Energy Release Rates, Flame Dimensions, and Spotting Characteristics of Crown Fires

Martin E. Alexander and Miguel G. Cruz

When a fire in a conifer forest stand crowns, additional fuel is consumed primarily in the form of needle foliage but also in mosses and lichens, bark flakes, and small woody twigs. The additional canopy fuel consumed by a crown fire combined with the increase in rate of fire spread after crowning can easily lead to the quadrupling of fireline intensity and, in turn, a dramatic increase in flame size within a few seconds (for example: from 800 to 3,200 British thermal units/second-foot [Btu/sec-ft]). Spotting activity can also very quickly increase in both density and distance. In such cases, there is little wonder why crown fires just seem to literally "blow up" (Byram 1959).

As the fireline intensity or rate of energy released per unit area of the flame front increases (figure 1A); flame size or volume increases due to a faster rate of spread and a larger quantity of fuel being volatilized in the flaming front. The relative increase in fireline intensity from a surface fire to full-fledged crowning in a conifer forest stand, as shown in figure 1A, will depend on the surface fuelbed characteristics and the canopy base height. Fireline intensities of wind-driven crown fires can easily reach 9,000 Btu/sec-ft and occasionally exceed 25,000 Btu/sec-ft (Anderson 1968).

Flame Front Dimensions

A fire's flame zone characteristics (depth, angle, height, and length) are a reflection of its heat or energy release rate. The flame depth of a spreading wildland fire is a product of its spread rate multiplied by the flame front residence time. The latter quantity represents the duration that a moving band or zone of continuous flaming combustion persists at or resides over a given location. Flame front residence times are dictated largely by the particle size(s) distribution, load, and compactness of the fuelbed (Nelson 2003).

Flame front residence times for conifer forest fuel types at the ground surface have been found to vary from 30 seconds to a minute (Taylor and others 2004), compared to 5 to 10 seconds in fully cured grass fuels (Cheney and Sullivan 2008). Crown fires are capable of producing very deep flame fronts (see figure 1B). The depth of the burning zone in the surface fuels of

Sequence of photos taken during the afternoon of August 22, 2005, near Coimbra, Portugal, showing some of the complexities involved in free-burning wildland fire behavior. An advancing wildfire in a maritime pine forest spotted into an opening (A), followed by (B and C) spot fires coalescencing, and (D) merging with the main flame front, resulting in a greatly increased flame height. The elapsed time between photos (A) and (D) was approximately 105 seconds. Photos by M.G. Cruz.

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a crown fire spreading at 66 yards/minute (60 m/min) would, for example, be around 49 yards/minute (45 m: 60 × 0.75 = 45). Residence times within the canopy fuel layer of a crown fire are approximately one-half to one-third those experienced at ground level (Despain and others 1996). This is reflected in the gradual convergence of the flaming zone depth with height, ending in the flame tip above the tree crowns.

The flame front of a crown fire on level ground appears to be vertical or nearly so (Stocks 1987). This appearance has led to the popular phrase "wall of flame" when it comes to describing crown fire behavior. The fact that the flames of a crown fire stand so erect is a direct result of the powerful buoyancy associated with the large amount of energy released in the flame front.

Radiation from the crown fire flame front can produce painful burns on exposed skin at more than 109 yards (100 m) from the fire edge. Such would have been the case during the major run of the 1985 Butte Fire on the Salmon National Forest in central Idaho had firefighters not had protective fire shelters to avert thermal injuries (Mutch and Rothermel 1986).

Given the difficulty of gauging the horizontal depth of the burning zone in a crown fire, flame height constitutes a more easily visualized dimension than flame length. However, efforts to objectively estimate flame heights of crown fires are complicated by the fact that sudden ignition of unburned gases in the convection column can result in flame flashes that momentarily extend some 300 feet (90 m) or more into the convection column aloft. Such flashes can easily result in overestimates of average

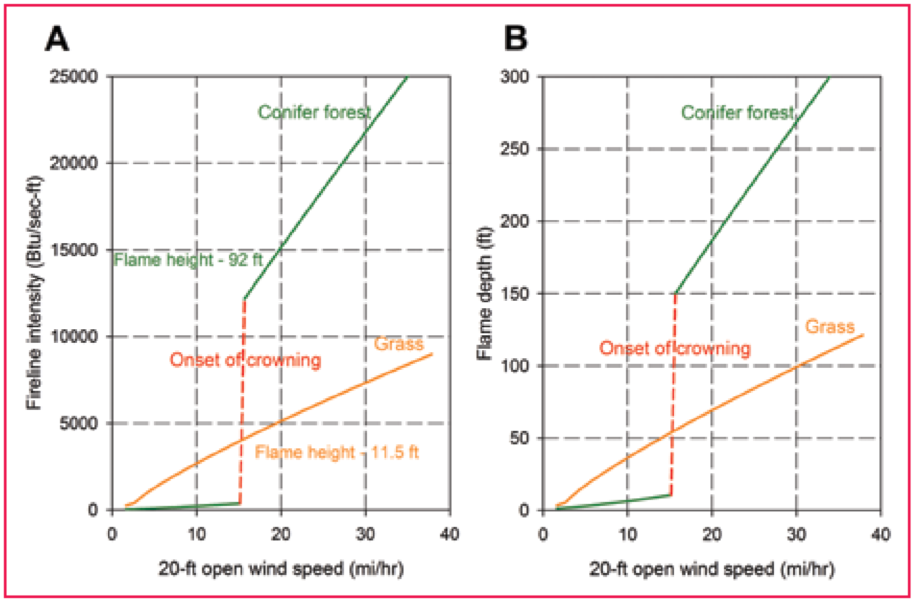

Figure 1.—*The variation in (A) fireline intensity and (B) flame depth in relation to wind speed for a conifer forest stand compared to a grassland fuel complex (after Alexander and Cruz 2011). The "kink" in the curves associated with the conifer forest represents the point of surface-to-crown fire transition.*

flame heights, which usually range from about 50 to 150 feet (15 to 45 m) on high-intensity crown fires (Byram 1959).

The average flame heights of active crown fires are generally regarded as being about two to possibly three times the stand height (Stocks 1987, Stocks and others 2004). This simple rule of thumb is not applicable to tall—say, 80 feet (25 m)—conifer forest stands with moderately high canopy base heights (that is: greater than 40 feet/12 m) unless a dense understory tree component exists (Burrows and others 1989).

Spotting Activity

The general effect of spotting on crown fire rate of spread is determined by the density of ignitions and distances of these ignitions ahead of the main fire. These two characteristics are intimately linked, as density typically decreases with increased distance from the main advancing flame front.

Spotting from crown fires is also effective in breaching major barriers to fire spread, including large water bodies and other nonfuel areas (for example, rock slides or barren ground). Thus, constructing fuelbreaks comprised of vegetation of low flammability can, depending on their width, be an effective buffer against crown fires—but only to a point.

When fire environment conditions are uniform and winds aloft are favorable, spotting can contribute to the overall spread and growth of crown fires provided that the spot fires are able to burn independently of the main advancing fire front. In most high-intensity wildfires that involve crowning, spot fires originating ahead of the advancing flame front are typically overrun and thus incorporated into the larger fire perimeter before they are able to develop and spread independently or otherwise be influenced by the main fire (for example: by in-draft winds).

For a crown fire spreading at a rate of 150 chains/hour (50 m/min) or 1.9 miles/hour (3.0 km/hr) and burning under homogeneous fuel, weather, and topographic conditions, spotting distances would have to exceed approximately 1,650 to 2,300 feet (500 to 700 m)—depending on the ignition delay which can be as much as 5.0 to 10 minutes—to have the potential to increase a fire's overall rate of spread through a "leap frog" effect (figure 2). If there are sufficient spot fires at or just beyond this distance and they can rapidly coalesce, this "mass ignition" effect will temporarily lead to the formation of pseudoflame fronts (Wade and Ward 1973) with greatly increased flame heights.

Spotting distances of up to about 1.2 miles (2 km) are commonly observed on wind-driven crown fires in conifer forests, but spotting distances close to 3.1 miles (5 km) have been documented (Haines and Smith 1987). Spot fire distances of 3.7 to 6.2 miles (6 to 10 km) were reported to have occurred in the Northern Rocky Mountains during the 1910 and 1934 fire seasons (Gisborne 1935).

Under exceptional circumstances, spotting distances greater than 6.2 miles (10 km) have been described. Especially noteworthy are the 10- to 12-mile (16 to 19 km) spot fire distances associated with the 1967 Sundance Fire in northern Idaho (Anderson 1968). Similar distances are reported to have occurred in radiata pine plantations during the major run of the 1983 Mount Muirhead Fire in South Australia (Keeves and Douglas 1983), although the responsible embers may have arisen from native eucalypt trees within the plantation.

Estimating Maximum Spot Fire Distances

Albini (1979) developed a physical-based model for predicting the maximum spotting distance from single or group tree torching that covers the case of intermediate-range spotting of perhaps 1 to 2 miles (1.5 to 3.0 km); he also developed similar models for burning piles of slash or "jackpots" of heavy fuels and wind-aided surface fires in non-tree canopied fuel complexes such as grass, shrubs, and logging

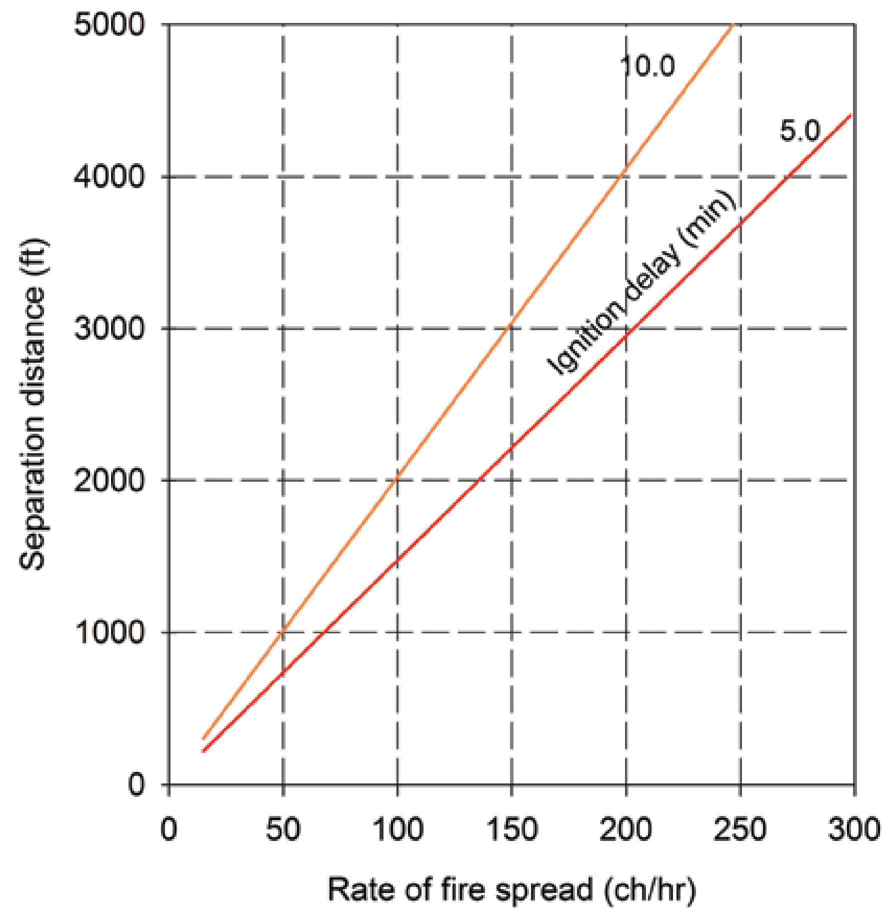

Figure 2.—*Minimum separation distance required for a newly ignited spot fire to avoid being overrun by the main flame front of an advancing crown as a function of rate of spread and ignition delay (after Alexander and Cruz 2006). Ignition delay represents the elapsed time between a firebrand alighting, subsequent ignition, and the onset of fire spread.*

Wildfire Observations of Spotting Distances†

Behavior records including rate of spread were made during 33 days of observation on 10 large fires in Oregon and Washington. With one possible exception, most of the spread resulted from wind-carried embers that started spot fires ahead of the main fire. As fuels became drier, volume of fuel greater, or wind stronger, the rate of spread by spotting increased. Spot fires ¼ -mile (0.4 km) ahead of the main fire were common and, in a few cases, spot fires suddenly appeared as far as 2 miles (3.2 km) ahead of any other visible fire.

†Adapted from U.S. Department of Agriculture (1952)

slash. As with any of Albini's maximum spot fire distance models, determining whether a given ember or firebrand will actually cause a spot fire must still be assessed based on its ignition probability.

A predictive system was recently developed for estimating the maximum spotting distance from active crown fires as a function of the firebrand particle diameter upon alighting on the surface fuelbed based on three inputs: canopy top height, free flame height (that is: flame distance above the canopy top height), and the wind speed at the height of the canopy (Albini and others 2012). Although the system has not been specifically validated, the estimates produced by the system (figure 3) appear realistic in light of existing documented observations.

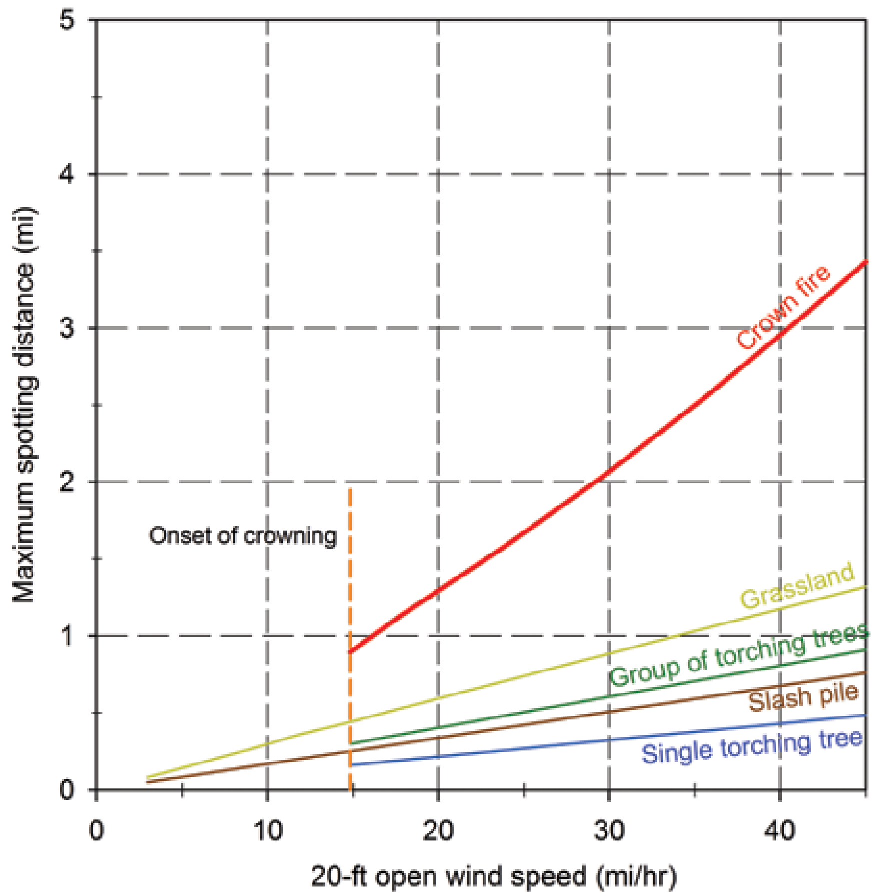

Figure 3.—*Comparison of predictions for maximum potential spotting distance over level terrain as a function of wind speed, based on models developed by Frank A. Albini (after Albini and others 2012).*

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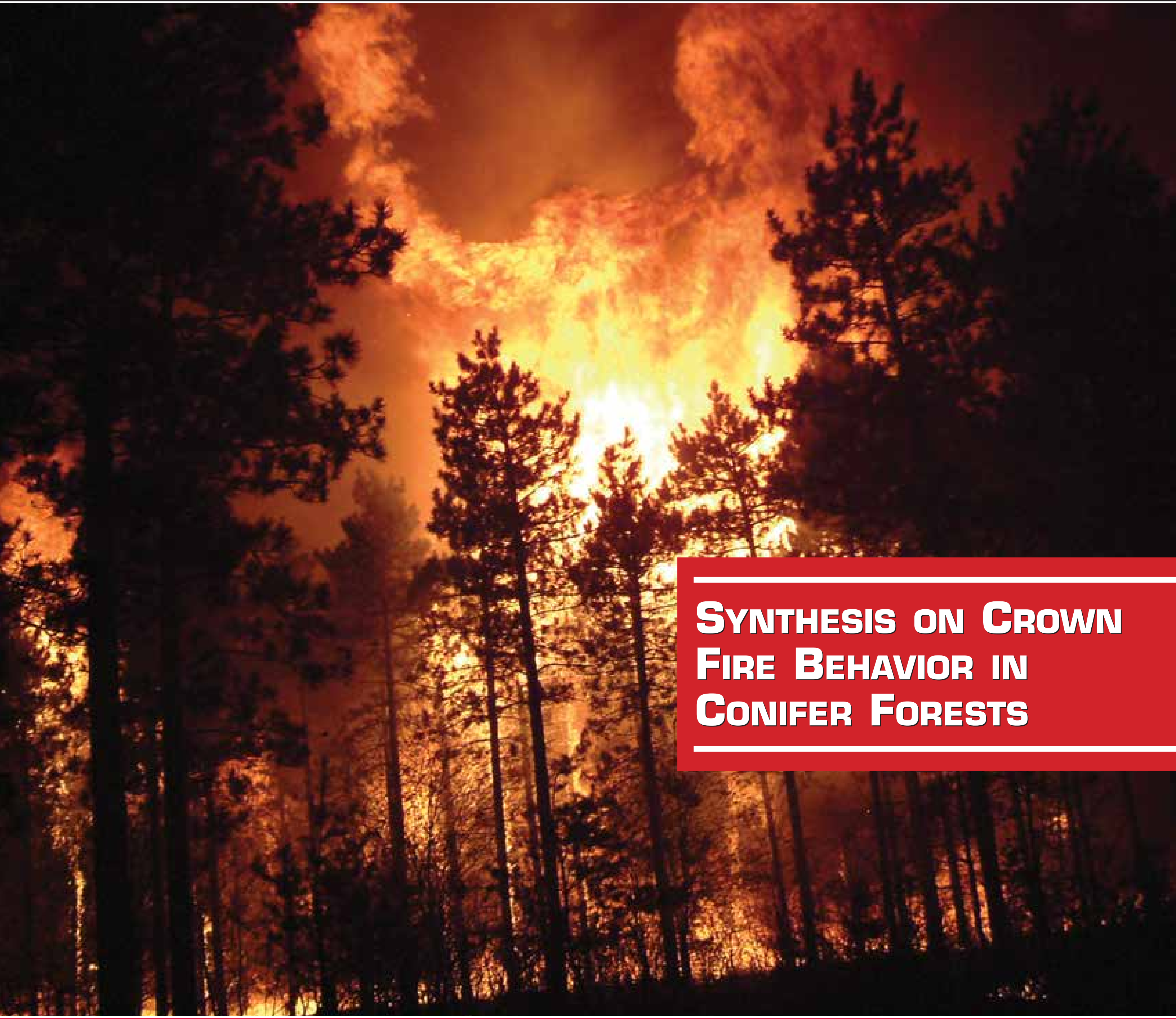

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On the Cover:

Crowning associated with the major run of the Cottonville Fire in central Wisconsin at 5:11 p.m. CDT on May 5, 2005, in a red pine plantation. Photo taken by Mike Lehman, Wisconsin Department of Natural Resources.

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