Technical Background of the FireLine Assessment MEthod (FLAME)

Jim Bishop[1]

Abstract—*The FireLine Assessment MEthod (FLAME) provides a fireline-practical tool for predicting significant changes in fire rate-of-spread (ROS). FLAME addresses the dominant drivers of large, short-term change: effective windspeed, fuel type, and fine-fuel moisture. Primary output is the ROS-ratio, expressing the degree of change in ROS. The application process guides and instills a systematic methodology, utilizing a simple worksheet. The information developed provides a basis for safety judgments and for applying Lookouts, Communications, Escape routes, Safe zones (LCES). The ROS-ratio can be applied to observed fire spread to provide a timeline of future fire spread. Compared to four BehavePlus examples FLAME is accurate to within an average error of 14 percent. In four fireline-fatality cases FLAME predictions match reconstructed ROS-ratios with an average error of 9 percent, and in every case could have foretold the rapid changes that impacted the crews. Adjustment factors are developed to account for variations of windspeed across terrain, and for flame height and sheltering by vegetation. Field application of FLAME is explained and demonstrated with examples.*

Part 1: The FLAME System

Essentially the FireLine Assessment MEthod (FLAME) applies fire behavior prediction science to the implementation of the fire order 'Base all actions on current and expected fire behavior.' With fireline-based observations firefighters apply it using only simple paper-and-pencil pocket tools. FLAME takes account of the 'current' fire behavior as a baseline, directs attention to the 'next big change' in fire behavior, and evaluates the magnitude of that change. The magnitude of the anticipated change in fire behavior is based on the relationships embodied in the Fire Behavior Prediction System (FBPS) as computed by BehavePlus, on grass fire behavior expressed in the Australian CSIRO model, and on observed rates of spread in grass, brush, and timber. The measure of the 'change in fire behavior' is expressed in FLAME as the factor by which fire rate-of-spread (ROS) will increase/decrease, the 'ROS-ratio'. (For example, an increase in ROS from 4 ch/hr to 24 ch/hr has an ROS-ratio = 24/4 = 6X.) Application of that ROS-ratio to the observation of current fire behavior provides an extrapolation of the fire spread-time, expressed most practically in terms of the fire's position on the landscape through time (using 'natural yardsticks,' things you can see on the land) rather than as a rate-of-spread in distance/time.

The two basic things that we must do: provide a systematic, practical, and effective tool to firefighters for evaluating fire behavior on the fireline, and effectively communicate and instill the important points of basic fire behavior training (as in S-290 Intermediate Fire Behavior). Application of FLAME in training and on the fireline supports both needs.

[1] Physicist, mathematician, geologist, formerly with the California Department of Forestry and Fire. cjbishop1991@sbcglobal.net

In assessing potential fire behavior firefighters need to be proactive, to consider all of the key factors, and not to simply be passively waiting to notice, or to be made aware of, a significant development in the fire's behavior. And they need to have a realistic sense of the impact such a change could have on them, the magnitude of the change. **Seat-of-the-pants assessments are not adequate.** A common tendency is for firefighters to rely too much on current fire behavior as a basis for their actions, with the expectation that they will simply notice any developing changes in time to react. **That failure to foresee dangerous (yet predictable) changes is evident in perceptions revealed again and again in fireline fatality cases.** Without an organized approach to that fire behavior assessment, it is too easy to miss something while being unaware of what information is missing, and too easy to be unaware of the magnitude of an impending change. Separate short papers (Bishop 2005, 2006) describe more fully the place for FLAME in training and on the fireline.

FLAME offers a systematic methodology that prompts and guides the user to explicitly consider the key factors that drive significant, sudden changes in fire behavior—based on a minimum number of inputs, usually only two: effective windspeed and fuel type. It is important that the process be usable, or it won't get used, so the emphasis in FLAME is on simple tools and the information that is available to the firefighter on the fireline, remembering that computers don't make it to the fireline. FLAME fills a need that is not addressed by the other applications of the fire model (nomograms, and so forth). It is far simpler to use, requires minimal materials, builds on observed fire behavior, directly addresses the important question of 'change' in fire behavior, and expresses outputs in terms that are easily applied (what's next, how much change, when will the fire be here).

FLAME application proceeds from basic to more refined steps and yields these three important results:

1. The identity and timing of the 'next big change'—Knowing the nature and timing of the pending change allows firefighters first of all to be aware of that potential, and also to better monitor the environment and maximize the value of fireline lookouts.
2. The magnitude of that change (expressed as the 'ROS-ratio', the degree of relative increase or decrease in ROS)—Knowing the magnitude of the pending change alerts the firefighter to the level of possible danger. In fact, large ROS-ratio might well be viewed as a universal common denominator in fireline accidents.
3. An estimate of the timeline of the fire's advance—Knowing the fire spread-time allows rational planning of escape routes and timing, as well as informing well-chosen tactics.

All in all, the FLAME information provides a solid basis for the implementation of LCES (Lookouts, Communications, Escape routes, Safe zones). It is, first and foremost, a tool for making sound safety decisions on the fireline, but also provides relevant information for tactical decisions.

Figure 1 illustrates the basic idea of combining a change in fuel type with a change in effective windspeed (EWS) to produce a measure of the resultant change in fire behavior (the ROS-ratio). Fuel type and EWS changes are the dominant changemakers. All of the details of how the FLAME 'standard curves' were derived and are used, and the relative sizes of fire behavior factors, are contained in sections below. This graphic simply portrays the basic FLAME inputs and output so that subsequent discussion makes more sense. The arrow depicts an example of change from 'current' (low windspeed, fire
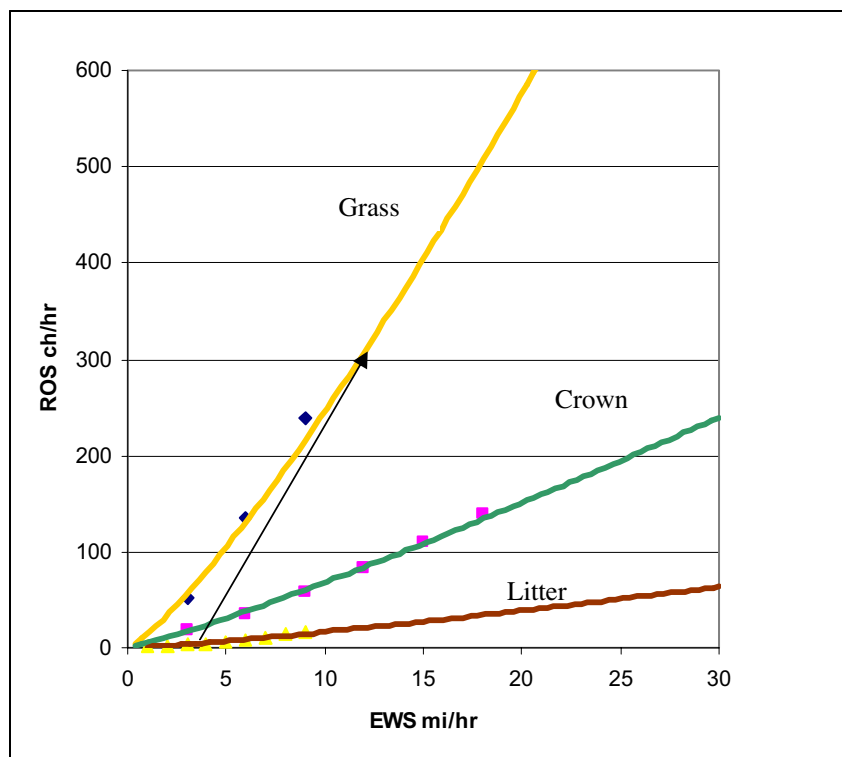
Figure 1—EWS vs. ROS for each of the major fuel types (litter, crown and grass). The arrow depicts an example in which fire in litter with an EWS of 3 or 4 mi/hr changes to fire in grass with EWS about 12 mi/hr. The initial and final ROS would be on the vertical axis, and the larger divided by the smaller would be the ROS-ratio for this change in fire behavior (approx. 70X).

in litter) to 'expected' (grass, moderate windspeed) fire behavior. The ROS-ratio would be the higher ROS on the vertical axis divided by the lower ROS on that axis. In this example the ROS would increase by a factor of about 70X as the fire moved from litter into grass and the EWS increased by between 3X and 4X. These curves form the basis for the FLAME predictions and illustrate the idea, but they are not the user-application tool (which is described in part 3).

The FLAME user observes the fuel type and current EWS affecting the fire, and looks ahead to the fuel type and EWS that will prevail after the anticipated change in conditions. The ratio of the larger EWS to the smaller EWS is obtained either by simple division or table look-up. With the fuel-type change and the EWS-ratio, use the FLAME table (table 2, later in this paper) to look up the ROS-ratio: join the EWS-ratio row with the column describing the fuel change, and read the ROS-ratio. For example, a 6X increase in EWS together with a transition from fire in the litter to crown fire would result in an increase in ROS of about 35X (or in the opposite case, a decrease of 35X). Associated diagrams and a field guide and worksheet help the user obtain inputs, move through the process, and determine the needed outputs.

The application of FLAME affords a range of information levels (corresponding to the aforementioned three important outputs), each with its own inherent degree of completeness and precision, and determined by the user and the circumstances on the fireline. In practice a firefighter can proceed from one level to the next, making use of the output at each stage, as time and information allow.

1. 'Initial application' level: user depicts/describes the current fire behavior, the expected fire behavior, and identifies the next big change; this stage involves only a qualitative assessment.

2. 'Standard application' level: user inputs current and expected conditions and predicts the ROS-ratio.

3. 'Complete application' level: user combines an observation of the current fire-spread timeline with the ROS-ratio to yield a predicted fire-spread timeline (or spread time). The spread-time line lays out at what time the fire will reach a given point. If the fire moved this far in a certain time under current conditions, how long will it take to go that far under expected conditions? It is related to ROS but is a projection of the fire's progress in terms of features visible on the landscape (natural yardsticks), rather than an explicit rate in units of distance/time.

The following examples illustrate the idea of the FLAME process, the application stages, and the kinds of outputs a firefighter can obtain, with suggestions on how the information relates to LCES. They are not intended to explain how FLAME is applied (inputs are simply given), and they are not to be 'over interpreted' in terms of tactical/operational considerations. Both examples are of dangerous changes in fire behavior, but the FLAME idea applies to any change in behavior, dangerous or benign.

Example 1—an upslope run:
- **Fireline observations**: Fire spreads over the course of 4 hours up the lower half of a forested 20 percent slope as a litter fire with midflame windspeed 2 mi/hr. By late morning, conditions will allow the midslope fire to transition to a crown fire and to be exposed to higher windspeeds on the upper slope.
- **Initial application**: The next big change expected is a transition to crown fire and the effects of the higher windspeeds on the upper half of the slope.
- **Standard application**: The litter-to-crown change in fuel will combine with a total 8X increase in effective windspeed (wind on the upper slope being 16 mi/hr at the crown-fire flame level) to produce an increase in ROS of 50X, ROS-ratio = 50X.
- **Complete application**: The fire took 4 hours spread up the lower half of the slope. The crown fire could run the upper half of the slope in about $1/50^{th}$ of 4 hours, or about 5 minutes.
- **LCES**: Lookouts—be especially vigilant for signs of the transition to crown fire, such as torching or short crown runs, and also to wind direction as revealed in the smoke column to anticipate which side of the upslope run might be most threatening to crews in the area. Communications—regular reporting of crown-fire precursors, RH, and wind direction. Escape—must take much less than 5 minutes and be located out of the line of the crown fire run.

Example 2—a major wind increase and direction change:
- **Fireline observations**: Fire is burning on a flank in litter under conifers; the head of the fire made a short crown-fire run earlier. The wind is predicted to blow across that flank at 20 mi/hr when a cold front arrives in the next 2 to 4 hours. The flanking fire has moved ¼ of the way to a road in the last 2 hours (a rate that puts it at the road in 6 more hours).
- **Initial application**: The next big change is a large increase in wind pushing the flank outward toward the road, and the fire is expected to transition to crown fire with the increase in wind. The change is expected in as little as 2 hours.

- **Standard application**: The litter-to-crown change in fuel will combine with a 20X increase in effective windspeed to produce an increase in ROS of 140X. (Effective wind on the flank is taken as 1 mi/hr, as will be explained in part 2.)
- **Complete application**: The fire could be halfway to the road in 2 more hours when the wind hits, and the wind-driven crown fire will complete the remaining half of the distance to the road in about $1/140^{th}$ of 4 hours, or about 2 minutes (less time if the fire is more than halfway to the road when the wind comes).
- **LCES**: Lookouts—besides having local lookouts, a remote lookout should be established 'upstream' of the fire to provide early warning of the approach of the cold front. Communications must be arranged with the remote lookout. Escape via the road would allow only about 2 minutes after the wind hits, so escape should be initiated earlier based on the reports of the remote lookout.

Why not stop at the 'initial application' stage? That is certainly a good start, and in some cases will be all one needs to know…to have identified the next big change. But going further, to the standard application, requires the firefighter to explicitly look at the big changemakers: effective windspeed (EWS), current and expected; fuel type; fine-fuel moisture (FFM) or RH, and therefore to either obtain those critical parameters or to become aware that important information is missing. Seeking the explicit ROS-ratio prediction directs a method that prompts and leads specific appraisal of the key fire behavior factors. The ROS-ratio gauges the magnitude of coming changes. The complete application provides a timeline that can provide a realistic sense of fire movement and can guide good choices about the timing of safety actions and effective control actions.

Focusing on the Dominant Changemakers

Many factors in the fire environment contribute to fire behavior: fuel physical/chemical characteristics, fuel arrangement, fuel moisture, slope, and wind. Fire behavior (as measured by ROS in FLAME) is less sensitive to some of these factors than to others, and some factors change less rapidly than others. In a given situation current fire behavior demonstrates the integrated effects of the prevailing fire environment factors…firefighters can observe that. If nothing much changes in the fire environment, prediction requires only extrapolation of observed fire behavior. But things eventually do change, often quickly, and the degree of change from that 'baseline' fire behavior can be predicted.

We focus on the major changemakers that will cause large changes in 'current' fire behavior on short timescales (those factors will be quantitatively identified below). In eliminating some detail in fire behavior inputs, a little accuracy is traded for practical applicability, but without compromising the basic capacity to predict significant change. Also, in order to focus on potentially dangerous fire behavior FLAME emphasizes the range of fuel conditions that accompany active fire behavior (meaning the lower FM ranges, typical of a late-season afternoon). The relative response of ROS to a change in effective wind or fuel type is similar over a range of fuel moistures, and here we use model guidance assuming fairly dry fuels (usually 1-hr FM 6 percent and live FM 80 percent). In other words, the ROS change due to a doubling of windspeed is essentially the same at 4 percent as at 8 percent FM.

We want to anticipate change that can be 'sudden', those changes that can develop in minutes ('minutes' is the timescale of escape) or tens of minutes.

Changes that evolve gradually over many hours, or days, present less of an imminent threat to fireline personnel, and one can remain current on such gradually changing fire behavior. So in seeking the dominant drivers of short-term change we look at fire behavior factors that *can* change significantly in roughly an hour or less. Whether such changes actually take place over several hours, or in just minutes, the FLAME application is still relevant. And while change can occur quickly, it may not get under way for hours. To extend a FLAME prediction, a firefighter simply updates the observation of ongoing fire behavior and looks ahead to further change.

Live, 10-hour, 100-hour, and 1000-hour fuel moisture are not drivers of large, short-term changes. Live fuel moisture (LFM) varies over the season. When LFM levels are low enough, fire can propagate through the crowns of shrubs or trees. The LFM usually continues to decline throughout the fire season, but for a given species of live fuel it usually doesn't drop more than another 20 percentage points or so after crowns become flammable. In extreme and prolonged drought it may drop by 40 percentage points in timber fuels after the time when crowns become flammable, typically less than that (about 20 percentage points) in chaparral.

However, the change in LFM in a given plant over an hour is much less than the seasonal changes. Consider a change in LFM of 5 percentage points (which is greater than would be typical in an hour), from 80 to 75 percent. As indicated by BehavePlus for Model 5, such a variation in LFM would result in a change in ROS of only about 5 percent.

Changes in 10-hour FM over the course of an hour are not likely to be more than about 2 percentage points. Consider the effect of a 2 percentage point 10-hr FM change on ROS in grass and in litter. For fuel model 1, and for fuel model 9, BehavePlus shows no change in ROS for a 2 percentage point variation in 10-hour FM. Hundred-hour and 1000-hour fuels will undergo even smaller changes in FM over an hour than do 10-hour fuels. Short-term moisture changes in larger-diameter fuels are not a significant moderator of large, sudden changes in ROS (though moisture in larger fuels certainly does affect the overall fire intensity).

Variations in fuel conditions on the fire can result from the fire's movement, as well as through overall change with time. For example, a fire can move from one slope-aspect to another, and fuels on those different slopes can have different fuel moistures. Such differences might be as high as a few percentage points of dead FM and 10 or 20 percentage points of live FM (in the same species of plant). Those variations certainly contribute to changes in ROS, of order approximately 20 percent, sometimes less. However, there are almost certainly other significant changes associated with such a slope-aspect change—in plant community, fuel architecture, and the wind-slope influence driving the fire. In the face of these significant changes in more dominant factors, the variations in live and larger-diameter dead fuel moistures on different slope aspects are a relatively minor influence on the changes in ROS.

For purposes of predicting significant changes in ROS that result from 1-hour-timescale changes in fuel conditions, live FM, 10-hour FM, 100-hour FM, and 1000-hour FM are considered essentially constant and a minor influence on ROS change. The effects of those factors on fire behavior will be manifested in, and observable in, current fire behavior, the baseline fire behavior.

1-hour fuel moisture plays a significant role—Changes in 1-hour FM (FFM, fine-fuel moisture) can be significant over 1-hour timescales. The combined effects of relative humidity, temperature, and time-of-day typical of 'summer

day' changes, might lead to a change in FFM on the order of 2 percentage points in an hour. As indicated by BehavePlus for fuel models 1 and 9 such a variation in FFM would lead to ROS changes of about 12 percent in grass or 17 percent in needle litter. If fire moves from an open south slope to a canopy-shaded north slope (or vice versa) it can experience a change in FFM of about 3 percentage points—corresponding to ROS changes of about 21 percent in grass or 32 percent in needle litter. The FLAME system handles changes in FFM with the following guideline (in two versions):

For a change of FFM of 'n' percentage points, the ROS (in a given fuel) will change by about 1.nX. For example, FFM dropping by 2 percentage points would yield roughly a 1.2X increase (a 20 percent increase) in ROS (compared to an average of 1.15X, or 15 percent, as per the BehavePlus example cited above).

An alternative way of doing essentially the same thing is based on the change in relative humidity (RH). Given that a change in RH of 5 percentage points leads to a change of about 1 percentage point in FFM, the change in ROS in fine dead fuels is about 2X(RH-change). For example, a drop in RH from 40 to 25 percent (= 15 percent) would increase ROS in fine dead fuels about 2X15 percent = 30 percent, or by a factor of 1.3X. Such adjustments can fine-tune the ROS-ratio that is based initially on just changes in fuel type and EWS, though such refinements are usually not necessary.

There can be more dramatic changes in FFM. A good example is the onset of foehn winds, where in a few 10s of minutes FFM might drop by about 6 percentage points. The direct effect of that FFM change would suggest roughly a 60 percent increase in ROS. But the other changes, likely a transition from surface fire to crown fire and the onset of high winds, would dwarf the direct effect of changes in FFM on ROS.

Probably the most important effect of changes in FFM on changes in fire behavior is the influence it has on transition to crown fire (an important change in fuel type) and on spotting. In the FLAME system FFM can be used to fine-tune predicted changes in ROS (for changes between largely fine-dead fuels grass and litter) as noted above, but more importantly FFM (and relative humidity) is explicitly considered in FLAME applications as a factor in the onset of crown fire (detailed in part 2).

Fuel type is a major changemaker—FLAME classifies fuels as litter, grass, or crown foliage (of shrubs and trees), a classification based on the ROS characteristics of those fuels, their similarity within a group. The reasons for treating fuels in that way are:

1. Those fuel types are quickly and easily recognized by firefighters, without the need for extensive training on determining fuel models.
2. ROS within each group of fuels is sufficiently characteristic of that fuel and distinct from the others to allow meaningful predictions of ROS-change as a function of fuel type.
3. Changes in fuel type contribute to major changes in ROS.

As a generalization, with other fire behavior factors constant, ROS in crown fuels is about 4X faster than in litter, and in grass fuels about 3X to 4X faster than in crown foliage. The total range in variation in ROS across the three fuel-type averages is on the order of 15X (for comparison, recall that changes in ROS due to short-term changes in fuel moisture are no more than about 1.2X for live FM and the heavier dead fuels, and about 1.6X for changes in FFM).

Effective windspeed is the greatest changemaker— Effective windspeed (EWS) is taken to be the midflame windspeed (MFWS) plus a component that accounts for the effect of slope on ROS. In these discussions in part 1 EWS is considered to be 'a given' and an appropriate measure of the combined effects of wind and slope on ROS. Guidelines for obtaining wind-adjustment/reduction factors used to determine EWS, and for obtaining the wind-equivalent of slope, are in part 2.

EWS has a great influence on ROS, and varies rapidly in time and place. It is by far the most dominant changemaker for short-term changes in fire behavior, capable of driving ROS changes of >200X. The influence of EWS on ROS is derived from the curves of ROS vs. EWS inherent in FBPS models, the CSIRO grass fire model, and observations of ROS in crown fuels.

In summary, the magnitudes of the short-term changes (~1 hour) in ROS produced by the various factors are listed below. It is clear that the dominant changemakers are EWS and fuel type, with FFM relevant but less influential as a direct factor (remaining useful for fine-tuning and for helping to reveal potential for crown fire).

- Fuel moisture in live and larger dead fuels ~ 1.2X (~20 percent)
- Fine-fuel moisture (and therefore RH) ~ 1.6X (~60 percent)
- Fuel type (litter, crowns, and grass) ~ 15X (~1400 percent)
- Effective windspeed (including slope) ~200X (~20,000 percent)

The Basic Data Used in FLAME

The dependence of ROS on fuel and EWS was derived from a combination of model outputs and observations. The model outputs were obtained from BehavePlus (1-hr FM 6 percent, 10-hr FM 7 percent, 100-hr FM 8 percent, live FM 80 percent) and from the CSIRO grass fire nomograms (Cheney 1997). The curve of ROS vs. EWS for each fuel type is derived from the averages of inputs summarized below.

1. Grass fuels are represented by FBPS fuel models 1 and 3, the CSIRO grassfire model, and at high windspeeds by observed spread of Australian grass fires (Cheney 1997).
2. Crown fuels are represented by FBPS fuel models 5, 6, and 7, and observations of crown fire in brush and in timber (including Range and others 1982, Rothermel 1991).
3. Litter fuels are represented by FBPS fuel models 8, 9, and 10.

Slash fuels are not explicitly considered in FLAME, as they are uncommon in wildfire environments, but they can be considered via adjustment of standard ROS-ratios. The number of permutations between fuels rises rapidly as the number of fuels considered increases, and to keep the system simple unnecessary variations in fuel type are not included. However, it is possible to address a lot of variation from the standard by making adjustments to the standard FLAME outputs. Specific adjustments to FLAME outputs are described later in this paper.

Crown fuel ROS observations—Summarized in figures 2 and 3 are observations of crown fire ROS as a function of 20-ft windspeed (which in FLAME is taken to be the midflame windspeed for crown fire). Best-fit 2nd-order polynomials are displayed on the graphs, together with the regression coefficients (here R represents regression coefficient, but later R represents ROS). Observed crown fire data used in the graphs are shown in the accompanying table. The data used to represent the crown-fuel group ROS values for the FLAME standard curves were derived from the regression plots.
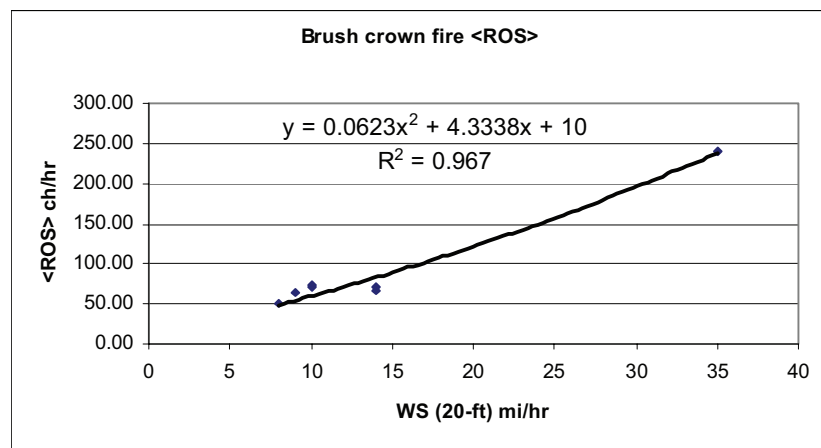
Brush fire cases	20-ft WS mi/hr	<ROS> ch/hr
Ely 1	10	70.40
Carson B	14	65.60
Carson C	14	70.40
Carson A	9	64.00
South Canyon	35	240.00
Pilot	8	49.60
Fort Ord	10	73.60

Figure 2—Observed crown fire ROS in brush fuels are plotted against 20-ft windspeed (for cases shown). Overall topographic slope in these cases was slight. Best-fit 2nd-order polynomial curve and regression coefficient are shown. <ROS> denotes the spread rates as averages.
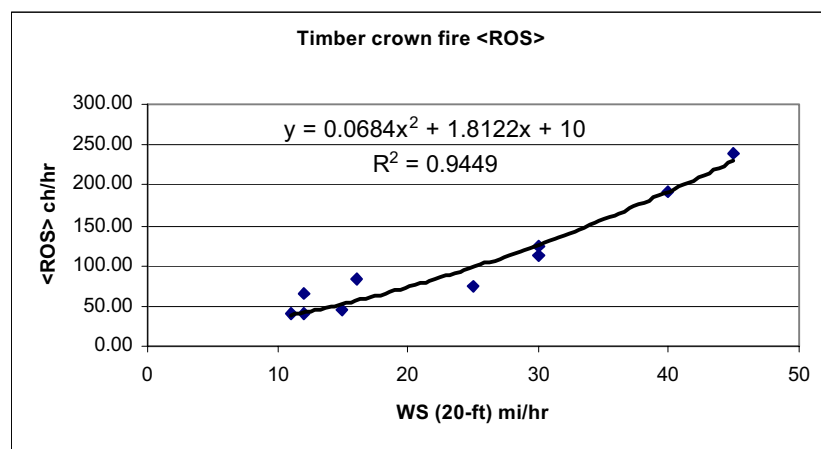
Timber fire cases	20-ft WS mi/hr	<ROS> ch/hr
Sundance	45	240.00
Sundance	30	112.00
Red Bench	12	41.60
Lily Lake	25	73.60
Sandpoint	16	83.20
Pattee Canyon	30	124.80
Mink Creek	15	44.00
Black Tiger	11	40.80
Scott Able	40	192.00
Butte Fire (Wallace Crk.)	12	65.60

Figure 3—Observed crown fire ROS in timber fuels are plotted against 20-ft windspeed (for cases shown). Overall slope was not a major direct influence on ROS. Best-fit 2nd-order polynomial curve and regression coefficient are shown. <ROS> denotes the spread rates as averages.

The data shown encompass considerable variation in species and structure, and in fuel moistures. The brush fires were in Great Basin shrubs (such as sagebrush and antelope brush), chaparral (both interior and maritime), and Gambel oak. The timber fuels (mostly from the Northern Rockies but also New Mexico, included pines, firs, and spruce). Each had its own live fuel moisture, and dead FMs varied as well. In spite of that variation there is strong and consistent correlation of ROS with windspeed in brush crowns and in timber crowns. Changes in ROS can be related to changes in EWS with good accuracy, over a broad range of crown fuel types. And crown fuels can be treated as a group with adequate results.

Overall, the ROS data for timber fuels tend to represent long-term spread, including periods of discontinuous crown fire. The brush fire data tend to represent shorter, more continuous crown-fire spread. An upward adjustment

of crown ROS by 1.7X (Rothermel 1991) to better reflect the faster continuous portions of the spread shows it to match the brush ROS data almost exactly (see fig. 4, later in this paper). The similarity in brush versus timber ROS, together with the well grouped FBPS model outputs, allow a treatment of crown fuels as a single fuel type with good results, as will be developed below.

Crown fuel-model representatives—FBPS fuel models 5 and 6 are good representatives for crown-foliage fire spread in shrub/brush fuels. Model 7 represents fire spread in crown fuels typical of the Southeastern United States. FBPS fuel model 4 tends to predict ROS that are too high. Calibrations of fuel model 4 suggest that its outputs be reduced by at least half. Given the other, more accurate models for fire spread in brush, and the crown fire observations, fuel model 4 was not used. Fuel models 5, 6, and 7 have very similar ROS outputs and, together with the above crown fire observations, are used to represent fire spread in crown foliage in constructing the FLAME standard curves.

Litter fuel representatives—FBPS fuel models 8, 9, and 10 are all used. ROS outputs for models 9 and 10 are similar. ROS outputs for fuel model 8 tend to be only about one-third of the litter-fuel average, and when such compact short-needle litter fuels dominate fire spread, the FLAME outputs can be adjusted (the ROS-ratio is increased) to reflect the slower spread in the litter.

Compiling the data—The following data were averaged to produce the points that define the FLAME 'standard curves' (fig. 4), the curves that characterize ROS for each fuel type as a function of EWS.
- Grass: The average of models 1 and 3, CSIRO grassfire model, and grass fire ROS observation on the Australian Narraweena Fire of 1983 (which helps to define the curve at high windspeeds); data points at EWS 1 through 10 mi/hr and 30 mi/hr (30 is an observation; model 1 hits wind limit at < 9 mi/hr)
- Crowns: The average of models 5, 6, & 7, and best-fit curves for observed ROS in brush and in timber (which also reflect higher windspeeds); data points at EWS (mi/hr) of 3, 6, 9, 12, 15, & 18.
- Litter: The average of models 8, 9, & 10; data points at EWS 1 through 9 mi/hr.

Deriving the Dependence of ROS on Fuel Type and EWS

The FLAME standard curves (fig. 4)—The data for each fuel type (grass, crown, litter) have some scatter within the group, but do not overlap; each fuel type is uniquely and separately characterized (especially when the faster components of average timber ROS are considered). The resulting degree of variation in predictions will be defined in discussions of accuracy below. You can visualize the 'sector' of fuels represented by each standard curve in figure 4:

- The grass group is at about '1 o'clock.'
- The crown group is at about '2 o'clock' and extends from the points above the curve to the first set below the curve (the brush and 'continuous timber' points, but not the 'average timber' points, as will be explained below).
- The litter group is at about '3 o'clock.'
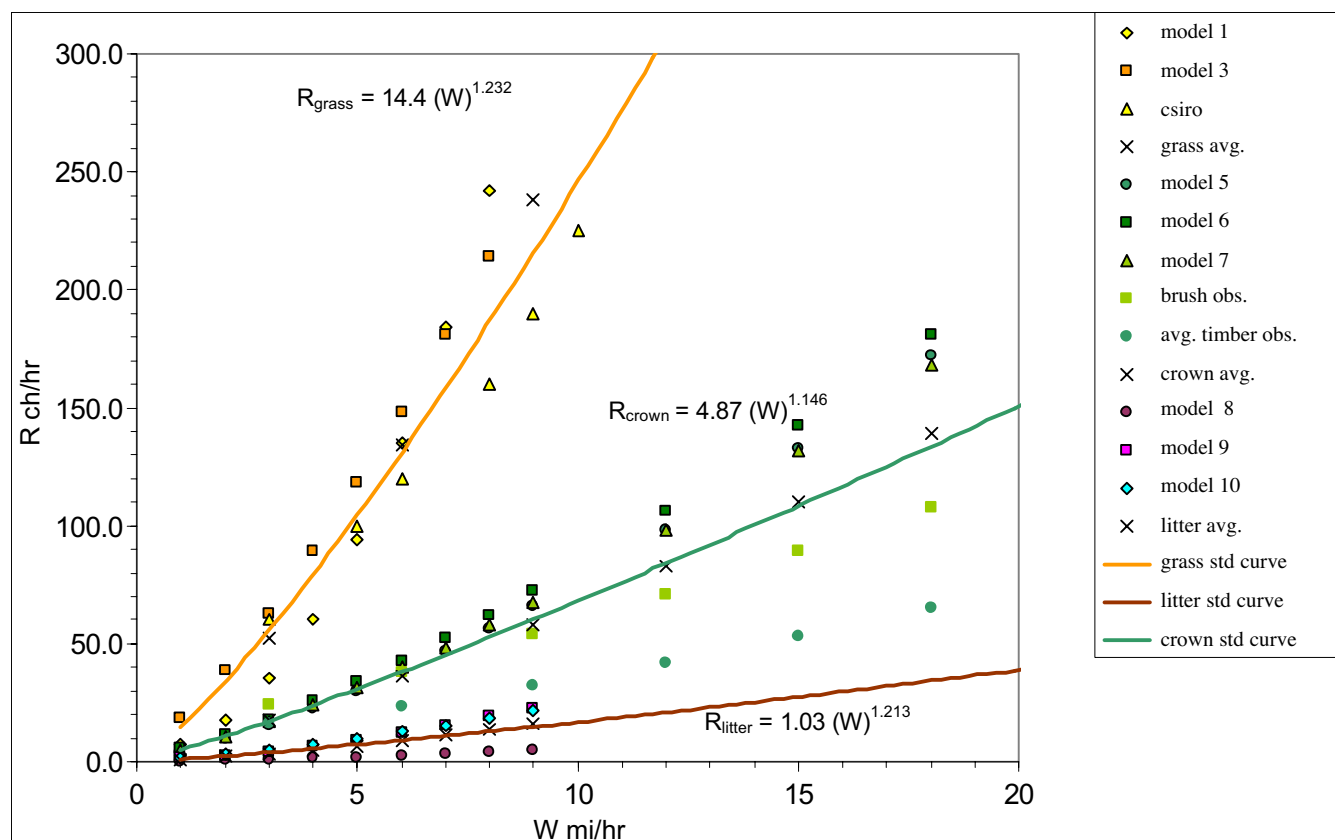
Figure 4—Standard FLAME curves. ROS (ch/hr) on the vertical axis as a function of EWS (mi/hr), for each model or observation set used to generate the standard curves (grass fuels in yellows, crown fuels in greens, litter fuels in purple, blue, and brown). Standard curves are the best-fit power curves for each fuel type, with the defining equation shown. As will be explained below the curves are effectively truncated at EWS = 0.5 mi/hr.

Best-fit FLAME curves could be defined by polynomials and would offer good approximation to the data. However, it is necessary to compare values (as a ratio) between standard curves, and quotients of polynomials are not easily handled analytically. Therefore the standard curves are defined by best-fit power curves, which are amenable to analytic solutions when combined as ratios. The fit of the power curves to the average ROS values within each fuel types is quite good, with regression coefficients of at least $r^2 = 0.99$. R, the ROS (not to be confused with earlier use of R as the regression coefficient), is in ch/hr; W, the EWS, in mi/hr.

The equations of the FLAME standard curves for each fuel type are (in the form expressed in equation 1 below):

- Grass: $R_{grass} = 14.4 \ (W)^{1.232}$
- Crown: $R_{crown} = 4.87 \ (W)^{1.146}$
- Litter: $R_{litter} = 1.03 \ (W)^{1.213}$

ROS-ratio for cases involving no change in fuel—Each fuel type has a unique ROS dependence on EWS, a unique wind response, as reflected in the exponent in the power equation (this paper would be a lot shorter if that were not so). To characterize changes in EWS in cases where there is no change in fuel the exponents are averaged, to give the 'no-fuel-change' dependence of

ROS-ratio on EWS-ratio (for all fuels), as derived below. The accuracy consequences of using an average wind-response coefficient are evaluated in treating the wind response of all fuels the same in the 'no-fuel-change' case.

The general ROS equation (from regression curves) for a given fuel type is:

$$R = \alpha \, (W)^{\beta} \qquad\qquad \text{Eq. 1}$$

Where R is ROS; α is the fuel coefficient; W is the EWS; β is the wind-response coefficient.

For change in EWS (in a given fuel), where $R_R = R_{larger} / R_{smaller}$ is the ROS-ratio, $W_R = W_{larger} / W_{smaller}$ is the EWS-ratio, the FLAME ROS-ratio will be

$$R_R = R_{larger} / R_{smaller} = [\alpha \, (W_{larger})^{\beta}] / [\alpha \, (W_{smaller})^{\beta}] = (W_R)^{\beta} \qquad \text{Eq. 2}$$

The average of $\beta_{grass} = 1.232$, $\beta_{crown} = 1.146$, and $\beta_{litter} = 1.213$ is: $\beta_{average} = 1.20$

Therefore for EWS changes only (no fuel change), the ROS-ratio is given by

$$R_R = (W_R)^{1.20} \qquad\qquad \text{Eq. 2a}$$

ROS-ratio for cases involving both a change in fuel type and in EWS—ROS-ratios are formed for change between litter and crown fuels, between crown and grass fuels, and between litter and grass fuels. Note that the equations express an ROS-ratio that can describe a fuel change in either direction (for example litter to crown, or crown to litter), and either a reduction or an increase in EWS. The conventions regarding whole-number (versus fractional) ROS-ratio are detailed below in the section on *The net effect on ROS*.

Consider a change from an initial fuel-type and initial EWS to a final fuel type and final EWS, as expressed by the ROS-ratio R_R. Here are the quantities involved (where R_R and W_R apply to a more general case than the ratios used in equation 2).

R_I = initial ROS; R_F = final ROS; W_I = initial EWS; W_F = final EWS; $W_R = W_F/W_I$

Using equation 1, where here parameters α_I and β_I correspond to the curve for the initial fuel, α_F and β_F to the curve for the final fuel (as shown on fig. 4):

Initial ROS $R_I = \alpha_I(W_I)^{\beta I}$; and final ROS $R_F = \alpha_F(W_F)^{\beta F}$

$R_R = R_F / R_I = [\alpha_F(W_F)^{\beta F}] / [\alpha_I(W_I)^{\beta I}]$; and since $W_F = (W_I)(W_R)$, then

$$R_R = (\alpha_F /\alpha_I) (W_I)^{(\beta F - \beta I)} (W_R)^{\beta F} , \text{ the basic ROS-ratio equation} \qquad \text{Eq. 3}$$

What do the terms in equation 3 mean?—Consider first the case in which $W_R = 1$, and the equation represents a case in which there is no change in EWS, strictly a change in fuel, then:

$$R_R = (\alpha_F /\alpha_I) (W_I)^{(\beta F - \beta I)} \text{ (for no change in EWS)}$$

For a given W_I, R_R above represents the ratio of ROS typical of fuels α_F & α_I at that EWS. The fraction (α_F /α_I) itself represents the ratio of ROS in the different fuels at an EWS of $W_I = 1$ mi/hr.

The term $(W_I)^{(\beta F - \beta I)}$ incorporates the fact that as W_I varies, the relative ROS between different fuel types changes, reflecting the difference in the

wind-response coefficients between fuel types. In other words, the relative ROS in the different fuels changes slightly as actual EWS changes…the relative ROS is slightly different at EWS of 3 mi/hr versus that at 6 mi/hr. One way to visualize it is that the relative spacing of the FLAME standard curves in figure 4 changes slightly as EWS varies, because each curve bends upward at slightly different rate (due to their different wind-response coefficients). If β_F and β_I were equal, the dependence of relative ROS for different fuels on EWS would vanish. As will be shown later in the sections on evaluating the accuracy of FLAME, the ROS-ratio is only weakly dependent on the term $(W_I)^{(\beta_F - \beta_I)}$, and that effect introduces only a small error (usually less than 10 percent).

We can consider $(W_I)^{(\beta_F - \beta_I)}$ to be a constant, C, once we've chosen a standard W_I. For changes from litter to/from either crown or grass fuels W_I will be set at 2 mi/hr, and for changes from crown to/from grass fuels W_I will be set at 15 mi/hr (as explained below in the section on *The specific equations for combining fuel and wind changes*). The consequences of those values of WI will be evaluated quantitatively in the section on *The dependence of ROS-ratio on actual EWS (in addition to the EWS-ratio)*.

The third term in equation 3, $(W_R)^{\beta_F}$, represents the influence on ROS-ratio of a change in EWS (via the EWS-ratio). The wind-response coefficients, β, are a bit greater than 1 (ranging from 1.146 to 1.232), which indicates that a given increase in EWS produces a little greater increase in ROS.

Rewriting Equation 3 with the constant C gives

$$R_R = C \, (\alpha_F / \alpha_I) \, (W_R)^{\beta_F} \qquad \text{Eq. 3a}$$

Equation 3a embodies the essential point of the FLAME process, with the fireline input shown in bold. A huge range of significant fire-behavior change, expressed by the ROS-ratio, R_R, can be described by just two things: the knowledge of the change in fuel types (represented by α_F / α_I), and the degree of change in windspeed (via the EWS-ratio, W_R). You can visualize the standardized fuel coefficients as representing the relative change in ROS between two different fuel-type curves at a standard EWS (either 2 mi/hr or 15 mi/hr), with the further effect of changes in EWS represented by movement along the appropriate standard curve an amount specified by the EWS-ratio.

The net change in ROS, slower or faster?—The expression in equation 3 is analytically complete and covers all possible cases of speeding up or slowing down. Initial fuels can be slower or faster than final fuels; initial EWS can be slower or faster than final EWS. An ROS-ratio <1 will indicate that the fire is expected to slow down as fuel and EWS change. But applying fractional EWS-ratios and interpreting fractional ROS-ratios can be awkward for the FLAME user, so equation 3 is used to generate a user-friendly lookup table containing only whole-number ROS-ratios and EWS-ratios.

For most real-world cases (especially those changes that threaten firefighter safety), the 'slower' fuel experiences the lesser wind, and the 'faster' fuel experiences the greater wind. For example, litter (the slowest fuel) under a stand will feel less wind than will overlying crowns (a faster fuel). So in practice ROS-ratio = (larger ROS)/(smaller ROS), and EWS-ratio = (larger EWS)/(smaller EWS). The user avoids working with fractional ratios, and simply keeps track of whether the change will be an increase or a decrease in ROS.

Table 1 shows the four possible combinations of 'faster' and 'slower' for fuels and EWS. The most common 'big change' combinations by far are those that fall into the upper left or the lower right quadrants of the table. Those are combinations where the change in fuel type and the change in EWS reinforce each other in increasing or in decreasing the fire ROS—they effectively multiply together to produce the final ROS-ratio that is shown in the main section of table 2, the basic FLAME table. The lower left and upper right quadrants show combinations where the change in fuel type and the change in EWS oppose each other, with the dominant change determining whether the net effect is to reduce or to increase the ROS. Direct changes between grass and crown fuels are the most likely possibility for such cases. For example, a fire backing in grass (a fast fuel) could then move up a slope with increased wind in crown fuels (a slower fuel). Such situations are covered in the rightmost two columns of the FLAME table (table 2), or by a technique described below in the section *When changes have opposing effects.*

Table 1—The several possible combinations of change in fuel type and change in **EWS** and the net change in ROS that could result.

Change in fuel type		Change in EWS	
		Faster	**Slower**
	Faster	ROS always increases	increase or decrease
	Slower	increase or decrease	ROS always decreases

Table 2—Rate-of-spread ratios (R_R in the equations) as a function of changes in fuel and changes in effective windspeed. The table is generated by application of equation 3a. The left-hand column shows the EWS-ratio (W_R in the equations), the factor by which EWS changes. Each column corresponds to a change between particular fuel types (or to no change). Table values express the ROS-ratio that results from the combined change in EWS and fuel. The left side applies to cases in which fuel and wind changes reinforce. Cases in which changes in wind and fuel have opposing effects are handled with the rightmost two columns. Highlighted ROS values define a range that includes situations associated with fireline fatalities.

FLAME Table (source of ROS-ratios)

EWS-ratio	No fuel change	EWS biggest in faster fuel			EWS less in grass	
		Litter to/from crown	Litter to/from grass	Crown to/from grass	Crown to/from grass	Litter to/from grass
No chg 1	1	4	14	4	*4*	*14*
2	2	10	30	8	*2*	*5*
3	4	15	60	13	1	*3*
4	5	20	80	20	2	*3*
5	7	30	100	27	2	*2*
6	9	35	130	35	3	*2*
8	12	50	180		4	1
10	16	60	240		5	1
12	20	80	300		6	2
16	30	100	440		8	2
20	40	140	600		10	3
24	50	180	700		13	3
30	60	220	1000		17	4
40	80	300	1300		23	6
50	110	400	1800		30	8
60	140	500	2200		40	10
80	200	700	3100		60	16

The specific equations for combining fuel and wind changes—The specific parameters (analogous to α and β in equation 1) for each fuel type are (see the FLAME standard curves in fig. 4):

- For grass fuels: $\alpha_G = 14.4$; $\beta_G = 1.232$
- For crown fuels: $\alpha_C = 4.87$; $\beta_C = 1.146$
- For litter fuels: $\alpha_L = 1.03$; $\beta_L = 1.213$

The 'α' coefficients measure the effects of fuel type on ROS (for the above values, at EWS = 1 mi/hr)—indicating that litter is the slowest fuel, crowns faster, and grass the fastest fuel. The 'β' coefficients measure the response of ROS to changes in EWS. β-coefficient comparisons reflect the fact that grass is a little more wind-responsive than litter fuels, and that litter fuels are a little more wind-responsive than crown fuels (as characterized by the FLAME standard curves).

The final equations 4, 5, and 6 (below) are obtained from equation 3 by inputting the above specific values of α and β to represent the initial and final fuels. For changes from litter to/from either crown or grass fuels the standard initial EWS is set at $W_I = 2$ mi/hr, and for changes between crown and grass fuels the standard EWS is set at $W_I = 15$ mi/hr. Those 'standard values' of EWS are chosen because each falls at the 'geometric' midpoint of a reasonable range of actual EWS (+/− 4X or +/− 3X). For cases in which there is no change in EWS, $W_R = 1$, and the approximate relative change in ROS between fuel types can be gauged from the fuel-change coefficients (4.51, 3.73, and 14.2)—that relationship varies slightly at W away from the standard W_I. ROS in crown fuels is roughly 4½ X faster than in litter (less difference with increasing EWS), ROS in grass fuels is roughly 3½ X faster than in crowns (more difference with increasing EWS). Those figures do not multiply to give exactly the relationship between litter and grass fuels because they represent different 'standard EWS' values (otherwise they would).

Litter to/from crown fuels:

$$R_C / R_L = (4.87/1.03)\ (2)^{(1.146-1.213)}\ (W_R)^{1.146} = 4.51(W_R)^{1.146} \qquad \text{Eq. 4}$$

Crown fuels to/from grass:

$$R_G / R_C = (14.4/4.87)\ (15)^{(1.232-1.146)}\ (W_R)^{1.232} = 3.73\ (W_R)^{1.232} \qquad \text{Eq. 5}$$

Litter to/from grass:

$$R_G/R_L = (14.4/1.03)\ (2)^{(1.232-1.213)}\ (W_R)^{1.232} = 14.2\ (W_R)^{1.232} \qquad \text{Eq. 6}$$

The above equations are used to generate the table of ROS-ratios used in FLAME (table 2 and appendix B table B2), as a function of the two fuels involved and of the EWS-ratio. In the main part of the table (center three columns) a change in fuel and the change in EWS are assumed to reinforce (which is usually the case) to cause a net decrease or net increase in ROS. The less common cases where the change in fuel opposes the change in EWS (such as fire backing down a slope in grass, then running up the next slope as a wind-driven crown fire) are handled in the rightmost two columns. Those exceptional cases can also be handled by a technique described briefly in the section below on *Adaptation to nonstandard cases*. The same ROS-ratio can describe either a net increase or a net decrease in ROS (in other words, a fire could go 6X faster or 6X slower). Tabled numbers have been rounded off (within about 10 percent accuracy) to make for easier application and

interpolation, and physically unrealistic combinations are left blank.

To use the table join the EWS-ratio row with the column describing the fuel change, and read the ROS-ratio. For example, a 6X increase in EWS together with a transition from fire in the litter into the crowns would result in an increase in ROS of about 35X (or in the opposite case, a decrease of 35X).

Adaptation to nonstandard fuels—There are cases where fire is burning in a mix of fuel types. In those cases FLAME can be applied assuming each of the fuel components separately, and then averaging the two predictions. For example, a litter fire moves into a fuelbed of grass and shrubs. The change can be separately treated as 'litter to grass' and as 'litter to crown', and the two ROS-ratios averaged.

Also, there are real-world fuels that are not a good match for one of the standard fuel types, and those can be treated as described above. For example, fuel model 2 'grass' is a mixed fuel that has typical ROS values that lie between crown and grass values (at a given windspeed), and averaging FLAME predictions for a change-to-crown with a change-to-grass gives workable results. For example, with a fuel change from litter (avg of models 8, 9, 10) at EWS = 4 mi/hr to 'model 2' at EWS = 12 mi/hr BehavePlus predicts ROS-ratio = 51X. The average of the separate FLAME ROS-ratios = 60X.

Slash fuels have average ROS values that are approximately 1.5X the average litter ROS. ROS-ratios for slash fuels can be estimated by adjustment of the ROS-ratio obtained using the litter fuel type. The ROS-ratio for litter-to-slash would be 1.5X the no-fuel-change ROS-ratio. The ROS-ratio for changes between slash and crowns (or slash and grass) would be two-thirds of the litter-to-crown (or litter-to-grass) ROS-ratio.

When changes have opposing effects—Consider the case of a change in fuel type and an opposing change in EWS, such as a backing fire in grass becoming a wind-driven upslope fire in crown fuels. There are two ways to do it.

1. Simply do the FLAME prediction in two parts. First, use the ROS-table to predict the effects of just a change in fuel type. Second, predict the ROS-ratio that would result from just the change in EWS. Then divide the bigger ROS-ratio by the smaller ROS-ratio (keeping track of whether the speed-up or the slow-down in ROS will dominate). For example, an EWS increase of 20X would alone produce an increase in ROS of 40X. A change from 'faster' grass to 'slower' crown fuels would alone produce a decrease in ROS of about 4X. So the net change in ROS would be about 40/4 = 10X. Note: this 'two-step' approach is applicable to any FLAME application.

2. The appropriate section of the FLAME table can also be used, 'EWS is less in grass'. For the above example an EWS-ratio of 20X combined with a change from grass to crown fuels yields an ROS-ratio of 10X. (Minor discrepancies between the methods can result from round-off errors, and because the wind response of each fuel differs slightly from the average used in the 'no-fuel-change' case.)

Evaluating the Accuracy Limits

The FLAME-prediction performance standard—FLAME should be simple and practical enough to be used, and accurate enough to be useful. Presently firefighters have no routine and systematic process for assessing fire behavior on the fireline, and for focusing on *changes*. The full application of the fire model requires more input information and more processing capability

than is realistic or available on the fireline, and yields outputs that require a map or a way of gauging distance in units such a feet or chains. FLAME is designed to fill that gap between no system and the full system. The specific goals for FLAME accuracy are:

1. That at least three-fourths of the predictions of ROS-ratio will be accurate within a factor of +/− 2X compared to FBPS predictions or to real-world observations. '+/− factor of 2X' means that the real ROS-ratio falls between the half of and twice the FLAME-predicted ROS-ratio—for example, for a FLAME ROS-ratio of 80X that the actual ROS-ratio falls in the range 40X to 160X. 'Factor of 2X' is easy to remember and apply, and spans a fairly realistic range of variations in many real-world processes. (The uncalibrated application of the FBPS is characterized as having that same level of accuracy, +/− factor of 2X.)

2. That no FLAME predictions mislead firefighters in their safety judgments. This qualitative accuracy goal, that FLAME predictions inform but do not mislead safety judgments, is the most relevant and important. This indeed could probably have called the first goal.

How might the accuracy range of ROS-ratio affect safety judgments, at each application level?

Initial application (identifying the next big change): Following the FLAME process a firefighter will be able to identify the large potential changemakers in the situation. The dominant changemakers are well characterized in FLAME (EWS and fuel type). The relative order of fuel types by ROS characteristics is correct and nonoverlapping, and the wind-dependence of ROS is well represented. So the initial application can be relied on to highlight the dominant changemakers, identify the next big change, and give the correct sense of decrease or increase in ROS.

Standard application (using the ROS-ratio as a guide to dangerous situations): Given that fireline fatalities correlate strongly with large ROS-ratios (preliminary data suggest ROS-ratio > approx. 60X is a common denominator), it is valuable for the predicted ROS-ratio to alert a firefighter to a potentially life-threatening situation. When the firefighter applies FLAME and obtains an ROS-ratio, he or she will double that prediction and consider the larger ROS-ratio as a guide to potential danger. And if the larger ROS-ratio is getting near the 'danger zone' prudence demands that safety judgments will be based on that potential. For example, if the predicted ROS-ratio is, say, 40X then twice that is 80X, and a firefighter should carefully evaluate the risks and benefits before committing to an action. Therefore, a FLAME ROS-ratio of 30X (while the actual ROS-ratio is 60X) would still alert the firefighter that he/she faces a level of change known to be associated with fireline fatalities. Also, the FLAME system tends to overpredict ROS-ratios.

Complete application (predictions of the fire-spread timeline): Consider two extreme possibilities: first a case of large ROS-ratio, and second a case of small ROS-ratio.

Large ROS-ratio: Suppose the ROS-ratio is 200X, with ROS increasing, and that it suggests the fire will reach a given point in about 10 minutes. Applying the error range of 2X means the fire's travel-time should be considered to fall between about 5 and 20 minutes. The difference between the predicted and actual travel times is only −5 minutes or +10 minutes, and

operationally that is not a huge difference….certainly one should not try to cut any safety-essential actions too close to save 10 minutes. Assume the worst case and act wisely (how better to spend the 'extra' 10 minutes?). The point is that the time scale is short in any case, and even the inaccuracies are only on the order of minutes. Suppose the ROS-ratio is 200X, but the fire will slow down, suggesting the fire might reach a certain point in 6 hours. Applying the factor of 2X means that fire travel-time should fall between 3 and 12 hours. The actual variation from predicted spread time, up to 6 hours, is a long time. But the important point is that the firefighter will have hours to continue to observe the fire and to reevaluate the FLAME prediction.

In a sense, the consequence (on predicted fire-spread times) of errors associated with large ROS-ratios is 'self limiting' in that for large increases in ROS the response time is short in any case, while for large decreases in ROS there is ample time to update and adjust the prediction.

Small ROS-ratio: A small ROS-ratio means that the fire behavior is not expected to change dramatically. In that case, changes from the current fire behavior will be gradual. Variations of 2X from that ROS could be noticed before creating the sudden and extreme changes that put lives in danger. With the expectation of modest changes in fire behavior the firefighter would have the chance to observe and update the FLAME prediction, all the while looking ahead to the next big change.

It is important to keep the accuracy of the FLAME system in perspective. It is not perfect, but it is much better to have a helpful prediction than to have none, to call attention to important factors and the potential for significant change than to be unaware. And any system, even the most accurate, is fundamentally limited by the accuracy of inputs on fire environment factors (an especially challenging one being the actual midflame windspeed). There will be cases where FLAME falls short of the '+/− factor-of-2X' standard. The same is true for any of the operational prediction systems. (For example, model-predicted ROS for a litter fuel that falls between fuel models 8 and 9, in a situation where the sheltering is between wind-reduction factors 0.1 and 0.2, could vary by a factor of 9X depending on the inputs a practitioner might reasonably choose.)

We can only provide the best tools we have and make users aware of their limits—much better to have a decent, if imperfect, tool than no tool.

The dependence of ROS-ratio on the chosen standard EWS—Even though the main cause of change in ROS (for a given fuel) is the change in EWS, there is a weak dependence of changes in ROS on the actual EWS involved. Recall the discussion above under *What do the terms in equation 3 mean?*. How much accuracy do we lose in using values of the fuel coefficients fixed at a 'standard' windspeed?

Consider two cases, otherwise identical, one in which the initial EWS is W_1 and the other in which it is W_2. Comparing the ROS-ratio in one case (R_{R1}) with that in the other case (R_{R2}), with the initial and final fuels being the same in both cases:

$$R_{R2}/R_{R1} = [(\alpha_F / \alpha_I) (W_2)^{(\beta F - \beta I)} (W_R)^{\beta F}] / [(\alpha_F / \alpha_I) (W_1)^{(\beta F - \beta I)}(W_R)^{\beta F}]$$

$$= (W_2 / W_1)^{(\beta F - \beta I)} \qquad\qquad\qquad\qquad\qquad \text{Eq. 7}$$

Note that W_2 / W_1 here represents the ratio of two possible initial EWS values, not an initial and final EWS. This can be viewed as a case where one of those EWS values is the chosen 'standard' EWS, and the other is the actual EWS for a particular fireline situation. The error in the ROS-ratio that results from

an actual EWS that differs from 'standard' EWS is a function of the ratio of those EWS values, (W_2 / W_1).

For fires in litter a realistic range in EWS values might be from EWS = 0.5 mi/hr (a backing fire) to EWS = 8 mi/hr. Compared to the assumed standard EWS which was set at EWS = 2 mi/hr, the maximum value of (W_2 / W_1) in equation 7 would be 4. For the case of transition from litter to crown fire, the variation introduced into the ROS-ratio by using that standard EWS would then be (using equation 7).

$R_{R2}/ R_{R1} = (4)^{(1.146 - 1.213)} = 0.91$, implying an error range of about +/− 9 percent

For the same assumed range in the actual EWS, and a transition from litter to grass,

$R_{R2}/ R_{R1} = (4)^{(1.232-1.213)} = 1.026$, which implies an error range of about +/− 3 percent

Similarly, for transitions between crown and grass fuels a variation in actual EWS from 5 mi/hr to 45 mi/hr, a maximum 3X deviation from the 'standard' EWS of 15 mi/hr, would result in:

$R_{R2}/ R_{R1} = (3)^{(1.232-1.146)} = 1.1$, which implies an error range of about +/− 10 percent

We can see from the above examples that the error introduced by assuming a standard EWS, and using the EWS-ratio alone to judge wind-induced change, is small, generally less than +/− 10 percent. Furthermore, due to its dependence on a small exponent, that error grows slowly with ranges of initial EWS much wider than assumed above.

Treating the wind response of all fuels the same in the 'no-fuel-change' case—For simplicity in application, changes in EWS only (with no fuel change) are treated with an equation that averages the wind-response effects (the β-coefficients) of the different fuels. How large is the error introduced by that approximation? We use equation 2 to express the ROS-ratio for an actual β (β_{act}) and for the average β (β_{avg}), and compare the resulting ROS-ratios. $R_{R\ ACT}$ and $R_{R\ AVG}$ represent the ROS-ratios using actual β-coefficients versus the average β-coefficient (= 1.20) respectively.

$$(R_{R\ ACT})/(R_{R\ AVG}) = W_R{}^{\beta act} / W_R{}^{\beta avg} = (W_R)^{(\beta act - \beta avg)} \qquad \text{Eq. 8}$$

Considering a large EWS-ratio in grass or litter to be on the order of 20X, and in crown fuels to be about 4X (the 'low end' of EWS pushing crown fires is much greater than for litter or grass, and therefore the total range in EWS-ratio for crown fires is less), the error introduced by using the average wind response in the 'no fuel change' case is about:

- for grass: $(R_{R\ ACT})/(R_{R\ AVG}) = 1.1$, which implies an error of 10 percent (with the FLAME prediction too low)
- for crowns: $(R_{R\ ACT})/(R_{R\ AVG}) = 0.93$, which implies an error of 7 percent (with FLAME prediction too high)
- for litter: $(R_{R\ ACT})/(R_{R\ AVG}) = 1.04$, which implies an error of 4 percent (with the FLAME prediction too low)

Such deviations fall well within the goal of factor-of-2X accuracy, and therefore simplifications embodied in the average wind-response factor for the 'no-fuel-change' case are not problematic.

Summary of accuracies of the above analytical simplifications—The various simplifications that are required to deal with the exponential dependence of ROS on EWS and with the different β-coefficients for each fuel type introduce errors in ROS-ratio that typically range from a few percent to about 10 percent. In a further 'direct test' comparisons of ROS-ratios computed directly using the raw ROS equations (equation 1, with specific coefficients for each fuel) with ROS-ratios computed from equations 4, 5, or 6 also show variations of less than 10 percent. Those errors are within the accuracy goal, and are normally subordinate to the errors introduced by imperfect inputs (especially of uncertainties in windspeed).

The variation of ROS within a FLAME fuel type—The largest simplification embodied in FLAME is treating a variety of fuels as a single fuel type, with regard to ROS. For example, crown fires in brush and in timber are considered all as one type of 'crown fire'. To assess the deviations introduced by the simplification of treating all fuels within a group as one fuel type, the following measure is used. For a given EWS, the associated ROS for a specific fuel is compared with the ROS associated with the FLAME standard curve (fig. 4) for that fuel type. For example, at EWS = 6 mi/hr, the grass-fuel curve shows ROS = 134 ch/hr, while fuel model 3 predicts 148 ch/hr. The deviation of fuel model 3 from the FLAME curve in that case is +9 percent. Similarly derived deviations are shown for a range of EWS values in tables 3 through 5 using the formula: [(fuel-specific value)/(standard-curve value) –1] X 100. Positive values of the deviation indicate that the specific fuel type is faster than the standard curve.

The standard curve for crown fuels is constructed from FBPS fuel models 5, 6, and 7, observed ROS in brush fuels, and observed ROS in timber fuels. The timber fuels are the slowest of the lot. However, the timber observations are dominated by averages over considerable times and distances, encompassing sustained crown runs and discontinuous crown fire. The brush observations are dominated by data from shorter, continuous crown runs. We can consider the shorter, sustained crown spread in timber to be faster than the long-term average (Rothermel 1991 estimates that maximum ROS in timber is often approximately 1.7X the average ROS), and that corresponds closely to the ROS observations for brush. The larger data set of longer-term-average timber ROS observations was used in constructing the standard curves, and overall

Table 3—Deviations of ROS for individual grass fuel representatives from the grass-fuel standard curve, at a range of effective windspeeds. Positive deviation values indicate that the actual ROS for a representative fuel would be higher than the ROS suggested by the FLAME standard curve; negative deviations indicate the representative ROS is lower than the standard curve. The apparent jump in average deviation at EWS = 9 mi/hr is due in part to the loss of fuel model 1 data points above its wind limit.

| | EWS in mi/hr | | | |
	3	6	9	30
Model 1	-33%	+1%		
Model 3	+19%	+9%	+20%	
CSIRO	+15%	-10%	-20%	-6%
Average absolute deviation from standard	**22%**	**7%**	**20%**	**6%**

Table 4—Deviations of ROS for individual crown fuel components from the crown-fuel standard curve, at a range of effective windspeeds. Positive deviation values indicate that the actual ROS for a representative fuel would be higher than the ROS suggested by the standard curve, negative deviations indicate the representative ROS for that fuel is lower than the standard curve. The FLAME standard curve for crown fuels is weighted toward the relatively higher ROS expressed in fuel models 5, 6, 7, and lies above observed crown fire ROS (except in one low-wind case). It is intentional to err on the side of not underpredicting the increase in ROS associated with the transition from litter fire to crown fire, because that dangerous event has too often killed firefighters. The original data for ROS in timber are dominated by observation of long-term averages (which include sustained runs and discontinuous crown fire). FLAME is aimed at predicting the shorter term, sustained fire behavior, so a comparison is also made here to a timber ROS adjusted by 1.7X to more realistically represent that behavior. In that comparison, timber ROS closely matches brush ROS, and therefore supports the strategy of treating all 'crown fuels' the same with regard to ROS.

	EWS in mi/hr				
	6	**9**	**12**	**15**	**18**
Models 5, 6, 7 averaged	+12%	+18%	+22%	+24%	+25%
Brush obserervation ROS	+6%	-7%	-14%	- 19%	-22%
Timber observation ROS	-36%	-45%	-49%	- 48%	-53%
Timber ROS adjusted by 1.7X to represent continuous runs	+9%	-6%	-14%	-18%	-21%
Average absolute deviation from standard using adjusted timber ROS	**9%**	**10%**	**17%**	**20%**	**23%**
Average absolute deviation from standard using long-term average timber ROS	16%	20%	26%	30%	30%

Table 5—Deviations of ROS for individual litter fuel representatives from the litter-fuel standard curve, at a range of effective windspeeds. Positive deviation values indicate that the actual ROS for a representative fuel would be higher than the ROS suggested by the standard curve, negative deviations indicate the representative ROS is lower than the standard curve. Fuel models 9 and 10 are similar in ROS, but fuel model 8 has much lower ROS (a factor of about 3X less than the standard curve). To more realistically treat a case involving 'slow' model 8 litter fuels, the user can apply a correction factor of 3X to the FLAME ROS-ratio. Deviations of 'model 8' litter fire ROS from a 'corrected' ROS are covered in the lower two rows of the table.

	EWS in mi/hr			
	1	**3**	**6**	**9**
Models 9 and10 averaged	+40%	+36%	+33%	+41%
Model 8	-70%	-70%	-67%	-72%
Average absolute deviation from standard	50%	47%	44%	51%
Model 8 deviation from 'adjusted' FLAME standard	-9%	-9%	0%	-15%
Average absolute deviation from standard curve with adjustment for 'compact' litter	**30%**	**27%**	**22%**	**32%**

the balance represented by the standard curve seems satisfactory. Even with the timber 'average' ROS values built into the standard FLAME curves, the standard curve is 'faster' than the observed-crown-fire representative points. Given the FLAME intent of predicting short-term changes, the comparison between the standard curve and the faster ROS in timber is a more appropriate measure of how a FLAME prediction might compare to actual continuous crown-fire runs in timber. Therefore, in evaluating the fit between 'timber' ROS and the standard crown-fuel curve the adjusted timber ROS is also considered.

The standard curve for litter is constructed from FBPS fuel models 8, 9, and 10. Fuel models 9 and 10 have similar ROS characteristics. Fuel model 8, representing compact, short-needle litter displays considerably slower ROS, about 3X slower than the litter fuel average. The effect of model 8 is to lower the standard curve, and the effect of lowering the standard curve is to over-state, if anything, the increase in ROS accompanying a transition to crown fire (FLAME intentionally leans toward not underpredicting such a dangerous change). Most litter fuels tend to be more like fuel model 9 or 10.

However, given that the ROS in litter is often the denominator in gener-ating an ROS-ratio, a large error could arise in cases where the fire was in 'model 8' litter. Such cases can be readily handled by multiplying the FLAME ROS-ratio by about 3X (though for simplicity, and because most litter is not as 'slow' as model 8, the practical adjustment guideline is to multiply the ROS-ratio by 2X when 'compact litter' is involved).

Dealing with the imprecision in fuel types—The simplest way to handle the variations of ROS within a given fuel type is to accept them—most of them fall well within the +/− factor-of-2X (−50 percent or +100 percent) goal. The notable exception is the 'slowness' of model-8 litter fuels, where actual ROS-ratios could exceed by 3X the FLAME-predicted ROS-ratio. The main consequence of such underprediction of a large increase in ROS-ratio would be on the fire-spread timeline. In cases of large ROS-ratio the operational impacts of such inaccuracies are small because they affect timescales that are already short enough to suggest the need for timely actions (as noted in a previous section, *Complete application)*. As with the FBPS, a practitioner can improve its accuracy considerably by observing and calibrating.

A practical and straightforward way to improve the accuracy of FLAME predictions is to make an adjustment to the ROS-ratio, or to average two ROS-ratios, based on known characteristics of the given fuel. For example: when dealing with compact litter ('model 8' fuels), double the predicted ROS-ratio; for 'model 2' fuels average the change-to-crown and change-to-grass outputs. See the section on *Adaptation to nonstandard fuels.*

A more sophisticated FLAME application tool could significantly improve the accuracy of predictions involving changes in fuel type. The key improve-ment in relating fuel types is to use the actual fuel coefficients (α) for the specific fuels involved. Array the fuels on paired logarithmic scales by fuel coefficient (like a slide rule), and apply user-friendly descriptions within each fuel group, such as 'sparse grass' or 'tall grass,' 'fluffy litter' or 'compact litter' to the scale. Sliding the scales to align the two fuels in question would then produce the ratio of their specific α-coefficients (exactly as a slide rule por-trays a quotient), and the scale index could act as a pointer to the appropriate column of ROS-ratios. The whole affair could easily be built in to a compact calculator. It could also be an application on a hand-held computer.

Comparing FLAME outputs to FBPS predictions—Following are several examples of fire behavior events in which the ROS-ratio based on BehavePlus output is compared to FLAME predictions (table 6). Where round-off errors in the FLAME table would complicate the comparisons the FLAME predictions are obtained directly from the FLAME equations (equations 4, 5, 6) rather than the tables. This is a clearer test of the basic system itself.

Table 6—Summary of the results of comparing FLAME ROS-ratio to the ROS-ratio generated by BehavePlus (and in example 4 also from Rothermel's 1991 crown fire nomograms). Absolute error averages 15 percent, standard deviation of the errors 8 percent, largest error 26 percent.

Summary of accuracy tests	BehavePlus ROS-ratio	FLAME ROS-ratio	Deviation from BehavePlus
Example 1	2.6X	2.3X	-12%
Example 2	500X	370X	-26%
Example 3	162X	174X	+7%
Example 4	56X	64X	+14%

Example 1: A fire in burns with 3 mi/hr midflame windspeed in litter on the lower portion of a 20 percent slope; as it moves onto the upper slope the midflame windspeed increases to 6 mi/hr.
BehavePlus (model 9): the initial ROS = 4.7 ch/hr; final ROS = 12.2 ch/hr; ROS-ratio = 2.6X
FLAME: ROS-ratio = 2.3X
Deviation of FLAME from BehavePlus = –12 percent

Example 2: A backing litter fire on a 30 percent slope crosses to the opposite slope and moves upslope in grass with an 6 mi/hr eye-level wind.
BehavePlus (models 9 and 1): initial ROS = 0.3 ch/hr; final ROS = 151 ch/hr; ROS-ratio = 500X
FLAME: ROS-ratio = 370X
Deviation of FLAME from BehavePlus = –26 percent

Example 3: A fire creeping in litter up a 30 percent slope (EWS = 1 mi/hr) transitions to crown fire in brush when the 20-ft wind increases to 24 mi/hr.
BehavePlus (models 8/9 combined, model 5): initial ROS = 1.6 ch/hr; final ROS = 263; ROS-ratio = 162X
FLAME: ROS-ratio = 174X
Deviation of FLAME from BehavePlus = +7 percent

Example 4: A fire in litter (EWS = 2 mi/hr) transitions to crown fire in timber with 20 mi/hr winds (at 20-ft level).
BehavePlus (model 9) and Rothermel formula for Rocky Mountain timber, adjusted by 1.7X to represent faster portions of the overall crown fire: initial ROS = 2.5 ch/hr; final ROS = 83 ch/hr X 1.7 = 141 ch/hr; ROS-ratio = 56X
FLAME: ROS-ratio = 64X
Deviation of FLAME from BehavePlus-Rothermel solution = +14 percent

All of above FLAME predictions fall within factor-of-2X accuracy compared to BehavePlus (which in this test is considered to represent the 'true' value of ROS-ratio). FLAME overpredicts the danger presented by a litter-to-crown fire transition (which errs on the side of safety). In the case of underpredicting the grass fire case, the high FLAME ROS-ratio would still alert the firefighter to the clear danger and would yield estimates of fire travel-time that were within minutes of the BehavePlus prediction. In the clearly 'dangerous' cases represented above (examples 2, 3, 4) the predicted FLAME ROS-ratios (370X, 174X and 64X) fall in the range associated with fireline accidents.

Comparing FLAME outputs to actual fireline incidents—The most relevant test of the accuracy of FLAME predictions is against real-world fireline situations. To provide a common basis for comparison of FLAME versus real-world observations the ROS-ratio derived from fireline accident investigations is compared to that predicted by FLAME (fig. 5). The details of the assumptions used for FLAME application to these cases are in appendix A. The FLAME prediction is based on the fireline information as it could have been available to a firefighter applying FLAME—the idea is to evaluate the FLAME process with good information, and not muddy the comparison with inaccurate input. The documentation of the incidents is derived from the official reports, also in the cases of the South Canyon and Dude fires from on-site examination, and in all four cases from discussion with people who were there or who have studied the incidents.

Incident	Documented ROS-ratio	FLAME ROS-ratio	Deviation from documentation
South Canyon Fire	500X	500X	0%
Dude Fire	480X	500X	+4%
30-mile Fire	96X	100X	+4%
Cramer Fire	124X	160X	+29%
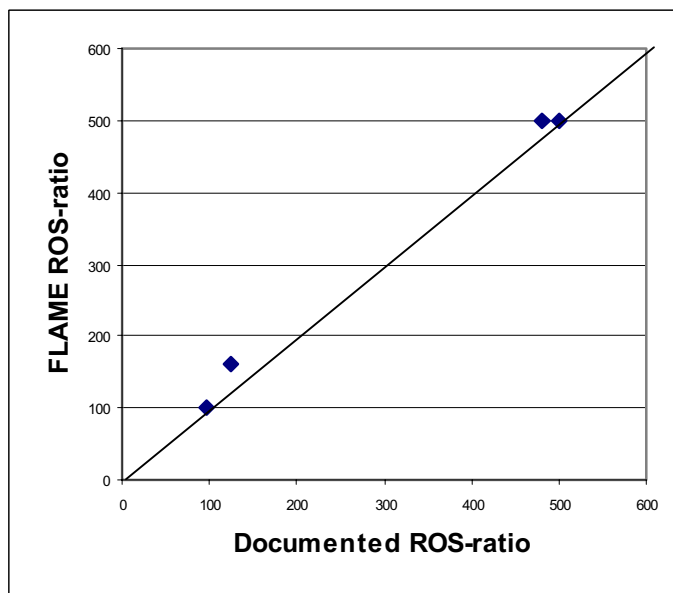
Figure 5—FLAME ROS-ratios versus documented ROS-ratios for fatality cases cited above. The diagonal represents perfect correlation between FLAME predictions and documented values. Average absolute error is 9 percent, standard deviation of errors 15 percent, and maximum error 29 percent.

In all of those cases, application of FLAME could have revealed the coming change, would have indicated clearly that it was of a magnitude that should be considered dangerous, and predicted with accuracies of order minutes the time it took for the fatal fire run.

Accuracy summary—By the most important accuracy standard—informing firefighter safety decisions and not providing misleading predictions that compromise safety—FLAME succeeds against BehavePlus calculations and in the four real-world cases above. Considering the three application levels, FLAME would be reliable in identifying the next big change, would provide good predictions of the magnitude of the ROS-ratio, and could suggest realistic timelines of the fire's advance.

The approximations inherent in the FLAME system—standardizing relative ROS between fuel types, using an average wind response for all fuels in cases of wind-change only, and treating similar fuels as a single fuel group—all fall within the 2X range, usually well within. The target quantitative accuracy standard (ROS-ratio within +/− factor-of-2X in at least 75 percent of the cases) is difficult to fully evaluate simply due to a lack of well-documented cases against which to test it. FLAME is within 2X of the four real-world cases (absolute error averaging 9 percent, standard deviation of the errors 15 percent, largest error 29 percent). And it is within 2X of the four BehavePlus examples (absolute error averaging 15 percent, standard deviation of the errors 8 percent, largest error 26 percent). But compared to other possible BehavePlus examples it might not meet the 'factor-of-2X' standard, and how do you choose a representative set of BehavePlus examples for which the 75 percent success rate is meaningful? As far as the incomplete set of comparisons above allows, FLAME meets the quantitative 'factor-of-2X' accuracy standard. Fuller evaluation awaits a larger set of real-world fire behavior cases.

A note on future improvements—No doubt, improvements in the basic fire behavior data, the models, and the application tools can make FLAME more accurate and more usable. Such improvements will not be difficult to incorporate and to disseminate to firefighters; they won't have to 'unlearn' anything. It might be as simple as issuing a new FLAME table with new ROS-ratio values, or it might involve an improved worksheet or a better 'field calculator'. The important thing is that firefighters will have already learned the process, a systematic process, of foreseeing the next big change, of evaluating the dominant changemakers, and of incorporating the expected fire behavior change into their fireline judgments. Assimilating a revised FLAME application tool will not be difficult.

Part 2: Obtaining Inputs

The main inputs to a FLAME prediction of ROS-ratio (table 2) are changes in fuel type and changes in EWS (effective windspeed). Changes in EWS are expressed as the ratio of the larger to the smaller EWS.

Changes in Fuel Type

New fuels ahead of the fire—The simplest change in fuel type occurs when the fire moves into new fuels ahead of the fire. Such changes are commonly encountered with changes in slope aspect, as fire crosses drainages or ridges.

A firefighter looks at what fuels lie out ahead of the fire, and can estimate the time of a potential fuel-type change by projecting the fire's current spread.

Transitions between surface and crown fire—An important change in fuel type, and a more challenging change to anticipate, is the transition of a fire in surface fuels into crown fuels. In essence, in a stand of trees or brush there are two fuel types juxtaposed, a surface fuel bed and crown-foliage fuel strata overlying it. The fire can transition between them rapidly, and undergo large changes in ROS and intensity.

The potential for fire to extend from surface fuels (usually a litter fuel type) into crown foliage depends on many factors. A major variable is the fuel moisture, both the live FM of the foliage and the FFM of the dead fuels.

The live FM 'sets the stage' when it drops below a threshold that permits sustained fire spread in the crown fuels. There is much variation of the threshold live FMs from one vegetation type to another, but some generalizations are possible and provide some guidance. At or below those live FM levels crown fuels are susceptible to sustained crown fire. The following represent such thresholds.

- California chaparral: live FM of 70 to 80 percent
- Great Basin shrubs: live FM of about 100 percent
- Rocky Mountain timber: live FM of about 120 percent
- Ponderosa pine: above 125 percent (maybe no practical upper limit)

The FFM plays a major role in the intensity of the surface fire, and the flammability of the dead attached component of the aerial fuels—essentially controlling the 'burner' under the foliage layer. FFM is strongly controlled by relative humidity (RH), and RH serves as a practical guide for firefighters. When live FM is in the range for potential crown fire, then RH (and FFM) dropping below a certain threshold-range greatly increases the potential for transition to crown fire. The threshold values of RH are surprisingly consistent over most vegetation types.

- Most fuels of the Western United States: RH below about 20 to 30 percent, especially below 20 percent
- Some fuels of the Southeastern United States: RH below about 35 percent

Firefighters can stay abreast of published trends in live FM and trends evidenced in the fire behavior, and they can monitor RH. The NFDRS is a valuable guide to crown fire potential. On the fireline the following accessible observations provide a practical guide/check-off list to suggest that transition to crown fire is a good possibility:

- Seasonal drought period prevails (meaning live FM is reaching the threshold of flammability).
- Overall drought makes matters worse (live FM will become critical sooner and go lower than normal).
- Recent crown fire, on other fires or your fire (crown fire possibility is demonstrated).
- Relative Humidity 35 to 20 percent, or less, especially RH below about 20 percent (FFM is low enough to trigger crown fire).
- Backing fire produces torchouts (a dead giveaway that headfire can crown).
- Fire moving up ladder fuels (early indicators of the transition to crown fire).
- Torchouts and short crown runs (with any worsening of burn conditions crown fire is imminent).

Determining the Effective Windspeed

EWS combines the influences of wind (at midflame level) and slope (as a bit of 'upslope wind') into one 'windspeed' that represents the driving force of wind and slope on the fire. Changes in EWS are the largest potential producers of changes in ROS. Making the determination of current and expected EWS is not easy, but it must be done as well as possible. Even though EWS is highly variable and subject to many influences firefighters can obtain worthwhile results from a few practical guidelines and observations. To not account for the variation in EWS, at least approximately, is to miss the largest potential source of change in fire behavior. In fact in some ways the firefighter on the fireline, making predictions of short-term significant changes in fire behavior, requires more detail about windspeed variation than is required for a typical longer term, average-fire-spread projection by an FBAN.

The following sections describe the adjustment methods for determining EWS as a function of topographic location, flame height, sheltering by vegetation, and slope. To predict changes in fire behavior the firefighter must estimate the windspeed currently affecting the fire and also the windspeed that will affect it in the future (to obtain the EWS-ratio).

Variations of EWS over the terrain—If even a steady, 'uniform' wind impinges on terrain it will vary greatly in speed and direction from one point to another across the landscape. It will be channeled by drainages, and its speed will be strongly influenced by the topographic obstacles it encounters. For unstable or neutrally stable unstratified airflows, typical of the well-mixed conditions of a sunny afternoon, the following patterns occur.

Windspeed will be topographically enhanced on upwind slopes, and diminished on downwind (lee) slopes; it will generally be higher on an upper slope than on a lower slope. A suitably accurate assessment of fire behavior depends on accounting for the variations in windspeed across the terrain. We want to gauge the windspeed on the upper slope (upper third or so) versus that on the lower slope (lower third or so), and on the downwind (lee) versus the upwind slope, and to relate them to the forecasted general or ridgetop windspeed. The guideline (illustrated in fig. 6) for estimating those variations is based on the several sources detailed below, all of which are compatible with such a guideline.
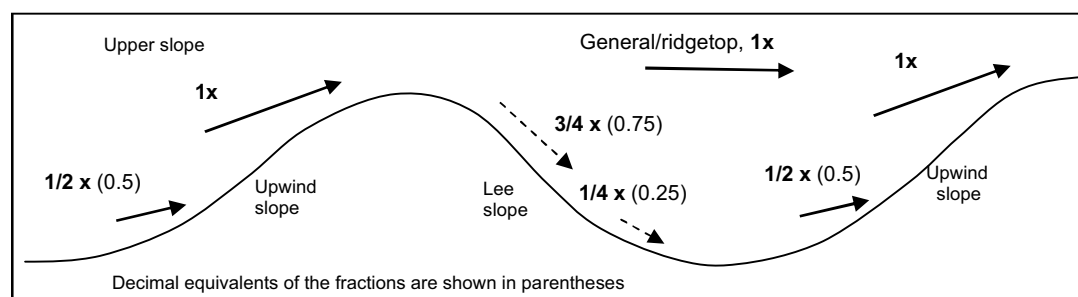
Figure 6—Schematic illustration of the FLAME guideline for estimating variations in windspeed over the terrain. Wind blows from left to right, values normalized to unity for general/ridgetop windspeeds. Lee-slope adjustments are valid only on slopes <30 percent and without sharp ridgetops. Winds described as 'winds of critical concern' by fire weather meteorologists and downslope winds are not subject to the above adjustments.

Equation 9 (below) can be used to estimate the 'speedup' of wind (ΔS_{max}, the excess of ridgetop windspeed above ambient over the plains) at the tops of hills or ridges (Barry 1992). The form below averages the coefficients for the 'isolated hill' case and the 'uniform ridge' case. Here 'h' is the height of the hill or ridge, and L* is the half width of the hill at its midelevation.

ΔS_{max} = 1.8 h/L* (note: units cancel in the ratio)   Eq. 9

For a hill having symmetrically equivalent topographic profiles on its upper and lower halves, equation 9 can be expressed in terms of slope (slope being approximately [h/L*]/2)

ΔS_{max} = 3.6X (slope), where slope is expressed as a decimal figure   Eq. 10

For a hill of moderate slope, say 30 or 40percent, that means the wind over the top will be about 2X the ambient wind that blows against the hill (remember that windspeed at the ridge = ambient + ΔS_{max}). For steeper slopes the ridgetop wind increases would be somewhat higher.

Detailed studies of windflow over hills and ridges are reported in Mason and Sykes (1979) and Taylor and others (1987). The pattern and magnitude of variations in windspeed as air flows around hills or over ridges are reasonably similar to each other, and are in accord with the 'speedup' described by equation 10. Figure 7 shows the results for two separate wind-speed profiles over an elongate ridge. The average values of windspeed at slope positions corresponding to figure 5, normalized to unity for the ridgetop are: 0.46X, 0.89X, 0.70X, and 0.26X (compared to 0.5X, 1X, 0.75X, and 0.25X for the FLAME guideline).
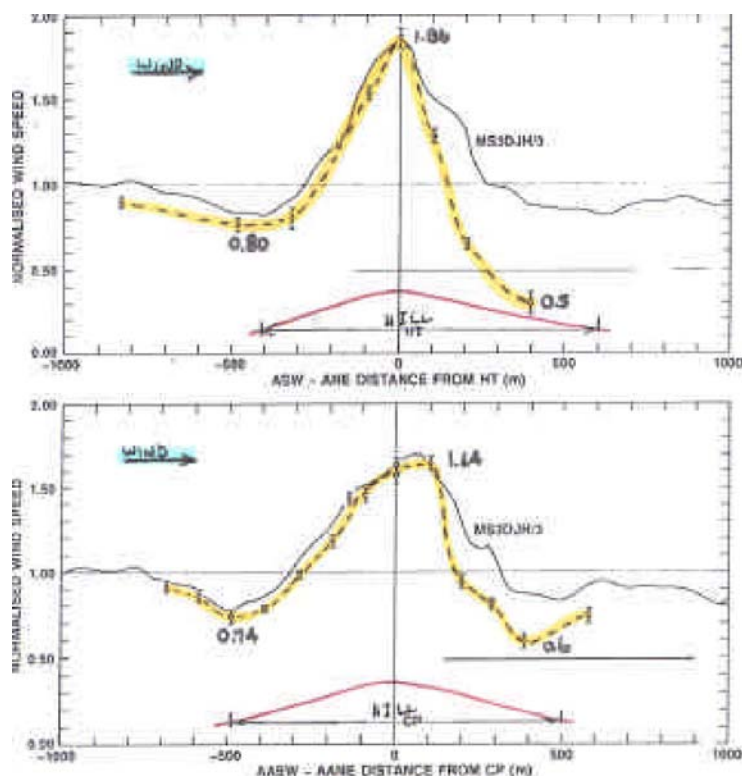
Figure 7—Profiles of windspeed over an elongate ridge at two locations (Taylor and others 1987). Wind blows more or less perpendicular to ridge axis; ridge topographic profiles shown in red. Windspeeds (yellow curve) are normalized to an ambient windspeed of one.

I have conducted several wind-speed surveys (often on S-290 field trips) over elongate ridges near Oroville and Susanville, California. Windspeeds were measured with handheld anemometers at eye-level, for either a 3-minute average, or by averaging 10 instantaneous observations taken over a couple of minutes. The normalized results are (moving with the wind from upwind to lee side): 0.5X (lower upwind slope), 1X (upper upwind slope), 0.8X (upper lee slope), and 0.2X (lower lee slope). This is close to figure 7 relative values and to the FLAME guidelines.

All of this pertains to neutrally stable or unstable airflows, but not to stable, stratified airflows such as sea breezes, outflow winds, night-time downslope winds, or foehn winds ('winds of critical concern')—these are often fastest on the downwind slope. I have not found data for a corresponding guideline in stable airflows, and one must simply use observed or forecasted windspeeds without extrapolation to other parts of the terrain. The scale of the topographic relief characterizing the observations is on the order of 100s of feet of elevation, and the observations were on slopes of 30 percent or less.

Table 7 compares the theoretical and observational data with the FLAME guidelines (which are arithmetically simplified to facilitate their application). Figure 8 illustrates a comparison between the FLAME guideline and an advanced airflow model.

Table 7—Summarizing the theoretical and empirical basis for the wind reduction factors (research studies and personal observations), and the FLAME guidelines, for approximating the variations in windspeeds as air flows over hills and ridges in neutrally stable or unstable conditions. Ridgetop windspeed is taken as the general windspeed, and the below values are normalized to ridgetop windspeed (as 1X).

	Equation 9	Taylor and others (1987)	Personal observation	FLAME guideline
Lower upwind slope	0.5X	0.46X	0.52X	**0.5X**
Upper upwind slope	1X	0.89X	0.88X	**1X**
Upper lee slope	NA	0.70X	0.64X	**0.75X**
Lower lee slope	NA	0.26X	0.24X	**0.25X**
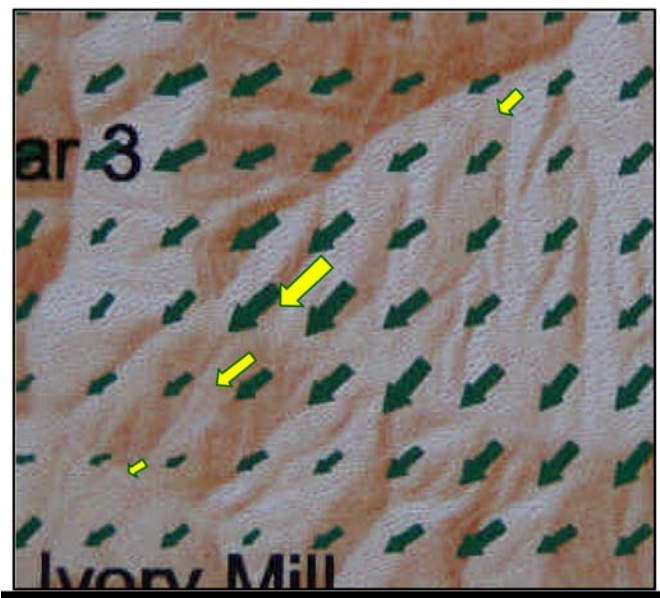
Figure 8—Comparison of FLAME guideline for windspeed variations over terrain with wind-field map generated by an advanced airflow-terrain model. Green arrows are model-generated. Yellow arrows along a line that crosses the ridge at the head of the basin are from the FLAME guideline, scaled to be (from upper right to lower left) 0.5X, 1X, 0.75X, and 0.25X. There is good overall agreement of the guideline with the model in predicting the magnitude of the variations in windspeed.

Variation of windspeed with flame height and sheltering by vegetation—What is needed for predicting fire ROS is the midflame windspeed (MFWS), or less formally the 'flame level' wind. For a given location on the terrain the MFWS depends upon the height of the flames and the wind obstruction by vegetation (for example, 1-ft flames under a stand of trees in litter versus 30-foot flames in an open brushfield).

The guidelines used in FLAME for adjusting wind for flame height and sheltering vegetation are equivalent to the 'wind reduction factors' of FBPS, and closely match that scale in relative terms. Using the adjustment factors to 'reduce' 20-ft winds conforms with the practice suggested by fire weather meteorologists and utilized in application of the FBPS.

The FLAME wind-reduction factors are keyed to each of the major fuel types, and are applied to the 20-ft windspeed. These values correspond closely to the FBPS reduction factors of 0.6X, 0.4X, and 0.15X (average for sheltered fuels), and bear nearly the same relative values. Reduction factors applied to 20-ft windspeeds for FLAME application are (expressed here as simple fractions for ease of use):

- crown fire MFWS (using the 20-ft wind directly) is 1X(20-ft WS)
- grass fire MFWS (and low/scattered brush) is (3/4)X(20-ft WS)
- litter fire MFWS (reflecting low flames and obstruction by the stand) is (1/4)X(20-ft WS)

Eye-level is the most practical wind observation level for people in the field. The following adjustments can be made to eye-level windspeeds for flame height and sheltering, based on the relative scale described above:

- crown fire MFWS is (1 1/3) X EL WS
- grass/low-shrub fire MFWS is 1X EL WS
- litter fire MFWS under a stand is (1/3) X EL WS

Where do the FLAME wind-reduction factors come from?—The basis for using the 20-ft windspeed at crown level, and the reduction factor for eye-level winds, lies in the following field observations and the logarithmic wind profile expressed in equation 11.

My observations of eye-level wind at two RAWS stations in open, scattered, low shrubs consistently yield eye-level values that are 0.8X of the corresponding 20-ft windspeed. The Australian CSIRO system (Cheney and Sullivan 1997) also applies a 0.8X reduction to obtain eye-level (2-m) windspeeds from 10-m windspeeds. In both cases the crown-fire MFWS, being several feet or more above eye-level, would be essentially those observed at 20 ft (or 10 m) or at least 0.9X of 20-ft windspeed.

The logarithmic expression for the boundary layer wind profile, applied with an average roughness coefficient characteristic of a mix of grass and low shrubs (0.09 m), is equation 11. Here u_z is the windspeed at height z; u_{z_o} is the windspeed at the reference height z_o. Heights are in meters.

$$u_z / u_{z_o} = [\ln (z/0.09 \text{ m})] / [\ln (z_o /0.09 \text{ m})] \qquad\qquad \text{Eq. 11}$$

From equation 11 the reduction factor for eye-level (taken as 1.8 m) compared to 20-ft (6 m) windspeed is 0.71X. Combining the logarithmic data with the observations at RAWS stations (and to keep the rule simple) yields a (3/4)X reduction factor for eye-level windspeed (applicable to fires in grass and low/scattered brush).

The FLAME wind reduction factor for fires in litter is (1/4)X. That value comes mainly from the relative reduction in winds for fully sheltered litter fuels compared to 'open fuels' (grass fuel models) and to fuel model 4 brush as embodied in the FBPS guidelines: 0.15X for the average of sheltered fuels, 0.4X for open fuels, and 0.6X for crown fire in deep brush fields. 0.15X is about one-third of 0.4X and is one-fourth of 0.6X.

The slope contribution to EWS—BehavePlus incorporates the influence of wind and slope on ROS by adding a wind coefficient and a slope coefficient to the propagating flux ratio (Rothermel 1972). The combined coefficients can be thought of as accounting for the 'effective windspeed' (EWS). FLAME handles slope in the same way, by adding an increment of 'upslope wind' that has the same effect on the ROS as does the actual slope.

The slope-equivalent wind is similar for all fuel types. It is greatest at low MFWS and on steep slopes. And in many realistic situations it tends to be a small factor compared to the actual MFWS. The variation of the actual windspeed induced by topography is much more important to variations in ROS than is the 'direct' effect of slope. The following guidelines for handling slope (with upslope wind and upslope fire spread, as is also assumed in the FBPS nomograms) are utilized to yield the EWS used in FLAME.

- Slope less than 20 percent, no correction to the actual MFWS
- Slope 20 to 40 percent, add 1 mi/hr to the MFWS
- Slope 40 to 60 percent, add 2 mi/hr to the MFWS
- Slope 60 to 80 percent, add 3 mi/hr to the MFWS
- Slope greater than 80 percent, add 5 mi/hr to the MFWS

Defining the EWS for a backing or flanking fire—At low EWS, and for backing (negative EWS) or flanking fires the ROS curve flattens and represents a slowly changing ROS. One cannot use a zero or negative EWS in determining the EWS-ratio. A 'backing-fire EWS' to use in representing backing fires on the standard curve must be determined.

Basically, the problem is that ROS does not go to zero when EWS goes to zero (even though the standard FLAME curve, a power function, would go through the origin). The physical reason is that fire propagates by processes other than wind alone, and does not stop spreading in the absence of wind. For fires backing into the wind and/or down a slope intra-fuelbed radiation and convective dominate heat transfer, and ROS is relatively insensitive to variations in windspeed or slope.

In the original work on which BehavePlus is based the 'backing' ROS was taken as simply the flat-table, zero-wind ROS (Rothermel, personal communication). The Australian work on grass fires defines a similar relationship in that backing-fire ROS is found to remain essentially constant up to windspeeds of 20 km/hr (Cheney and Sullivan 1997). Other reports show backing ROS to decline slowly with increasing slope.

An important fireline-safety situation involving backing fires is fire in litter backing down a slope under largely wind-sheltered conditions. Such instances are common, and the change between backing litter fire and running crown fire is an extremely important FLAME application. So the backing EWS used in FLAME is based largely on the litter fuel type. The backing-fire EWS (not the backing ROS) for grass is similar to that for litter. Because backing fires do not propagate directly through crown foliage, there is no crown-fuel backing-fire EWS in FLAME.

It is assumed that over a reasonable range of slopes and windspeeds that the backing ROS falls between the zero-EWS value and half of that value (for example between 0.6 and 0.3 ch/hr). So the representative backing ROS is taken as the average of those values, or 0.75X(ROS at EWS=0).

The question of what EWS to use to represent backing litter fires is then: 'What EWS on the litter standard curve corresponds to the representative backing ROS?' The representative backing ROS (not EWS) is 0.47 ch/hr, which is 75 percent of the average zero-EWS spread (which is 0.63 ch/hr) for fuel models 8, 9, and 10. The corresponding EWS is 0.5 mi/hr (fig. 9).

Litter Std Curve at low EWS

$$ROS = 1.03 \, (EWS)^{1.213}$$
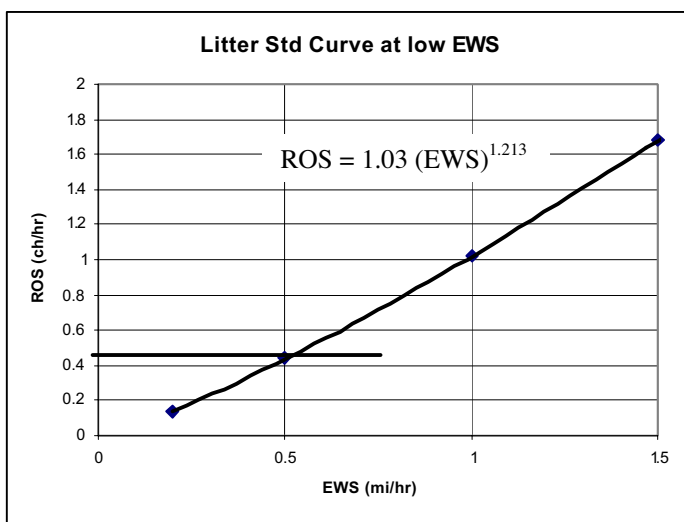
Figure 9—Standard curve for litter fuel type, with characteristic backing fire ROS at 0.47 ch/hr (which is 75 percent of the zero-EWS ROS of 0.63 ch/hr). The curves intersect at EWS = 0.5 mi/hr, and that is taken to be the EWS characteristic of backing fires. An EWS of 0.5 mi/hr is the lowest value of EWS used in FLAME. Comparisons (ROS-ratio) to other EWS and ROS values on the curve are mutually consistent. Vertical axis is ROS in ch/hr.

So, in FLAME the backing-fire EWS = 0.5 mi/hr. For flanking fires the EWS is taken to be 1.0 mi/hr (being slightly less retarded by the opposing influence of wind and slope, and given that even slight variations in wind on flanking flames can momentarily act to advance them).

A similar analysis to that above for grass yields a backing-fire EWS of 0.4 mi/hr. An adjustment can be made for cases involving grass, but most of the time it is not necessary to a useful FLAME result.

Basically, the use of a backing-fire EWS of 0.5 mi/hr states that a backing fire moves as if it were driven by a wind of 0.5 mi/hr in the absence of other heat-transfer processes, within the context of the ROS relationships expressed in the FLAME standard curves. That use of an 'equivalent wind' allows the comparison of ROS under backing conditions with ROS where effective wind is the dominant fire-spread influence. The standard curves are effectively truncated at EWS = 0.5 mi/hr, and that represents the slowest possible ROS.

Computing the EWS-ratio—Given the EWS associated with 'current' fire behavior, and an estimate of the EWS that is expected, the EWS-ratio is computed. Because it is easier to work with whole numbers versus fractions, the EWS-ratio is always the larger EWS divided by the smaller EWS. A FLAME user would simply keep in mind whether that change in EWS would be associated with an increase or a decrease in ROS (for example, will the fire go 6X faster, or 6X slower?). If the arithmetic is easy, the user can simply do the division. For example, if the larger EWS is 8 mi/hr and the smaller one is 2 mi/hr, the EWS-ratio = 8/2 = 4X. For cases where the arithmetic is not

so easy, table B1 in appendix B allows a simple look-up of the EWS-ratio; it is nothing more than a paper calculator. That EWS ratio is used to enter the left column of table 2.

Part 3: Application in the Field

The Field Worksheet, Stage by Stage

The worksheet is organized to follow the three 'application stages' described in the section *Flexibility in application*, initial, standard, and complete application. As seen in figure 10, where the sheet is divided left-right, the left side records 'current' conditions and the right side records 'expected' conditions. In the following discussion each application phase will be detailed, using the appropriate subsection of the worksheet. Notations and examples will explain each worksheet entry. Worked examples follow the illustration of the three application phases. Although this description is intended to illustrate the FLAME application process, it is not a complete training manual.

Figure 10—FLAME worksheet. Down to the 'EWS-ratio' entry the left side is for 'current' conditions and the right side for 'expected' conditions. Fuels are listed in order from slowest to fastest; the EWS spaces follow the adjustment process from raw values to EWS on the fire. The 'LCES' portion allows for notes about how those guidelines will be implemented.

Initial FLAME application—Considering the current and expected fire behavior, and identifying the next big change, make up the initial FLAME application. The following three examples show how the current and expected conditions can be depicted in various styles. The style or art work is not important. The critical thing is that the firefighter is prompted to consider those conditions; to be able to complete the pictures means having made a complete fire behavior assessment. If some box is empty you have not fully assessed the current and expected fire behavior and potential changes. No assessment is ever perfect or finished, but it represents the best you know with the present information and can reveal important gaps in your information.

Depict the current fire behavior and fire environment, and the situation you expect after the next big change. You can sketch a profile of the area, such as the two slopes, with the fire and fuel-types shown. You can sketch a map view, a diagram of the fire area. Show the winds you expect with arrows. Or you can simply list the key points of the description of fire and conditions. Note the 'next big change', and some idea of when it will come, in the space under the sketch.

Figures 11 and 12 show the components of the initial-application phase of the worksheet, and three examples of how they might be filled out.

Standard FLAME application—The heart of the *FLAME* process, the standard application, requires the specification of the fuel types and effective windspeeds, both current and expected. From that the ROS-ratio is determined, indicating the magnitude of the next big change. The magnitude of the change in ROS-ratio is suggestive of the potential danger posed by the change.

The standard-application phase requires the firefighter to obtain specific observations of relative humidity (RH), fuel type carrying the fire, and effective wind acting on the fire. It also requires the firefighter to predict the expected conditions of RH, fuel type, and effective wind. That in turn prompts projection of the fire's progress and attention to the current weather forecast. **The most important effect of completing the standard application phase is that it leads the firefighter to obtain specific information on the key fire behavior variables, which can make obvious the absence of critical information.** Determination of the ROS-ratio also provides a measure of the magnitude of change pending, which conveys a sense of the level of potential danger.
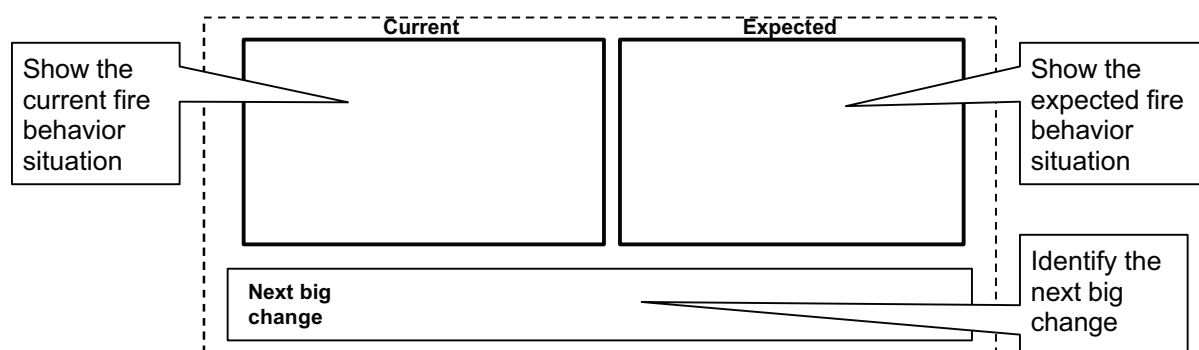
Figure 11—'Initial application' portion of the FLAME worksheet, annotated to describe the appropriate entries.
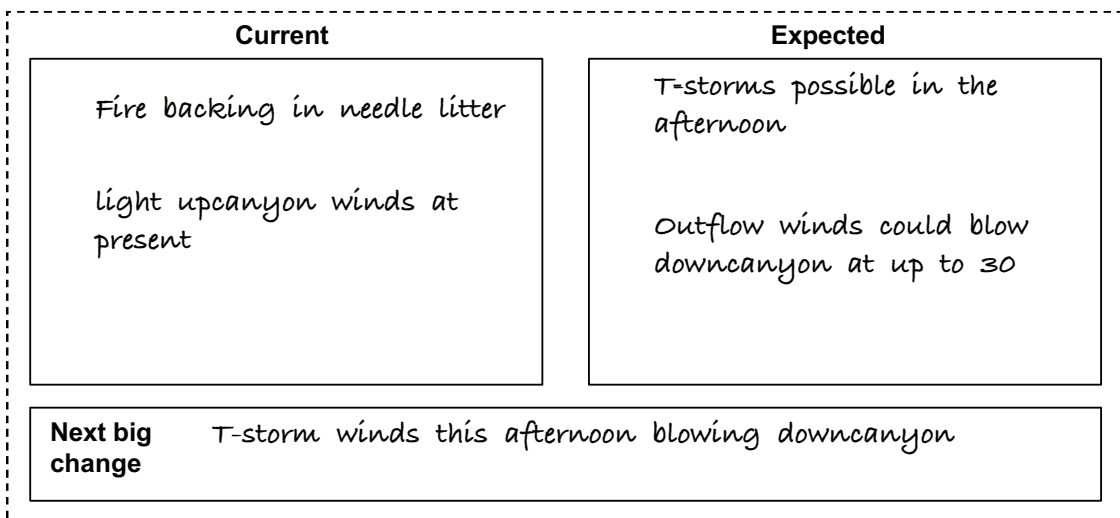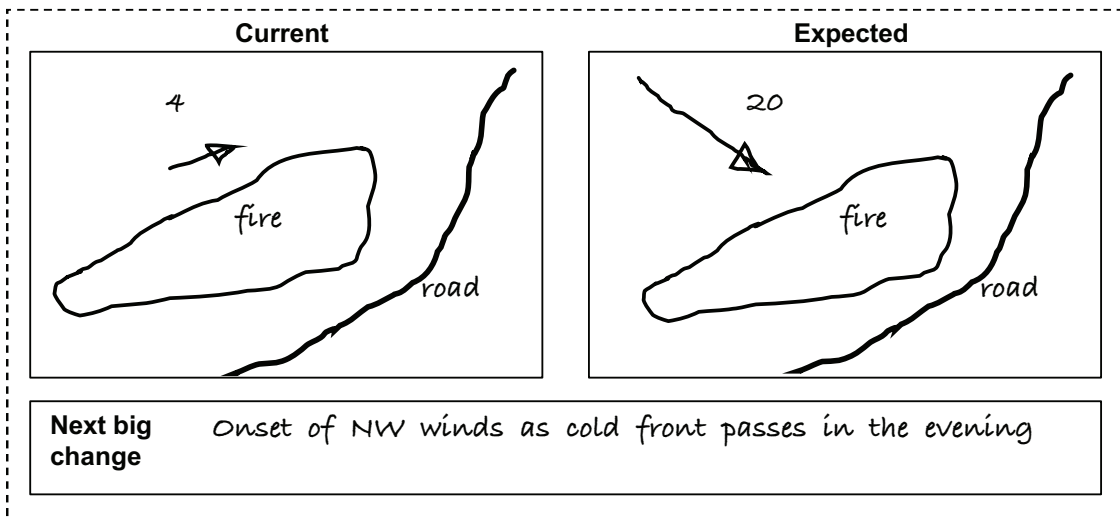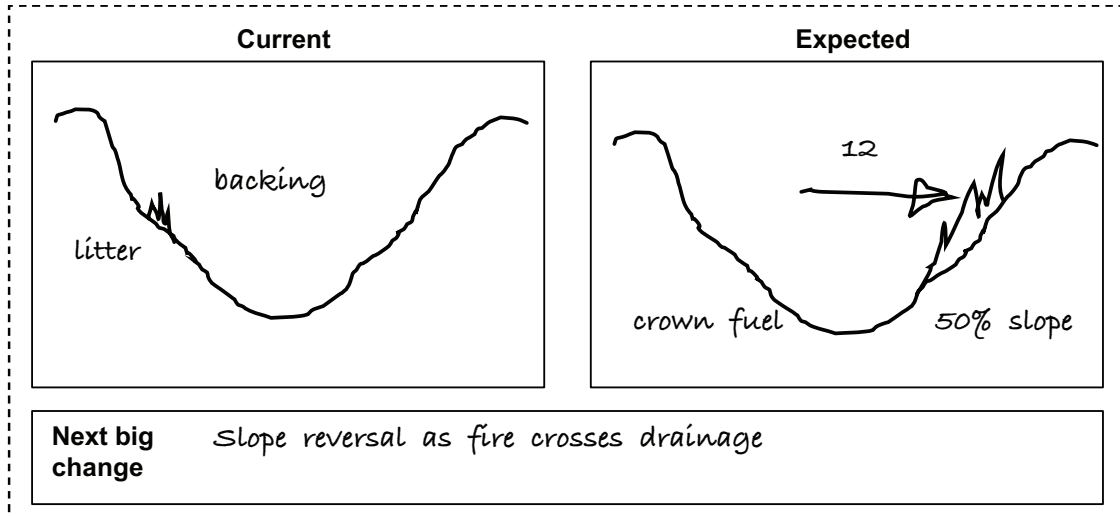
Figure 12—Three examples illustrating the current and expected conditions and identifying the next big change, using the worksheet format. The style of illustration is entirely up to the user, and three different situations are shown here as a terrain profile, a sketch map, and an outline to depict the current and expected conditions.

Figure 13 illustrates the components of the standard-application section of the worksheet and presents examples of how information would be developed in that section.
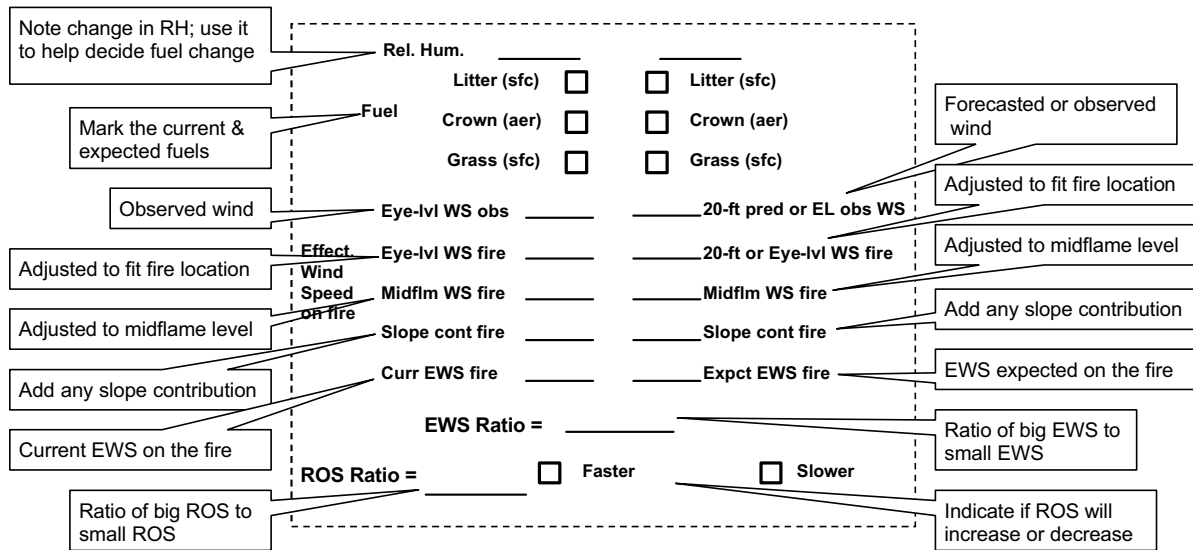
Figure 13—'Standard-application' portion of the FLAME worksheet, annotated to describe the appropriate entries. Entries on the left side represent current conditions, and on the right side the expected conditions. EWS-ratio and ROS-ratio express the degree of change between current and expected conditions.

Following are three different fire behavior examples illustrating different styles.

Example 1: A fire burns up a 30 percent grassy slope and will spread into forest litter. You have observed the eye-level wind at a point on the same slope not too far from the fire. Overall conditions are not expected to change significantly, though the RH will drop to about 38 percent. Crown fire potential is minimal. The next big change will be the passage of the fire from open grass into sheltered litter.

Current conditions: RH = 42 percent; Fuel is grass; Eye-level wind = 9 mph; Slope = 30 percent
Expected conditions: RH = 38 percent; Fuel will be litter; No large wind changes expected; Slope = 30 percent
    The completed worksheet section would look like this. The small effect of the RH drop can be estimated as in the upper right box.
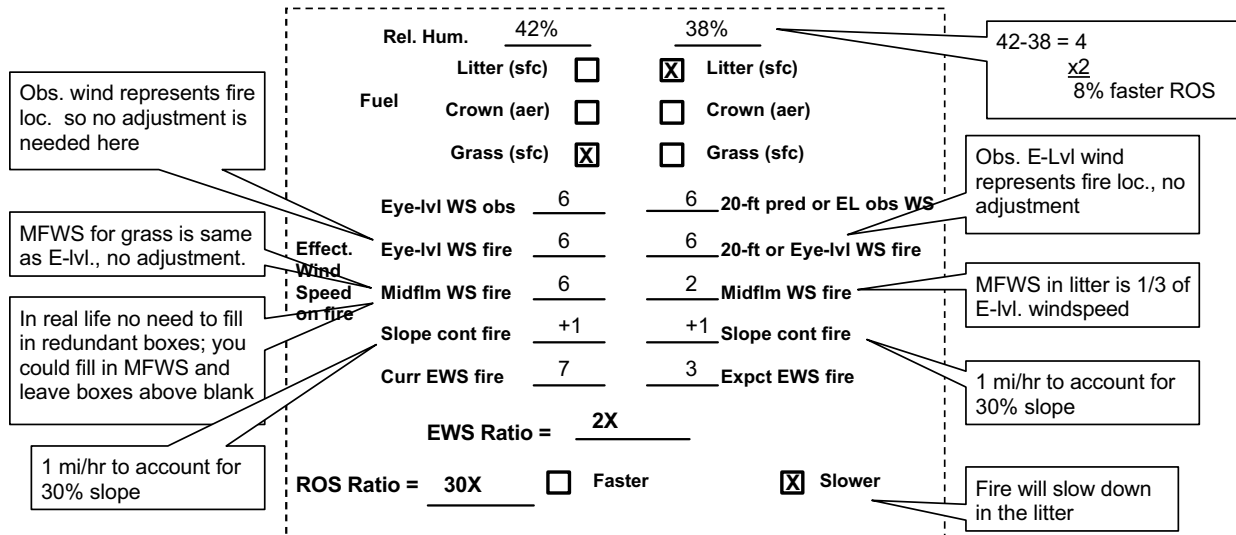
Example 2: A fire backs down a slope in litter, RH = 30 percent. It is expected to cross the drainage and spread up the next slope (an upwind 50 percent slope) as a crown fire. The ridgetop windspeeds are forecast to be 20 mph, and RH to be 20 percent. The next big change will be the transition from backing litter fire to running crown fire, and it will affect the lower slope first. RH value helps evaluate the potential for crown fire, but no adjustment for RH change is made for crown fuels.

Example 3: A fire is burning up a 45 percent lower slope in litter, midmorning, RH = 36 percent. By afternoon it will reach the upper half of the slope and is expected to transition to crown fire. You directly observe the wind on the litter fire, at litter flame height, to be 3 mph upslope. The afternoon wind will be in the same upslope direction, and 20-ft windspeed is forecast to be 8 to 12 mph, RH will be 15 to 20 percent. The next big change will be the transition to crown fire this afternoon on the upper slope.

Complete FLAME application—Develops a fire spread-time by applying the expected change in ROS to the observed spread-time under current conditions. The spread is gauged against 'natural yardsticks' (such as a slope, an open field, utility or fence poles, road intersections, the distance the fire has moved). For example, a fire might be observed to move down a slope in 12 hours, or halfway across a field in 20 minutes. Such observations constitute the 'observed spread' (left hand space in fig. 13).

If the ROS increases, the fire would be expected to spread a similar distance in a fraction of the time. For example, if the ROS-ratio is 24X, then a fire backing down a slope in 12 hours would be expected to go back up the same slope, or up the opposing slope, a similar distance in $1/24^{th}$ of 12 hours, or one-half hour. In other words, the expected spread time when ROS increases is the observed spread time divided by the ROS-ratio (middle box in fig. 14).

Similarly, if the ROS decreases, then the expected spread time will be the observed spread time multiplied by the ROS-ratio (right hand box in fig. 14). For example, if a fire observed to cross half a field in 20 minutes slows down by 3X, then it will cross the other half of the field in about 60 minutes.
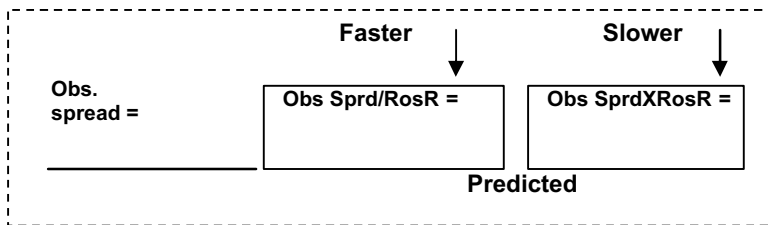

Figure 14—'Complete application' portion of the worksheet. Observed spread of the fire is noted on the left. The 'faster' or 'slower' expected fire ROS directs the user to the appropriate box, in which is the formula for calculating the expected spread time over a similar distance. In the case of faster expected ROS the predicted spread time will be the observed spread time divided by the ROS-ratio; in the case of slower ROS the predicted spread time will be the observed spread time multiplied by the ROS-ratio.

Example 1: A fire moves down a slope in 12 hours, and is expected to spread up the adjacent slope 24X faster, an ROS-ratio of 24X and an increase in ROS.
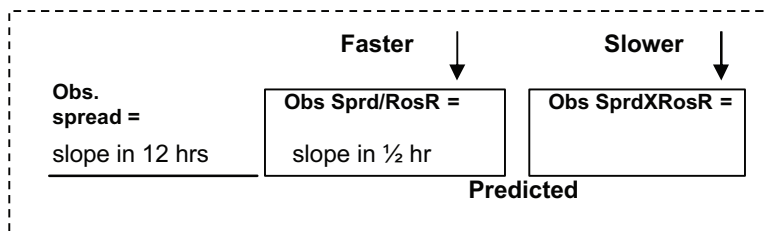
Example 2: A fire moves halfway across a field in 20 minutes. The wind is expected to decrease, and the fire is expected to move 3X slower after that, an ROS-ratio of 3X and a decrease in ROS.
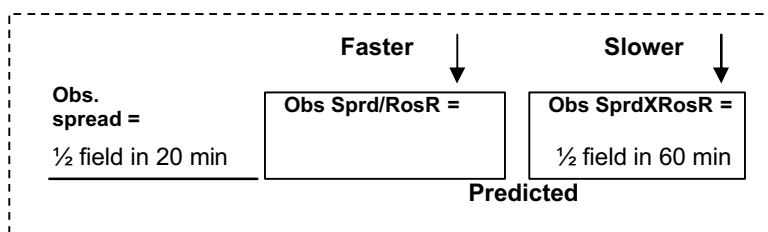
Illustrating the FLAME Application Process in Full

Example 1: A fire burns up a lower SW slope (over 60 percent) in litter under a stand of pine trees, where observation shows RH = 24 percent and eye-level windspeed 6 mi/hr. The fire advances at a rate that will cover the lower half-slope in about 3 hours. As the fire moves up the slope it will begin to feel more wind, RH is declining, and the fire will transition to a crown fire on the upper slopes. Forecasted winds are SW 15-20 mi/hr, RH dropping to 15 to 20 percent range. Consider a crown fire run on the upper slope.

   The RH values help determine the potential for crown fire, but are not a significant guide to fine-tuning the predicted ROS-ratio.
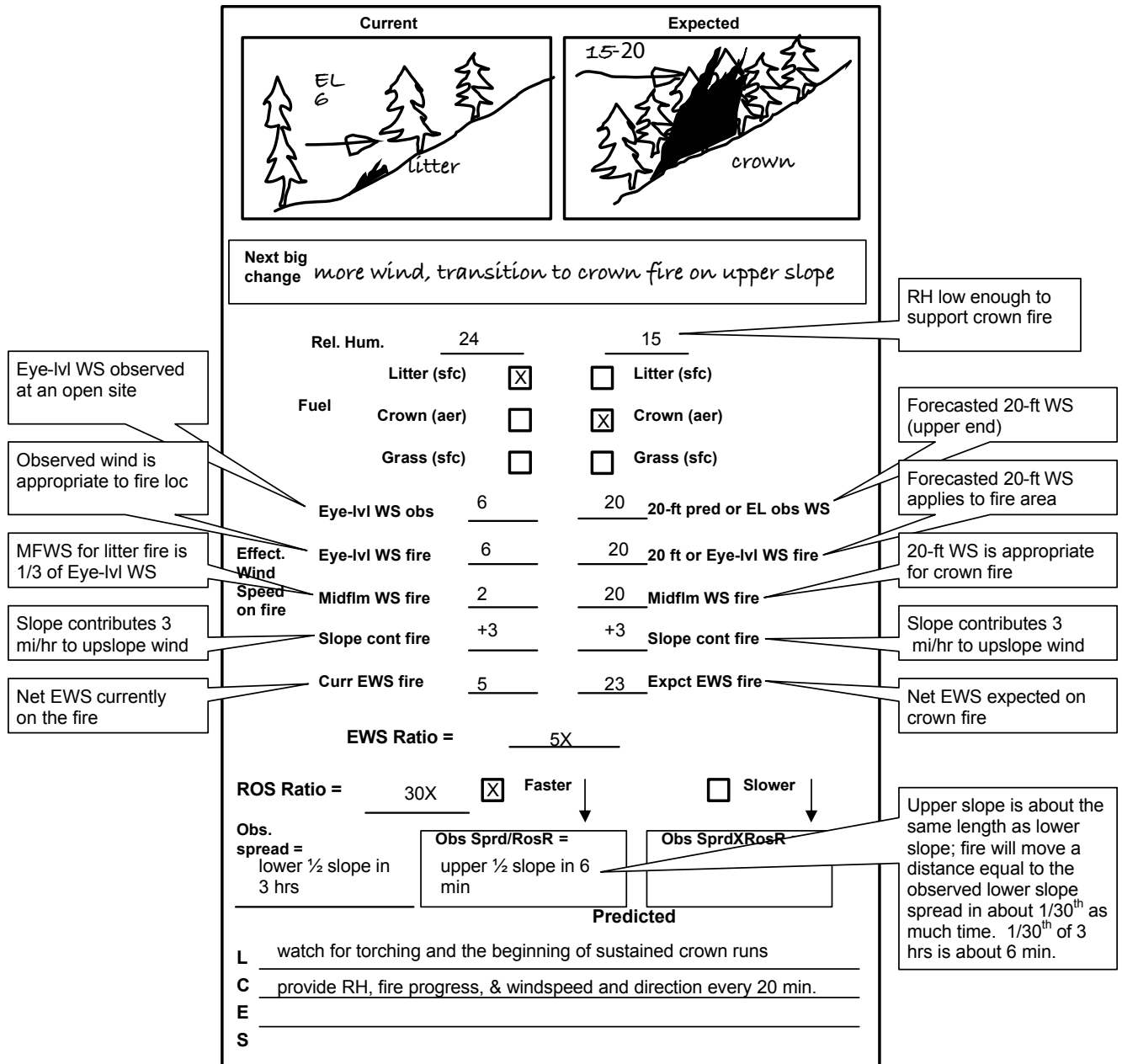
Example 2: Fire in litter under conifer and shrub stands is backing downslope into a small canyon; RH is 40 percent. It has backed the previous late afternoon and night and is expected to reach the canyon floor by midmorning, a total of 18 hours. General winds of 12 mi/hr are blowing above the nocturnal inversion in the up-canyon direction. With the development of up-drainage winds, combined with the general wind, the upslope wind in the afternoon is forecasted to be 12-16 mi/hr. Foliage is dry and will support crown fire; afternoon RH is expected to be in the high teens. Canyon slopes are 40 to 50 percent.

Example 3: Fire will run to the top of a 60 percent slope as a crown fire in timber. Sustained runs have taken about 20 minutes to sweep up the slope in late afternoon. RH is 20 percent, but will be increasing to 30 percent shortly after sundown. Eye-level winds on the lower part of the timbered slope were observed to be 6 mi/hr. Over the ridgetop the lee slope is primarily grass.

Current — crown, EL wind 6

Expected — backing, grass

Next big change: *slope reversal, change from crown to grass fuel type*

Change in RH is not used to fine tune ROS-ratio because a crown fuel is involved

Rel. Hum.: 20 | 30

Fuel:
- Litter (sfc) ☐ | Litter (sfc) ☐
- Crown (aer) ☒ | Crown (aer) ☐
- Grass (sfc) ☐ | Grass (sfc) ☒

Obs E-lvl WS on lwr slope

E-lvl WS on upper slope would be 2X6 = 12 mi/hr. Average upper & lwr to represent overall WS on the whole slope, 9 mi/hr

Effect. Wind Speed on fire:
- Eye-lvl WS obs: 6 | 20-ft pred or EL obs WS
- Eye-lvl WS fire: 9 | 20 ft or Eye-lvl WS fire
- Midflm WS fire: 12 | Midflm WS fire
- Slope cont fire: +3 | Slope cont fire
- Curr EWS fire: 15 | back — Expct EWS fire

Crown WS is 1 1/3 of E-lvl WS; (1 1/3)x9=12

Slope contributes 3 mi/hr to upslope wind

The fire is backing, and the EWS is taken to be 'backing' (EWS = ½). No need to fill in other boxes.

EWS Ratio = 30X

15/(0.5) = 30

ROS-ratio reflects 60X slowdown due to less EWS, and a 4X increase due to faster fuel (grass vs crown)

ROS Ratio = 17X | ☐ Faster | ☒ Slower

Obs. spread = up slope as crown fire run in 20 min

Obs Sprd/RosR =

Obs SprdXRosR = down slope in grass in about 6 hours

Assuming the slopes are about the same size; fire will move a distance equal to the observed upslope spread in about 17X as much time. 17X 20 min is about 6 hrs

Predicted

watch for spotting from crown fire down the grassy slope; upslope runs pushed by wind eddying on the lee slope

relate wind, RH, fire progress, & smoke drift every 30 min.

L
C
E
S

Appendix A: Input Data for FLAME Application to Case Studies

FLAME outputs are compared to the reported fire behavior that has been reconstructed in the incident investigations. FLAME is applied as it might be by a firefighter who sees the 'current' fire behavior as the ongoing behavior that is characteristic of the early phases of the work shift, and considering 'expected' fire behavior that would arise from conditions that did occur in connection with the burnover. The expected conditions may not have been clearly seen or considered at the time, but they could have been. FLAME is here being tested as a tool applied to what could have been known.

The reported fire behavior is typically a mix of model outputs, informal observations, and reconstructions from travel times, videos, and photographs. Even though it is here termed 'actual' fire behavior it is subject to many assumptions and approximations. Still, the well investigated cases offer the best documented examples available of 'before and after' fire behavior in realistic situations.

The application of FLAME to these fatality cases is based on the fire behavior setting and events that took place, a test of FLAME in realistic situations. The purpose is to test the applicability and accuracy of FLAME, so the best known conditions are utilized, even though conditions may not have been that accurately known to fireline personnel at the time. There is no intent here to evaluate or to judge operational or safety decisions.

South Canyon Fire *(Butler and others 1998)*

FLAME is applied as if crews were evaluating the effects of a 'next big change' that included a crown run back upslope under the influence of the forecasted frontal winds.

'Current' fire behavior is taken to be the long, downslope spread of a backing fire from the ridgetop to into the West Drainage, once that spread was well established, on and after 3 July 1994. The average rate displayed by the fire over that interval was 32 ft/hr, and at that rate it would take about 60 hours to back down the slope. While there was some grass in the fuelbed, the fuel carrying the fire was predominantly litter.

'Expected' fire behavior is taken to be the upslope spread of the fire from the West Drainage bottom at a time estimated to be 1605 hours on the reconstructed perimeter map, a point below the crews and near the beginning of the upslope run, to where the constructed fireline left the ridgetop. Upslope winds are taken as the 30 mi/hr midpoint of the modeled '25 to 35 mi/hr' slope winds reported in appendix C of Butler and others (1998). The 10 percent RH is taken as an approximation from the Rifle RAWS record.

Actual ROS-ratio is calculated from the spread rates reconstructed in the report, and distances scaled from the map, over the time interval from 1605 to 1614 hours. FLAME ROS-ratio assumes an EWS increase from backing to 30 mi/hr, EWS-ratio = 60X, and a change from litter to crown fuels. Applied to the 60-hour downslope transit of the fire, FLAME predicts a 7 to 8 minute upslope run.

'Actual' ROS-ratio = (267 ft/min X 60 min/hr)/(32 ft/hr) = 500X; Reconstructed upslope run is 9 minutes

FLAME ROS-ratio = 500X; Prediction of 'expected' upslope run is about 7 minutes [(60 hr)/500 = 7.2 min)]. (This differs from the actual spread time largely due to the downslope and upslope spread distances being unequal.)

Dude Fire *(USDA 1999)*

FLAME is applied as if crews were evaluating the effects of a 'next big change' that included the possibility of a thunderstorm outflow, originating over the fire or on the other side of it, on the active fire edge above their proposed control line.

'Current' fire behavior is taken as the backing fire on the slope above the crews. The backing fire ROS is calculated with BehavePlus, assuming Fuel Model 9, 1- hr FM 3 percent, 10-hr 4 percent, and 100-hr 6 percent (based on NFDRS reported values), and slope about 20percent. The predicted ROS for a backing fire under those conditions is 0.5 ch/hr. From the estimated position of the fire on the slope above the crews (approximately 200 to 300 yards) that backing fire would have reached the bottom in roughly 20 hours.

'Expected' fire behavior is taken to be the downslope spread of the main fire toward the line being constructed, as a crown fire driven by 30 mi/hr outflow winds. Even though the windspeeds have been estimated as greater than that by firefighters on the incident, my experience is that windspeed estimates by most observers are not very accurate, especially when there is fire and smoke and danger involved, and tends to emphasize gust speeds rather than average speeds. In the Dude Fire Investigation Reports (1999), Goens estimates that the first 5 or 10 minutes the wind was at its estimated 40 to 60 mph maximum, and about half that for the next 30 minutes. The comparison here involves an observation of ROS that took place over about a half hour, so the relevant average wind is what prevailed during that half-hour run. That windspeed average is taken as about 30 mi/hr (avg. 50 mi/hr for 5 to 10 min., then avg. 25 mi/hr for 20 to 25 min.). Several indicators, including the torching of trees by the backing fire, show the potential for transition to crown fire.

After the onset of the winds the fire was observed to advance about 1.5 miles in 30 minutes, for an approximate ROS of 3 mi/hr or 240 ch/hr. Actual ROS-ratio is calculated from the observed ROS of the crown fire (240 ch/hr) and the modeled ROS of the backing fire in needle litter (0.5 ch/hr).

'Actual' ROS-ratio = (240 ch/hr)/(0.5 ch/hr) = 480X; Comments from the investigation refer to the crews having a couple of minutes to see the fire as it runs down the slope toward them.

FLAME ROS-ratio = 500X; Prediction of downslope run to reach the crews is about 2 or 3 minutes [(20 hrs)/500 = 2.4 min], which is in line with comments from the crews.

Thirtymile Fire *(USDA 2001)*

FLAME is applied as if crews were evaluating the effects of a crown fire pushed by the afternoon upcanyon winds.

'Current' fire behavior is that which prevailed during the hours of the early suppression efforts and is termed 'Initial Phase' in the report. The fire behavior consisted predominantly of surface spread in litter, both flanking and backing, with some light downcanyon wind. The modeled ROS is reported as 1.3 ch/hr. FLAME Application assumes backing and flanking fire in litter.

'Expected' fire behavior is the sustained crown fire that moved up the canyon in the late afternoon and is termed 'Deployment Phase' in the report.

The modeled ROS is reported as 125 ch/hr. The 20-foot windspeed up the canyon is reported as being 9 to 11 mi/hr, and in the FLAME application is taken to be 10 mi/hr.

'Actual' ROS-ratio = (125 ch/hr)/(1.3 ch/hr) = 96X

FLAME ROS-ratio = 100X (based on an average of backing and flanking current fire behavior)

Cramer Fire *(USDA 2003; Kelley Close, Investigation FBAN, personal communication)*

FLAME is applied as if crew on the ridgetop were evaluating the possibility that the fire that had been backing into the drainage could spread up the drainage under the influence of westerly winds and become a crown fire.

'Current' fire behavior is taken as predominantly in litter on the slope above Cache Bar Creek. The fire had originally moved over the ridge and into the drainage the previous night and had backed actively all but the several hours before dawn. The total fire movement downslope into the drainage is estimated as taking about 17 hours and extends into the early afternoon. The backing distance, scaled from the map, is about 0.2 miles, or 1060 ft. The overall backing ROS is estimated to be 1 ft/min. There is reported to be some grass in the surface fuels, but for this application the spread is presumed to be predominantly in litter (and may account for the estimated 1 ft/min ROS being a little higher than would be predicted for just litter).

'Expected' fire behavior is the spread that moved up the canyon in the afternoon, becoming crown fire in low brush and eventually in trees, under the influence of increasing westerly winds (which blow up the canyon, gradually becoming more NW and impinging strongly on NW slopes at the head of the canyon). Windspeeds during that period average about 10 to 12 mi/hr at Lodgepole RAWS, and are taken as reasonable for winds in the canyon. Highest winds are estimated at over 20 mi/hr on the top of the NW slopes. To characterize the overall wind flow throughout the upcanyon spread of the fire, the 20-ft general windspeed is taken as the average of 12 and 24 mi/hr, or 18 mi/hr. Windspeeds at the bottom of the slopes would be approximately half that or 9 mi/hr. So the overall 20-ft windspeed associated with the upcanyon and upslope spread of the fire, throughout the depth of the canyon is roughly 14 mi/hr. Since much of the spread was in low brush, with flame heights less than the tree heights, the flame level winds are estimated to be approximately eye-level or about 11 mi/hr. Many assumptions are built into this windspeed, but it is not unreasonable for the average that prevailed throughout the vertical range of the fire as it spread along the drainage and up onto the upper wind-exposed slopes. The average overall ROS of the up-drainage/upslope run is estimated from the reconstructed fire perimeters to be 124 ft/min. The reconstructed ROS on the upper slopes was considerably greater, but the average ROS is what is used to compare to the overall ROS increase estimated from FLAME. The movement of the fire up the drainage (as scaled from the map) is about 4X the distance that it backed down into the drainage.

'Actual' ROS-ratio = (124 ft/min)/(1 ft/min) = 124X; Reconstructed overall upcanyon spread took about 34 minutes (1450 hrs to 1524 hrs).

FLAME ROS-ratio = 160X; Predicted upcanyon spread would be about 26 minutes [4X(17 hr)/160 = 26 min].

Tuolumne Fire *(CDF Fire and USDA 2004, 2005; Larry Hood, Investigation Team FBAN, personal communication)*

FLAME is applied as if crews were evaluating the effects of a wind gust on the backing fire edge, as they constructed control line nearby.

'Current' fire behavior is described as fire in litter backing slowly into a steady upcanyon wind of 3 to 5 mi/hr. Backing ROS is modeled using fuel model 9, 1-hr FM 4 to 5 percent, wind 4 mi/hr with no appreciable influence of slope on the backing fire spread. Modeled ROS = 0.5 ch/hr, or approximately ½ ft/min. At that rate the travel time to the crew working approximately 7 to 30 ft away is roughly 15 to 60 min.

'Expected' fire behavior is anticipated to be a mix of surface fire and crown fire spread, as a gust of wind blows across the fire edge and pushes the fire toward the crew. There are no actual onsite observations that provide a measure of the conditions that prevailed. The wind shift is estimated in the report to be between 90° and 120°. I have estimated a wind gust of 12 mi/hr, deviating by between 90° and 180° from upcanyon and blowing at an angle outward across the fire edge toward the crews. Gusts of 12 mi/hr were observed at the Buck Meadows RAWS station on the canyon rim above the fire, and it is common for gusts to exceed the average windspeed on a well-mixed afternoon by somewhat over 2X. Also, I lived, worked, sailed, and operated portable weather stations in that unit for many years, and I have observed the common occurrence of turbulent gusts in the major canyons deviating strongly from the average upcanyon direction, even blowing in the opposite direction. The expected conditions assumed here are hypothetical, but are plausible and would have been a realistic expectation upon which to base a FLAME application for a crew working close to the fire edge and therefore 'within reach' of even a momentary surge of the fire.

Actual ROS ratio is not accurately known. Estimates of the duration of the flareup, made by crew members and by Air Tactics 440, fall in the range from about 10 to 30 seconds.

FLAME ROS-ratio = 90X (the average of a transition to crown fuels with continuing spread in litter). The expected travel time of the fire to the crews when the wind gust hits is approximately 10 to 40 sec. [(15 to 60 min)/90 = (10 to 40 sec)].

Appendix B: Lookup Tables

Table B1—EWS-ratio lookup table. Larger EWS on left, smaller EWS across top. Look up the EWS-ratio (=EWS$_{LARGE}$/EWS$_{SMALL}$) for corresponding large and small EWS values. For example, the EWS-ratio for a backing fire that will in the future have an EWS of 12 mi/hr is 24X. Tabled values are rounded off to avoid unnecessary detail.

EWS-ratio Table

Smal > / v Lrg	Bck	Flnk	2	3	4	5	6	7	8	10	12	14	16	20	24	30
40	80	40	20	13	10	8	7	6	5	4	3	3	2.5	2	2	1.5
36	72	36	18	12	9	7	6	5	5	4	3	3	2	2	1.5	1
32	64	32	16	11	8	6	5	5	4	3	3	2	2	1.5	1.5	1
28	56	28	14	9	7	6	5	4	4	3	2	2	2	1.5	1	
24	48	24	12	8	6	5	4	4	3	2	2	2	1.5	1	1	
20	40	20	10	7	5	4	3	3	3	2	2	1.5	1.5	1		
16	32	16	8	5	4	3	3	2	2	1.5	1	1	1			
14	28	14	7	5	4	3	2	2	2	1.5	1	1				
12	24	12	6	4	3	2.5	2	2	1.5	1	1					
10	20	10	5	3	2.5	2	1.5	1.5	1	1						
8	16	8	4	3	2	1.5	1	1	1							
6	12	6	3	2	1.5	1	1									
5	10	5	2.5	2	1	1										
4	8	4	2	1	1											
3	6	3	1.5	1												
2	4	2	1													
Flnk	2	1														

Table B2—Rate-of-spread ratios as a function of changes in fuel and changes in effective windspeed. The left-hand column shows the EWS-ratio, the factor by which EWS changes. Each column corresponds to a change between particular fuel types (or to no change). Table values express the ROS-ratio that results from the combined change in EWS and fuel. The left side applies to cases in which fuel and wind changes reinforce. Cases in which changes in wind and fuel have opposing effects are handled with the rightmost two columns. Highlighted ROS values define a range that includes situations associated with fireline fatalities.

FLAME Table

EWS-ratio	No fuel change	EWS biggest in faster fuel			EWS less in grass	
		Litter to/from crown	Litter to/from grass	Crown to/from grass	Crown to/from grass	Litter to/from grass
No chg 1	1	4	14	4	4	14
2	2	10	30	8	2	5
3	4	15	60	13	1	3
4	5	20	80	20	2	3
5	7	30	100	27	2	2
6	9	35	130	35	3	2
8	12	50	180		4	1
10	16	60	240		5	1
12	20	80	300		6	2
16	30	100	440		8	2
20	40	140	600		10	3
24	50	180	700		13	3
30	60	220	1000		17	4
40	80	300	1300		23	6
50	110	400	1800		30	8
60	140	500	2200		40	10
80	200	700	3100		60	16

References

Andersen, H.E. 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. General Technical Report INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Barry, R.G. 1992. Mountain Weather and Climate 2nd Ed. Routledge.

Bishop, J. 1999. FireLine Assessment MEthod—A practical means for predicting wildland fire behavior from fireline observations. National Interagency Fire Behavior Workshop Proceedings. Phoenix, AZ. 1-5 March 1999.

Bishop, J. 2005. Better Fireline Safety Decisions Using The FireLine Assessment MEthod, FLAME. Unpublished.

Bishop, J. 2006. The FLAME (FireLine Assessment MEthod) Idea in a Nutshell. S-290 Course Materials.

Blumen, W., ed. 1990. Atmospheric Processes Over Complex Terrain. American Meteorological Society, Vol. 23, Number 45.

Butler, B.W.; and others. 1998. Fire Behavior Associated with the 1994 South Canyon Fire on Storm King Mountain, Colorado. Research Paper RMRS-RP-9. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Butler, B.W.; and others. 2000. A Method for Evaluating the Effectiveness of Firefighter Escape Routes. Proceedings of 2000 International Wildfire Safety Summit, Edmonton, AB, Canada. 10-12 Oct. 2000.

CDF Fire and USDA. 2004. CDF Helitack 404 Crew Burnover. CDF Greensheet & USFS 72-hour Report.

CDF Fire and USDA. 2005. CDF Helitack 404 Crew Burnover Accident Investigation Report. Tuolumne Fire. CA-STF-2191.

Cheney, P.; Sullivan, A. 1997. Grassfires, fuels, weather and fire behavior. Australia: CSIRO Publishing.

Close, K. 2005. Cramer Fire Investigation Fire Behavior Analyst. Personal communication.

Close, K. 2005. Fire Behavior vs. Human Behavior: Why the Lessons from Cramer Matter. Unpublished.

Hartford. R.A.; Rothermel, R.C. 1991. Fuel Moisture as Measured and Predicted During the 1988 Fires in Yellowstone Park. Research Note INT-396. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Houze, R. 1993. Cloud Dynamics. San Diego, CA: Academic Press.

Mason, P.; Sykes, R. 1979. Flow over an isolated hill of moderate slope. Quarterly Journal of the Royal Meteorological Society. 105: 383-395.

Maclean, J. 1999. Fire on the Mountain. New York, NY: William Morrow and Co.

Oke, T. 1987. Boundary Layer Climates 2nd Ed. Methuen & Co.

Range, P.; and others. 1982. Great Basin Rate-of-Spread Study, Fire Behavior Fire Effects. Reno, NV: U.S. Department of the Interior, Bureau of Land Management, Nevada State Office.

Rothermel, R.C. 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Rothermel, R.C. 1983. How to Predict the Spread and Intensity of Forest and Range Fires. General Technical Report INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Rothermel, R.C. 1991. Predicting Behavior and Size of Crown Fires in the Northern Rocky Mountains. Research Paper INT-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Shaw, R. 1988. Boundary-Layer Meteorology. Davis: University of California.

Taylor, P.; and others. 1987. Boundary-Layer Flow Over Low Hills. Boundary-Layer Meteorology. 39: 107-132

U.S. Department of Agriculture. 2003. Accident Investigation Factual Report, Cramer Fire Fatalities. 0351-2M48-MTDC. Salmon, ID: U.S. Department of Agriculture, Forest Service, Region 4, Salmon Challis National Forest, North Fork Ranger District.

U.S. Department of Agriculture. 1999. Dude Fire Staff Ride. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region.

U.S. Department of Agriculture. 2001. Thirtymile Fire Investigation Report. Washington, DC: Forest Service.

Walmsley, J.; and others 1989. Simple Guidelines for Estimating Windspeed Variations due to Small-scale Topographic Features—an Update. Climatological Bulletin. 23: 3-14

Whiteman, D. 2000. Mountain Meteorology. New York, NY, and Oxford, England: Oxford University Press.