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Spot Fire Distance Equations for Pocket Calculators

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ABSTRACT

This note presents equations for calculating maximum spot fire distance from firebrand sources in the Intermountain West based on prevailing windspeed, vegetation cover, and terrain in the area. The equations include the capability to predict spotting distance from a torching tree(s) or from a continuous flame source such as slash piles or jackpots of heavy fuels. The equations can be used on a programmable pocket calculator. Potential uses are seen in fire management planning and real-time fire behavior predictions. For copies of a program for the Texas Instruments TI-59, send seven blank TI-59 magnetic cards to the author.

KEYWORDS: spot fire, spotting, firebrands, fire management

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The ability to predict spot fire distance from a firebrand source gives fire management personnel another work tool. This research note presents equations for predicting maximum spotting distance from sources such as torching trees and burning piles of debris in the Intermountain West. Tree species considered have been confined to those common to the Intermountain West where data and personal experience of researchers corroborate the relationships used. To provide a simple mechanized process of calculation, these equations can be programmed on a pocket calculator. Here the calculation process is implemented on the programmable Texas Instruments TI-59.

The equations are based on the model by Albini (1979), who employed a nomogram solution. The nomogram solution was simplified and used as the basis of the Fire Behavior Officers' (FBO) field procedure.² The original model has been extended (Albini 1981) to apply when transport of the firebrand is over nonforested terrain, or when the flame source is continuous (such as slash piles, jackpots of heavy fuels) as opposed to the brief, transitory flame from a torching tree. The spotting model is applicable under conditions of intermediate fire severity in which spotting distances up to a mile or two might be expected, and intensities would be sufficiently high to occasionally involve overstory fuels.

The equations presented here are those for the FBO field procedure with these additional features:

1. Multiplication factors to account for simultaneous burning of several identical trees that produces a single merged flame.
2. Correction of flat-terrain spotting distance for use in mountainous terrain.
3. Prediction of spotting distance from a continuous flame source.
4. Allowance for transport over short grass, bare ground, or water as appropriate.

The assumption was made in the FBO field procedure that wind at treetop level is two-thirds of the wind 20 ft (6 m) above the canopy. That assumption is retained here.

In his model, Albini had six submodels, each based on a host of assumptions. Not all those assumptions need to be stated here. It is sufficient to recognize that Albini described ideal conditions to maximize firebrand transport distance-- firebrands sufficiently small to be carried some distance, yet large enough to still be viable when coming to rest, wind blowing steadily in one direction, and so forth. Conditions as they exist in the field seldom conform to this ideal. For example, winds in forested mountains vary greatly both in speed and direction. However, any variation from the ideal assumed in the model would serve only to decrease the spot fire distance. The user should expect actual spotting distance to fall short of the prediction when deviation is observed.

Albini points out factors not considered in his approach:

1. *Probability of tree(s) torching out.* Instead, the model describes what would happen *if* trees torch out.

²National Wildfire Coordinating Group. Fire behavior officers' (FBO) field reference. USDA For. Serv. National Adv. Resource Technology Center, Marana Air Park, AZ, looseleaf.

2. *Availability of optimum firebrand material.* There may or may not be a firebrand particle capable of being carried the maximum distance.

3. *Probability of spot fire ignition.* Not addressed is whether the firebrand material lands in an area with easily ignited fuels, and whether enough spark or ember remains to cause ignition.

4. *Number of spot fires.* More information about the first three items is needed before this question can be considered.

The purpose of this note is to document the equations used in mechanizing the calculation of spotting distance. The remainder of the text presents the equations used, the calculator program, and operating procedures. Development of the equations is given in the appendix. The TI-59 program uses U.S. units of measure, so only U.S. units appear in this text. However, in the summary of equations (next section), metric units are added for those who may be interested.

SUMMARY OF EQUATIONS

<u>Symbol</u>	<u>U.S. units</u>	<u>Metric units</u>	<u>Description</u>
d	inch	cm	Diameter at breast height (d.b.h.) of tree(s) torching out
h	ft	m	Height of burning tree(s)
\bar{h}	ft	m	Mean vegetation cover height downwind of source
\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
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
H_f	ft	m	Continuous flame height for pile burning
$z(0)$	ft	m	Initial firebrand height above ground
F	mi	km	Flat-terrain spotting distance
D	mi	km	Ridge-to-valley horizontal distance (map)
H	1000's ft	multiples of 300 m	Ridge-to-valley elevational difference
S	mi	km	Mountainous-terrain spotting distance (map)
M	none	none	Code number for location of firebrand source 0=midslope, windward side 1=valley bottom 2=midslope, leeward side 3=ridgetop

Equations Using U.S. Units

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

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

$$z(0) = \begin{cases} 4.24d_F^{0.332}(h_F) + h/2, & h/h_F \geq 1 \\ 3.64d_F^{0.391}(h_F) + h/2, & 0.5 \leq h/h_F < 1 \\ 2.78d_F^{0.418}(h_F) + h/2, & h/h_F < 0.5, d_F < 3.5 \\ 4.70(h_F) + h/2 & h/h_F < 0.5, d_F \geq 3.5 \\ 12.2H_F, & \text{pile burning option} \end{cases}$$

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

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

$$F = 7.18 \times 10^{-4} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*} \right)^{1/2} \frac{1}{2} \ln \left(\frac{z(0)}{\bar{h}^*} \right) \right\}$$

$S = D \cdot X_6$, where X_6 is from the iteration:

$$X_0 = A$$

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

$$A = F/D$$

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

Equations Using Metric Units

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

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

$$z(0) = \begin{cases} 4.24d_F^{0.332}(h_F) + h/2, & h/h_F \geq 1 \\ 3.64d_F^{0.391}(h_F) + h/2, & 0.5 \leq h/h_F < 1 \\ 2.78d_F^{0.418}(h_F) + h/2, & h/h_F < 0.5, d_F < 3.5 \\ 4.70(h_F) + h/2, & h/h_F < 0.5, d_F \geq 3.5 \\ 12.2H_F, & \text{pile burning option} \end{cases}$$

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

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

$$F = 1.30 \times 10^{-3} U \bar{h}^{*1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}^*} \right)^{1/2} \frac{1}{2} \ln \left(\frac{z(0)}{\bar{h}^*} \right) \right\}$$

$S = D \cdot X_6$, where X_6 is from the iteration:

$$X_0 = A$$

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

$$A = F/D$$

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

THE TI-59 PROGRAM

The program is recorded on one card (magnetic strip) and is accompanied by six data cards for various tree species. The TI-59 program can be used with data cards for species other than those shown in the equation summary. A prerequisite is that, for any species, the curves for flame height and flame duration can be represented as power curves of the form $y = ax^b$. (See the appendix for directions on how to make data cards for other tree species.)

Copies of the program may be obtained by sending seven blank magnetic cards for the TI-59 to the author at the Northern Forest Fire Laboratory.

The program has two options:

1. The firebrand source is a burning tree(s) that is torching out--torching tree option.
2. The source is a burning pile of debris (or fuel of similar nature) where the flame is "continuous"--pile burning option.

Input requirements, listed below, differ for the options. (Guidelines for selecting input values are given in the section on operating procedure.)

Torching tree option

Species data
Torching tree d.b.h.
Torching tree height
Mean cover height
20-foot windspeed
Number of trees (burning at once)
Ridge/valley elevation difference
Ridge/valley horizontal distance
Spotting source location code

Pile burning option

Mean cover height
20-foot windspeed
Observed flame height
Ridge/valley elevation difference
Ridge/valley horizontal distance
Spotting source location code

There are no checks made on the validity of input data. The operator must be careful to select reasonable values and to enter those data without error.

OPERATING PROCEDURE

The spotting distance program may be run with any solid state module in the calculator (such as NFDERS/Fire Behavior module, library module, statistics module) or with no module in the calculator.

I. Preliminaries

1. Turn on the calculator. If it is already on, turn it off momentarily to clear program and data registers.
2. Press **[I]**. Feed side 1 of the program card 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 2.

3. Press 2 . Feed side 2 of the program card into the slot. If the display flashes, press CLR and repeat step 3.

II. Initialization and input

1. Input species data (omit for pile burning option): Press SBR STO and feed either side of the data card for the desired species into the TI-59 (the data are recorded on both sides of the card). A 4. should appear in the display; if the display flashes, press CLR and try again. These data remain in the TI-59 until replaced with data for another species by simply repeating this step with a different species card. Species data need not be cleared to run the pile burning option.
2. Press SBR CLR . This should be done before each run to clear subroutine return registers and to clear flags that signal operating options. Although it is only necessary following a run of the pile burning option or when a run was manually stopped before its normal termination, it is better to make it a part of routine procedure to prevent problems. With the exception of continuous flame height for pile burning, it does not remove inputs. The continuous flame height is reset to 0 by this step.
3. Record the required inputs on the worksheet (fig. 1). Except for continuous flame height, the presence of additional inputs that are not required does not affect calculations. Enter the required items in any order as follows:

--Enter diameter at breast height (d.b.h.) in inches
of the tree(s) torching out.

Press A .

--Enter height in feet of tree(s) torching out.

Press B .

--Enter mean cover height, in feet, of the area downwind
of the firebrand source. Albin called this "mean
treetop height" and uses this value to characterize
the general forest cover as it influences the wind.
If there is broken forest cover, he suggests using
half the treetop height of the forest-covered portion.
If there is little or no forest cover, enter vegetation
height.

Press C .

--Enter average windspeed, in miles per hour, 20 ft
above the vegetation.

Press D .

--Enter the number of identical trees burning at once
to produce a single flame.

Press E .

--Enter elevational difference in feet from ridgetop
to valley bottom as would be shown on a map. Note
that the entry is in feet even though the equations
use multiples of 1,000 ft. The calculator makes the
required conversion. The assumption made in Albin's
model is that terrain resembles a washboard. If this
simple representation of terrain does not describe
your situation, perhaps the model will not give you
a good approximation of spotting distance.

Press 2nd A .

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

Press 2nd B .

Name _____ Date _____ Sheet _____ of _____

Purpose _____

<u>INPUT</u>	<u>KEY</u>	<u>Reg. No.</u>
*Species	SBR STO	
*Torching tree d.b.h., inch	A	34
*Torching tree height, ft	B	35
Mean cover height, ft	C	36
20-foot windspeed, mi/h	D	37
*Number of trees torching together	E	38
Ridge/valley elevational difference, ft	2nd A	39
Ridge/valley horizontal distance, mi	2nd B	40
Spotting source location code	2nd C	41
0 - midslope, windward side		
1 - valley bottom		
2 - midslope, leeward side		
3 - ridgetop		
**Continuous flame height, pile burning, ft	2nd E	42
<u>OUTPUT</u>		
Flat-terrain max. spot. distance, mi	SBR =	22
Mountainous-terrain max, spot. distance, mi	SBR 2nd =	23
Flame height, ft	R/S	
Torching tree option (flashing)		24
or		
Pile burning option (continuous)		42

*Not needed for the pile burning option

**An entry specifies pile burning option; no entry specifies torching tree option

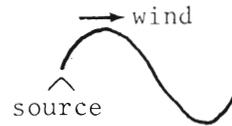
Figure 1.--TI-59 MAXIMUM SPOTTING DISTANCE WORKSHEET

--Enter the spotting source location code from the following list:

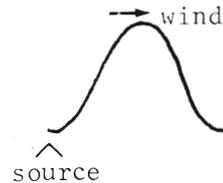
Press **2nd** **C**.

Enter for

0 midslope, windward side



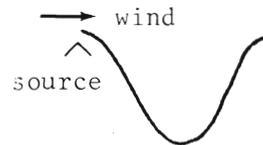
1 valley bottom



2 midslope, leeward side



3 ridgetop



--OMIT FOR TORCHING TREE OPTION: Enter estimated flame height in feet from observation of continuous flame (see fig. 2). This value signals the calculator to use the pile burning option and must be entered for each run of this option even if it remains unchanged. (Entry of 0 here while using the torching tree option will cause a flashing display of an erroneous flat-terrain spotting distance in the output section. If this occurs, press **CLR** and start the run again.)

Press **2nd** **E**.

III. Recall and correction of input

1. Recall first input item by pressing **SBR** **RCL**. Follow with a series of **R/S** to obtain successive inputs in the order listed on the worksheet. The recall subroutine can be entered only at the beginning of the list.

For mean cover height, the value recalled will depend on whether **SBR** **RCL** is performed before or after calculations. Before calculations,

the mean cover height that was input will be displayed. After calculations, \bar{h}^* will be displayed (see equation summary).

When continuous flame height is recalled, a steady numerical display of that value indicates that the pile burning option is being run. Flashing nines at that point indicate that the torching tree option is being used, so no continuous flame height should exist. Press **CLR** and continue.

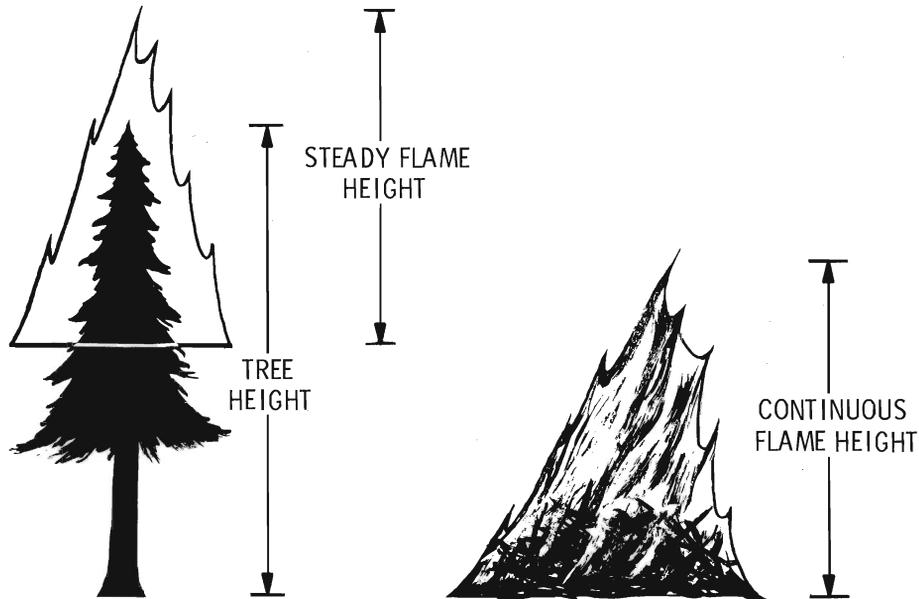


Figure 2.--The steady flame height is the perpendicular distance from the base of the flame (within the crown of the tree) to the tip of the flame. Continuous flame height is the distance from the ground to the tip of the flame.

2. To change any item(s) of input, re-enter the desired value as in part II, step 3.

IV. Performing calculations

1. Press **SBR** **=**. When calculations cease, the flat-terrain spotting distance in miles will appear in the display. Record it on the worksheet.
2. Press **SBR** **2nd** **=**. The flat-terrain spotting distance is corrected for mountainous terrain, and the map location spotting distance in miles is displayed. *Step 1 must be performed prior to this step for each run.* Record the result on the worksheet.
3. Press **R/S**. *This step must follow immediately after step 2.* The flame height (ft) will be displayed. In the pile burning option, the display of the input value will be continuous. In the torching tree option, the calculated flame height will be a flashing display. Note that this is not the distance from the ground to the tip of the flame (see fig. 2). After recording the value, press **CLR** to halt the flashing display.

V. Making successive runs

1. Change species data, if necessary.
2. Repeat part II, step 2 (SBR CLR).
3. Change any input values desired.
4. Enter estimated flame height if the pile burning option is being run.
5. Perform calculations.

WORKED EXAMPLES

Figure 3 contains the inputs and outputs of two sample problems--one for the torching tree option and one for the pile burning option.

CONDENSED INSTRUCTIONS

- I. Press 1, feed side 1 (flashing: CLR , try again). Press 2, feed side 2 (flashing: CLR , try again).
- II.
 1. SBR STO . Enter species data card.
 2. SBR CLR .
 3.

<u>Input</u>	<u>Press</u>
D.b.h. (inch)	A
Height (ft)	B
Mean cover height (ft)	C
Wind (mi/h)	D
Number of trees	E
Ridge/valley elevation difference (ft)	2nd A
Ridge/valley horizontal distance (mi)	2nd B
Spotting source location code	2nd C
0 - midslope, windward side	
1 - valley bottom	
2 - midslope, leeward side	
3 - ridgetop	
Continuous flame height (ft)	2nd E
- III. SBR RCL ; follow by series of R/S
2nd R/S mean cover height: { value input displayed before calculations
 { h* displayed after calculations

8th R/S continuous flame height: { value input displayed in pile burning option
 { flashing nines in torching tree option
- IV. SBR [=] : display flat-terrain spotting distance (mi)
SBR [2nd] [=] : display mountainous-terrain spotting distance (map mi)
R/S : display flame height (ft)--flashing display in torching tree option,
 continuous display in pile burning option

Figure 3.--TI-59 MAXIMUM SPOTTING DISTANCE WORKSHEET. Sample problems.

Name _____ Date _____ Sheet _____ of _____

Purpose _____

<u>INPUT</u>	<u>KEY</u>				<u>Reg. No.</u>
*Species	SBR STO	Grand fir	----		
*Torching tree d.b.h., inch	A	20	----		34
*Torching tree height, ft	B	137	----		35
Mean cover height, ft	C	130	100		36
20-foot windspeed, mi/h	D	20	15		37
*Number of trees torching together	E	1	----		38
Ridge/valley elevational difference, ft	2nd A	4000	2000		39
Ridge/valley horizontal distance, mi	2nd B	.25	1		40
Spotting source location code	2nd C	3	1		41
0 - midslope, windward side					
1 - valley bottom					
2 - midslope, leeward side					
3 - ridgetop					
**Continuous flame height, pile burning, ft	2nd E	----	45		42
<u>OUTPUT</u>					
Flat-terrain max. spot. distance, mi	SBR =	0.34	0.25		22
Mountainous-terrain max, spot. distance, mi	SBR 2nd =	0.31	0.21		23
Flame height, ft	R/S				
Torching tree option (flashing)		77			24
or					
Pile burning option (continuous)			45		42

*Not needed for the pile burning option

**An entry specifies pile burning option; no entry specifies torching tree option

REGISTER ASSIGNMENTS

<u>Register</u>	<u>Symbol</u>	<u>Contents</u>
34	d	Torching tree d.b.h.
35	h	Torching tree height
36	$\left\{ \begin{array}{l} \bar{h} \\ h \end{array} \right.$	$\left\{ \begin{array}{l} \text{Mean cover height input} \\ \text{Mean cover height used in computation} \end{array} \right.$
37	U	20-foot windspeed
38	n	Number of trees torching together
39	1000H	Ridge/valley elevation difference
40	D	Ridge/valley horizontal distance
41	M	Spotting source location code
42	H_F	Continuous flame height (pile burning)
24	h_F	Adjusted steady flame height
25	d_F	Adjusted flame duration
28	$z(0)$	Initial firebrand height
22	F	Flat-terrain spotting distance
23	S	Mountainous-terrain spotting distance

PUBLICATIONS CITED

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1979. Spot-fire distance from burning trees--a predictive model. USDA For. Serv. Res. Pap. INT-56, 73 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

APPENDIX

FORMULATION OF EQUATIONS

Equations were generated that approximate the curves for flame height and duration and for firebrand height in the FBO field reference. They were obtained by regressing points from the FBO curves to get power curve approximations. These equations appear in the figures accompanying the step-wise summary of the solution method presented below. The steps formed the basis of the FBO method of manually determining spotting distance and provide the rationale behind the equations presented.

1. The steady flame height is determined by relationships developed by Albini (1979) through the artifice of relationships between tree diameter and foliar biomass. The amount of foliar biomass and how it burns provides the linkage between diameter and flame height. Curves fitted to these relationships are shown in figure 4. Then, to obtain the equations appearing in the summary, the steady flame height is corrected by a factor of $n^{0.4}$ (Albini 1979), where n is the number of trees burning simultaneously.

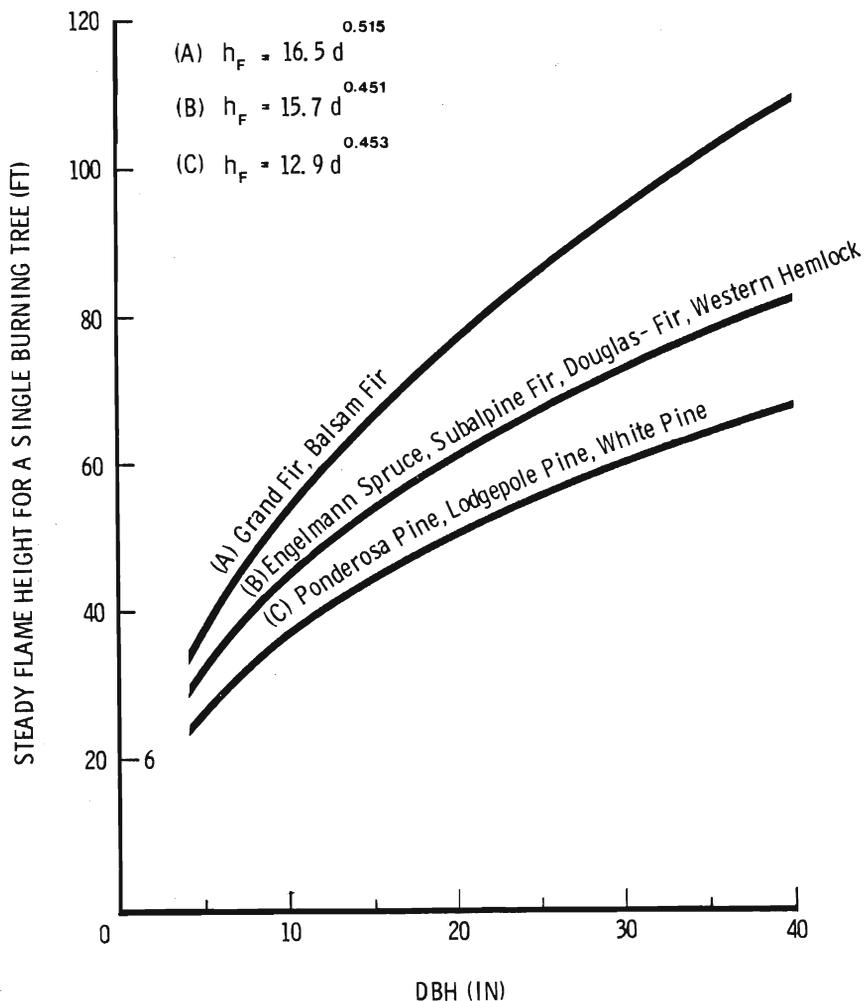


Figure 4.--Height of "steady" flame from burning of one tree crown in still air.

2. Dimensionless steady flame duration is determined by relationships developed by Albin (1979), again through the artifice of relationships between tree diameter and foliar biomass. Curves fitted to these relationships are shown in figure 5. Then, to obtain the equations appearing in the summary, the steady flame duration is corrected by a factor of $n^{-0.2}$ (Albin 1979), where n is the number of trees burning simultaneously.

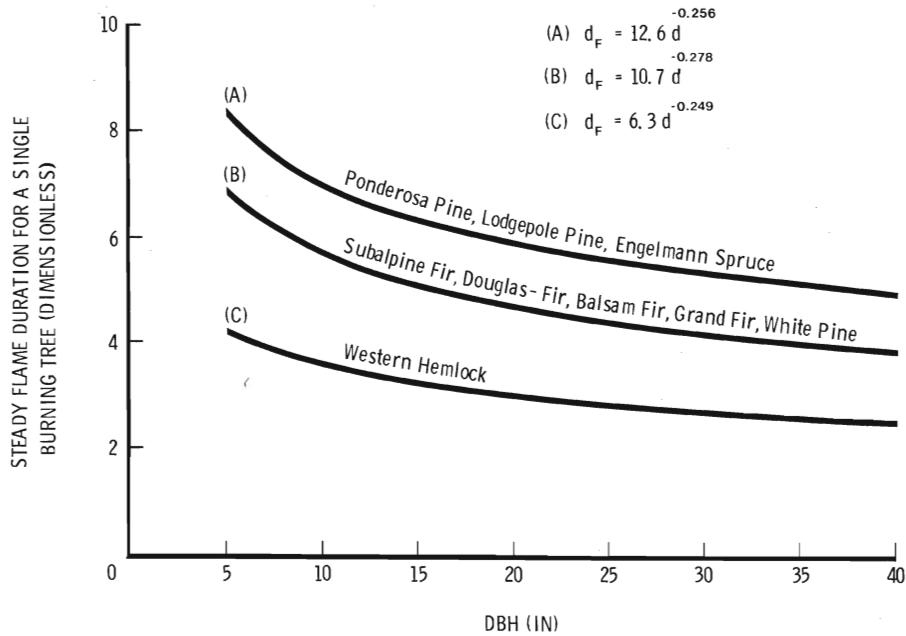


Figure 5.--Steady flame duration for individual tree torching out.

3. The ratio of lofted firebrand height to steady flame height is determined using figure 6. That quantity is multiplied by steady flame height and added to half of the torching tree's height to obtain initial firebrand height, $z(0)$.

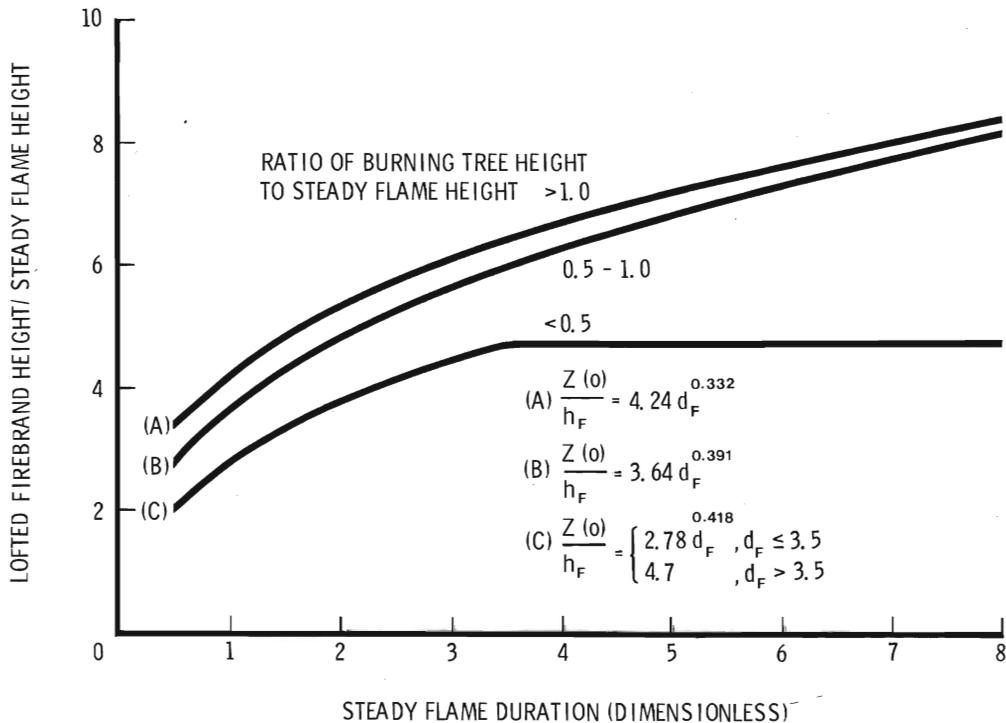


Figure 6.--Height of firebrands lofted by burning trees.

When the firebrand-lofting flame is continuous as opposed to the brief transitory flame from a torching tree, the first three steps above are replaced by a simple multiplication. The maximum height of a viable firebrand lofted by a continuous flame of height H_F is given by $z(0) = 12.2H_F$ (Albini 1981).

4. Flat-terrain spotting distance is calculated next. Albini's equation for flat-terrain spotting distance over forest-covered terrain is:

$$F = 21.9U_h \left(\frac{\bar{h}}{g}\right)^{1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}}\right)^{1/2} \frac{1}{2} \ln\left(\frac{z(0)}{\bar{h}}\right) \right\}$$

where

F = flat-terrain spotting distance (mi)

U_h = wind at treetop height (mi/h)

\bar{h} = mean height of vegetation cover along the firebrand's flight path (ft)

g = acceleration of gravity (ft/h²)

$z(0)$ = initial firebrand height (ft).

Using the assumption that U_h is two-thirds of the 20-ft wind, substituting $g = 32 \text{ ft/s}^2$ and converting seconds to hours, the equation becomes

$$F = 7.18 \times 10^{-4} U \bar{h}^{-1/2} \left\{ 0.362 + \left(\frac{z(0)}{\bar{h}}\right)^{1/2} \frac{1}{2} \ln\left(\frac{z(0)}{\bar{h}}\right) \right\},$$

where U = windspeed at 20 ft (mi/h). If transport is over terrain which is not forest-covered, then the "effective" height, h_c , is used in the above equation instead of \bar{h} (Albini 1981).

5. The flat-terrain spotting distance must be corrected for use in mountainous terrain. Albini's equation for maximum horizontal distance is

$$F = S + \frac{(1 + \alpha)a}{m(z_G - \bar{z}_T)} \left\{ \cos(m(S + X_1)) - \cos(mX_1) \right\}$$

where

F = flat-terrain spotting distance (mi)

S = mountainous-terrain spotting distance (mi)

$2a$ = total elevation difference, ridge to valley = ΔH_{RV} (ft)

D = horizontal distance from ridge to valley (map mi)

$m = \pi/D$

X_1 = distance of firebrand source from windward midslope (map mi)

\bar{z}_T = mean terrain height above sea level (ft)

z_G = altitude of top of surface-influenced airflow layer (ft)

α = a dimensionless constant related to the gross structure of the surface-influenced atmosphere.

Using $\alpha = 0.2$ and $(z_G - \bar{z}_T) = 6,000$ ft, we have

$$F = S + \frac{(1.2)\Delta H_{RV}/2}{6,000\pi/D} \left\{ \cos\left(\pi \frac{S}{D} + mX_1\right) - \cos(mX_1) \right\}.$$

So

$$\frac{F}{D} = \frac{S}{D} + \frac{\Delta H_{RV}}{\pi(10^4)} \left\{ \cos\left(\pi \frac{S}{D} + mX_1\right) - \cos(mX_1) \right\}.$$

Let $H = \Delta H_{RV}/1000$, $F/D = A$, and $S/D = X$. Thus

$$X = A - \frac{H}{10\pi} \left\{ \cos(\pi X + mX_1) - \cos(mX_1) \right\}.$$

Consider the four cases:

mX_1	<u>Location of firebrand source</u>
0	midslope on windward side of ridge
$-\pi/2$	valley bottom
$-\pi$	midslope on leeward side of ridge
$-3\pi/2$	ridgetop

So $mX_1 = -M\pi/2$, where M is 0, 1, 2, or 3, respectively, for the cases listed. Let $B = H/10\pi$, then

$$X = A - B \left\{ \cos(\pi X - M\pi/2) - \cos(M\pi/2) \right\}.$$

This equation can be solved by the iteration:

$$X_0 = A$$

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

X_n converges sufficiently within six iterations for use here.

SPECIES DATA CARDS

To make a species data card, the formulas for steady flame height and for flame duration must be expressed as power curves of the form (see, for example, the curves in Albini 1979):

$$h_F = xd^Y$$

$$d_F = zd^W$$

where

h_F = steady flame height, ft

d_F = flame duration (dimensionless)

d = diameter at breast height, inch.

Using the equation for steady flame height and taking the logarithm of both sides

$$\ln h_F = \ln x + y \ln d.$$

When several points (d, h_F) are chosen on the curve, linear regression can be used to fit a straight line to the data points³ $(\ln d, \ln h_F)$. The y-intercept will be $\ln x$ and the slope will be y .

The derivation of the formula for flame duration parallels that for steady flame height.

Then, the list of data register contents for the data card is:

<u>Register number</u>	<u>Contents</u>	
00	0	
01	x	
02	y	
03	z	
04	w	
05	4.24	] Constants applicable to all species
06	0.332	
07	3.64	
08	0.391	
09	2.78	
10	0.418	
11	4.7	
12-29	0	

To prepare the data card:

1. Turn on your calculator. If it is already on, turn it off momentarily to clear all storage registers.

2. For each register numbered 1 through 11: Enter the contents from the list into the display and press STO nn where nn is the register number.

³The TI-59 applied statistics module contains a curve-fitting program (ST-12) that accepts as input the points (d, h_F) and provides x and y as output. This eliminates the transformation to $(\ln d, \ln h_F)$.

3. Press $\boxed{4}$ $\boxed{2nd}$ $\boxed{R/S}$ and feed in one side of the blank data card. A 4. should appear in the display indicating that the data has been recorded. If the display flashes, press \boxed{CLR} and repeat step 3.

4. Repeat step 3, feeding in the other side of the data card.

PROGRAM DUPLICATION

Program Cards

1. Turn on your calculator. Enter the program into memory by performing part I of the operating procedure using the program card to be duplicated.

2. Press $\boxed{1}$ $\boxed{2nd}$ $\boxed{R/S}$ and feed in side 1 of the blank program card. If the display flashes, press \boxed{CLR} and repeat step 2.

3. Press $\boxed{2}$ $\boxed{2nd}$ $\boxed{R/S}$ and feed in side 2 of the blank program card. If the display flashes, press \boxed{CLR} and repeat step 3.

Data Cards

1. Press $\boxed{4}$ and feed in one side of the data card to be duplicated. If the display flashes, press \boxed{CLR} and try again.

2. Press $\boxed{4}$ $\boxed{2nd}$ $\boxed{R/S}$ and feed in one side of the blank card. If the display flashes, try again. Repeat step 2 for the other side of the blank card.

PROGRAM LISTING

000	22	INV	059	86	STF	118	42	STD	177	06	6
001	58	FIX	060	01	01	119	26	26	178	42	STD
002	22	INV	061	92	RTN	120	08	8	179	00	00
003	86	STF	062	76	LBL	121	42	STD	180	76	LBL
004	01	01	063	95	=	122	27	27	181	71	SBR
005	00	0	064	70	RAD	123	61	GTD	182	53	(
006	42	STD	065	87	IFF	124	53	(	183	43	RCL
007	42	42	066	01	01	125	76	LBL	184	32	32
008	91	R/S	067	32	X:T	126	45	YX	185	75	-
009	76	LBL	068	71	SBR	127	05	5	186	43	RCL
010	42	STD	069	22	INV	128	42	STD	187	33	33
011	22	INV	070	71	SBR	129	26	26	188	65	x
012	58	FIX	071	23	LNx	130	06	6	189	53	(
013	04	4	072	76	LBL	131	42	STD	190	53	(
014	92	RTN	073	52	EE	132	27	27	191	89	π
015	76	LBL	074	43	RCL	133	76	LBL	192	65	x
016	11	A	075	31	31	134	53	(	193	43	RCL
017	42	STD	076	32	X:T	135	71	SBR	194	30	30
018	34	34	077	01	1	136	24	CE	195	75	-
019	92	RTN	078	22	INV	137	76	LBL	196	43	RCL
020	76	LBL	079	77	GE	138	54	)	197	41	41
021	12	B	080	45	YX	139	71	SBR	198	65	x
022	42	STD	081	93	.	140	44	SUM	199	89	π
023	35	35	082	05	5	141	58	FIX	200	55	+
024	92	RTN	083	22	INV	142	02	02	201	02	2
025	76	LBL	084	77	GE	143	91	R/S	202	54)
026	13	C	085	34	FX	144	76	LBL	203	39	CDS
027	42	STD	086	43	RCL	145	90	LST	204	75	-
028	36	36	087	25	25	146	00	0	205	53	(
029	92	RTN	088	32	X:T	147	32	X:T	206	43	RCL
030	76	LBL	089	03	3	148	43	RCL	207	41	41
031	14	D	090	93	.	149	40	40	208	65	x
032	42	STD	091	05	5	150	67	EQ	209	89	π
033	37	37	092	77	GE	151	85	+	210	55	+
034	92	RTN	093	35	1/X	152	53	(	211	02	2
035	76	LBL	094	01	1	153	43	RCL	212	54)
036	15	E	095	01	1	154	22	22	213	39	CDS
037	42	STD	096	42	STD	155	55	+	214	54)
038	38	38	097	26	26	156	43	RCL	215	54)
039	92	RTN	098	01	1	157	40	40	216	42	STD
040	76	LBL	099	02	2	158	54	)	217	30	30
041	16	A*	100	42	STD	159	42	STD	218	97	DSZ
042	42	STD	101	27	27	160	32	32	219	00	00
043	39	39	102	61	GTD	161	42	STD	220	71	SBR
044	92	RTN	103	53	(	162	30	30	221	53	(
045	76	LBL	104	76	LBL	163	53	(	222	43	RCL
046	17	B*	105	35	1/X	164	43	RCL	223	30	30
047	42	STD	106	09	9	165	39	39	224	65	x
048	40	40	107	42	STD	166	55	+	225	43	RCL
049	92	RTN	108	26	26	167	01	1	226	40	40
050	76	LBL	109	01	1	168	00	0	227	54)
051	18	C*	110	00	0	169	00	0	228	42	STD
052	42	STD	111	42	STD	170	00	0	229	23	23
053	41	41	112	27	27	171	00	0	230	91	R/S
054	92	RTN	113	61	GTD	172	55	+	231	76	LBL
055	76	LBL	114	53	(	173	89	π	232	55	+
056	10	E*	115	76	LBL	174	54	)	233	87	IFF
057	42	STD	116	34	FX	175	42	STD	234	01	01
058	42	42	117	07	7	176	33	33	235	65	x

236	43	RCL	297	43	RCL	358	02	2	419	36	36
237	24	24	298	38	38	359	54	)	420	54)
238	33	X²	299	45	YX	360	53	(	421	53	(
239	94	+/-	300	93	.	361	42	STD	422	42	STD
240	34	FX	301	04	4	362	28	28	423	29	29
241	91	R/S	302	00	0	363	45	YX	424	23	LNX
242	76	LBL	303	05	5	364	93	.	425	55	÷
243	65	x	304	54	)	365	03	3	426	02	2
244	43	RCL	305	53	(	366	03	3	427	65	x
245	42	42	306	42	STD	367	07	7	428	43	RCL
246	91	R/S	307	24	24	368	65	x	429	29	29
247	76	LBL	308	35	1/X	369	02	2	430	34	FX
248	43	RCL	309	65	x	370	93	.	431	85	+
249	43	RCL	310	43	RCL	371	02	2	432	93	.
250	34	34	311	35	35	372	75	-	433	03	3
251	91	R/S	312	54	)	373	04	4	434	06	6
252	43	RCL	313	42	STD	374	93	.	435	02	2
253	35	35	314	31	31	375	00	0	436	54)
254	91	R/S	315	92	RTN	376	54	)	437	65	x
255	43	RCL	316	76	LBL	377	32	XIT	438	53	(
256	36	36	317	23	LNX	378	43	RCL	439	43	RCL
257	91	R/S	318	53	(	379	36	36	440	36	36
258	43	RCL	319	43	RCL	380	22	INV	441	55	÷
259	37	37	320	03	03	381	77	GE	442	03	3
260	91	R/S	321	65	x	382	28	LOG	443	02	2
261	43	RCL	322	43	RCL	383	92	RTN	444	54)
262	38	38	323	34	34	384	76	LBL	445	34	FX
263	91	R/S	324	45	YX	385	28	LOG	446	65	x
264	43	RCL	325	43	RCL	386	32	XIT	447	43	RCL
265	39	39	326	04	04	387	42	STD	448	37	37
266	91	R/S	327	65	x	388	36	36	449	65	x
267	43	RCL	328	43	RCL	389	92	RTN	450	93	.
268	40	40	329	38	38	390	76	LBL	451	00	0
269	91	R/S	330	45	YX	391	32	XIT	452	00	0
270	43	RCL	331	93	.	392	53	(	453	04	4
271	41	41	332	01	1	393	43	RCL	454	00	0
272	91	R/S	333	09	9	394	42	42	455	06	6
273	22	INV	334	09	9	395	65	x	456	54)
274	87	IFF	335	94	+/-	396	01	1	457	42	STD
275	01	01	336	54	)	397	02	2	458	22	22
276	33	X²	337	42	STD	398	93	.	459	92	RTN
277	43	RCL	338	25	25	399	02	2	460	76	LBL
278	42	42	339	92	RTN	400	54	)	461	25	CLR
279	92	RTN	340	76	LBL	401	53	(	462	81	RST
280	76	LBL	341	24	CE	402	42	STD	463	76	LBL
281	33	X²	342	53	(	403	28	28	464	85	+
282	00	0	343	73	RC*	404	55	÷	465	43	RCL
283	35	1/X	344	26	26	405	43	RCL	466	22	22
284	92	RTN	345	65	x	406	36	36	467	42	STD
285	76	LBL	346	43	RCL	407	54	)	468	23	23
286	22	INV	347	25	25	408	42	STD	469	91	R/S
287	53	(	348	45	YX	409	29	29	470	71	SBR
288	43	RCL	349	73	RC*	410	61	GTD	471	55	÷
289	01	01	350	27	27	411	54	)	472	00	0
290	65	x	351	65	x	412	76	LBL	473	00	0
291	43	RCL	352	43	RCL	413	44	SUM	474	00	0
292	34	34	353	24	24	414	53	(	475	00	0
293	45	YX	354	85	+	415	43	RCL	476	00	0
294	43	RCL	355	43	RCL	416	28	28	477	00	0
295	02	02	356	35	35	417	55	÷	478	00	0
296	65	x	357	55	÷	418	43	RCL	479	00	0

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.

Field programs and research work units of the Station are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

