United States
Department of
Agriculture

Forest Service

**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Note
INT-346

December 1984

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-59[2] 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 table1 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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[2]The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

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
	Seconds	
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	n	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

$$z(0) = \begin{cases} 4.24 d_F^{0.332}(h_F) + h/2, & h/h_F \geq 1 \\ 3.64 d_F^{0.391}(h_F) + h/2, & 0.5 \leq h/h_F < 1 \\ 2.78 d_F^{0.418}(h_F) + h/2, & h/h_F < 0.5,\ d_F < 3.5 \\ 4.70(h_F) + h/2 & h/h_F < 0.5,\ d_F \geq 3.5 \end{cases} \quad \text{torching tree option}$$

$$z(0) = 1.055E^{1/2}, \quad \text{wind-driven surface fire option}$$

$$z(0) = 12.2H_F, \quad \text{pile burning option}$$

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)

$E = I \cdot f(U)$

$$F = \begin{cases} 7.18 \times 10^{-4} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*}\right)^{1/2} (½) \ln\left(\frac{z(0)}{\bar{h}^*}\right) \right\}, & \text{torching tree, pile burning options} \\ 7.18 \times 10^{-4} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*}\right)^{1/2} (½) \ln\left(\frac{z(0)}{\bar{h}^*}\right) \right\} + 2.78 \times 10^{-4} U z(0)^{0.643}, & \text{wind-driven surface fire option} \end{cases}$$

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:

$$X_o = A$$

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

$$A = F/D$$

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

Equations Using Metric Units

$$z(0) = \begin{cases} 4.24 d_F^{0.332}(h_F) + h/2, & h/h_F \geq 1 \\ 3.64 d_F^{0.391}(h_F) + h/2, & 0.5 \leq h/h_F < 1 \\ 2.78 d_F^{0.418}(h_F) + h/2, & h/h_F < 0.5,\ d_F < 3.5 \\ 4.70(h_F) + h/2 & h/h_F < 0.5,\ d_F \geq 3.5 \end{cases} \quad \text{torching tree option}$$

$$z(0) = 0.173 E^{1/2}, \quad \text{wind-driven surface fire option}$$

$$z(0) = 12.2 H_F, \quad \text{pile burning option}$$

where

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

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

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

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

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

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:

$$X_o = A$$

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

$$A = F/D$$

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

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.

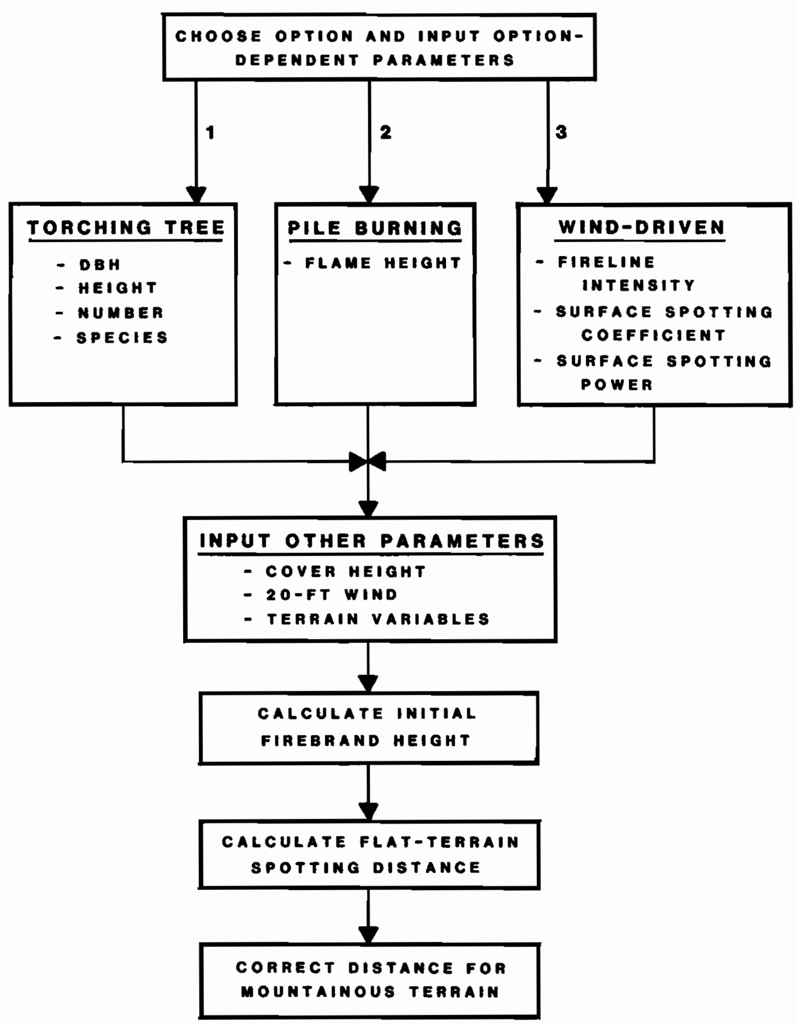


Figure 1.—This chart shows the general organization of the program to predict maximum spotting distance.

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.

Name____________________ Date____________ Sheet______ of ______

Purpose____

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

INPUTS

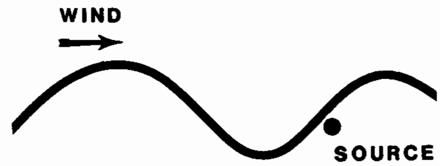
Option-dependent parameters	Reg. no.	Option: Tree 1	Option: Pile 2	Option: Surface 3	Option: Tree 1	Option: Pile 2	Option: Surface 3	Before entry	After entry
Torching tree d.b.h., inches	39	____			____				A
Torching tree height, ft	38	____			____				R/S
Number of trees torching together	37	____			____				R/S
Species	(read card)	____			____			4	
Continuous flame height, ft	31		____			____			B
Fireline intensity, Btu/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	____	____	____	____	____	____		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 0=midslope, windward side 1=valley bottom 2=midslope, leeward side 3=ridgetop	32	____	____	____	____	____	____		R/S
OUTPUT									
Maximum spotting distance corrected for mountainous terrain, mi	21	____	____		____	____	____	SBR =	

Exhibit 1.—Maximum Spotting Distance Worksheet

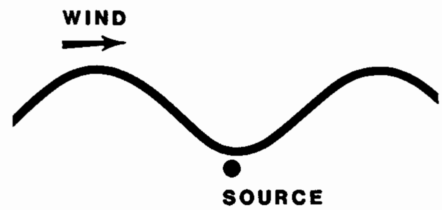
4. **Cover**
   —Enter the mean cover height, in feet, of the area downwind of the firebrand source. Where timber or shrub cover exists, enter the height. If there is broken forest cover, enter one-half the treetop height of the forest-covered portion. If there is little or no forest cover (as is the 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.

Name Sample Problems Date ______ Sheet 1 of 2

Purpose ______

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

INPUTS

Option-dependent parameters	Reg. no.	Option: Tree (1)	Option: Pile 2	Option: Surface 3	Option: Tree 1	Option: Pile (2)	Option: Surface 3	Before entry	After entry
Torching tree d.b.h., inches	39	20							A
Torching tree height, ft	38	137							R/S
Number of trees torching together	37	1							R/S
Species	(read card)	Grand fir						4	
Continuous flame height, ft	31					45			B
Fireline intensity, Btu/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	130				100			D
20-foot windspeed, mi/h	36	20				15			E
Ridge/valley elevational difference, ft	34	4000				2000			2nd A
Ridge/valley horizontal distance, mi	33	.25				1			R/S
Spotting source location code	32	3				1			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	.31	.21	SBR =	

Exhibit 2a.—Maximum Spotting Distance Worksheet

Name Sample Problems Date ______ Sheet 2 of 2

Purpose ______

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

INPUTS

Option-dependent parameters	Reg. no.	Option 1: Tree 1	Option 1: Pile 2	Option 1: Surface (3)	Option 2: Tree 1	Option 2: Pile 2	Option 2: Surface (3)	Before entry	After entry
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, Btu/ft/s	30	Fuel model 1		580	Fuel model 4		14400		C
Surface spotting coefficient (A)	29			545			301		R/S
Surface spotting power (B)	28			-1.21			-1.05		R/S
Other parameters									
Mean cover height, ft	35			1			6		D
20-foot windspeed, mi/h	36			10			35		E
Ridge/valley elevational difference, ft	34			0			1000		2nd A
Ridge/valley horizontal distance, mi	33			-			.25		R/S
Spotting source location code	32			-			0		R/S

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

OUTPUT

	Reg. no.	Option 1	Option 2	
Maximum spotting distance corrected for mountainous terrain, mi	21	0.27	1.58	SBR =

Exhibit 2b.—Maximum Spotting Distance Worksheet

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

Preliminaries

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).

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.

REFERENCES

Albini, Frank A. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1976. 92 p.

Albini, Frank A. Spot fire distance from burning trees—a predictive model. Gen. Tech. Rep. INT-56. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979, 73 p.

Albini, Frank A. Spot fire distance from isolated sources—extensions of a predictive model. Res. Note INT-309. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 9 p.

Albini, Frank A. Potential spotting distance from wind-driven surface fires. Res. Pap. INT-309. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 27 p.

Anderson, Hal E. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 22 p.

Andrews, Patricia L. A system for predicting the behavior of forest and range fires. In: Proceedings, 1983 SCS conference on computer simulation in emergency planning; 1983 January 27-29; San Diego, CA. LaJolla, CA: Simulation Councils, Inc.; 1983: 75-78.

Andrews, Patricia L. BEHAVE: fire behavior prediction and fuel modeling system—BURN subsystem. Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory; review draft.

Burgan, Robert E. Fire danger/fire behavior computations with the Texas Instruments TI-59 calculator: user's manual. Gen. Tech. Rep. INT-61. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 25 p.

Burgan, Robert E.; Rothermel, Richard C. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. Gen. Tech. Rep. INT-167. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 126 p.

Byram, G. M. Combustion of forest fuels. In: Davis, Kenneth P., ed. Forest fire control and use. New York: McGraw-Hill; 1959: 90.

Catchpole, Wendy R. [Letter to Dick Rothermel]. 1983 October 31. Located at: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, Missoula, MT; RWU 2103 files.

Chase, Carolyn H. Spot fire distance equations for pocket calculators. Res. Note INT-310. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 21p.

Rothermel, Richard C. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 161 p.

Roussopoulos, Peter J.; Johnson, Von J. Help in making fuel management decisions. Res. Pap. NC-112. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1975. 16 p.

APPENDIX
PROGRAM LISTING

```
000 25 CLR
001 91 R/S
002 76 LBL
003 22 INV
004 53 (
005 43 RCL
006 01 01
007 65 ×
008 43 RCL
009 39 39
010 45 Y^X
011 43 RCL
012 02 02
013 65 ×
014 43 RCL
015 37 37
016 45 Y^X
017 93 .
018 04 4
019 54 )
020 53 (
021 42 STO
022 27 27
023 35 1/X
024 65 ×
025 43 RCL
026 38 38
027 54 )
028 32 X:T
029 01 1
030 22 INV
031 77 GE
032 23 LNX
033 93 .
034 05 5
035 22 INV
036 77 GE
037 24 CE
038 43 RCL
039 26 26
040 32 X:T
041 03 3
042 93 .
043 05 5
044 77 GE
045 32 X:T
046 01 1
047 01 1
048 42 STO
049 23 23
050 01 1
051 02 2
052 42 STO
053 22 22
054 61 GTO
055 47 CMS
056 76 LBL
057 32 X:T
058 09 9
059 42 STO
060 23 23
061 01 1
062 00 0
063 42 STO
064 22 22
065 61 GTO
066 47 CMS
067 76 LBL
068 24 CE
069 07 7
070 42 STO
071 23 23
072 08 8
073 42 STO
074 22 22
075 61 GTO
076 47 CMS
077 76 LBL
078 23 LNX
079 05 5
080 42 STO
081 23 23
082 06 6
083 42 STO
084 22 22
085 76 LBL
086 47 CMS
087 92 RTN
088 76 LBL
089 34 √X
090 53 (
091 43 RCL
092 03 03
093 65 ×
094 43 RCL
095 39 39
096 45 Y^X
097 43 RCL
098 04 04
099 65 ×
100 43 RCL
101 37 37
102 45 Y^X
103 93 .
104 02 2
105 94 +/-
106 54 )
107 42 STO
108 26 26
109 92 RTN
110 76 LBL
111 35 1/X
112 71 SBR
113 22 INV
114 71 SBR
115 34 √X
116 76 LBL
117 33 X^2
118 53 (
119 73 RC*
120 23 23
121 65 ×
122 43 RCL
123 26 26
124 45 Y^X
125 73 RC*
126 22 22
127 65 ×
128 43 RCL
129 27 27
130 85 +
131 43 RCL
132 38 38
133 55 ÷
134 02 2
135 54 )
136 61 GTO
137 42 STO
138 76 LBL
139 44 SUM
140 53 (
141 01 1
142 02 2
143 93 .
144 02 2
145 65 ×
146 43 RCL
147 31 31
148 54 )
149 61 GTO
150 42 STO
151 76 LBL
152 45 Y^X
153 43 RCL
154 35 35
155 32 X:T
156 53 (
157 02 2
158 93 .
159 02 2
160 65 ×
161 43 RCL
162 25 25
163 45 Y^X
164 93 .
165 03 3
166 03 3
167 07 7
168 75 -
169 04 4
170 54 )
171 22 INV
172 77 GE
173 52 EE
174 42 STO
175 17 17
176 92 RTN
177 76 LBL
178 52 EE
179 32 X:T
180 42 STO
181 17 17
182 92 RTN
183 76 LBL
184 53 (
185 53 (
186 93 .
187 00 0
188 00 0
189 00 0
190 07 7
191 01 1
192 08 8
193 65 ×
194 43 RCL
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199 34 √X
200 65 ×
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214 34 √X
215 55 ÷
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219 43 RCL
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230 92 RTN
231 76 LBL
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256 85 +
257 43 RCL
258 24 24
259 54 )
260 42 STO
261 24 24
262 61 GTO
263 55 ÷
264 76 LBL
265 95 =
266 58 FIX
267 02 02
268 87 IFF
269 01 01
270 65 ×
271 87 IFF
272 02 02
273 93 .
274 22 INV
275 87 IFF
276 03 03
277 36 PGM
278 61 GTO
279 75 -
280 76 LBL
281 65 ×
282 87 IFF
283 02 02
284 30 TAN
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285 76 LBL
286 93 .
287 87 IFF
288 03 03
289 30 TAN
290 61 GTO
291 75 -
292 76 LBL
293 30 TAN
294 03 3
295 06 6
296 94 +/-
297 34 ΓX
298 91 R/S
299 76 LBL
300 36 PGM
301 00 0
302 35 1/X
303 91 R/S
304 76 LBL
305 75 -
306 87 IFF
307 01 01
308 35 1/X
309 87 IFF
310 02 02
311 44 SUM
312 53 (
313 53 (
314 53 (
315 43 RCL
316 29 29
317 65 ×
318 53 (
319 93 .
320 04 4
321 07 7
322 04 4
323 65 ×
324 43 RCL
325 36 36
326 54 )
327 45 Y×
328 43 RCL
329 28 28
330 54 )
331 65 ×
332 43 RCL
333 30 30
334 54 )
335 34 ΓX
336 65 ×
337 01 1
338 93 .
339 00 0
340 05 5
341 05 5
342 54 )
343 76 LBL
344 42 STO
345 42 STO
346 25 25
347 71 SBR
348 45 Y×
349 71 SBR
350 53 (
351 87 IFF
352 03 03
353 54 )
354 76 LBL
355 55 ÷
356 00 0
357 32 X:T
358 43 RCL
359 33 33
360 67 EQ
361 85 +
362 43 RCL
363 34 34
364 67 EQ
365 85 +
366 53 (
367 43 RCL
368 24 24
369 55 ÷
370 43 RCL
371 33 33
372 54 )
373 42 STO
374 20 20
375 42 STO
376 19 19
377 53 (
378 43 RCL
379 34 34
380 55 ÷
381 01 1
382 00 0
383 00 0
384 00 0
385 00 0
386 55 ÷
387 89 π
388 54 )
389 42 STO
390 18 18
391 06 6
392 42 STO
393 00 00
394 76 LBL
395 61 GTO
396 53 (
397 43 RCL
398 20 20
399 75 -
400 43 RCL
401 18 18
402 65 ×
403 53 (
404 53 (
405 01 1
406 08 8
407 00 0
408 65 ×
409 43 RCL
410 19 19
411 75 -
412 43 RCL
413 32 32
414 65 ×
415 09 9
416 00 0
417 54 )
418 39 COS
419 75 -
420 53 (
421 43 RCL
422 32 32
423 65 ×
424 09 9
425 00 0
426 54 )
427 39 COS
428 54 )
429 54 )
430 42 STO
431 19 19
432 97 DSZ
433 00 00
434 61 GTO
435 53 (
436 43 RCL
437 19 19
438 65 ×
439 43 RCL
440 33 33
441 54 )
442 42 STO
443 21 21
444 91 R/S
445 76 LBL
446 85 +
447 43 RCL
448 24 24
449 42 STO
450 21 21
451 91 R/S
452 76 LBL
453 43 RCL
454 87 IFF
455 01 01
456 71 SBR
457 87 IFF
458 02 02
459 37 P/R
460 22 INV
461 87 IFF
462 03 03
463 48 EXC
464 61 GTO
465 38 SIN
466 76 LBL
467 71 SBR
468 87 IFF
469 02 02
470 39 COS
471 76 LBL
472 37 P/R
473 87 IFF
474 03 03
475 39 COS
476 61 GTO
477 38 SIN
478 76 LBL
479 39 COS
480 03 3
481 06 6
482 94 +/-
483 34 ΓX
484 91 R/S
485 76 LBL
486 48 EXC
487 00 0
488 35 1/X
489 91 R/S
490 76 LBL
491 38 SIN
492 87 IFF
493 01 01
494 94 +/-
495 87 IFF
496 02 02
497 28 LOG
498 09 9
499 94 +/-
500 34 ΓX
501 91 R/S
502 43 RCL
503 30 30
504 91 R/S
505 43 RCL
506 29 29
507 91 R/S
508 43 RCL
509 28 28
510 91 R/S
511 76 LBL
512 29 CP
513 43 RCL
514 35 35
515 91 R/S
516 43 RCL
517 36 36
518 91 R/S
519 43 RCL
520 34 34
521 91 R/S
522 43 RCL
523 33 33
524 91 R/S
525 43 RCL
526 32 32
527 91 R/S
528 00 0
529 35 1/X
530 91 R/S
531 76 LBL
532 94 +/-
533 01 1
534 94 +/-
535 34 ΓX
536 91 R/S
537 43 RCL
538 39 39
539 91 R/S
540 43 RCL
541 38 38
542 91 R/S
543 43 RCL
544 37 37
545 91 R/S
546 61 GTO
547 29 CP
548 76 LBL
549 28 LOG
550 04 4
551 94 +/-
552 34 ΓX
553 91 R/S
554 43 RCL
555 31 31
556 91 R/S
557 61 GTO
558 29 CP
559 76 LBL
560 11 A
561 86 STF
562 01 01
563 42 STO
564 39 39
565 91 R/S
566 42 STO
567 38 38
568 91 R/S
569 42 STO
570 37 37
571 04 4
572 91 R/S
573 76 LBL
574 12 B
575 86 STF
576 02 02
577 42 STO
578 31 31
579 91 R/S
580 76 LBL
581 13 C
582 86 STF
583 03 03
584 42 STO
585 30 30
586 91 R/S
587 42 STO
588 29 29
589 91 R/S
590 42 STO
591 28 28
592 91 R/S
593 76 LBL
594 14 D
595 42 STO
596 35 35
597 91 R/S
598 76 LBL
599 15 E
600 42 STO
601 36 36
602 91 R/S
603 76 LBL
604 16 A'
605 42 STO
606 34 34
607 91 R/S
608 42 STO
609 33 33
610 91 R/S
611 42 STO
612 32 32
613 91 R/S
614 76 LBL
615 25 CLR
616 81 RST
```

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 (supersedes 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.

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

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

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

$$2.93 \text{ m} = \text{effective cover height}$$

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

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

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

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

*U.S. GOVERNMENT PRINTING OFFICE: 1984-0-576-040/10,520

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