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Spotting Distance from Wind-Driven Surface Fires — Extensions of Equations for Pocket Calculators

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ABSTRACT

Extends equations for calculating the maximum spot fire distance to include wind-driven fires burning in surface fuels as a firebrand source. Predictions are based upon prevailing windspeed, vegetational cover, and local terrain. The equations can be used on a programmable pocket calculator. Previous methods of calculating spotting distance from torching trees and burning piles are also included. For copies of a program for the Texas Instruments TI-59, send eight blank TI-59 magnetic cards to the author. (Only two cards are required if the user has the previous version of the program.) Potential uses are in fire management planning and in predicting real-time fire behavior.

KEYWORDS: spot fire, spotting, firebrands, fire management

MODEL DESCRIPTION

Spot fires ignited by flying embers from wildfires and prescribed fires have long been a problem for fire managers. Spotting is difficult to prevent; therefore it is useful to be able to forecast when spotting is likely to occur and predict its maximum distance and direction.

Roussopoulos and Johnson (1975) and Rothermel (1983) provide guidelines based on fireline intensity that indicate when severe fire behavior such as torching, crown fires, and spot fires can be expected. Albini (1979, 1981) and Chase (1981) document calculation of the maximum distance firebrands can travel when the source of the firebrands is:

1. The transient flame produced by a torching tree (or group of trees burning with a single flame structure), and
2. A continuous steady flame as provided by burning piles of slash or "jackpots" of heavy fuel.

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Albini (1983) considers another source of firebrands:

3. A wind-driven fire burning in surface fuels (such as grass, shrubs, litter) without timber cover.

This note extends the equations for predicting maximum spotting distance to include the third case, and documents a revised program for the Texas Instruments TI-59² calculator that includes all three sources.

In all three instances an updraft lofts burning material vertically; then it is carried horizontally by the wind while also falling back to earth to land some distance downwind from the source. In the case of wind-driven fires burning in surface fuels, the firebrand drifts downwind as it is being lofted. When firebrands are produced by surface fires, significant overstory or timber cover may provide a barrier for the firebrands and interfere with the development of an updraft that lofts the firebrands vertically. Consequently, spotting distance in these situations is generally insignificant.

Albini's model covers intermediate range spotting (generally a few tenths of a mile to a mile). It does not address short-range spotting of a few tens of yards from fires of low intensity or very long-range spotting associated with severe fire behavior such as crown fires and firewhirls. The firebrand of interest is the one of optimum size. That is the particle whose dimensions, weight, and aerodynamics allow the wind to loft it a considerable distance and that is still burning when it lands. Particles smaller than optimum could travel farther, but would burn up before landing. Particles larger than optimum would often be burning when they land, but would not travel as far. The model does not consider the numbers of optimum firebrands produced by a fire. If particles of optimum size are not present, spot fire distance will be less than the maximum predicted. The model does not address whether the firebrand causes an ignition, or the number of spot fires caused.

Mountainous terrain is modeled as a washboard. If this simple representation does not describe your situation, perhaps the model will not give you a good approximation of spotting distance.

The surface-fire spotting model requires two fuel-model-dependent parameters used to relate thermal energy to windspeed. Albini (1983) derives these parameters for 12 of the 13 standard NFFL fuel models (Albini 1976; Anderson 1982) and they are presented in table 1 as parameters A and B. A is used as a coefficient in the windspeed function and B is used as a power. Some models ordinarily have overstories, but are sometimes used to represent fuels without overstory cover. Model 9 (hardwood litter) can be used when the deciduous overstory is bare of leaves or the stand is sparse. Model 10 (timber litter and understory) is sometimes used to represent timber harvest debris overgrown with shrubs or other vegetation. Model 8 (closed timber litter) was omitted in Albini's analysis because it is seldom used to represent a model without cover.

The model-dependent parameters can also be derived for custom fuel models (Burgan and Rothermel 1984). Calculation speed and memory considerations preclude calculation of these parameters in the TI-59 program. Current plans are to include derivation of surface-spotting parameters for custom fuel models in the expected update of the BEHAVE system of interactive computer programs (Andrews 1983; Andrews, review draft; Burgan and Rothermel 1984).

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Table 1.—Corrected values of windspeed function parameters for 12 of the 13 NFFL fuel models (erratum notice, Albini 1983). Units of A are seconds; B is dimensionless.

Fuel model	Coefficient A	Power B
	<i>Seconds</i>	
Grass and litter		
1 Short grass	545	-1.21
2 Grassy understory	709	-1.32
3 Tall grass	429	-1.19
9 Hardwood litter	1121	-1.51
Shrub types		
4 Mature chaparral	301	-1.05
5 Young chaparral	235	- .92
6 Dormant brush	242	- .94
7 Southern rough	199	- .83
Logging slash		
10 Overgrown slash	224	- .89
11 Light conifer slash	179	- .81
12 Medium conifer slash	163	- .78
13 Heavy conifer slash	170	- .79

When available, these parameters can be entered in the TI-59 program according to the operating procedures described subsequently.

Users who desire to use NFFL model 8 (closed timber litter) as a surrogate for fuels without overstory should create a custom model with the BEHAVE system using parameters for model 8. The updated version of BEHAVE will then calculate the surface spotting parameters required.

The predictions provided by the program are only as good as the model on which they are based. Confidence in predictions can be improved by field verification. Personal communication (Catchpole 1983) indicates that the model may underpredict maximum spotting distance in eucalyptus forests due to the aerodynamical nature of the tree bark. The author invites submission of any validation data obtained.

Equations are given for English and metric units of measure. The TI-59 program uses English units, so only English units appear in the text. The transformation of the 20-foot reference windspeed to windspeed at heights required for input to Albini's (1983) model has been incorporated in the equations. The logarithmic windspeed profile and the power law profile both yield similar results when referenced near the surface and projected upwards; therefore the power law profile was used because it is simpler.

Table 3 of Albini (1983) presents values necessary for the derivation of the spotting parameters. The table was later found to contain inaccuracies. Corrected table entries are presented in the Appendix (table A). Also presented in the Appendix are the corrected values for the numerical examples appearing in Albini (1983).

SUMMARY OF EQUATIONS

Symbol	English units	Metric units	Description
Torching tree option			
d	inches	cm	Diameter at breast height (d.b.h.) of tree(s) torching out
h	ft	m	Height of burning tree(s)
n	none	none	Number of trees burning simultaneously to produce a single merged flame and buoyant plume structure
h_F	ft	m	Adjusted steady flame height (perpendicular measurement from base of flame to tip of flame)
d_F	none	none	Adjusted steady flame duration
Pile burning option			
H_F	ft	m	Continuous flame height for pile burning
Wind-driven surface fire option			
A	s	s	Fuel model-dependent parameter used as coefficient in windspeed function (see table 1)
B	none	none	Fuel model-dependent parameter used as power in windspeed function (see table 1)
f(U)	s	s	Windspeed function
E	Btu/ft	kJ/m	Strength of a thermal updraft generated by a wind-driven line fire
I	Btu/ft/s	kW/m	Fireline intensity
Common to all options			
\bar{h}	ft	m	Mean vegetation cover height downwind of source (see "Operating instructions")
\bar{h}_c	ft	m	Minimum value of \bar{h} used to calculate spotting distance using the logarithmic windspeed variation with height (Albini 1981)
\bar{h}^*	ft	m	The greater of \bar{h} and \bar{h}_c
U	mi/h	km/h	Windspeed 20 feet (6 m) above vegetation
D	mi	km	Ridge-to-valley horizontal distance (map)
H	1000's of ft	mult. of 300 m	Ridge-to-valley elevational difference
M	none	none	Code number for location of firebrand source 0 = midslope, windward side 1 = valley bottom 2 = midslope, leeward side 3 = ridgetop
z(0)	ft	m	Initial firebrand height above ground
F	mi	km	Flat-terrain spotting distance
S	mi	km	Mountainous-terrain spotting distance (map)

Equations Using English Units

$$z(0) = \left\{ \begin{array}{l} 4.24d_F^{0.332}(h_F) + h/2, \\ 3.64d_F^{0.391}(h_F) + h/2; \\ 2.78d_F^{0.418}(h_F) + h/2, \\ 4.70(h_F) + h/2 \\ 1.055E^{1/2}, \\ 12.2H_F, \end{array} \right. \left. \begin{array}{l} h/h_F \geq 1 \\ 0.5 \leq h/h_F < 1 \\ h/h_F < 0.5, d_F < 3.5 \\ h/h_F < 0.5, d_F \geq 3.5 \end{array} \right\} \begin{array}{l} \text{torching tree option} \\ \text{wind-driven surface fire option} \\ \text{pile burning option} \end{array}$$

where

$$h_F = \begin{cases} 16.5d^{0.515}n^{0.4}, & \text{grand fir, balsam fir} \\ 15.7d^{0.451}n^{0.4}, & \text{Engelmann spruce, subalpine fir, Douglas-fir, western hemlock} \\ 12.9d^{0.453}n^{0.4}, & \text{ponderosa pine, lodgepole pine, white pine} \end{cases}$$

$$d_F = \begin{cases} 12.6d^{-0.256}n^{-0.2}, & \text{ponderosa pine, lodgepole pine, Engelmann spruce} \\ 10.7d^{-0.278}n^{-0.2}, & \text{subalpine fir, Douglas-fir, balsam fir, grand fir, white pine} \\ 6.3d^{-0.249}n^{-0.2}, & \text{western hemlock} \end{cases}$$

$f(U) = A (0.474 U)^B$, where A and B are fuel model-dependent parameters (see table 1)

$$E = I \cdot f(U)$$

$$F = \left\{ \begin{array}{l} 7.18 \times 10^{-4} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*} \right)^{1/2} \left(\frac{1}{2} \right) \ln \left(\frac{z(0)}{\bar{h}^*} \right) \right\}, \\ 7.18 \times 10^{-4} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*} \right)^{1/2} \left(\frac{1}{2} \right) \ln \left(\frac{z(0)}{\bar{h}^*} \right) \right\} + 2.78 \times 10^{-4} U z(0)^{0.643}, \end{array} \right. \begin{array}{l} \text{torching tree,} \\ \text{pile burning options} \\ \text{wind-driven} \\ \text{surface fire option} \end{array}$$

where

$$\bar{h}_c = 2.2z(0)^{0.337} - 4.0$$

$$\bar{h}^* = \max(\bar{h}, \bar{h}_c)$$

$$S = D \cdot X_6,$$

where X_6 is from the iteration:

$$X_0 = A$$

$$X_{n+1} = A - B (\cos(\pi X_n - M\pi/2) - \cos(M\pi/2))$$

$$A = F/D$$

$$B = H/(10\pi)$$

Equations Using Metric Units

$$z(0) = \left\{ \begin{array}{l} 4.24d_F^{0.332}(h_F) + h/2, \\ 3.64d_F^{0.391}(h_F) + h/2, \\ 2.78d_F^{0.418}(h_F) + h/2, \\ 4.70(h_F) + h/2 \\ 0.173E^{1/2}, \\ 12.2H_F, \end{array} \right. \left. \begin{array}{l} h/h_F \geq 1 \\ 0.5 \leq h/h_F < 1 \\ h/h_F < 0.5, d_F < 3.5 \\ h/h_F < 0.5, d_F \geq 3.5 \end{array} \right\} \begin{array}{l} \text{torching tree option} \\ \\ \\ \text{wind-driven surface fire option} \\ \text{pile burning option} \end{array}$$

where

$$h_F = \begin{cases} 3.11d^{0.515}n^{0.4}, & \text{grand fir, balsam fir} \\ 3.14d^{0.451}n^{0.4}, & \text{Engelmann spruce, subalpine fir, Douglas-fir, western hemlock} \\ 2.58d^{0.453}n^{0.4}, & \text{ponderosa pine, lodgepole pine, white pine} \end{cases}$$

$$d_F = \begin{cases} 16.0d^{-0.256}n^{-0.2}, & \text{ponderosa pine, lodgepole pine, Engelmann spruce} \\ 13.9d^{-0.278}n^{-0.2}, & \text{subalpine fir, Douglas-fir, balsam fir, grand fir, white pine} \\ 7.95d^{-0.249}n^{-0.2}, & \text{western hemlock} \end{cases}$$

$f(U) = A (0.295 U)^B$, where A and B are fuel model-dependent parameters (see table 1)

$$E = I \cdot f(U)$$

$$F = \left\{ \begin{array}{l} 1.30 \times 10^{-3} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*} \right)^{1/2} \left(\frac{1}{2} \right) \ln \left(\frac{z(0)}{\bar{h}^*} \right) \right\}, \\ 1.30 \times 10^{-3} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*} \right)^{1/2} \left(\frac{1}{2} \right) \ln \left(\frac{z(0)}{\bar{h}^*} \right) \right\} + 5.03 \times 10^{-4} U z(0)^{0.643}, \end{array} \right. \begin{array}{l} \text{torching tree,} \\ \text{pile burning options} \\ \\ \text{wind-driven} \\ \text{surface fire option} \end{array}$$

where

$$\bar{h}_c = z(0)^{0.337} - 1.22$$

$$\bar{h}^* = \max(\bar{h}, \bar{h}_c)$$

$$S = D \cdot X_6,$$

where X_6 is from the iteration:

$$X_0 = A$$

$$X_{n+1} = A - B (\cos(\pi X_n - M\pi/2) - \cos(M\pi/2))$$

$$A = F/D$$

$$B = H/(10\pi)$$

THE TI-59 PROGRAM

The program for predicting maximum spot fire distance (Chase 1981) had to be extended to include spotting from wind-driven surface fires. Some user convenience in program operation was given up to obtain the advantage of having a single set of program cards, one set of operating instructions, and a single worksheet covering all options. In this revised version, the user may have to reenter up to three unchanged inputs to revise a single value. The user must also be careful to select reasonable data and enter those data without error since there are no checks on the validity of input data.

Maximum spot fire distance is predicted from three sources of firebrands: torching trees, burning piles, and wind-driven surface fires. Figure 1 is a chart showing program flow. Species data cards for the torching tree option from the original program (Chase 1981) contain data that are still valid, but the cards must be rerecorded under a new memory partition before being used with the revised version. Directions for rerecording these cards are given in the section entitled "Program Duplication."

The program is recorded on two cards (magnetic strips). A listing is in the appendix. A prerecorded copy of the program may be obtained by sending two blank magnetic cards for the TI-59 (eight cards if species data cards are also desired) to the author at the Northern Forest Fire Laboratory.

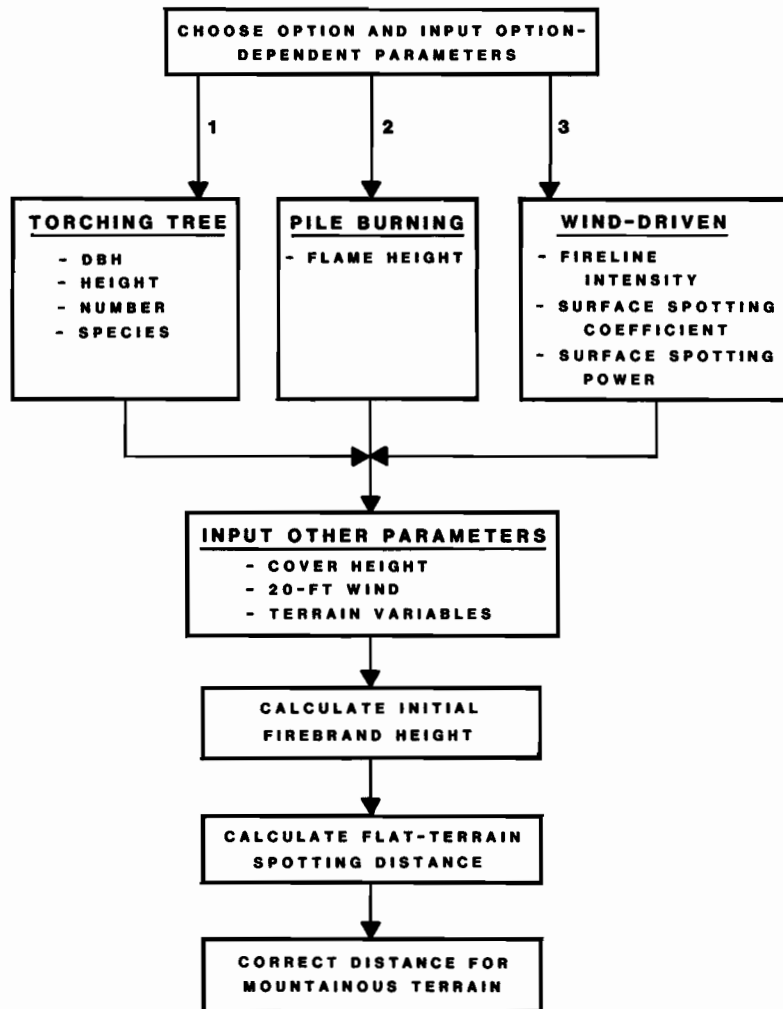


Figure 1.— This chart shows the general organization of the program to predict maximum spotting distance.

OPERATING INSTRUCTIONS

The program for calculating spot fire distance may be run on the TI-59 with any solid-state module in the calculator (such as NFDR/fire behavior module, library module, statistics module) or with no module in place.

Preliminaries

1. Turn on the calculator. (If it is already on, turn it off momentarily to clear program and memory registers.)
2. Partition memory before reading in the program. Press **4** **2nd** **OP** **1** **7**. The display should read 639.39.
3. Press **1**. Feed side 1 of the program cards into the lower slot on the right side of the calculator. The motor will start and stop automatically. If the display flashes, press **CLR** and repeat step 3.
4. Press **2**. Feed side 2 of the program into the slot. If the display flashes, press **CLR** and repeat step 4.
5. Press **3**. Feed side 3 of the program into the slot. If the display flashes, press **CLR** and repeat step 5.

Inputs

Record the necessary inputs on the worksheet (exhibit 1). Enter **one** of the following **three** groups of option-dependent inputs. The inputs in the selected group must be entered in the order given. The group number represents the option selected:

1. **Torching tree option:** Input of this group of values indicates choice of the torching tree option
 - Enter diameter at breast height (d.b.h.) in inches of tree(s) torching out Press **A**
 - Enter height in feet of tree(s) torching out Press **R/S**
 - Enter the number of identical tree(s) burning at once to produce a single flame Press **R/S**
 - A **4** will appear in the display; feed in the tree species data card for the species desired
2. **Pile burning option:** Input of this value indicates choice of the pile burning option.
 - Enter estimated flame height in feet from observation of continuous flame Press **B**
3. **Wind-driven surface fire option:** Input of this group of values indicates choice of the wind-driven surface fire option
 - Enter the fireline intensity in Btu/ft/s (for assistance in obtaining this input, see section entitled "Estimating Fireline Intensities") Press **C**
 - Enter the surface spotting coefficient (A) for the fuel model which represents your fuel complex (see table 1 for models 1-7, 9-13; 1985 BEHAVE for custom fuel models) Press **R/S**
 - Enter surface spotting power (B) for your fuel model (see table 1 for models 1-7, 9-13; 1985 BEHAVE for custom models) Press **R/S**

Enter all of the following groups of inputs. Groups may be entered in any order, but inputs within a group must be entered in the order specified.

Purpose (4) 2nd OP 1 7

INPUTS

Option-dependent parameters	Reg. no.	Option			Before entry	After entry
		Tree 1	Pile 2	Surface 3		
Torching tree d.b.h., inches	39				A	
Torching tree height, ft	38				R/S	
Number of trees torching together	37				R/S	
Species	(read card)				4	
Continuous flame height, ft	31				B	
Fireline intensity, Bru/ft/s	30				C	
Surface spotting coefficient (A)	29				R/S	
Surface spotting power (B)	28				R/S	
Mean cover height, ft	35				D	
20-foot windspeed, mi/h	36				E	
Ridge/valley elevational difference, ft	34				2nd A	
Ridge/valley horizontal distance, mi	33				R/S	
Spotting source location code	32				R/S	

- 0=midslope, windward side
- 1=valley bottom
- 2=midslope, leeward side
- 3=ridgetop

OUTPUT

Maximum spotting distance corrected for mountainous terrain, mi 21 SBR = _____

4. Cover

—Enter the mean cover height, in feet, of the area downwind of the firebrand source. Where timber or shrub cover exists, enter the height. If there is broken forest cover, enter one-half the treetop height of the forest-covered portion. If there is little or no forest cover (as is the case for option 3), enter vegetation height. This value is used to characterize the general forest cover as it influences the wind.

Press **D**

5. Wind

—Enter the average windspeed, in miles per hour, 20 feet above the vegetation

Press **E**

6. Terrain variables

—If terrain is flat, enter zero here (do not skip this step—an incorrect nonzero value may be carried over from a previous run), then proceed to “Recall and Correction of Input”. If terrain is not flat, enter average elevational difference in feet from ridge-top to valley bottom as would be shown on a map. (The model is not very sensitive to this input; rounding to nearest thousand is probably adequate.) The entry is in feet even though the equations use multiples of 1,000 feet.

Press **2nd** **A**

—Enter the ridgetop-to-valley bottom horizontal distance in miles as would be shown on a map.

Press **R/S**

—Enter the firebrand source location code from the following list.

Press **R/S**

Enter

for

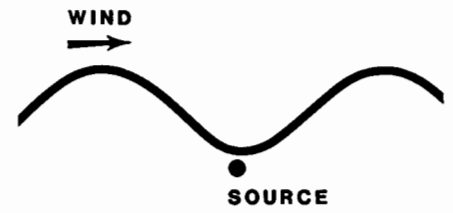
0

Midslope, windward side



1

Valley bottom



2

Midslope, leeward side



3

Ridgetop



Recall and Correction of Input

1. Recall flashing display of option number chosen by pressing **SBR** **RCL**. If flashing 9's appear in the display, no option has been chosen. If a flashing 6 appears, more than one option has been chosen. Press **CLR** to halt the flashing display. Press **SBR** **CLR** to clear option flags. Enter the group of option-dependent inputs desired and repeat this step.
2. Follow with a series of **R/S** to view successive inputs for the selected option in the order listed on the worksheet. Items appearing in parentheses are not recalled (i.e., tree species in torching tree option is not recalled). The number of **R/S** required for each option is:

Torching tree	8
Pile burning	6
Surface spotting	8

If an additional **R/S** is pushed, flashing 9's will appear in the display to signal the end of the recalled values. Press **CLR** to halt the flashing display.
3. To change any item of input, reenter the group of inputs down through the correction for the wrong value as described in the input section.

Performing Calculations

1. Press **SBR** **=**. When calculations are completed, the mountainous terrain spotting distance in miles will appear in the display. A flashing display at this point indicates an invalid calculation in the computation sequence. A list of conditions known to cause a flashing display here follows. There may be other causes.

Cause	Option	Flashing display
Windspeed = 0	1, 2, 3	0.00
Windspeed less than 0	1, 2, 3	Nonzero
Fireline intensity = 0	3	0.00
Custom model spotting coefficient = 0	3	0.00
Number of trees torching = 0	1	Nonzero
No option selected	1, 2, 3	9's
More than one option selected	1, 2, 3	6.00

Press **CLR** to halt a flashing display and check your inputs.

Making Successive Runs

1. If changing options, press **SBR** **CLR** to clear option flags. Reenter group of option-dependent variables desired (group 1, 2, or 3).
2. Change one or more other groups of inputs by entering the group as described in input section. Then check entire input list, using **SBR** **RCL**, **R/S**, **R/S**,
3. Perform calculations (**SBR** **=**).

Following are some tips for users who don't wish to reenter valid inputs needlessly, but are willing to remember extra procedures:

1. If not changing options, the user can input a changed value manually by entering **value** **STO** **nn** where nn is the register number where that value is stored (see exhibit 1).
2. Proceed to reinput the group of parameters, but stop after all changed values have been entered.
3. If changing options, but valid inputs from a prior run are still in place, input only the first value in the group of option-dependent parameters. This serves to set the option flag.

Purpose _____

(4) (2nd) (OP) (1) (7)

INPUTS

<u>Option-dependent parameters</u>	Reg. no.	Tree	Option Pile	Surface	Tree	Option Pile	Surface	Before entry	After entry
		(1)	2	3	1	(2)	3		
Torching tree d.b.h., inches	39	<u>20</u>							A
Torching tree height, ft	38	<u>137</u>							R/S
Number of trees torching together	37	<u>1</u>							R/S
Species	(read card)	<u>Grand fir</u>						4	

Continuous flame height, ft	31					<u>45</u>			B
Fireline intensity, Bru/ft/s	30								C
Surface spotting coefficient (A)	29								R/S
Surface spotting power (B)	28								R/S

Other parameters

Mean cover height, ft	35	<u>130</u>				<u>100</u>			D
20-foot windspeed, mi/h	36	<u>20</u>				<u>15</u>			E
Ridge/valley elevational difference, ft	34	<u>4000</u>				<u>2000</u>			2nd A
Ridge/valley horizontal distance, mi	33	<u>.25</u>				<u>1</u>			R/S
Spotting source location code	32	<u>3</u>				<u>1</u>			R/S

0=mid slope, windward side
 1=valley bottom
 2=mid slope, leeward side
 3=ridgetop

OUTPUT

Maximum spotting distance corrected for mountainous terrain, mi	21	<u>.31</u>				<u>.21</u>			SBR =
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Exhibit 2a. — Maximum Spotting Distance Worksheet

Sample Problems

Name _____ Date _____ Sheet 2 of 2

Purpose

(4) (2nd) (OP) (1) (77)

INPUTS

Option-dependent parameters

Reg. no.	Tree 1	Option Pile 2	Surface 3	Tree 1	Option Pile 2	Surface 3	Before entry	After entry
39							A	A
38							R/S	R/S
37							R/S	R/S
(read card)							4	
31							B	B
30							C	C
29							R/S	R/S
28							R/S	R/S
35							D	D
36							E	E
34							2nd A	2nd A
33							R/S	R/S
32							R/S	R/S

Other parameters

Mean cover height, ft

20-foot windspeed, mi/h

Ridge/valley elevational difference, ft

Ridge/valley horizontal distance, mi

Spotting source location code

0=midslope, windward side

1=valley bottom

2=midslope, leeward side

3=ridgetop

OUTPUT

Maximum spotting distance corrected for mountainous terrain, mi

21 0.27

1.58

SBR =

ESTIMATING FIRELINE INTENSITIES

You may wish to use fire behavior calculations (Burgan 1979) to produce realistic fireline intensity values for input to the spot fire program. In this case, the NFDR/fire behavior CROM (custom read only memory) must be in place.

Switching from calculator to module memory (from spot fire distance to fire behavior calculations) and vice versa causes memory problems due to partitioning. Overcoming the problems involves a cumbersome procedure. Therefore it is recommended that the user make all the runs he/she wishes using one program, momentarily turn the calculator off and then on again, then access the other program (by pressing **2nd** **PGM** **2** **SBR** **R/S** [see Burgan 1979] or by reading the program cards) to make the desired runs.

Note that 20-foot windspeed is the input for the spot fire program, while midflame windspeed is used for fire behavior. Refer to Rothermel (1983) for guidelines in adjusting windspeeds.

Another method of estimating fireline intensity for real-time predictions is to use observed flame lengths in Byram's (1959) formula, which relates fireline intensity and flame length:

$$I = 5.66L^{2.17}$$

where

I = fireline intensity, Btu/ft/s

L = flame length, ft

SAMPLE PROBLEMS

Exhibits 2a and 2b contain the inputs and outputs for four examples — one for torching tree option, one for pile burning, and two for the surface spot fire option.

CONDENSED INSTRUCTIONS

1. **4** **2nd** **OP** **1** **7**
2. Press **1**, feed side 1 (flashing: **CLR**, try again).
3. Press **2**, feed side 2 (flashing: **CLR**, try again).
4. Press **3**, feed side 3 (flashing: **CLR**, try again).

Preliminaries

Input

Enter	Press
Torching tree d.b.h.	A
Group 1 Torching tree height	R/S
No. trees torching together	R/S
Read species card	
or	
Group 2 Observed flame height	B
or	
Fireline intensity	C
Group 3 Surface spotting coefficient (A)	R/S
Surface spotting power (B)	R/S
Group 4 Mean cover height	D
Group 5 20-foot windspeed	E
Ridge/valley elevational difference	2nd A
Group 6 Ridge/valley horizontal distance	R/S
Firebrand source location code	R/S

Check Inputs **SBR** **RCL**; follow by series of **R/S**

Calculations **SBR** **=**

**To Clear Option
Flags** **SBR** **CLR**

REGISTER ASSIGNMENTS

For completeness, the following list gives memory locations assigned to the inputs, outputs, and selected intermediate values.

Register	Symbol	Contents
39	d	Torching tree d.b.h.
38	h	Torching tree height
37	n	Number of trees torching together
31	H _F	Continuous flame height
30	I	Fireline intensity
29	A	Surface spotting coefficient
28	B	Surface spotting power
35	\bar{h}	Mean cover height
36	U	20-foot windspeed
34	1000H	Ridge/valley elevation difference
33	D	Ridge/valley horizontal distance
32	M	Spotting source location code
17	\bar{h}^*	Cover height used in calculations
16	none	Downwind drift during lofting
25	z(0)	Initial firebrand height
26	d _F	Adjusted steady flame duration
27	h _F	Adjusted steady flame height
24	F	Flat terrain spotting distance
21	S	Corrected spotting distance

PROGRAM DUPLICATION

The program recorded on one set of magnetic cards can be duplicated on another blank set as follows:

Program Cards

1. Turn on your calculator. Enter the program into memory using the set of cards to be duplicated.

4 **2nd** **OP** **1** **7**

1; feed side 1 (if flashing; press **CLR**, try again)

2; feed side 2 (if flashing; press **CLR**, try again)

3; feed side 3 (if flashing; press **CLR**, try again)

2. Press **1** **2nd** **R/S** and feed in side 1 of the set of blank cards. If the display flashes, press **CLR** and repeat step 2.

3. Press **2** **2nd** **R/S** and feed in side 2 of the set of blank cards. If the display flashes, press **CLR** and repeat step 3.

4. Press **3** **2nd** **R/S** and feed in side 3 of the set of blank cards. If the display flashes, press **CLR** and repeat step 4.

5. Label the cards appropriately, using a pen with permanent, fast-drying ink. A suggestion for labeling is shown in figure 2.

1		2		
REVISED SPOT FIRE DISTANCE				
TERRAIN				
TORCH	PILE	SURFACE	COVER HT	20-FT WIND

4		4	
DATA CARD : SPOT FIRE DISTANCE			
	SPECIES NAME		
			REVISED

Figure 2.—Suggested labeling for spot fire program cards.

Data Cards

To re-record data cards for original program under new partition for revised program.

1. Turn on calculator.
2. Read card for original program:
Press **4**; feed card (either side) (if flashing; press **CLR**, try again).
3. Repartition memory: **4** **2nd** **OP** **1** **7**
4. Re-record:
Press **4** **2nd** **WRITE**; feed card; (if flashing; press **CLR**, try again)
Repeat step 4 for all sides of cards for this species.
5. Label the card appropriately (see fig. 2).
6. If there are data cards for another species to re-record:
6 **2nd** **OP** **1** **7**
Repeat steps 2-5.

To duplicate valid data cards for the revised program:

1. Turn on calculator.
Repartition memory: **4** **2nd** **OP** **1** **7**
2. Press **4** and feed in one side of the data card to be duplicated. If the display flashes, press **CLR** and try again.
3. Press **4** **2nd** **RS** and feed in one side of the blank card. If the display flashes, try again. Repeat step 3 for the other side of the blank card.
4. Label the card appropriately (see fig. 2).
Repeat steps 2 through 4 for remaining data cards.

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**APPENDIX
PROGRAM LISTING**

000	25	CLR	057	32	X↑T	114	71	SBR	171	22	INV	228	42	STD
001	91	R/S	058	09	9	115	34	FX	172	77	GE	229	24	24
002	76	LBL	059	42	STD	116	76	LBL	173	52	EE	230	92	RTN
003	22	INV	060	23	23	117	33	X²	174	42	STD	231	76	LBL
004	53	(	061	01	1	118	53	(	175	17	17	232	54)
005	43	RCL	062	00	0	119	73	RC*	176	92	RTN	233	53	(
006	01	01	063	42	STD	120	23	23	177	76	LBL	234	53	(
007	65	x	064	22	22	121	65	x	178	52	EE	235	93	.
008	43	RCL	065	61	GTO	122	43	RCL	179	32	X↑T	236	00	0
009	39	39	066	47	CMS	123	26	26	180	42	STD	237	00	0
010	45	Yx	067	76	LBL	124	45	Yx	181	17	17	238	00	0
011	43	RCL	068	24	CE	125	73	RC*	182	92	RTN	239	02	2
012	02	02	069	07	7	126	22	22	183	76	LBL	240	07	7
013	65	x	070	42	STD	127	65	x	184	53	(	241	08	8
014	43	RCL	071	23	23	128	43	RCL	185	53	(	242	65	x
015	37	37	072	08	8	129	27	27	186	93	.	243	43	RCL
016	45	Yx	073	42	STD	130	85	+	187	00	0	244	36	36
017	93	.	074	22	22	131	43	RCL	188	00	0	245	65	x
018	04	4	075	61	GTO	132	38	38	189	00	0	246	43	RCL
019	54	)	076	47	CMS	133	55	÷	190	07	7	247	25	25
020	53	(	077	76	LBL	134	02	2	191	01	1	248	45	Yx
021	42	STD	078	23	LNx	135	54	)	192	08	8	249	93	.
022	27	27	079	05	5	136	61	GTO	193	65	x	250	06	6
023	35	1/X	080	42	STD	137	42	STD	194	43	RCL	251	04	4
024	65	x	081	23	23	138	76	LBL	195	36	36	252	03	3
025	43	RCL	082	06	6	139	44	SUM	196	65	x	253	54)
026	38	38	083	42	STD	140	53	(	197	43	RCL	254	42	STD
027	54	)	084	22	22	141	01	1	198	17	17	255	16	16
028	32	X↑T	085	76	LBL	142	02	2	199	34	FX	256	85	+
029	01	1	086	47	CMS	143	93	.	200	65	x	257	43	RCL
030	22	INV	087	92	RTN	144	02	2	201	53	(	258	24	24
031	77	GE	088	76	LBL	145	65	x	202	93	.	259	54)
032	23	LNx	089	34	FX	146	43	RCL	203	03	3	260	42	STD
033	93	.	090	53	(	147	31	31	204	06	6	261	24	24
034	05	5	091	43	RCL	148	54	)	205	02	2	262	61	GTO
035	22	INV	092	03	03	149	61	GTO	206	85	+	263	55	÷
036	77	GE	093	65	x	150	42	STD	207	53	(	264	76	LBL
037	24	CE	094	43	RCL	151	76	LBL	208	43	RCL	265	95	=
038	43	RCL	095	39	39	152	45	Yx	209	25	25	266	58	FIX
039	26	26	096	45	Yx	153	43	RCL	210	55	÷	267	02	02
040	32	X↑T	097	43	RCL	154	35	35	211	43	RCL	268	87	IFF
041	03	3	098	04	04	155	32	X↑T	212	17	17	269	01	01
042	93	.	099	65	x	156	53	(	213	54	)	270	65	x
043	05	5	100	43	RCL	157	02	2	214	34	FX	271	87	IFF
044	77	GE	101	37	37	158	93	.	215	55	÷	272	02	02
045	32	X↑T	102	45	Yx	159	02	2	216	02	2	273	93	.
046	01	1	103	93	.	160	65	x	217	65	x	274	22	INV
047	01	1	104	02	2	161	43	RCL	218	53	(	275	87	IFF
048	42	STD	105	94	+/-	162	25	25	219	43	RCL	276	03	03
049	23	23	106	54	)	163	45	Yx	220	25	25	277	36	PGM
050	01	1	107	42	STD	164	93	.	221	55	÷	278	61	GTO
051	02	2	108	26	26	165	03	3	222	43	RCL	279	75	-
052	42	STD	109	92	RTN	166	03	3	223	17	17	280	76	LBL
053	22	22	110	76	LBL	167	07	7	224	54	)	281	65	x
054	61	GTO	111	35	1/X	168	75	-	225	23	LNx	282	87	IFF
055	47	CMS	112	71	SBR	169	04	4	226	54	)	283	02	02
056	76	LBL	113	22	INV	170	54	)	227	54	)	284	30	TAN

285	76	LBL	352	03	03	419	75	-	486	48	EXC	553	91	R/S
286	93	.	353	54	)	420	53	(	487	00	0	554	43	RCL
287	87	IFF	354	76	LBL	421	43	RCL	488	35	1/X	555	31	31
288	03	03	355	55	+	422	32	32	489	91	R/S	556	91	R/S
289	30	TAN	356	00	0	423	65	x	490	76	LBL	557	61	GTO
290	61	GTO	357	32	X!T	424	09	9	491	38	SIN	558	29	CP
291	75	-	358	43	RCL	425	00	0	492	87	IFF	559	76	LBL
292	76	LBL	359	33	33	426	54	)	493	01	01	560	11	A
293	30	TAN	360	67	EQ	427	39	CDS	494	94	+/-	561	86	STF
294	03	3	361	85	+	428	54	)	495	87	IFF	562	01	01
295	06	6	362	43	RCL	429	54	)	496	02	02	563	42	STD
296	94	+/-	363	34	34	430	42	STD	497	28	LOG	564	39	39
297	34	FX	364	67	EQ	431	19	19	498	09	9	565	91	R/S
298	91	R/S	365	85	+	432	97	DSZ	499	94	+/-	566	42	STD
299	76	LBL	366	53	(	433	00	00	500	34	FX	567	38	38
300	36	PGM	367	43	RCL	434	61	GTO	501	91	R/S	568	91	R/S
301	00	0	368	24	24	435	53	(	502	43	RCL	569	42	STD
302	35	1/X	369	55	+	436	43	RCL	503	30	30	570	37	37
303	91	R/S	370	43	RCL	437	19	19	504	91	R/S	571	04	4
304	76	LBL	371	33	33	438	65	x	505	43	RCL	572	91	R/S
305	75	-	372	54	)	439	43	RCL	506	29	29	573	76	LBL
306	87	IFF	373	42	STD	440	33	33	507	91	R/S	574	12	B
307	01	01	374	20	20	441	54	)	508	43	RCL	575	86	STF
308	35	1/X	375	42	STD	442	42	STD	509	28	28	576	02	02
309	87	IFF	376	19	19	443	21	21	510	91	R/S	577	42	STD
310	02	02	377	53	(	444	91	R/S	511	76	LBL	578	31	31
311	44	SUM	378	43	RCL	445	76	LBL	512	29	CP	579	91	R/S
312	53	(	379	34	34	446	85	+	513	43	RCL	580	76	LBL
313	53	(	380	55	+	447	43	RCL	514	35	35	581	13	C
314	53	(	381	01	1	448	24	24	515	91	R/S	582	86	STF
315	43	RCL	382	00	0	449	42	STD	516	43	RCL	583	03	03
316	29	29	383	00	0	450	21	21	517	36	36	584	42	STD
317	65	x	384	00	0	451	91	R/S	518	91	R/S	585	30	30
318	53	(	385	00	0	452	76	LBL	519	43	RCL	586	91	R/S
319	93	.	386	55	+	453	43	RCL	520	34	34	587	42	STD
320	04	4	387	89	#	454	87	IFF	521	91	R/S	588	29	29
321	07	7	388	54	)	455	01	01	522	43	RCL	589	91	R/S
322	04	4	389	42	STD	456	71	SBR	523	33	33	590	42	STD
323	65	x	390	18	18	457	87	IFF	524	91	R/S	591	28	28
324	43	RCL	391	06	6	458	02	02	525	43	RCL	592	91	R/S
325	36	36	392	42	STD	459	37	P/R	526	32	32	593	76	LBL
326	54	)	393	00	00	460	22	INV	527	91	R/S	594	14	D
327	45	YX	394	76	LBL	461	87	IFF	528	00	0	595	42	STD
328	43	RCL	395	61	GTO	462	03	03	529	35	1/X	596	35	35
329	28	28	396	53	(	463	48	EXC	530	91	R/S	597	91	R/S
330	54	)	397	43	RCL	464	61	GTO	531	76	LBL	598	76	LBL
331	65	x	398	20	20	465	38	SIN	532	94	+/-	599	15	E
332	43	RCL	399	75	-	466	76	LBL	533	01	1	600	42	STD
333	30	30	400	43	RCL	467	71	SBR	534	94	+/-	601	36	36
334	54	)	401	18	18	468	87	IFF	535	34	FX	602	91	R/S
335	34	FX	402	65	x	469	02	02	536	91	R/S	603	76	LBL
336	65	x	403	53	(	470	39	CDS	537	43	RCL	604	16	A'
337	01	1	404	53	(	471	76	LBL	538	39	39	605	42	STD
338	93	.	405	01	1	472	37	P/R	539	91	R/S	606	34	34
339	00	0	406	08	8	473	87	IFF	540	43	RCL	607	91	R/S
340	05	5	407	00	0	474	03	03	541	38	38	608	42	STD
341	05	5	408	65	x	475	39	CDS	542	91	R/S	609	33	33
342	54	)	409	43	RCL	476	61	GTO	543	43	RCL	610	91	R/S
343	76	LBL	410	19	19	477	38	SIN	544	37	37	611	42	STD
344	42	STD	411	75	-	478	76	LBL	545	91	R/S	612	32	32
345	42	STD	412	43	RCL	479	39	CDS	546	61	GTO	613	91	R/S
346	25	25	413	32	32	480	03	3	547	29	CP	614	76	LBL
347	71	SBR	414	65	x	481	06	6	548	76	LBL	615	25	CLR
348	45	YX	415	09	9	482	94	+/-	549	28	LOG	616	81	RST
349	71	SBR	416	00	0	483	34	FX	550	04	4			
350	53	(	417	54	)	484	91	R/S	551	94	+/-			
351	87	IFF	418	39	CDS	485	76	LBL	552	34	FX			

CORRECTED VALUES

Table A.—Corrected values of the standard deviation of fire intensity, as a percentage of the mean intensity (coefficient of variation) for 12 fuel models that occur without timber cover (supercedes Albini, 1983, table 3).

Fuel model	Mean horizontal windspeed at 10 m ht, m/s					
	5	10	15	20	25	30
Grass and litter						
1 Short grass	37.5	27.9	22.0	18.0	15.0	12.8
2 Grassy understory	56.5	45.6	37.3	31.0	26.1	22.4
3 Tall grass	49.1	35.9	27.2	21.3	17.2	14.2
9 Hardwood litter	70.4	63.3	56.2	49.8	44.3	39.6
Shrub types						
4 Mature chaparral	40.0	24.9	17.3	13.0	10.3	8.42
5 Young chaparral	24.4	14.1	10.0	7.75	6.32	5.33
6 Dormant brush	48.9	33.1	24.2	18.8	15.3	12.8
7 Southern rough	43.4	27.6	19.9	15.4	12.5	10.5
Logging slash						
10 Overgrown slash	55.1	39.7	30.3	24.4	20.3	17.4
11 Light conifer slash	52.1	35.5	26.5	21.0	17.4	14.8
12 Medium conifer slash	50.1	33.4	24.6	19.3	15.9	13.4
13 Heavy conifer slash	49.6	32.5	23.8	18.7	15.4	13.0

Following are corrected example calculations (Albini 1983) using the author's equation numbers and nomenclature.

Example 1.

$$f(U) = AU^B = 545 \times (5)^{-1.21} = 77.7 \text{ s} \quad (9)$$

$$E = I f(U) = (2000)(77.7) = 155\,400 \text{ kJ/m} \quad (10)$$

$$H = 0.173 E^{1/2} = (0.173)(155\,400)^{1/2} = 68.2 \text{ m} \quad (11)$$

2.93 m = effective cover height

$$F = \text{flat terrain spotting distance} = 0.30 \text{ km} \quad (13)$$

$$U(68) = U(10\text{m}) \times \left(\frac{68}{10} \right)^{1/7} = (5)(1.32) = 6.6 \text{ m/s} \quad (14)$$

$$X = (2.78)(6.6)(68.2)^{1/2} = 151 \text{ m} = 0.151 \text{ km} \quad (15)$$

Spotting distance = 0.30 + 0.15 = 0.45 km

Example 2.

$$f(U) = AU^B = 301 (20)^{-1.05} = 13.0 \text{ s} \quad (16)$$

$$E = I f(U) = (50\,000)(13.0) = 650\,000 \text{ kJ/m} \quad (17)$$

$$H = 0.173 E^{1/2} = (0.173)(806) = 139 \text{ m} \quad (18)$$

$$F = 1.87 \text{ km}$$

$$U(139) = U(10) \times \left(\frac{139}{10} \right)^{1/7} = 29.1 \text{ m/s} \quad (19)$$

$$X = (2.78)(29.1)(139)^{1/2} = 954 \text{ m} = 0.954 \text{ km} \quad (20)$$

Spotting distance = 1.87 + 0.95 = 2.82 km

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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