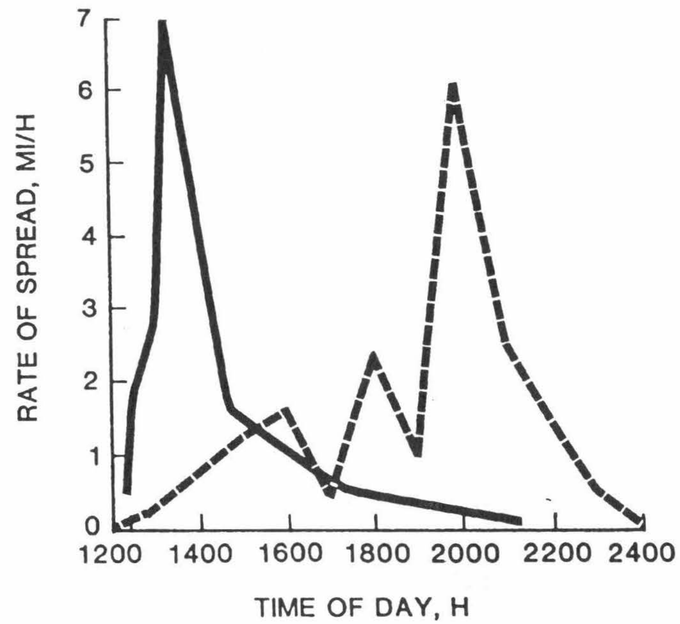


Figure 2.20. *Rate of spread for Sundance fire (dashed line) and Mack Lake fire (solid line).* From Rothermel (1991c).

fire, or spreading independently of fire in the surface fuels. Rothermel (1991c) further categorized fully developed crown fires as wind-driven fires or as fires dominated by their convection column, called plume-dominated fires. These two types of crown fire are based on Byram's (1959) analysis of the relationship between the power of the fire and the power of the wind.

The nature of the convection column is the most easily recognized feature for indicating the type of fire (Figure 2.21). If the power of the wind is greater than the power of the fire, a wind-driven fire will develop. Note that the wind velocity profile shows the wind velocity increasing with height. Consequently, the wind not only drives the fire, but bends the convection column sharply in the direction of the wind. A fire in which a strong convection column builds vertically above the fire is a characteristic of a plume-dominated fire. It is hypothesized that momentum feedback from the vertical velocity within the column causes turbulent indrafts which promote rapid combustion. The resulting increase in turbulence and fire intensity increases both convective and radiant heat transfer; accelerated fire spread is thus possible. This is a positive reinforcement process that can result in a towering convection column and spread rates that are unexpectedly fast for the wind conditions.

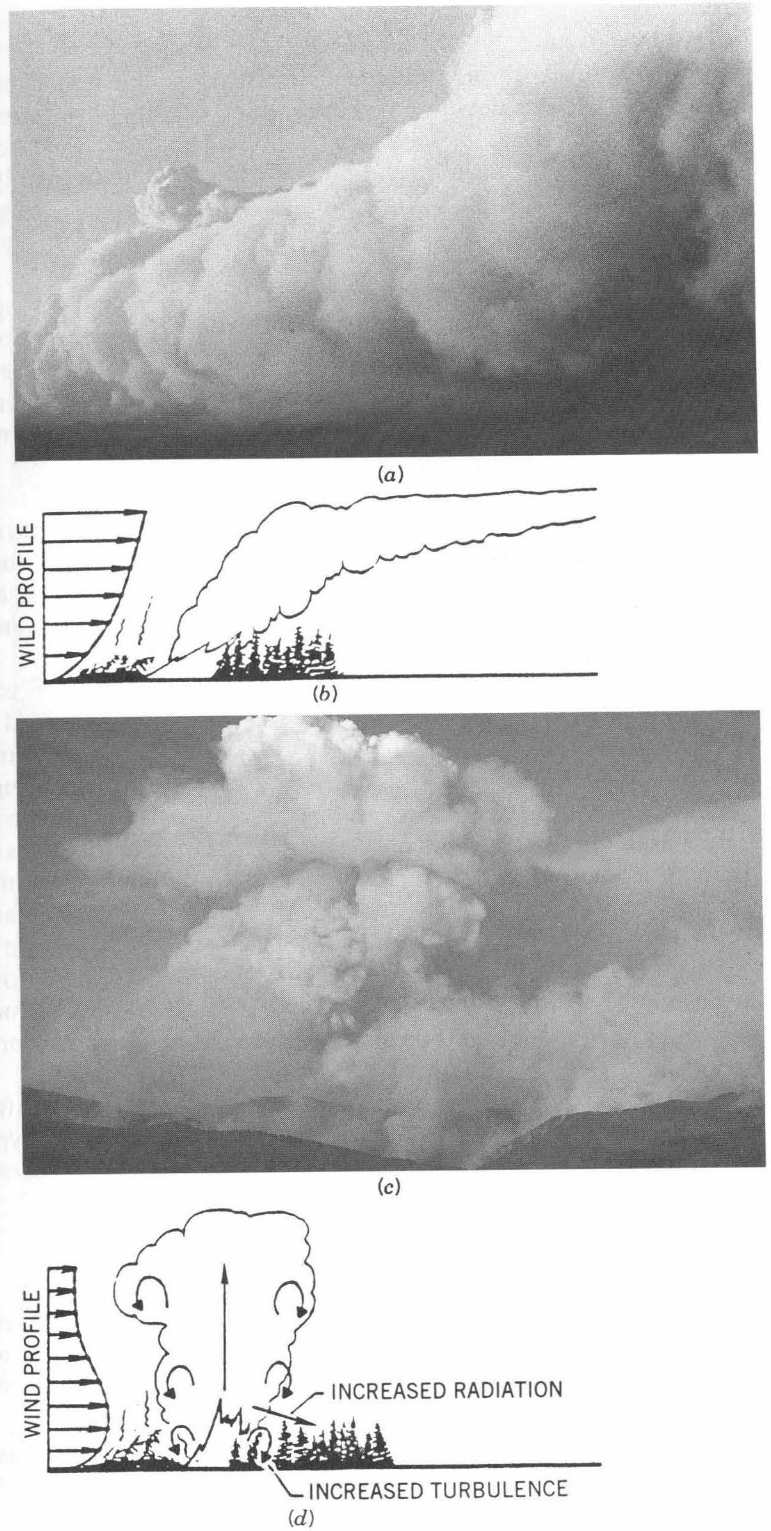


Figure 2.21. *Crown fires can be wind-driven or plume-dominated.* Diagrams from Rothermel (1991b). *Upper photo: Typical appearance of the convection plume above a wind-driven fire. Canyon Creek fire, 1988, Montana, grew from 57,000 to 247,000 acres in 16 hours. Lower photo: Typical appearance of the convection column above a plume-dominated fire (Silver fire in Southern Oregon, 1987).* From Rothermel (1991c).

A variation of plume-dominated fire behavior that can be extremely dangerous is one in which a downburst or microburst of wind blows outward near the ground from the bottom of the convection cell. For a short period, the fire is driven by wind. These winds can be very strong and can greatly accelerate a fire. Downburst conditions are initiated by evaporative cooling and precipitation that cools surrounding air, causing it to descend rapidly and spread horizontally at the ground level.

The transition from surface fire to crown fire marks a dramatic change in fire dynamics. Van Wagner (1977) proposed criteria for ignition and propagation of crown fires, depending on the fireline intensity of the surface fire and the distance between the base of the crown layer and the surface fuel layer. He defined the critical surface fire intensity for crowning in terms of the crown base height and the foliar moisture content.

Van Wagner also identified a condition to be satisfied if a crown fire is to propagate, relying on continuing ignition from below, afforded by the burning of surface fuels. This criteria comes from a parameter given by the product of spread rate and the global mass density of foliar fuel in the crown layer; it can be viewed as a lean flammability limit. In other words, the demise of a crown fire is predicted if it does not spread rapidly enough.

Beighley and Bishop (1990) list conditions favorable for a crown fire: 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 these conditions are encountered, the intensity of a fire in surface fuels increases and flames reach into the crowns or climb ladder fuels into the crowns where the needle foliage will ignite and torching of one or more crowns occurs. Torching is the sudden involvement of the 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 of trees. 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 can be spread by the wind.

A running crown fire can result when winds increase and the flames from torching trees are driven into adjacent trees. 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.

Horizontal Roll Vortices

Crown fires sometimes leave distinctive patterns of burned and unburned vegetation. For example, long strips, called streets, of conifer crowns with unburned (although usually scorched) needles are often seen in otherwise

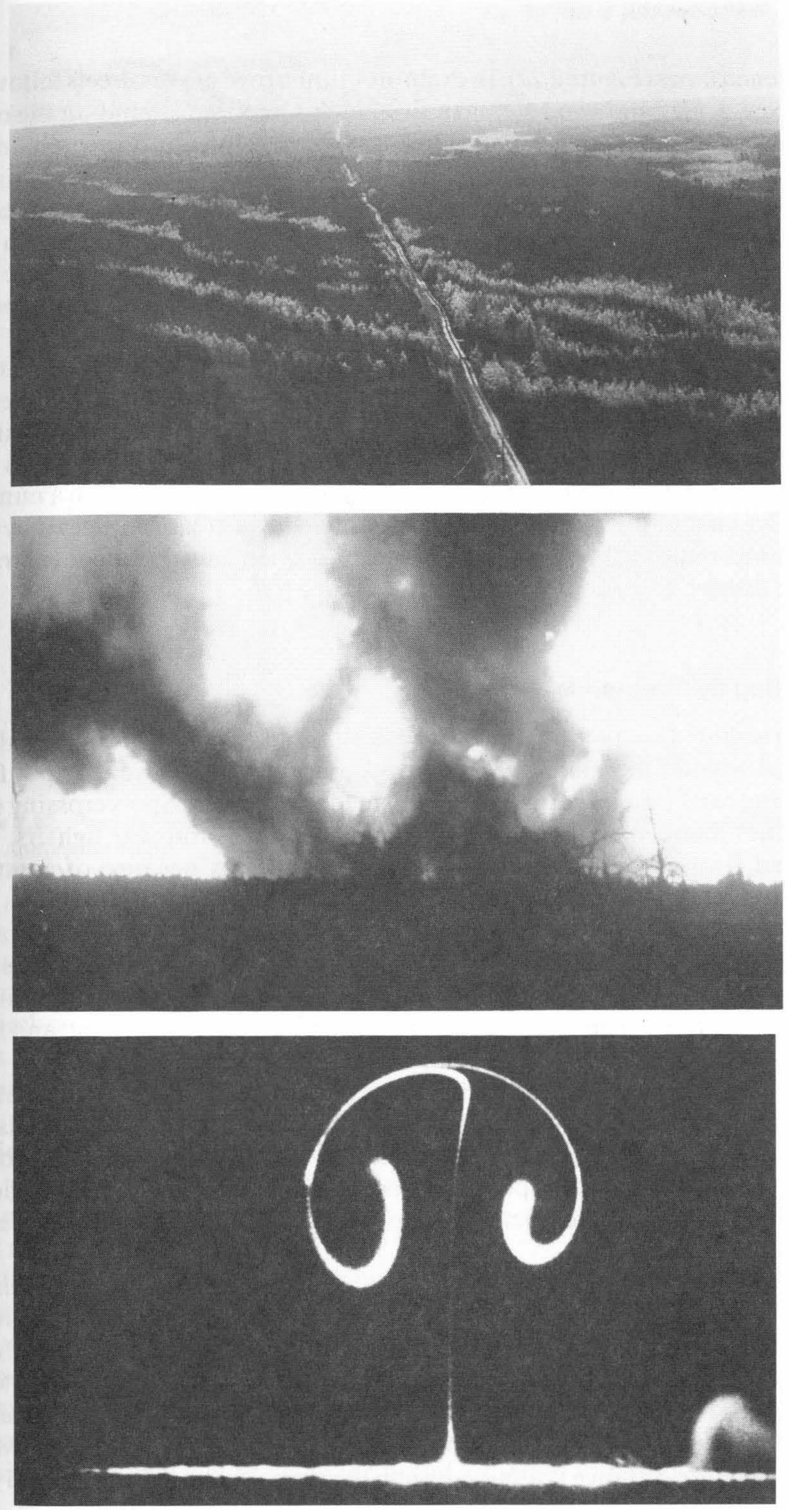


Figure 2.22. *Unburned tree crown streets on the Mack Lake fire. Smoke column split on the New Miner fire. Wind tunnel simulation.* From Haines (1987) and Haines and Smith (1983).

blackened areas (Figure 2.22). In examining unburned crown streets following one New Jersey and two Michigan fires, high scorch was found on the outer (opposite) sides of closely spaced tree trunks, with little or no scorch on the inner (facing) sides, indicating significant airflow outward from within all streets. Haines (1987) hypothesized that downward air movement caused by horizontal roll vortices formed these tree-crown streets and trunk-scorch patterns. He suggested that relatively cool air flowing downward from these vortices kept fire out of the crowns, and that as this air neared the ground, it spread out horizontally, in opposite directions from within the streets.

The hypothesis of the formation of tree-crown streets suggests that the action of a single vortex along the perimeter results in a single crown street. As the perimeter enlarges, that vortex dissipates and another vortex forms along the new perimeter, causing a second crown street. Continued formation and dissipation of vortices along the enlarging perimeter would result in a number of crown streets. Wind tunnel tests suggest chat downstream vortices may be a common boundary layer structure in wildfires where burning is concentrated along the fire's flanks.

Spotting by Firebrands

A fire is said to be spotting when firebrands, or pieces of burning material, are carried beyond the main perimeter and cause new starts, called spot fires. Spotting can be an important mechanism for fire growth. Spots crossing control lines hamper suppression efforts and sometimes trap fire fighters. Prescribed fires can escape their intended boundaries because of spotting. Spotting occurs over a wide range of distances. Under extreme conditions new fires can start miles in front of the main fire. On the other hand, short-range spotting may have little effect, because the main fire often overruns the spots before they can contribute to the spread. In black spruce in Alaska, spotting is a primary mechanism for fire growth and spread. Trees torch, spot, and start new surface fires which again cause the trees to torch and spot.

There are basically three aspects to the spotting issue: (1) the source of the firebrands—their type, size, and number; (2) the distance that firebrands are carried, the means of transport; (3) ignition of spot fires. There is a probabilistic question of how many spot fires there might be under certain conditions. This is difficult to predict because information on all three elements is needed but not available.

Many natural fuels make suitable firebrands: cone scales, grass clumps, bark flakes, parts of branchwood, and moss (Figure 2.23). One of the most effective firebrands is eucalyptus bark. The shaggy bark is easily lifted from the trees, and the curled shape gives it aerodynamic features that allow it to be carried for long distances. For a firebrand to be effective, it must continue to burn as it is transported and still be a viable heat source when it lands. Maximum spot fire distance is attained when the particle is nearly consumed just

Figure 2.23. *Possible firebrand material found on an airport runway near the Sundance fire.* From Anderson (1968).

as it returns to the ground. Smaller particles would travel further but burn out before reaching the ground; larger ones could not travel so far.

Firebrands can be carried from surface fires, but they are more common from torching trees or from burning piles of debris. Spotting is an important factor in running crown fires. Firebrands are lifted by the convective buoyancy of the flaming zone. The convective updraft generated by the fire lofts particles upward where they become entrained in the ambient winds. They can also be lifted to the height where they are carried in the convection column. And firebrands can be carried by fire whirls, as described in the next section.

Albini (1979) developed a predictive model for the maximum distance between a source of firebrands—a burning tree or group of trees—and a potential spot fire (Figure 2.24). The model is an assemblage of six separate submodels, each for a distinct aspect of the overall process involved. The six submodels describe the following processes or phenomena: (1) the structure of a steady flame from the foliage of a tree or from a group of identical trees burning simultaneously that provides the initial lofting of a firebrand particle; (2)

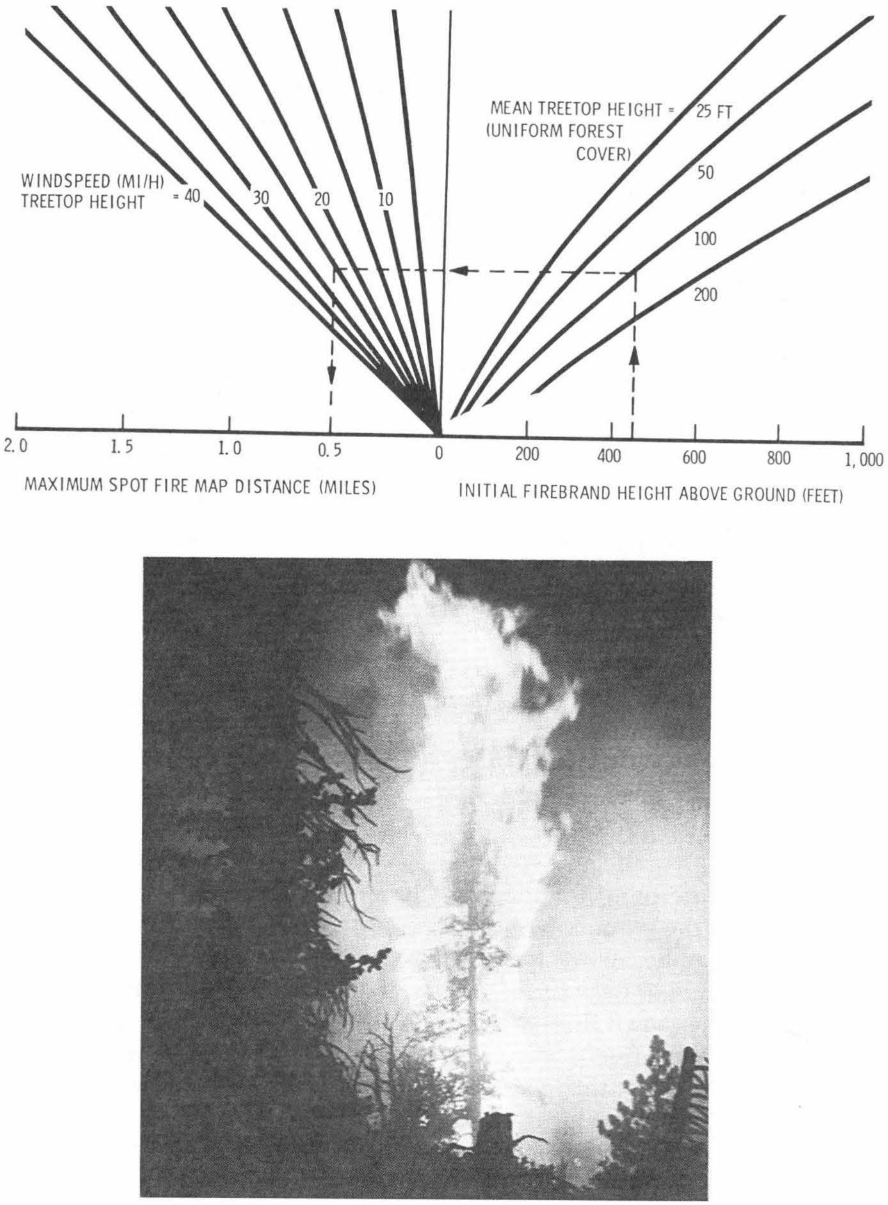


Figure 2.24. *Spotting distance nomogram and torching tree.* From Albini (1979). Photo courtesy of USDA Forest Service.

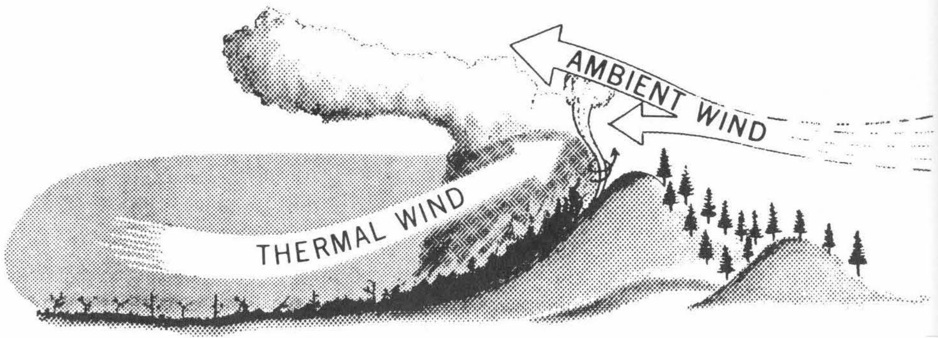
the structure of the steady, buoyant plume established by the flame that provides the lofting of the particle to its ultimate height; (3) the rate at which a woody particle burns as it moves through the atmosphere; (4) the trajectory of the firebrand in the steady flow field of the flame and the buoyant plume above it; height is predicted as a function of time; (5) the structure of the surface wind field over rough terrain—idealized as a sinusoidal elevation-versus-distance contour—that transports the firebrand from its maximum height above its burning tree origin to its downwind destination; and (6) the trajectory of a burning woody cylinder in a steady, but nonuniform, wind field.

Albini (1981) also extended the model to predict maximum spot fire distance from burning piles where there is a continuous steady flame from an isolated source such as burning piles of harvest debris or "jackpots" of heavy fuel. A further extension of the model (Albini 1983b) predicts maximum spot fire distance from wind-driven surface fires. A wind-driven fire in surface fuels without timber cover can give rise to significant spotting. Generally, the greater the intensity of the fire, the more severe the spotting problem it causes. Particles are lofted by strong thermals generated by the fire. Maximum viable firebrand height was shown to be proportional to the square root of the thermal strength, and the downwind drift distance during lofting proportional to the product of windspeed and the square root of the loft height. Once the maximum viable firebrand height is known, it can be used to predict the distance downwind that the particle will travel before it returns to the ground.

Fire Whirls

A fire whirl is technically a vortex, a gas mass with rotational motion (Figure 2.25). Fire whirls are an important element in safety and in wildfire and prescribed fire control considerations. They can be a major factor in causing spot fires beyond the fire area, by moving out of the area or by lifting and throwing firebands. Fire whirls vary greatly in size, strength, and duration. Most are small, but occasionally a large one of destructive size and force develops. They have been known to twist off trees more than 3 ft in diameter and to uproot and carry whole burning shrubs. Fire whirls can occur almost everywhere—on flat or mountainous terrain, in light or heavy fuel, and in stable or unstable atmosphere.

Fire whirls generally originate near the ground surface, like a dust devil; but they occasionally develop above the surface and then extend to the ground, like a tornado. Like a dust devil, fire whirl development depends on a supply of heated, buoyant air. Superheated air near the surface tends to rise in columns, which draw in more of the hot surface air. Some columns develop a strong rotational motion. The fact that some of the columns develop into fire whirls, whereas most do not, is probably due to mechanical action, such as friction with obstructions, starting the air rotation. Once started, the rotation is intensified by the upward-moving, buoyant air.



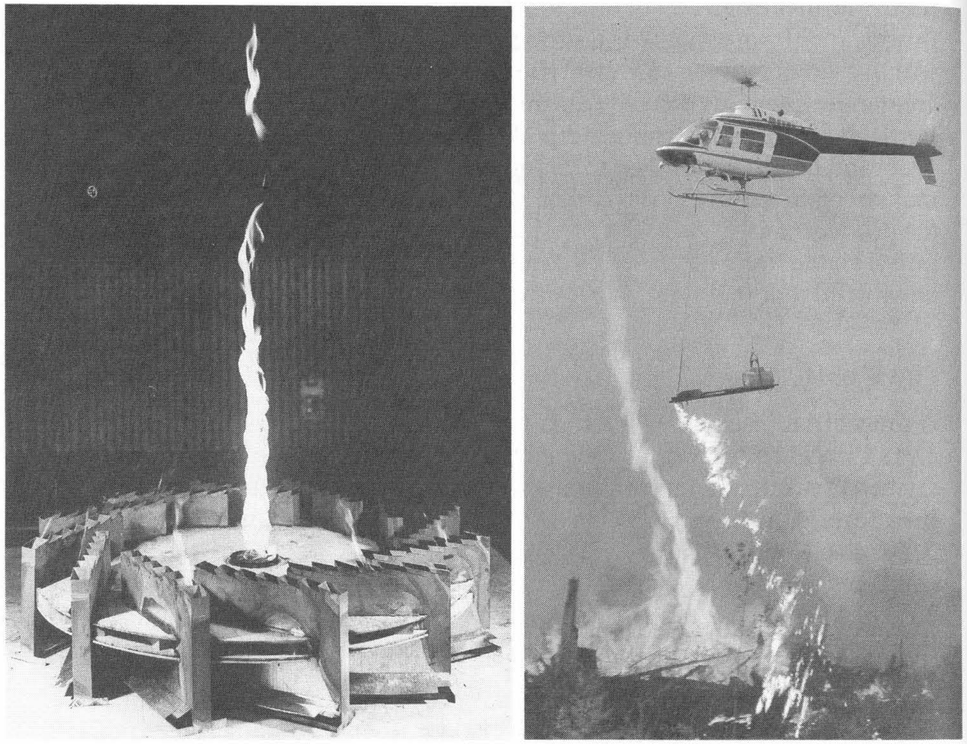


Figure 2.25. Fire whirls. A common site for formation of firewhirls is on the leeward side of a ridge. From Countryman (1971). Photographs courtesy of USDA Forest Service. Prescribed fire photograph by Colin C. Hardy.

The airflow pattern in and around a fire whirl can affect fire behavior. Moderately strong fire whirls about 50 ft in diameter have been observed to affect horizontal air flow up to 500 ft from the whirl itself. In the central core of a well-developed whirl, the air movement is likely to be downward. Adjacent to the core, however, is a strong updraft. Speed of the rotating air is greatest closest to

the core, and decreases with the distance from the core. The rapidly moving air and effects of centrifugal force tend to prevent air from entering the vortex from the side. Most of the air must enter near the ground surface where the rotational flow is slowed by friction. Thus, a relatively thin layer of horizontally moving air flowing into the vortex from all sides is created.

The increase in combustion rate in a whirl is significant. In laboratory experiments with liquid fuels, the combustion rate increased to 5 to 6 times the rate in still air. The increased burning rate means increased fire intensity and more complete fuel consumption.

The high windspeeds in a whirl permit it to pick up burning debris, increasing the amount and extent of spotting. Because larger firebrands are picked up, they can burn longer and travel further before they burn out. Fire whirls can be stationary, but when they move out of the fire area they usually lose their active fire. They scatter their firebrands into unburned fuel a short distance ahead of the fire. The many resulting spot fires can create an intense fire front very quickly. A fire whirl can move at the speed of the prevailing wind speed. Ordinarily fire spread is much slower than the wind speed. Fast-moving fire whirls are more likely to occur on flat terrain, since they dissipate rather quickly on moving out of a fire in rough country.

Atmospheric instability is often favorable for development of fire whirls. In stable atmosphere, a parcel of air displaced vertically tends to return to its original level; in an unstable atmosphere it will tend to keep moving. Atmospheric instability encourages the strong updrafts that start fire whirls.

Fire whirls frequently appear where eddies in the airflow can be expected, either natural or generated by the fire. Thus, whirls can be expected on the lee side of obstructions, at sharp bends in canyons, and at the confluence of two or more canyons. They often develop on the lee side of a fire, particularly near the outside edges of the fire front. The most favorable situation for fire whirls is a fire burning on the lee side of a ridge. The heated air from the fire is sheltered from the general winds. Mechanical eddies that are produced as the wind blows across the ridge can serve as the triggering mechanism to initiate the whirl.

Fire whirls occur most frequently where heavy concentrations of fuels are burning and a large amount of heat is being generated in a small area. These are the conditions that can be present in prescribed fire where aerial ignition is used to ignite an area quickly.

2.5 PREDICTING FIRE BEHAVIOR

Fire behavior prediction is a combination of art and science. It is based on experience and on an understanding of the principles of fire behavior described in this chapter—the effect of topography, weather, and fuel, and recognition of conditions that lead to extreme fire behavior. Predictions can also be based on mathematical models that integrate important factors in a consistent way. Not all of the elements of fire behavior discussed in this chapter have been modeled, and it is not probable that that will ever be the case. Some aspects of fire behavior do, however, lend themselves to modeling.

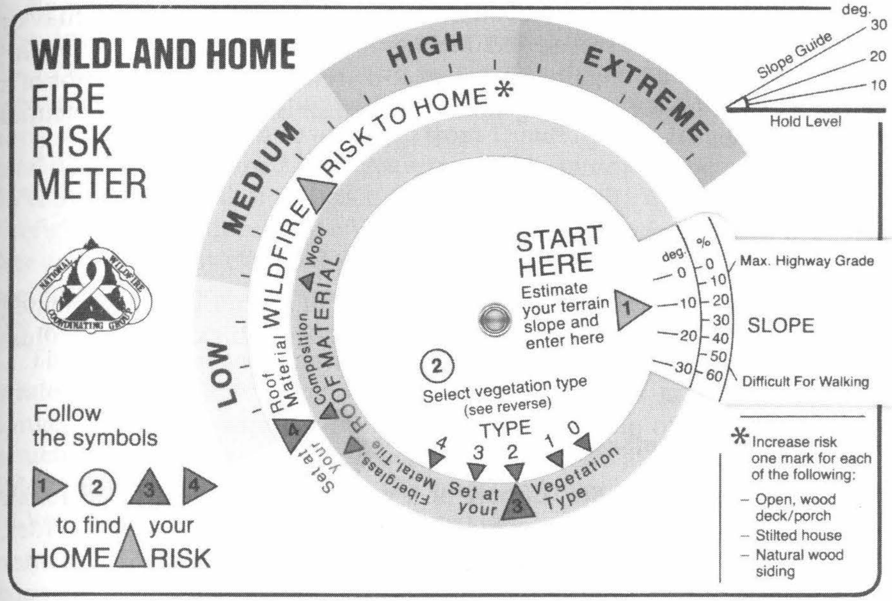
Mathematical models are no substitute for experience, but they do provide a way to quantify fire behavior and to predict behavior based on analysis of the fire environment. An important feature of mathematical models is that they are repeatable—given the same input, they give the same answer. This is especially important in planning activities where alternative scenarios are examined. Model results can be compared to determine the effect of a change in wind, moisture, or fuel.

Fire behavior prediction is much more than use of a model to do the calculations. The process also includes determining the proper inputs for the calculations and interpreting the results for the application at hand. The spread and intensity models, for example, require windspeed as an input value. For an ongoing wildfire the value might be the wind measured on the fireline or it might come from a fire weather forecast. On the other hand, for prescribed fire planning, windspeeds for 0, 2, 4, and 6 mi/h might be used in determining the prescription; beyond a specific windspeed, the model might indicate that there would be control problems. After the fire behavior analyst on a wildfire does the calculations, the results are not communicated to decision-makers on the fire not in terms of numbers, but rather in general terms related to fire potential. Linking analytical calculations and experienced judgment is the key to fire behavior prediction.

Models and guidelines are often packaged into systems to aid decision-making. Systems take many forms (Figure 2.26), ranging from a simple cardboard meter designed for use by homeowners in assessing fire potential around their homes to a simulation model that uses sophisticated computers to simulate fire growth and behavior over uneven terrain, through variable fuel, under changing weather conditions. A system that has been widely used for prediction of fire behavior in the United States is called BEHAVE. It is a set of computer programs that includes models for spread, intensity, moisture, spotting, fire size, and so on (Figures 2.8 and 2.17 are examples taken from BEHAVE). The BEHAVE system also includes programs that help a person develop fire behavior fuel models for fuels that are not represented by one of the standard 13 fuel models.

As described by Rothermel (1991a), there are limitations to being able to predict fire behavior. Application of even expert talent and advanced prediction techniques was inadequate to the task of long-term fire growth prediction during the large fires of Yellowstone National Park in 1988. Limitations in long-range forecasting for local weather, significant precipitation, and especially wind, limit the prospects for success in predicting fire behavior more than a day or two into the future.

Fire behavior prediction is different from fire danger rating, which is reviewed in Chapter 4. The objective of fire behavior prediction is to estimate what a fire will do, while fire danger rating is a process for integrating and



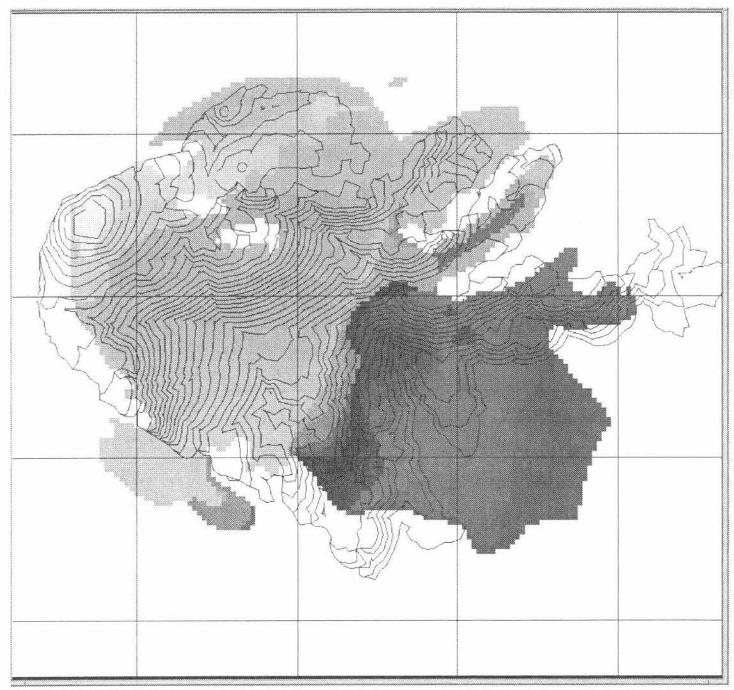


Figure 2.26. *Systems designed to aid decisionmaking take on many forms. Simple cardboard home risk meter (Simmerman and Fischer 1990). Fire spread patterns recorded for the Horizon prescribed natural fire at Yosemite National Park, California (shading), compared to daily perimeters predicted by the FARSITE simulation Finney and Andrews (1996).*

interpreting seasonal weather as an indicator of fire potential. Fire behavior prediction relates to the spread and intensity of a specific fire, whether for real-time prediction of an ongoing fire or what-if scenarios for the behavior of a hypothetical fire in the planning mode. Fire danger is a rating of fire potential for a large area.

2.6 SELECTED EXAMPLES

The following case studies offer brief synopses of several well-documented historical fires. Fire behavior principles discussed in this chapter are illustrated through examination of these fires.

Black Tiger Fire, Colorado, 1989

The Black Tiger fire is an example of a wildland/urban interface fire, an increasingly common occurrence. It started on 9 July 1989 near Boulder, Colorado. The final size was about 2100 acres. Within the first 5 to 6 hours after ignition, 44 homes and other structures were destroyed, and many others were damaged. More than 500 firefighters worked to contain the fire and protect homes. The distance from the point of origin to the northwest terminus of the fire at Sugerloaf Mountain is 2.5 miles. The spread rates and intensity of the Black Tiger fire were compared to those of the Sundance fire in Figure 2.19.

As stated in the case study prepared by the National Fire Protection Association (1989), "The conditions on Sunday, July 9 in that part of Colorado had all the elements in place for a dangerous fire, lacking only an ignition source." The fire was accidentally set, probably by a carelessly discarded cigarette. When first reported it was a small grass fire, about 40 × 10 ft. Residents were not successful in their attempts to extinguish it. Firefighters arrived on the scene 15 min after the first report; the fire was about 40 × 100 ft. The fire was crowning in another 4 min. The steep terrain and rate of spread upslope made a direct suppression attack on the fire's head from the point of origin impossible.

The principal vegetation across the Black Tiger fire area was tall grass under open ponderosa pine. Pockets of dense lodgepole pine and Douglas-fir were found on shaded slopes and along riparian zones. In the previous 10 years, the area had been ravaged by mountain pine beetles, leaving many of the pine trees dead and building up a thick carpet of needles on the ground. Dead and down fuels had been removed on some areas, but remained on others. The fire started in an area where ponderosa pine predominated. It then moved into an area of mixed conifers. Heavy forest litter buildup of dead trees, limbs, and brush in conjunction with low branches of live trees formed ladder fuels.

Rain had not fallen for at least 30 days during a period of high temperatures. The dry conditions were long term; snow pack the previous winter was only 25–75% of normal. Dry winds were blowing up the Black Tiger Gulch with greater force than usual. Firefighters estimated the upslope windspeeds in the early stages of the fire to have ranged from 15 and 25 mi/h. The slope over the total distance of the fire, 2.5 miles, averaged 23%, some parts being as much as 35%. Spotting ahead of the main fire front diluted the number of available firefighters and reduced the effectiveness of firelines, roads, and other fuel-free areas normally expected to help slow or stop a spreading wildfire. Aerial reconnaissance found burning roofs a quarter-mile or more ahead of the main fire front.

This fire, which soon outran the fire defenses in difficult terrain, demonstrated the predictable effects of a combination of factors: lack of rainfall, prolonged heat spell, wind, sloping topography, buildup of forest fuels, construction factors affecting the susceptibility of homes to fire, use of combustible construction materials, poor site access for emergency vehicles, and lack of home site maintenance for fire protection.

Sundance Fire, Idaho, 1967

The Sundance fire made a dramatic run of 16 miles and 50,000 acres on 1 September 1967. The fire occurred in Northern Idaho and spread through mixed conifer stands interspersed with logged areas. It took the lives of two firefighters (tractor operators) caught in its path.

As documented by Anderson (1968), the fire resulted from a lightning storm on 11 August. Four other fires from that storm were extinguished before the Sundance fire was discovered on 23 August. By the next day the Sundance fire was contained at 35 acres. Suppression activities continued for the next five days. Late in the evening of 29 August, it was reported to have jumped the line. Prevailing northeast winds and normal nighttime downslope winds resulted in a wind-driven fire moving downslope, with spotting up to $\frac{1}{2}$ mile ahead of the fire. By the morning of 30 August it was 2000 acres; it was 4000 acres on 1 September when it began its run.

The run was a result of a combination of dry fuels from a sustained drought, low humidities for over 72 h, increasing winds sustained for a period of 9 h, and a 4-mile active fire front existing on the morning of 1 September. The fire advanced 16 miles in 9 h (1400–2300) and created spot fires 10 to 12 miles northeast of the place of origin (Figure 2.27). Spotting activity increased during the day, reaching a maximum intensity during the period of highest winds in the late afternoon. Whereas spot fires early in the day contributed to the fire spread, late in the day a multitude of spot fires created fuel voids leading to the breakdown of the main front and contributing to the fire's termination. Other factors influencing the decreasing rate of spread were increasing humidity and decreasing wind after 2200, the downslope direction of burning, and to

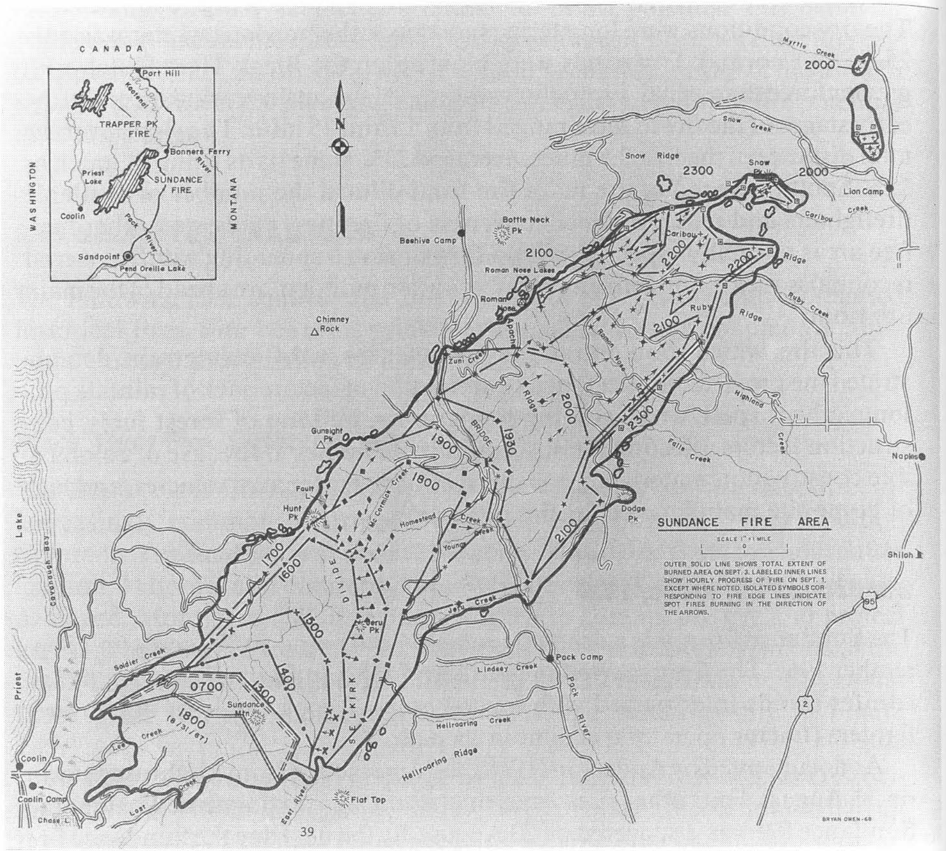


Figure 2.27. Sundance fire area. From Anderson (1968).

some degree the disruption of fuel continuity due to prior logging activities in the area.

The average rate of spread ranged from 1 to 6 mi/h, with brief periods having higher or lower values. The fire intensity built up to 22,500 Btu/ft·s and was releasing nearly 500 million Btu/s. A convection column rose to 35,000 ft. Extensive firebrand activity and debris were transported from the fire (see Figure 2.23). The brands were either lifted as high as 18,000 ft and transported by the wind or carried in vortices produced by the wind blowing around the convection column. Fire-induced winds that caused extensive blowdown could have been greater than 95 mi/h.

The spread rates and intensity of the Sundance Fire were compared to those of the Black Tiger fire in Figure 2.19. The rates of spread for the Sundance Fire were compared to those of the Mack Lake fire in Figure 2.20.

Air Force Bomb Range Fire, North Carolina, 1971

The Air Force Bomb Range fire burned in pocosins and marshlands along the coastal plain of eastern North Carolina and was documented by Wade and Ward (1973). The fire began on the morning of 22 March 1971, from a practice bomb on an Air Force range (an interesting example of ignition source). More than 23,000 acres of the 29,300 acre total burned during two major runs within the first 20 hours.

While topography was a major factor in both the Black Tiger fire and the Sundance fire, the Air Force Bomb Range fire occurred on virtually flat terrain. The fuel type was mainly evergreen pocosin shrubs, whose foliage and stems reach a minimum annual moisture content between 70 and 100% immediately prior to the initiation of new growth, usually in early April. Some of the area had been sprayed with herbicides two years before. A prescribed burn that followed was low intensity and did not cover much of the area. Thus, most of the desiccated shrubs on these quadrants were still standing. Grass on the area was also very flammable because it was still in the cured stage.

Because of the dry fuel and 20-mi/h winds, the fire was beyond control before the standby crew stationed on the range reached it. The fire crowned through more than 15,000 acres of pond pine during the next 20 h. The initial 14-mile run produced a narrow elongated shape pushed by high winds. Rates of spread averaged over 2 mi/h for 4 h and was near 5 mi/h during a 1-h period. Unburned tree crown streets can be seen in Figure 2.28. The fire eventually ran out of dry fuel after traveling 14 miles in about 7 hours.

The flanks remained active throughout the night of the 22nd until a cold front passed over the area before dawn on the 23rd. Passage of a dry cold front early the next morning resulted in a 6-mile run perpendicular to the first. This second run terminated because of wet fuel. A high water table prevented the consumption of large quantities of organic soils, but because the damp peat would not support the usual tractor-plow units, final control of the fire was not achieved until over an inch of rain and snow fell on the area.

Mack Lake Fire, Michigan 1980

The Mack Lake fire was an escaped prescribed fire. The prescribed fire was ignited in jack pane logging slash the morning of 5 May 1980 in the Huron National Forest. The purpose of the burn was to remove logging debris in preparation for replanting jack pine. The ultimate objective was habitat improvement. Within 2 hours the fire had spotted across the control line and was declared a wildfire. Within 10 more hours, and most of that confined to 6 peak hours of burning, the fire had burned 24,000 acres and released energy on the order of 3 trillion Btu's, as much as 90 thunderstorms or 9 times the energy released by the Hiroshima atomic bomb. In the process one firefighter (a tractor-plow operator) died and fire swept through the town of Mack Lake, destroying 44 residences. The fire was documented by Simard and others (1983).

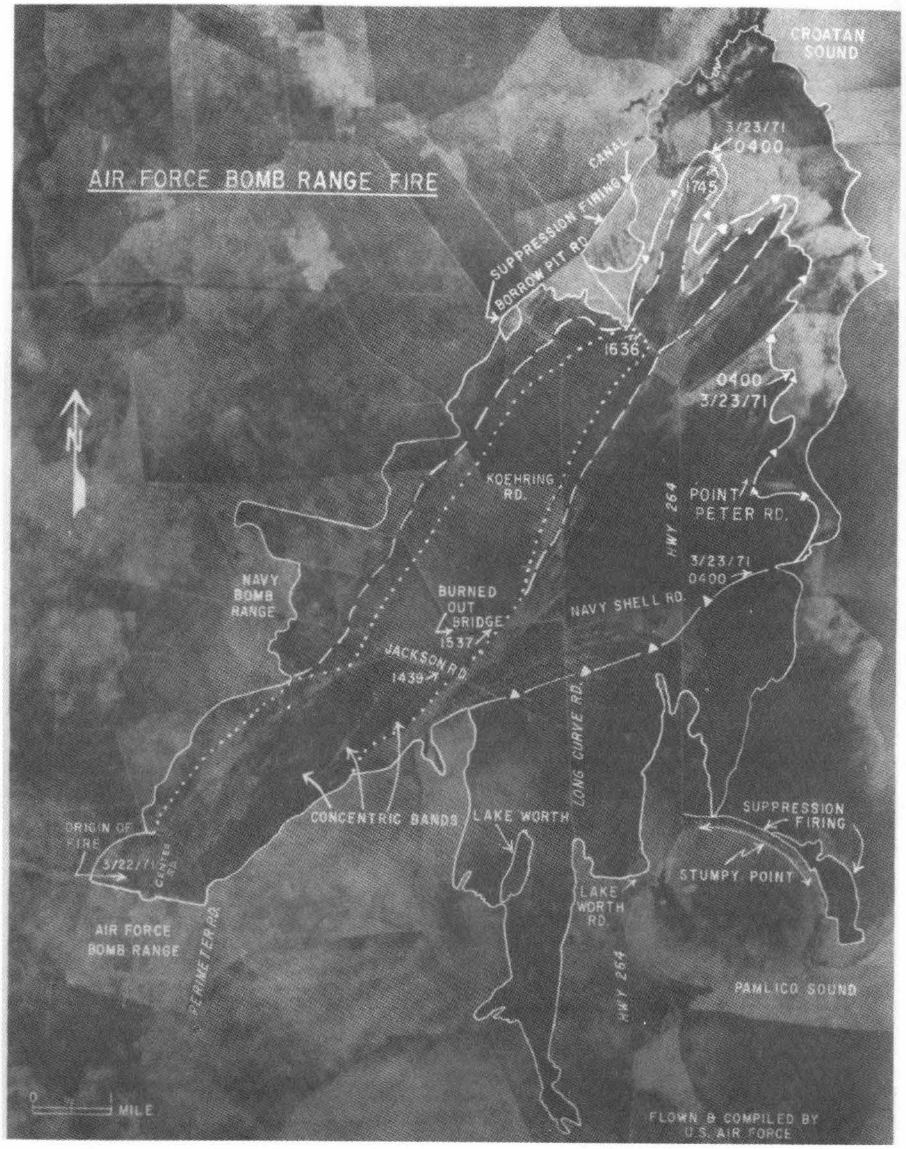


Figure 2.28. *Airforce Bomb Range fire area.* From Wade and Ward (1973).

No unusual fire activity was noted for the first 45 min. The piled slash burned vigorously, with flame lengths of 10 to 15 ft, but flame lengths between the piles were only 6 to 12 inches. Although some spot fires crossed the control line, they were easily contained and firing resumed. Then the fire spotted into standing jack pine timber adjacent to and upslope of the fire area. The area was more exposed to the wind and had heavier fuel loadings, resulting in a much higher rate of spread than experienced in the prescribed burn. Other spots occurred across the highway. An increase in windspeed was noted at this time. The fire began crowning 100 ft after it entered an extensive sapling-sized jack pine stand.

In the first 3.5 h, during which the fire advanced 7.5 miles, no amount of fireline or road width held or even slowed the fire. After the fire had advanced 4 miles, the passage of a dry cold front turned the southwest flank into a head fire. Aided by the change in fuels and ameliorating burning conditions, suppression crews contained the fire by constructing 35 miles of fireline just 30 h after it started.

Drought was not a factor in this fire. The fire occurred 6 days after 0.5 inch of rain fell, and only a slight precipitation deficit was recorded during the 4 months preceding the fire. Several conditions contributed to the escape of the prescribed fire: spotting from slash piles, irregular groups of uncut trees adjacent to the prescribed fire area, location of control lines near the top of a 25% slope, high windspeeds (15+ mi/h), low relative humidity (21%), and low fine fuel moisture (7%).

During its major run the fire traveled 7.5 miles in 3.5 h, with an average forward rate of spread of 2.1 mi/h. Surges occurred, with velocities of 6–8 mi/h. Fireline intensity for this period averaged 9300 Btu/ft·s. During the wind shift associated with frontal passage, the southern flank spread more vigorously, developing several small heads. With completion of the frontal passage, the onset of poorer evening burning conditions, and the exhaustion of jack pine fuels, the fire eventually expired. The increase in final size from the size attained during the major run was negligible.

Horizontal roll vortices may account for the residual burn pattern of unburned strips and burned bands in the crown fuels (see Figure 2.22).

Greater Yellowstone Area Fires, Wyoming and Montana, 1988

In the summer of 1988, Yellowstone National Park and adjoining areas within the National Forests, commonly referred to as the Greater Yellowstone Area (GYA), experienced the most extensive forest fires seen in the Western states since the great Northwest fires of 1910. Initially, some of the fires within Yellowstone Park were allowed to burn as prescribed natural fires, as provided in the Park's fire management plan. But when early summer rains did not materialize, the threat of drought necessitated that fire suppression measures be undertaken. By 24 July all the prescribed natural fires had been declared wildfires.

A total of 249 fires occurred in the GYA in 1988, about twice the average for the area. Thirty-one of those fires were initially classified as prescribed natural fires, 28 of these in Yellowstone National Park. Twelve of the 28 fires burned out at less than 1 acre; the remaining 16 later were declared wildfires and grew to large size despite intensive suppression efforts. Of the 249 fires in the GYA, 210 were suppressed at less than 10 acres. The North Fork fire was started on July 22 just outside the western boundary of the park by a woodcutter on the

Targee National Forest. It became the GYA's largest fire, burning 531,182 acres by the end of the burning season. During the 5-day period from 6 through 10 September, the total size of the GYA fires increased by 614,618 acres (Figure 2.29). The area encompassed by the final perimeter of the fires was about 1.7 million acres. Within the Park, the actual burn area was about 65% of the perimeter area after accounting for irregular fire perimeter and islands of unburned fuel (See Figure 2.11).

Despain (1990) had categorized the predominately lodgepole pine forest into five types based on age, growth, and decay of the forest. These ranged from recently burned stands containing seedlings and young trees to decadent stands of 300- to 500-year-old trees, many of which had fallen to the ground to produce extremely high concentrations of dead surface fuel interspersed with alpine fir regeneraton.

The size of the fires and length of exposed fireline contributed to the control problem. A young lodgepole pine forest does not have extensive litter on the ground; thus surface fire will usually not reach the tree crowns. But when the

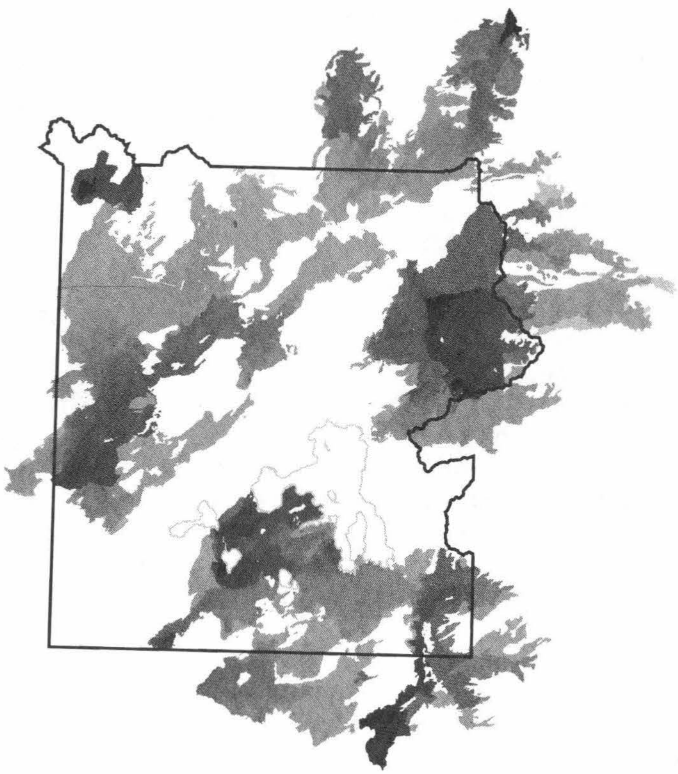


Figure 2.29. *Greater Yellowstone Area fire map, 1988. Fire progression is shaded from black to light gray by date from 30 June to 1 October 1988.* Based on Rothermel, Hartford, and Chase (1994).

fire perimeter becomes large enough to include several fuel types, there is a high probability of a flare-up somewhere along the fire line, thereby initiating crowning. The dry conditions and presence of beetle-killed trees heightened the probability of fire moving into the crowns. There were several other reasons for the phenomenal fire growth of the Yellowstone fires. The continued drought was a major factor, not just because fires spread faster in dry fuels, but because it made fire suppression difficult, and on some fires, virtually impossible. Burning embers were lofted across fire control lines, highways, and rivers, descending on easily ignited fuels almost everywhere they fell.

As the season progressed, the increase in fire activity was dramatic. In early August the fires were averaging about 1 mile of spread per day, by late August about 3 miles a day, and in September strong winds caused runs of 7–14 miles a day. By the middle of August, daily burn times increased significantly as the fires burned into the night. On 10 September the weather changed and slowed the fires; humidity rose, rain began, and snow capped the higher peaks.

FURTHER READING

Rothermel describes methods and examples of fire behavior prediction in "How to Predict the Spread and Intensity of Forest and Range Fires" (1983) and "Predicting the Behavior and Size of Crown Fires in the Northern Rocky Mountains" (1991c). Andrews (1986) and Andrews and Chase (1989), in describing the BEHAVE fire behavior prediction system, give an overview of fire behavior and associated models, including assumptions and limitations of the models, example calculations, and technical references. The Forestry Canada Fire Danger Group (1992) describes the Canadian system in "Development and Structure of the Canadian Forest Fire Behavior Prediction System". Albini discusses fire behavior modeling in "Wildland Fires" (1984) and in "Dynamics and Modeling of Vegetation Fires: Observations" (1992). The U.S. National Wildfire Coordinating Group (NWCG) training courses (1993, 1994) developed by many people in the wildland fire community describe all aspects of fire behavior from an introduction to advanced calculations.