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A Simple Method for Computing Spotting Distances From Wind-Driven Surface Fires

Glen A. Morris[1]

ABSTRACT

Summarizes past efforts to model fire spotting from wildland fires. Explains how Albini's spotting model for wind-driven surfaces was simplified with no loss in accuracy and the resulting model implemented in the BEHAVE fire prediction and fire modeling computer system and on the HP-71B calculator.

KEYWORDS: wildland fires, fire behavior, fire modeling, fire physics, fire management, spotting, firebrand

A mathematical model has been developed (Albini 1979, 1981, 1983) to predict maximum distances spot fires will be ignited by and ahead of wildland surface fires. The firebrand sources treated are:

1. Torching trees,
2. Burning piles, and
3. Wind-driven surface fires.

This note describes the nature of spotting from wind-driven surface fires as it affects practical fire behavior modeling. It describes how Albini's spotting model (Albini 1979, 1981, 1983) was simplified without adverse effect on accuracy. The simplified model has been implemented in the BEHAVE fire prediction and fuel modeling computer system (Andrews and Chase in preparation), and on the Hewlett-Packard HP-71B calculator[2] (Susott and Burgan 1986). Part of this note describes these implementations.

[1]Mathematician, located at Intermountain Station's Intermountain Fire Sciences Laboratory, Missoula, MT.

[2]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

SPOTTING MODEL

Albini's spotting model provides that, regardless of the source, all firebrand trajectories are similar except for the first phase of the trajectory in which the lofting height (initial firebrand height) is attained. Calculation of lofting height for torching trees or burning piles is now a simple matter. In order to implement the simplified method for calculating lofting heights from wind-driven surface fires, Albini began with a complex approach. Fireline intensity pulses that cast firebrands aloft were modeled by means of a best-fit frequency spectrum. This computation-intensive model, known as the spectral model, estimates the energy in a typical pulse (the thermal energy).

Albini then proposed a simpler model, called the "lofting energy model" (Albini 1983), which is derived from the spectral model. The lofting energy model requires two parameters to be derived by exercising the spectral model. The two parameters are fuel dependent and must be computed for each condition of fuel type and moisture.

The lofting energy model estimates mean thermal energy per foot of fireline (E) at the front of wind-driven surface fires spreading at a uniform rate under good burning conditions:

$$E = IA(0.474U)^B \text{ (btu/ft)} \quad (1)$$

I = fireline intensity (btu/ft/s)

U = windspeed at 20 ft (mi/h)

A = the fuel-dependent time parameter (s)

B = the fuel-dependent shape parameter

or in power-law form:

$$E/I = A(0.474U)^B \text{ (s)} \quad (2)$$

Each fuel condition specifies a different pair of values for A and B.

The following section recounts how A and B were obtained for each fuel model. The paper then deals with the sensitivities involved and shows how further simplification was achieved.

CALCULATING THE FUEL-DEPENDENT PARAMETERS

For each of the 13 fire behavior fuel models (Anderson 1982), seven moisture levels and six windspeeds were chosen. For each combination of fuel, moisture, and windspeed (U), the following was done:

1. Rate of spread (R) and Byram's fireline intensity (I) were obtained using the BEHAVE fire behavior processor (Andrews and others in preparation).
2. Thermal energy was computed using Albini's spectral model, with R and I as inputs (Albini 1982b). Appendix A describes this calculation in detail.

This provided a value of thermal energy for each of the six windspeeds for each fuel and moisture combination.

As long as the 20-ft windspeed does not go below 4.2 mi/h, with few exceptions, a close and meaningful curve fit is obtained that provides reasonable values for A and B. Once the log linear least squares curve has been fitted, the pair (A,B) should reflect the fuel conditions; that is, the particular power-law will look different when plotted for each fuel type or moisture level. This entire process is performed by the computer program ABGEN (on file at the Intermountain Fire Sciences Laboratory), which is based on procedures explained by Albini (1982a, 1982b, 1983).

Albini had independently performed the calculation of the two fuel-dependent parameters for each of 12 of the standard fuel models (Albini 1983). Analysis of his A and B parameters revealed an error in earlier work. A correction to tables 3 and 4 of the cited publication was published in Chase (1984).

SENSITIVITIES OF MAXIMUM SPOTTING DISTANCE

The parameters A and B were determined for the 91 combinations of fuel model and moisture level mentioned above. From the extreme values in this array of parameters, I was able to demonstrate the effect of A and B on maximum spotting distance and found that the influence of both fuel type and moisture level upon the maximum distance is largely accounted for by their effect on fireline intensity.

Appendix B treats this matter in some detail. By argument and calculation, it shows that moisture impacts the maximum distance only indirectly through the fireline intensity. So, for the purpose of demonstrating the direct impact of fuel model on maximum spotting distance, the moisture level did not have to be precisely determined. In each case a low value was chosen but care was taken to avoid values beyond the capability of the fire model (Rothermel 1972). The levels chosen ranged from 3 to 8 percent.

Table 1 lists the coefficients by fuel model. For each model we have an (A,B)-pair characterizing the power-law response of E/I to windspeed. As A increases, the curve steepens and lofting becomes efficient, especially at low 20-ft windspeeds (5 mi/h is considered low for spotting). From table 1 it would appear that fuel type is important.

Table 1—Ranked listing of the fuel-dependent parameters for computing the energy (E) in a typical fireline thermal. Knowing the mean fireline intensity (I) and the 20-ft mean windspeed (U), one estimates the thermal energy as

$$E = IA(0.474U)^B \text{ (btu/ft)}$$

These values agree with Chase (1984), a corrected version of those originally published in Albini (1983)

	Fire behavior fuel model	A (s)	B
9	Hardwood litter	1,121	−1.51
2	Grassy understory	709	−1.32
1	Short grass	545	−1.21
3	Tall grass	429	−1.19
4	Mature chaparral	301	−1.05
8	Conifer litter	262	−.97
6	Dormant brush	242	−.94
5	Young chaparral	235	−.92
10	Overgrown slash	224	−.89
7	Southern rough	199	−.83
11	Light conifer slash	179	−.81
13	Heavy conifer slash	170	−.79
12	Medium conifer slash	163	−.78

Fire-pulse energies tend to increase more in response to decreasing wind for some fuels than for others. Even so, the condition that favors stronger vertical pulses is the condition that shortens horizontal travel of firebrands.

Consequently, we would expect that spotting distance is not highly sensitive to either A or B. Figure 1 confirms this, showing that the maximum distance is primarily a function of fireline intensity and windspeed. Obtained by exercising the spotting model, it shows that the direct effect of fuel type on maximum distance is considerably less than that of windspeed or fireline intensity. Even if two fuel models are drastically different, their effects on maximum distance differ by roughly 20 percent. If we were to use a single (A,B)-pair to represent all fuel models, the maximum error is conservatively about 10 percent—readily acceptable for the simplification provided.

Because variations in A and B have relatively little effect on the maximum distance traveled, one pair of values will suffice for all the standard models. In addition, there is no reason to believe that custom fuel models (Burgan and Rothermel 1984) will call for coefficients that vary more than those encountered; consequently, both standard and custom fuel models are represented by a single (A,B)-pair. The logical choice for these values was the averages of the parameters listed in table 1. Averaging the A and B values in the table and using the averaged coefficients in equation (1), we have

$$E = 322I(0.474U)^{-1.01} \cong 322I/(0.474U) \text{ (btu/ft)} \quad (3)$$

which encompasses all fuel conditions for estimating maximum spot-distance. This equation is implemented in BEHAVE. (A and B values for all 13 fire behavior fuel models were computed and included in the averaging, even though the model for spotting from wind-driven surface fires is not applicable under significant canopy cover.)

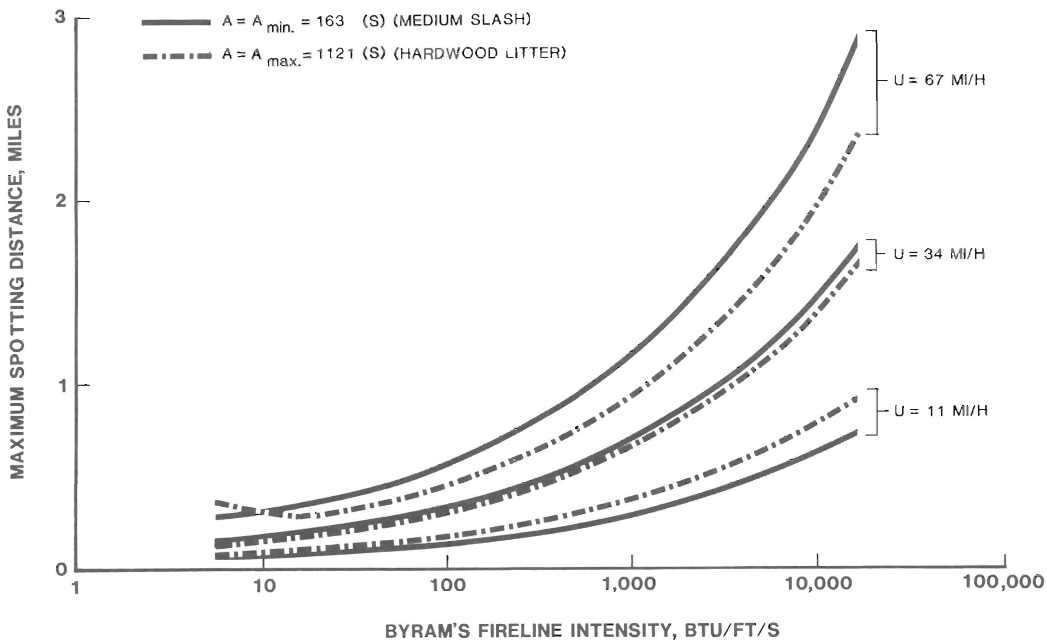

Figure 1—Sensitivities of maximum spotting distance to mean fireline intensity, mean 20-ft windspeed (*U*), and fuel model.

THREE-GROUP IMPLEMENTATION IN THE HP-71B

At the time the wind-driven surface spotting model was being implemented on the HP-71B (Susott and Burgan 1986), the simplification of thermal strength calculations had not been completed; consequently, the HP-71B version is not a simple use of equation 3. The standard fuel models were divided into three broad groups and one set of parameters (within-group averages of A and of B) assigned to each group (see table 2). A simple classification scheme was devised to decide which of three (A,B)-pairs should be assigned to a custom fuel model.

Based on the assumption that fuel that burns well should produce energetic fireline pulses, Wilson's (1985) fuel-surface-area to fuel-bed-area ratio (S) was used to classify fuel models:

$$S = \sigma\beta\delta = \sigma w_o/\rho \qquad (7)$$

where

σ = surface-to-volume ratio (ft^{-1})
β = packing ratio
δ = fuel depth (ft)
w_o = fuel loading (lb/ft^2)
ρ = bulk density (lb/ft^3)

It was found that S provides an adequate "discriminator" for classifying fuel models into the three groups.

Just as fuel model parameters (loading, etc.) are stated for dead or live fuel by size class, S can also be expressed this way. The components of S used are:

S_1 = S for dead 1-hour fuel
S_{10} = S for dead 10-hour fuel
S_{100} = S for dead 100-hour fuel
S_H = S for live herbaceous fuel.

Table 2—Grouping of the fuel-dependent parameters used in the equation

$$E = IA(0.474U)^B \text{ (btu/ft)}$$

To estimate the typical thermal energy (E) of a fireline, one needs to know (1) the mean fireline intensity (I), (2) the 20-ft mean windspeed (U), and (3) the classification (group number, n). The three groups correspond to the three-group implementation of the spotting model implemented on the HP-71B calculator

	Fuel model	*A* (s)	*B*	Group *n*	*A*	*B*
9	Hardwood litter	1,121	−1.51	1	560	−1.25
2	Grassy understory	709	−1.32			
1	Short grass	545	−1.21			
3	Tall grass	429	−1.19			
4	Mature chaparral	301	−1.05	2	240	−.95
8	Conifer litter	262	−.97			
6	Dormant brush	242	−.94			
5	Young chaparral	235	−.92			
10	Overgrown slash	224	−.89			
7	Southern rough	199	−.83			
11	Light conifer slash	179	−.81	3	170	−.80
13	Heavy conifer slash	170	−.79			
12	Medium conifer slash	163	−.78			

Table 3—Ratios of fuel surface area to fuel bed area (S) for standard fuel models

Fire behavior fuel model	S_1 1-h	S_{10} 10-h	S_{100} 100-h	S_W Live herbaceous	S_H Live woody
1	3.7	0	0	0	0
2	8.6	0.2	0.02	1.1	0
3	6.5	0	0	0	0
9	10.5	.1	.01	0	0
11	3.2	.7	.2	0	0
12	8.6	2.2	.7	0	0
13	15	3.6	1.2	0	0
4	14	.6	.1	0	11
5	2.9	.1	0	0	43
6	3.8	.4	.1	0	0
7	2.8	.3	.1	0	.8
8	4.3	.2	.1	0	0
10	8.6	.3	.2	0	4.3

Table 3 gives the value for each of these components in the 13 fire behavior fuel models. A dynamic fuel model would adjust S_1 and S_H to simulate the curing of live fuel through the season (Andrews and others in preparation).

By inspection of data such as table 3, the following rule was devised for classifying a given fuel model. The group number n is set between 1 and 3, according to the following rules.

$$n = \begin{cases} 1 \text{ if } S_{100} \text{ does not exceed 0.05, } S_H \text{ does not exceed 2, and } S_{10} \text{ is less than 0.5} \\ 3 \text{ if } S_{100} \text{ exceeds 0.05, } S_H \text{ does not exceed 2, and } S_{10} \text{ is not less than 0.5} \\ 2 \text{ otherwise} \end{cases}$$

In descriptive terms, a fuel model is likely to belong to group 1 if it is very light (grass, etc.), to group 3 if rather heavy, as is slash, and to group 2 if between these extremes.

Once the fuel model is classified, a reasonable (A,B)-pair can be assigned to it as shown in table 2. The fuel models in Group 1 have large A-parameters; the power-law for these fuel models is steep, and lofting efficiency sensitive to windspeed. Heavy slash, on the other hand, sure to fall into group 3, will be assigned an (A,B)-pair representing insensitivity of lofting efficiency to windspeed.

Testing of this algorithm has been meager. It correctly classified three custom fuel models known to belong to group 3 and one known to belong to group 2, and it classifies the 13 fire behavior fuel models correctly. The scheme has been adopted on these empirical grounds and implemented on the HP-71B calculator.

As far as maximum spotting distance is concerned, it makes little difference whether the three-group version is used or the BEHAVE version (equation 3).

RECOMMENDATIONS

Further testing is recommended. In addition, further research should address the question: how often is maximum distance attained? Because frequency of thermals is now calculated in the simplified model, part of the answer is at hand. But to fully answer the question we must also consider the effect of firebrand size.

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APPENDIX A: USING THE SPECTRAL MODEL

Each value of thermal energy (E) is obtained by the following three-step process, which evaluates the spectral equations (Albini 1982b). For a given fuel-type, moisture level, and mean 20-ft windspeed, the following is done:

1. Calculate Albini's frequency sprectrum (S_I) for wind-driven fireline intensity variations. This is a spectral density function.
2. Locate the frequency (W_{max}) of maximum spectral density (S_{max}) and integrate S_I to get the variance (σ^2) for the intensity variations.
3. Find a random-interval pulse train consisting of rectangular alternating pulses that matches certain features of the spectrum S_I. This is done by specifying the pulse amplitude (A'), period (T), and frequency of occurrence (P_{on}):

$$T = 0.742(2\pi/W_{max}) \quad (4)$$

$$A' = \sigma/P_{on} \quad (5)$$

The value of P_{on} is chosen so as to match the pulse-train spectral peak to $S_{max}/(\sigma^2/T)$. Under good burning conditions, a wind-driven surface fire will often pulse and have an observable mean pulse rate and, also, a typical amount of energy (E) per pulse. This says that a typical value for E should exist for each condition. This is the basis for trying to match a single-rate constant-amplitude pulse train. The typical thermal energy should be the pulse-train's pulse energy:

$$E = A'T/2 \text{ (btu/ft)} \quad (6)$$

Steps 1, 2, and 3 and the evaluation of equation 6 were performed for the six windspeeds for each of the 91 curve fits mentioned.

APPENDIX B: EFFECT OF FUEL TYPE AND MOISTURE ON MAXIMUM SPOT-DISTANCE

Albini provided a mathematical proof (on file at the Intermountain Fire Sciences Laboratory) that most of the variation in thermal energy (E) is due to fireline intensity. The proof consists in showing that E is roughly proportional to $I\,R_o^{-1/2}$. We write

$E \propto I\,R_o^{-1/2}$, where

R_o = rate of spread at zero windspeed.

We might prove this by considering the frequency response of normalized fireline intensity variations ($\Delta I/I$) (Albini 1982b). The response increases more or less linearly up to some cutoff frequency (w_c) above which the spectral lobes are relatively small. The cutoff is well below the peak frequency of the wind spectrum. The wind spectrum increases up to w_c; therefore, w_c will be the lowest peak-frequency for the wind-driven intensity spectrum. Now this spectrum is for the normalized intensity variations so we have as variance $(\sigma/I)^2$. We expect that

$$(\sigma/I)^2 \propto w_c$$

because of the approximate linearity of the final spectrum up to w_c.

Using a random-interval repeated square wave to represent fireline intensity pulses, Albini (1983) has us match the wave to fuel-dependent spectra by matching the pulse period (T) and amplitude (A'):

$$T \propto 1/w_c$$

$$P_{on}A'A' = \sigma^2$$

where

P_{on} is insensitive to w_c

Consequently,

$$A' \propto \sigma \propto I\sqrt{w_c}$$

and

$$A'T \propto I/\sqrt{w_c}$$

and

$$E = A'T/2 \propto I/\sqrt{w_c}$$

But as Albini shows

$$w_c \cong 2\pi R_o/\delta$$

where

δ = fuel depth.

Consequently,

$$E \propto I\,R_o^{-1/2}$$

Thus, the particle-lofting energy depends on fuel conditions only indirectly, and that effect is accommodated by the fireline intensity.

Now this argument does not convince the author; however, figure 2 is further confirmation that, in most cases, fuel moisture is not important for calculating maximum spotting distance. Most of the curves are nearly flat, the exceptions being cases where the intensity frequency spectrum is poorly represented by any square pulse train. These exceptional cases seem to imply considerable sensitivity of A (and B) to moisture; however, it turns out that these coefficients have little control over maximum spotting distance (see fig. 1).

We have, then, both a heuristic argument and a numerical demonstration that the effect of fuel type and moisture on maximum spot distance is, in practical terms, accounted for by the mean fireline intensity.

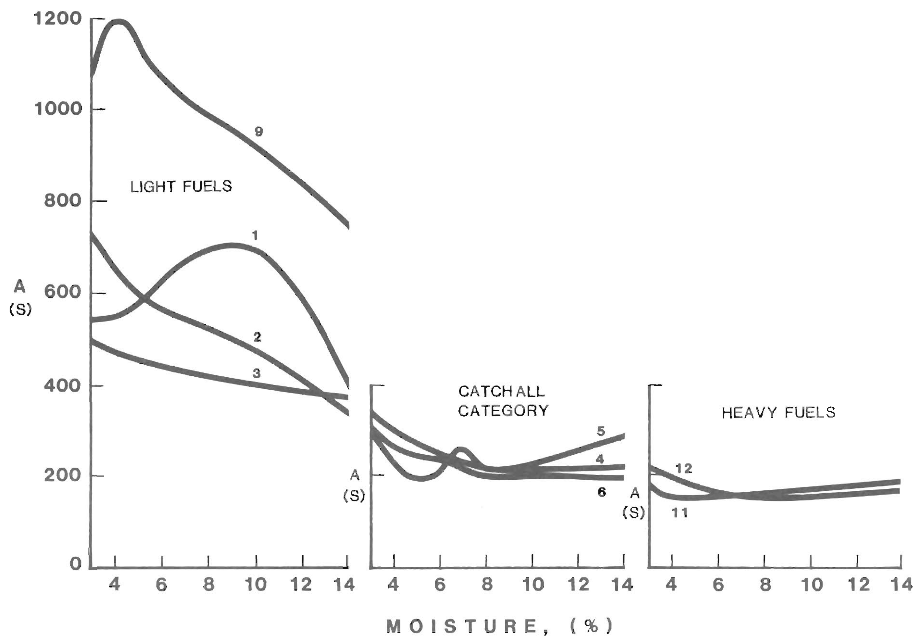

Figure 2—Response of particle lofting tendency, as reflected by the power-law coefficient A, to dead fuel moisture level. Note: The three fuel type groups are plotted separately, the numbers indicating fuel model number (see table 2). Models 7, 10, and 13 are omitted because they differ little from others in their group.

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Intermountain Research Station
324 25th Street
Ogden, UT 84401