3289
Extra

United States
Department of
Agriculture

Forest Service

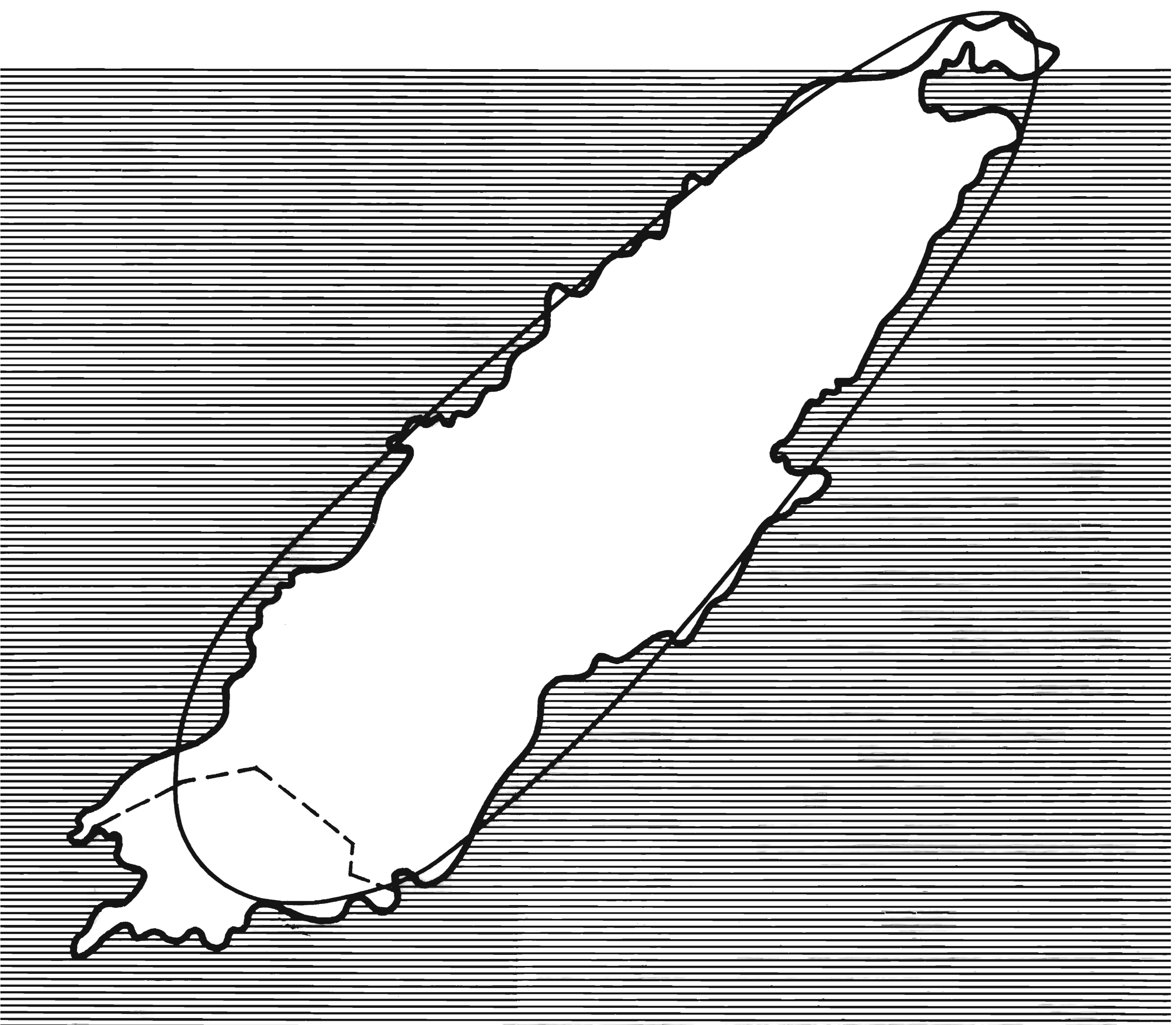
**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Paper
INT-305

February 1983

Predicting Wind-Driven Wild Land Fire Size and Shape

Hal E. Anderson



THE AUTHOR

HAL E. ANDERSON has been team leader of the basic research section of the Fire Fundamentals Research Work Unit since 1979. He joined the staff at Intermountain Station's Northern Forest Fire Laboratory in Missoula, Mont., in 1961 and served as project leader of the fire physics project from 1962 to 1966 and of the fuel science project from 1966 to 1979. He previously worked with General Electric Company from 1952 to 1961 on thermal and nuclear instrumentation. He received his B.S. degree in physics from Central Washington University in 1952.

RESEARCH SUMMARY

Fire behavior predictions have become part of the initial fire assessment, both for fire as a treatment or fire as a force to be suppressed. How fast a fire may grow in size and how much fireline there may be are valuable information factors to fire management staff. Critical analysis of wild land fire records and previous wind tunnel research on fire growth provided the basis for a mathematical approach to estimating fire size and shape using a double ellipse model. Equations have been developed to estimate the flank and backing fire spread rates, fire area, perimeter, and length to width ratio, and to plot fire shape.

Graphs and tables present the relationships developed, and five wild land fires show how the estimation matches field situations. In addition, the simple ellipse concept is presented with a quadratic equation solution for determining minor and major axes. These results are compared to the fire size and perimeter tables carried in most fireline notebooks.

CONTENTS

United States
Department of
Agriculture

Forest Service

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

Research Paper
INT-305

February 1983

Predicting Wind-Driven Wild Land Fire Size and Shape

Hal E. Anderson

INTRODUCTION

When an unplanned wild land fire occurs, the fire management staff needs to know the expected size and shape so the impact on land resources can be assessed and suppression forces dispatched. Early attempts to satisfy the need included analysis of fire records by Hornby (1936) that provided a table of minimum, probable, and maximum perimeter for various fire sizes. This table is in the Forest Service Handbook, FSH 5109.12, Fireman's Handbook, June 1966, amendment No. 4, figure 2, page 33.5—3, and has been reemphasized by Cargill (1970) in terms of forward rate of spread and elapsed time. Most Forest Service regions carry some form of this table in their Fireline Handbook supplements.

Rothermel's (1972) mathematical model provides the means for predicting how far a fire would travel in a given situation, but in the early 1970's there was no way to use that information to estimate fire size and shape. However, Fons[1] in 1940 provided data that could be applied to the problem. Fons' work will be referred to throughout this paper. It was possible to develop from Fons' data an approach where only the downwind spread distance and the windspeed at midflame height were needed to estimate the fire's acreage, perimeter, and shape.[2] This approach is used for estimating fire behavior, utilizing computer facilities for calculations, and evaluating fire hazards of slash (Albini 1976a, 1976b; Puckett and others 1979). In addition, the procedure is incorporated into the S-590 Fire Behavior Officer course conducted at the National Advanced Resource Technical Center at Marana, Ariz., and the proposed S-390 Fire Behavior training package (see appendix I).

This paper (1) documents the development and formulation of the procedure, (2) reviews observations and methods of assessment, and (3) provides examples that will aid testing the procedure. Illustrations show how this model can be used to confirm other fire behavior models.

BACKGROUND

Firefighters and researchers generally agree that wild land fires are circular in shape immediately after ignition, but as wind, slope, and other environmental factors influence the fire, its shape becomes elliptical (Hawley and Stickel 1948; Brown and Davis 1973; Peet 1967; Pirsko 1961; McArthur 1966; Curry and Fons 1938; Mitchell 1937). McArthur (1966) states that the stronger the wind the more narrow and elongated the fire burns. He presents a relationship between fire shape and wind velocity, using a straightforward ellipse where the length to width ratio varied from 1.0 to approximately 6.0. This range in length to width ratio primarily reflects the grassland fuels being considered. The most probable ratio selected by Cheney and Bary (1969) is 4:1 for grasslands, while Van Wagner (1969) uses a ratio of 2:1 as an example for a forest fire. This compares with the average fire shape found by Hornby (1936) where the perimeter is about 1.5 times the perimeter of a circle of equal area. An ellipse with a length to width ratio of 5:1 represents that average fire shape. Work by Peet (1967) in the western Australia Jarrah Forest indicated the ratio of 2:1, but he noted the fires became more ovoid in shape as rate of forward spread increased.

Similar observations by Curry and Fons (1938) show the change with a steady wind or a variable direction wind. An additional display of fire shapes presented by Fons (1946) contribute to using two semiellipses to define size and shape. Mitchell (1937) observes that fires become oval or egg-shaped after a few minutes, with the narrow end being in the direction of forward spread. These features of wind-influenced wild land fires become more obvious with the use of infrared imagery for fire

[1] Fons, Wallace L. Forest fuels progress report No. 6, May 20, 1940. California Forest and Range Experiment Station, copy on file at the Pacific Southwest Forest and Range Experiment Station, Forest Fire Laboratory, Riverside, CA.

[2] Anderson, Hal E. Memorandum to R. C. Rothermel and W. C. Fischer, on file at Northern Forest Fire Laboratory, Missoula, MT, August 10, 1973.

mapping and detection (Hirsch and others 1968). The Sundance Fire (Anderson 1968), with documented weather and fire spread history, was mapped by infrared imagery (Hirsch 1968). The long elliptical shape was evident, although some of the narrowness was due to nonlinear features of the scanning portions of the infrared mapping equipment.

Aerial photography points out such characteristics as shown in the examples given by Wade and Ward (1973). The Air Force Bomb Range Fire and the Exotic Dancer Fire show elliptical patterns in the vegetation bands that outline the fire's perimeter at progressive stages of development. Controlled burning in the Everglades has generated the same pattern of burning in sawgrass stands (Klukas 1972). The initial circular, then oval, shape of the fire's perimeter is usually lost in the subsequent burnout of the area.

McArthur (1966) showed that the length to width ratio is a function of windspeed, so only an estimate of the forward spread rate is needed to calculate fire size. Van Wagner (1969) used an ellipse to estimate fire size and perimeter. Although it is a simple and flexible mathematical method, it is necessary to know or estimate three rates of spread at the head, flanks, and rear of the fire. A similar but expanded approach is provided by Simard and Young (1978) who define the spread rate at the head, two flanks, and the rear of the fire. This approach provides a means to evaluate aerial and ground suppression options against fire growth. A fire potential assessment model developed by Van Gelder (1976) determines the length to width ratio by slope, windspeed, and fuel characteristics. Fire size is estimated by use of available fire weather reports and a fuel model to apply Rothermel's (1972) fire spread model. Examples show that the elliptical model is useful for rapid evaluation of the fire potential of given situations. Earlier application of the concept presented by Storey (1972) uses input parameters of size at discovery, the length to width ratio, and the forward rate of spread. An expansion by Bratten (1978) considers the size at attack and size at containment. Length to width ratios and forward spread rates were used as defining parameters. Other work on the containment problem by Albini and others (1978)—involving a complex analysis incorporating forward, flank, and backing rates of spread—show that the general shape follows an elliptical profile.

Experimental Results of 1939

Fons reported on a series of 198 test fires conducted in a low velocity wind tunnel. The objective was to establish the effect of compactness in pine litter on the spread of surface fires with varying wind velocity and moisture content (table 1). Wind velocity that was measured 1 ft (0.3 m) above the fuel surface was varied from 2 to 12 mi/h (3.2 to 19.3 km/h). This measurement is comparable to midflame height. Fires were started from a point source and allowed to grow until they were approximately 18 inches (45.7 cm) in width. At that point, wind generation was stopped and the fire was quenched with water to preserve the fire's shape (fig. 1).

The notation used in the development of the mathematical description of fire size and shape is in figure 1. The focus, f_1, represents—the origin of the fire and the point from which all measurements to the perimeter were made by Fons. The forward distance traveled with a given rate of spread for a given interval of time is defined by d. The other dimensions are defined as:

Table 1.—Forward spread of firs in ponderosa pine needles under various conditions (from Fons[1])

Wind velocity	Fuel moisture content	Fuel bed compactness (inches) 0.06	0.08	0.10	0.12	0.14	0.16
Miles per hour	*Percent*	*Forward spread - feet per minute*					
0	4	0.38	0.54	0.67	0.76	0.84	0.97
0	8	0.30	0.42	0.49	0.55	0.60	0.67
0	12	0.19	0.27	0.32	0.36	0.38	0.42
0	16	0.10	0.15	0.18	0.18	0.19	0.20
2.0	4	0.93	1.32	1.62	1.78	1.85	2.15
2.0	8	0.72	0.98	1.17	1.28	1.30	1.58
2.0	12	0.51	0.68	0.82	0.89	0.90	1.00
2.0	16	0.30	0.42	0.45	0.51	0.45	0.58
4.0	4	1.80	2.53	3.12	3.34	3.50	3.90
4.0	8	1.40	1.93	2.29	2.42	2.53	2.85
4.0	12	1.02	1.39	1.62	1.70	1.80	2.00
4.0	16	0.60	0.85	1.00	1.03	1.03	1.22
6.0	4	2.89	4.09	4.98	5.38	5.75	6.60
6.0	8	2.26	3.18	3.74	4.01	4.20	4.75
6.0	12	1.68	2.30	2.68	2.85	3.00	3.40
6.0	16	1.00	1.45	1.72	1.78	1.80	2.20
8.0	4	4.16	6.02	7.40	8.10	8.70	10.35
8.0	8	3.34	4.74	5.56	6.15	6.60	7.35
8.0	12	2.50	3.45	4.09	4.37	4.63	5.35
8.0	16	1.58	2.25	2.66	2.83	2.95	3.50
10.0	4	5.69	8.40	10.52	11.75	12.90	15.30
10.0	8	4.70	6.68	8.00	8.97	9.70	10.75
10.0	12	3.57	4.95	5.95	6.46	6.83	7.75
10.0	16	2.34	3.32	4.00	4.24	4.58	5.25
12.0	4	7.59	11.32	14.40	16.70	18.70	21.65
12.0	8	6.36	9.13	11.16	12.52	13.40	14.95
12.0	12	4.93	6.88	8.30	9.15	9.60	10.85
12.0	16	3.40	4.84	5.84	6.36	6.70	7.60

[1]See footnote 1 in text.

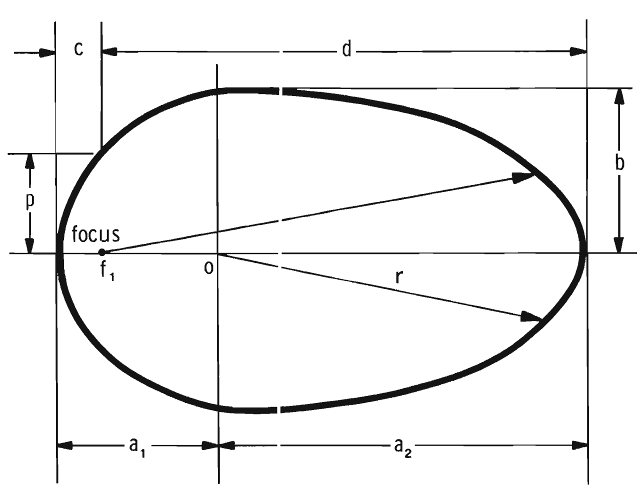


Figure 1.—Definitions of dimensions used for a two semiellipse model of fire shape.

a_1 = major axis of semiellipse at the rear of the fire,
a_2 = major axis of semiellipse at the front of the fire,
b = the common minor axis, the maximum flanking fire spread distance,
c = the portion of axis, a_1, that is the backing fire spread distance,
p = semilatus rectum of the rear semiellipse and represents the flanking fire at the origin.

Fons made measurements of the downwind distance from the origin to the perimeter at various angles from the direction of maximum spread (table 2). He used data from the experiments to generate a series of cross plots involving windspeed, compactness, and moisture content. With these cross plots, differences between the observed data and the fitted data provided residuals that were used for obtaining the final set of curves. Table 1 shows the values of forward spread from the final curves and table 2 presents the statistical measures Fons computed for forward spread at each windspeed.

Table 2.—Statistical measures of ratios of forward spread to spread at other angular distances[1]

Cases	Wind velocity	Direction from maximum spread[2] 10°	20°	30°	40°	60°	90°	130°	180°
Number	*Miles per hour*								
		Mean spread ratio (actual)							
32	2.2	0.943	0.843	0.739	0.649	0.525	0.431	0.362	0.328
34	4.3	.882	.724	.600	.510	.399	.312	.246	.218
40	6.4	.815	.607	.468	.377	.276	.205	.157	.142
35	8.4	.753	.522	.391	.311	.223	.163	.119	.105
33	10.5	.689	.443	.314	.243	.169	.115	.079	.066
24	12.5	.664	.413	.293	.226	.154	.103	.066	.057
		Standard deviation of spread ratio							
32	2.2	0.025	0.041	0.050	0.060	0.054	0.049	0.073	0.084
34	4.3	.040	.063	.073	.073	.069	.063	.058	.057
40	6.4	.045	.062	.062	.056	.045	.034	.035	.043
35	8.4	.041	.052	.049	.043	.033	.028	.030	.032
33	10.5	.041	.046	.039	.033	.027	.021	.023	.025
24	12.5	.054	.053	.044	.037	.028	.021	.020	.020
		Standard deviation of spread ratio - percent							
32	2.2	2.7	4.9	6.8	9.2	10.3	11.4	20.2	25.6
34	4.3	4.5	8.7	12.2	14.3	17.3	20.2	23.6	26.1
40	6.4	5.5	10.2	13.2	14.9	16.3	16.6	22.3	30.3
35	8.4	5.4	10.0	12.5	13.8	14.8	17.2	25.2	30.5
33	10.5	6.0	10.4	12.4	13.6	16.0	18.3	29.1	37.9
24	12.5	8.1	12.8	15.0	16.4	18.2	20.4	30.3	35.1

[1]See footnote 1 in text.
[2]Directions expressed as angular distances in degrees from direction of maximum spread.

Fons assumed that the shape of the burned area in any one fuel type is independent of compactness and moisture content. He confirmed this by comparing the means of the ratio of angular spread distance to maximum spread distance obtained within each wind class for the upper and lower ranges of compactness and moisture content (see examples in table 3). The analysis found that the shape of the burned area was dependent only upon the wind velocity. The ratio of maximum length to width for mat beds of ponderosa pine needles was found to be a function of wind velocity by:

$$\frac{(d + c)}{b} = 1.0 + 0.50\,U \qquad (1)$$

where:
c + d = total spread distance, according to figure 1,
b = minor axis, according to figure 1,
U = wind velocity in miles per hour, at midflame height.

For field tests in ponderosa pine needles, the constant was found to be 0.44 rather than 0.50.

Table 3.—Samples of Fons'[1] data illustrating that compactness and moisture content do not influence fire shape

Moisture content	Compactness	Wind-speed	Fractional spread in different directions from origin 10°	20°	30°	40°	60°	90°
Percent	*Inches*	*Mi/h*	*Ratio of angular distance to distance of maximum spread*					
6.8	0.067	2.2	1.00	0.83	0.75	0.58	0.50	0.42
6.9	.160		.93	.87	.73	.67	.53	.47
11.9	.067		1.00	.80	.80	.80	.60	.40
11.6	.160	2.2	1.00	.90	.80	.70	.60	.50
5.3	.067	6.4	.90	.71	.52	.43	.33	.29
4.8	.160		.81	.61	.49	.40	.28	.19
11.2	.067		.84	.63	.47	.42	.31	.26
12.1	.160	6.4	.87	.65	.52	.39	.32	.26
4.7	.067	12.5	.76	.53	.39	.30	.21	.14
6.2	.140		.64	.33	.22	.16	.10	.06
11.1	.067		.64	.39	.27	.21	.14	.11
13.7	.160	12.5	.62	.42	.30	.24	.16	.11

[1]See footnote 1 in text.

Development of Fire Shape Model

Analysis of the above data show that the elliptical shape describes results closely. The best fit of the experimental data was found to be with two semiellipses.

The original development[3] considered the spread distance at various angles as fractions of the forward spread distance, d, as presented in Fons' data tables 1 and 2. The dimensions of the double ellipse were analyzed as functions of windspeed using data in Fons' tables and from the curves of fire shape at various windspeeds (fig. 2). Relationships between dimensions of an ellipse besides log regressions were used to express each dimension as a function of windspeed. The minor semiaxis, b, was defined in terms of p and a_1 using the semilatus rectum expression for an ellipse. Further study showed that b could be better described as a log function of windspeed. The dimensions of Fons' curves were reevaluated as fractions of the spread distance, d (table 4).

A least-square fit of log regressions for the following dimensions provided equations as functions of windspeed and fractions of the forward spread distance:

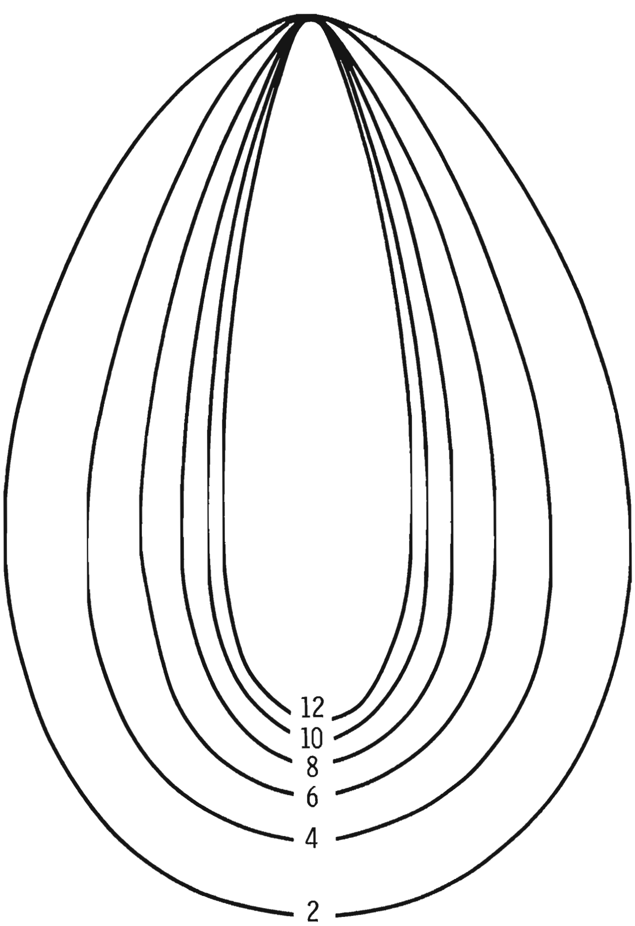


Figure 2.—Diagrams showing influence of wind velocity on shape of burns.

[3]See footnote 2, page 1.

Table 4.—Summary of data measured from Fons'— curves (fig. 2) for fire shape and used for equations 2, 3, 4, and 6

Windspeed	a_1 fraction	b fraction	c fraction	p fraction
Mi/h				
0		0.500	0.500	0.500
2	0.560	.465	.348	.432
4	.416	.348	.230	.315
6	.346	.260	.160	.226
8	.358	.210	.112	.160
10	.346	.163	.072	.119
12	.315	.140	.058	.093

[1]See footnote 1 in text.

$$c = 0.492 \text{ EXP } [-0.1845 \text{ U}], \quad r^2 = 0.996 \tag{2}$$
$$S\hat{y} \cdot x = 0.162$$

$$p = 0.542 \text{ EXP } [-0.1433 \text{ U}], \quad r^2 = 0.993 \tag{3}$$
$$S\hat{y} \cdot x = 0.140$$

$$a_1 = 2.502\, [88\text{U}]^{-0.30}, \quad r^2 = 0.918 \tag{4}$$
$$S\hat{y} \cdot x = 0.046$$

$$a_2 = 1 + c - a_1 \tag{5}$$

$$b = 0.534 \text{ EXP } [-0.1147 \text{ U}], \quad r^2 = 0.988 \tag{6}$$
$$S\hat{y} \cdot x = 0.143$$

These equations provide a means of quantifying important dimensions of the double ellipse representation of fire shape. When these values along with the spread distance are used in equations for area and perimeter, we can estimate fire growth. In addition, the length to width ratio and the envelope of the burn area can be estimated.

Calculations of area and perimeter require multiplying the fractional expressions of ellipse dimensions by the forward spread distance. The following equations have been used or adapted to make estimates of the fire dimensions (Albini 1976a, 1976b; Albini and Chase 1980):

$$\text{Area} = A = \frac{\pi b d^2}{2}(a_1 + a_2); \text{ ft}^2, \text{m}^2, \text{etc.} \tag{7}$$

$$\text{Perimeter} = P = \frac{\pi k_1 d}{2}(a_1 + b) + \frac{\pi k_2 d}{2}(a_2 + b); \text{ ft, m.} \tag{8}$$

$$k_n = 1 + \frac{M_n^2}{4} + \frac{M_n^4}{64} + \frac{M_n^6}{256} \ldots \tag{9}$$

(Bauneister 1958)

$$M_n = (a_n - b)/(a_n + b) \tag{10}$$

(Bauneister 1958)

Equation 9 can be simplified for ease of computation with a less than 1 percent loss in accuracy by eliminating the terms after M_n^2:

$$k_n = 1 + \frac{M_n^2}{4} \tag{9}$$

For graphic presentation of the fire shape, the perimeter is plotted by using the intercept of the major and minor axes, 0, as the origin. This is possible because the minor axis is common to both semiellipses and both semimajor axes can be defined in terms of d, the forward distance traveled along the major axis, and U, the windspeed. Any point on the perimeter is defined by:

If $\mathrm{Cos}\,\emptyset \geq 0$, a positive value:
$x = (a_2 \mathrm{Cos}\theta)d$
$y = (b \mathrm{Sin}\theta)d$

If $\mathrm{Cos}\,\theta < 0$, a negative value:
$x = (a_1 \mathrm{Cos}\theta)d$
$y = (b \mathrm{Sin}\theta)d$

where θ = angular degrees from the forward direction with 0 as the origin. The origin of the fire is defined as $c - a_1$, the focus of the semiellipse containing the backing fire.

With these equations and conditional statements, it is possible to predict the area burned by a fire and the distance around its perimeter. Windspeed and the forward rate of spread are the only inputs needed.

ANALYSIS RELATED TO FIRE SIZE AND SHAPE

Just how well these mathematical models match Fons' graphic data (fig. 2) was analyzed by comparing measured fire data with calculated values. The fire shapes of figure 2 were scaled at 1 inch = 1,000 ft (8.3 cm = 1 km). As size and shape dimensions were calculated, a plot of the fire shape was generated so computations could be compared to results obtained from figure 2 and the plotted shapes. The plotted shapes were prepared for windspeeds of 2, 6, and 12 mi/h (3.2, 9.6, and 19.3 km/h). The values computed and those measured were found to be within ±2 percent of each other. Fons' fire shapes of figure 2 and the model generated plots were within ±9 percent of each other for area measurements and within ±3 percent for perimeter measurements. The area and perimeter measurements were made with a compensating polar planimeter for area and a map measurer for the perimeter. The measured and computed values are presented in table 5 and shown in figures 3 and 4.

Perimeter may be underestimated because of the natural variability that exists in the field. A few of the variables contributing to an irregular and longer fire edge are windspeed and direction, slope and topography, and changes in fuel distribution.

The greatest benefit of using these equations is that only two input variables—wind at midflame height and rate of spread (distance for a given time)—are needed to compute area, perimeter, backing fire distance, flanking fire distance, their ratios to the heading fire, and the maximum length to width ratio. These estimates have proven valuable to various elements of fire management, but it must be remembered that the original data were taken on fires burning through pine needle beds without variation in wind direction. Outputs such as the length to width ratio may show that fuel size (surface area to volume ratio) and fuel bed packing ratio (fuel volume per unit volume) have an influence.

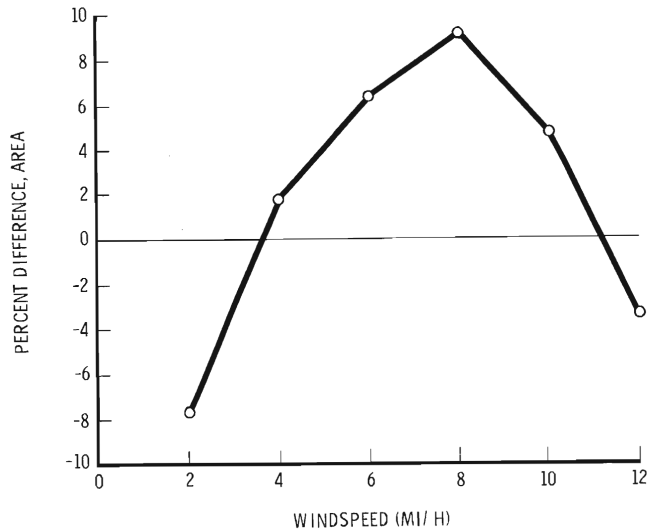


Figure 3.—Deviations of mathematical model versions from Fons' diagrams for fire size and shape, area.

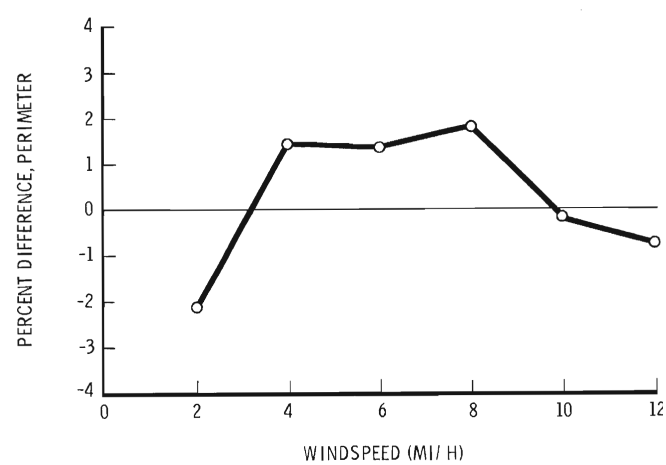


Figure 4.—Deviations of mathematical model versions from Fons' diagrams for fire shape, perimeter.

Table 5.—Comparison of Fons'[1] diagrams with fire size and shape mathematical model outputs using a forward spread distance of 5,000 ft

Version	Windspeed Mi/h	Graphic acres	Computed acres	Graphic miles	Computed miles
Fons	2	556.4		3.38	
Model		512.8	513.5	3.28	3.31
Fons	4	369.5		2.88	
Model			376.0		2.92
Fons	6	265.1		2.59	
Model		281.5	282.0	2.60	2.63
Fons	8	196.0		2.37	
Model			214.0		2.42
Fons	10	157.5		2.27	
Model			165.0		2.26
Fons	12	132.4		2.17	
Model		127.9	128.0	2.12	2.15

[1]See footnote 1 in text.

Comparison of Fire Size Properties

Hornby (1936), using 146 fire records and 102 hypothetical fires, showed that for a constant area reference, the most probable perimeter was 1.5 times that of a circle with equal enclosed area. In addition, he found that 92 percent of the fire shapes investigated would have perimeters less than 2 times that of a circle of equal area. These are equivalent to length to width ratios of 5:1 and 9.7:1, respectively. Mitchell (1937) related the head fire rate of spread to the rate of perimeter increase using the relationship for circles of the perimeter to the diameter. He suggested the simplest approach was to multiply the head fire rate of spread by 3 for an estimate of the rate of perimeter increase. Hanson's (1941) analysis of 140 fires in the Forest Service's Region 4 relates the length of line in chains to the final acreage of the fire. Brown's (1941) analysis of 65 class "C" fires in Region 2 produced a graph of minimum, average, and maximum control line lengths in chains for fires up to 1,000 acres (404.7 ha) at control. He found that π times the long axis of the fire agreed closely to the perimeter. For fires under 20 acres (8.1 ha) he found the most probable perimeter to be 1.67 times the perimeter of a circle of equal area.

Length to width ratios did not appear to receive much attention until McArthur published his Australian research on grassland fires (1966). He recognized that the elliptical shape provides a good approximation of fire shape. With the statement on his "grassland fire danger meter" that perimeter increase can be taken as 2.5 times the forward spread, fire sizes can be analyzed in terms of perimeter, area, and length to width ratio. Assuming an elliptical shape, we have a unique solution for any fire where two of these dimensions are known.

Using the concept of equal area shapes as Hornby (1936) introduced, we can establish the minimum perimeter an elliptical fire can have unless control action has truncated the fire shape. Working with the simple ellipse we need to use the equations for area and perimeter:

$$\text{Area} = \pi ab = A, \text{ units}^2 \tag{11}$$

$$\text{Perimeter} = (a + b)\, k\pi = P, \text{ units} \tag{12}$$

where:

a = semimajor axis,
b = semiminor axis,
k = equation (9).

By using the area equation (11) to define b we can substitute into equation (12) and reduce it to a quadratic equation:

$$\pi k a^2 - aP + kA = 0 \tag{13}$$

The two axes, a and b, can be calculated from:

$$a = P + \frac{\sqrt{P^2 - 4\pi k^2 A}}{2\pi k} \tag{14}$$

and

$$b = P - \frac{\sqrt{P^2 - 4\pi k^2 A}}{2\pi k} \tag{15}$$

and by successive approximations determine the unique combination of area, perimeter, k, and length to width ratio that fit a given set of conditions.

Using this technique, a series of areas and perimeters were evaluated and length to width ratios, ℓ/w, were determined (fig. 5). Note that area will be the square of the unit of measure used for perimeter—ft^2 for area when perimeter is in feet, for example. Perimeter may be any unit of length that is suitable.

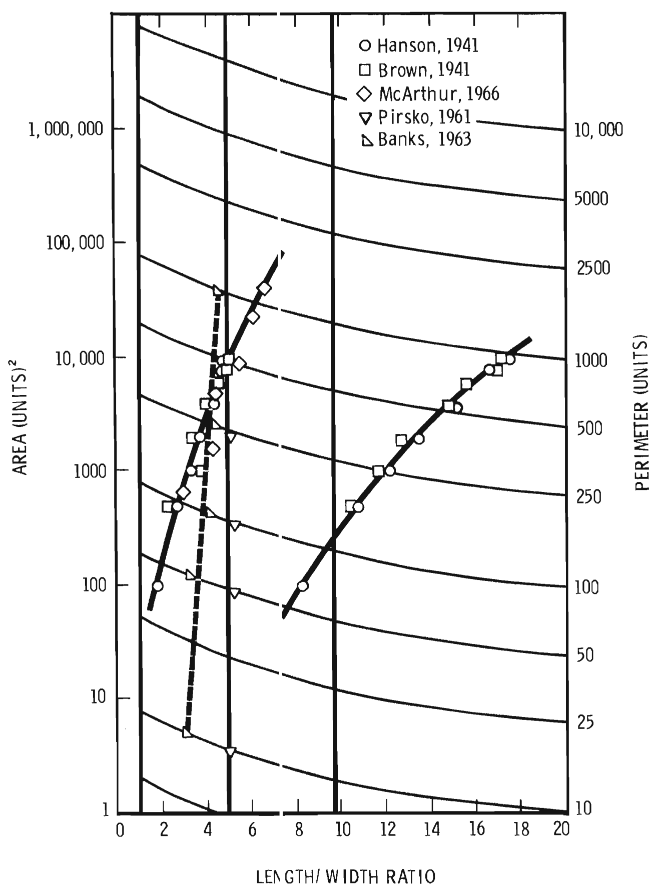


Figure 5.—The relationship of area, perimeter, length to width ratio for elliptical-shaped fires and comparison of several appraisals of fire size and shape relationships.

Hornby (1936) expresses fire size and shape in terms of the length of perimeter for an ellipse to the circumference of a circle of equal area. For the no-wind, no-slope condition, the circle and the ellipse are equal in perimeter and the ℓ/w ratio is 1:1. He expressed the most probable fire size as when the perimeter of the ellipse is 1.5 times the circumference of a circle of equal area and the ℓ/w ratio is 5:1. The fires Hornby analyzed showed that 92 percent of all the perimeters investigated were less than 2.0 times the circumference of a circle with equal area—or having a ℓ/w ratio of 9.7:1. These three descriptions of fire size and shape are identified in figure 5 by the vertical lines at:

1. Minimum perimeter = circumference = 1:1 ℓ/w ratio,
2. Most probable perimeters 1.5 circumference = 5:1 ℓ/w ratio,
3. Maximum perimeter – 2.0 circumference = 9.7:1 ℓ/w ratio.

Figure 5 presents the data previously cited by Hanson (1941), Brown (1941), McArthur (1966), Pirsko (1961), and Banks (1963), and shows how the other interpretations compare to Hornby's.

Brown (1941) and Hanson (1941) both used an analysis method of fire size and shape that used the standard error to define the expected minimum and maximum values of perimeter for a given fire size. McArthur's (1966) values for area and perimeter, when wind is a factor, agree with the most probable values found by Brown and Hanson. These results for most probable and maximum values are shown in figure 5 as the solid lines through the data points for ℓ/w ratios from 2:1 to 7:1 and 8:1 to 17:1. These data points can be expressed mathematically in empirically determined equations:

For ℓ/w ratios < 7
$A = 4.74\,(\ell/w)^{4.638}$, area.
For ℓ/w ratios > 7
$A = 1.62 \times 10^{-4}\,(\ell/w)^{6.285}$, area.

This suggests that a greater range of combinations for area, perimeter, and ℓ/w ratio occurs than the procedure used by Hornby (1936) can accommodate. This is a result of constraining the perimeters to 1.5 and 2 times the circumference of a circle with equal area. The ℓ/w ratios are then fixed at 5 and 9.7 as representing the most probable and the expected maximum ℓ/w ratio respectively.

The relationship of the length to width ratio to the average wind on the flame can be expressed with the equations developed from Fons' wind tunnel data. Using the dimensions of figure 1 where d equals 1 for normalizing, we can describe the ratio of total fire length to maximum fire width:

$$\ell/w = (1 + c)/2b \tag{16}$$

Since the backing and flanking dimensions are expressed as fractions of the forward rate of spread distance, the forward distance has a value of unity. Combining equations 2 and 6 as indicated above and clearing the fractional form, we can express the length to width ratio (fig. 6) by:

$$\ell/w = 0.936\,\mathrm{EXP}(0.1147U) + 0.461\,\mathrm{EXP}(-0.0692U) \tag{17}$$

where U = windspeed at 1.5 ft or midflame miles per hour.

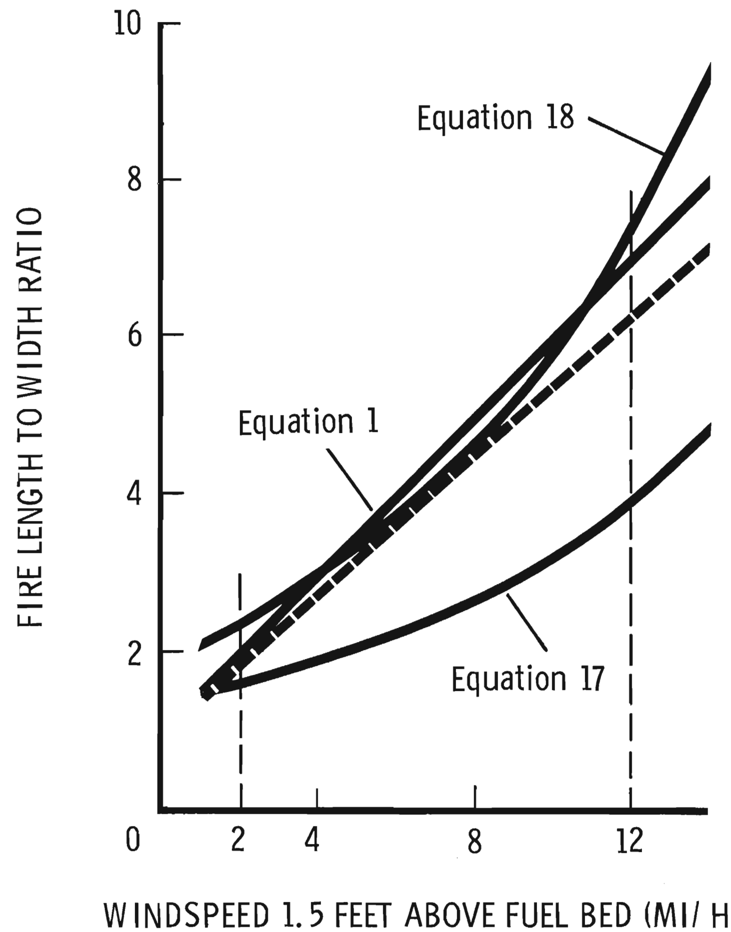


Figure 6.—Relation of the length to width ratio and windspeed 1.5 ft (45.7 cm) above the fuel bed. The dotted lines at 2 and 12 mi/h (3.2 and 19.3 km/h) show the range of experimental data used by Fons.[1]

Fons found a relationship of length to width to wind that is linear in nature over the range of winds examined:

$$\frac{d + c}{2b} = 1.0 + 0.5\,U \tag{1}$$

where U is miles per hour. The solid line in figure 6 represents this equation, and the dashed line presents a similar equation with a coefficient of 0.44 for fires burning in ponderosa pine needle litter beds in the forest.

These equations have nearly twice the slope of equation 16 or 17, primarily because only the downwind distance and the distance to one side of the centerline of the fire shape are used. Equation 16 can be reduced to a similar form by disregarding the backing distance, c, and using the minor axis dimension, b, as the width:

$$d/b = 1/b = 1/0.534\mathrm{EXP}[-0.1147U] \tag{18}$$
$$\text{or } 1.873\,\mathrm{EXP}[0.1147U]$$

This curve matches the line from equation 1 from 2 to 12 mi/h (3.2 to 19.3 km/h) windspeeds.

Because it is generally difficult to identify the fire starting point and establish the centerline of the fire shape, it is recommended that the total fire length and width be considered for field applications. This also conforms to the general use of the simple ellipse as is currently being done. However, it must be remembered that the distance, d, is from the focus opposite the head of the fire and not the major axis of a simple ellipse (see fig. 1).

The application of the results of this analysis must consider the average wind on the flame. This may require calculating that value from wind measurements made at some other height. The variability of the wind along with the array of fuels and topography that a fire may encounter are probably the most significant factors in establishing a fire's size and shape. How well the double ellipse or simple ellipse matches field observations will depend on how wisely an observer selects a windspeed and a fuel bed description so reasonable inputs are made to the mathematical models.

Initial tests of the model and the assumptions used have been made with historical data and are tabulated in appendix II. These are checks for the reasonableness of the model and provide indications of how wind, fuels, and topography must be considered as validation opportunities become available. The documented values from field observations in appendix II are compared to computed values from the double-ellipse mathematical model and the quadratic equation approach to the single ellipse model.

Interpretation of the combinations of fire size and shape parameters must be given careful consideration if historic fires are to be used as data for developing aids to fire management. An example is the Wisconsin Fire Suppression Handbook,[4] which contains examples of fires with no control and good control. In figure 7 the data from appendix II of this report are plotted to show the differences. Fire "A" was not controlled and shows that for given weather and fuel conditions the ℓ/w ratio remains constant while the area and perimeter continue to increase. Fire "B" shows the results of good flanking fire control and pinching off attack on the fire front. The area and perimeter are increasing at a decreasing rate while the ℓ/w ratio increases rapidly. When utilizing historic fires it must be recognized that either good fire control or a sudden increase in windspeed or a change in wind direction can change ℓ/w ratios.

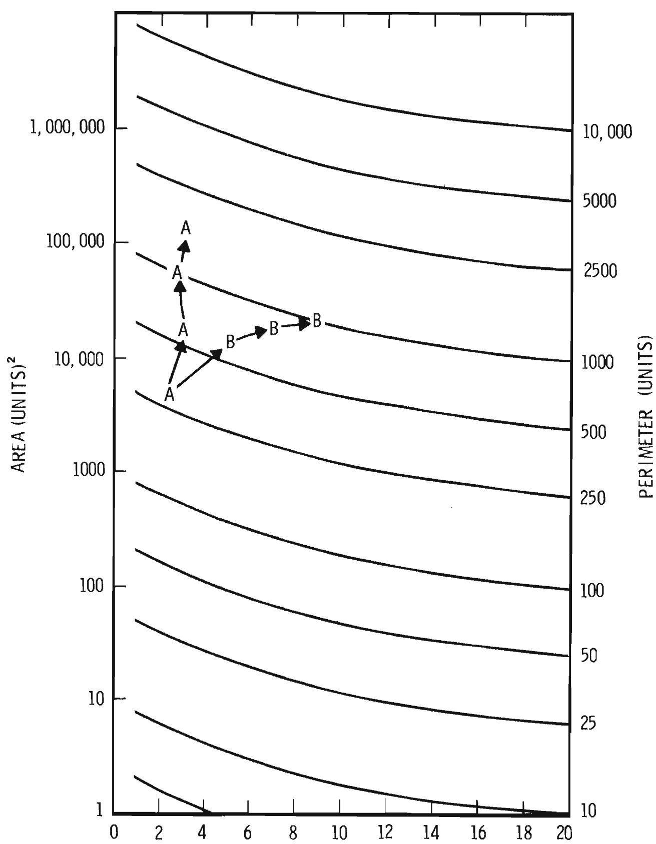


Figure 7.—Wisconsin's Fire Suppression Handbook examples of fire size and shape with and without good control action.

Comparison to Field Observations of Wildfires

The following five fires had enough documentation to show how fire shape and size relationships change with time. The time histories of fire shape and size, graphically presented in figure 8, show that Hornby's (1936) approach is reasonable. Time since fire start is in the direction the arrows point. When the wind is stable and fuels are constant, the fires tend to orient vertically in figure 8.

Close agreement can be achieved between the field observations and the mathematical computation when the wind profile is considered. Albini and Baughman (1979) present a procedure that is used to depict the average wind on the flame by reducing the windspeed at 20 ft (6 m) above the vegetation cover to what would be present at the location of the flame front. Winds may be reduced to the value at the vegetation upper surface or to a point within the cover depending on whether a crown fire or a surface fire occurred.

Following are brief summaries of each example. These comparisons are valid only to the extent that effective suppression action or major fuel changes have not taken place, restricting fire growth.

[4]Excerpts provided by Jim Miller, Fire Staff Specialist, Rhinelander, Wis.

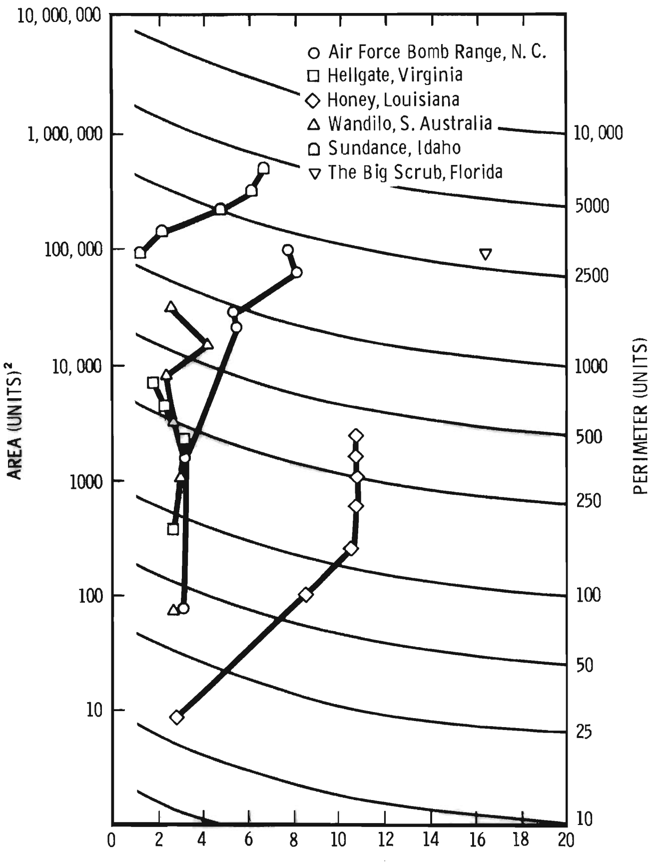


Figure 8.—Fire size and shape changes during the history of observed fires.

Example Fires with the Critical Values Tabulated

Example 1:

Air Force Bomb Range Fire on March 22, 1971 (Wade and Ward 1973) started at 1028 and began crowning about 1230. This continued until 1745, after which the fire encountered wet fuel and wind changes occurred with fronts moving through the area. Wind direction changes complicate use of the ellipse model and make results more uncertain. Notice that the wind acting on the flame to match observations was to reduce the 20 ft (6.1 m) wind to 9.4 mi/h (15.0 km/h) for the fire burning in grass and low shrubs. After 1230 the observed wind was only reduced to 15 mi/h (24.0 km) because the fire was carried in the crown of the pond pine (*Pinus serotina* Michx.) plantation. The fit of the adjusted double ellipse is shown in figure 9.

Example 1. The Air Force Bomb Range Fire in Florida started in brush and grassy fuels and about 2 hours later started crowning in pine plantations (*P. serotina*). Fire start was 1028 on March 22, 1971.

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	1100.0 hours			
Area	8.0 acres	8	5.6	8
Perimeter	.5 miles	.5	.5	.5
Distance	.2 miles	.2	.2	.2
Windspeed	W 20.0 mi/h		12.2	9.4
ℓ/w	3:1	3.2:1	4:1	3:1
Time	1226			
Area	155	155	102	159
Perimeter	2.1	2.1	2.0	2.2
Distance	.9	.9	.9	.9
Windspeed	WSW 20		13.0	9.5
ℓ/w	3.1:1	2.8:1	4.3:1	3:1
Time	1439			
Area	2,094	2,094	2,845	2,099
Perimeter	10.2	10.2	10.3	9.9
Distance	4.6	4.6	4.9	4.6
Windspeed	SW 15		12.5	15.0
ℓ/w	5.4:1	5.8:1	3.5:1	5.4:1
Time	1537			
Area	2,975	2,975	4,589	2,982
Perimeter	11.6	11.6	12.3	11.5
Distance	5.3	5.6	5.3	5.3
Windspeed	SW 15		10.9	14.4
ℓ/w	5.3:1	5.2:1	3.5:1	5.1:1
Time	1636			
Area	6,518	6,518	6,297	6,485
Perimeter	20.5	20.5	20.8	20.9
Distance	10.1	10.1	10.1	10.1
Windspeed	SSW 20		19.0	18.8
ℓ/w	8.1:1	7.8:1	8.4:1	8.2:1
Time	1745			
Area	9,796	9,796	12,434	9,819
Perimeter	29.1	29.1	25.6	25.1
Distance	12.1	14.4	12.1	12.1
Windspeed	SW 20		16.3	18.3
ℓ/w	7.8:1	10.7:1	6.2:1	7.8:1

Fire size and shape at 1100, 1226, and 1439 hours, 3/26/71. Dashed lines are double ellipse fire shape estimates. See Appendix I for perimeter, area, and l/ w ratio values.

Fire size and shape at 1537 hours, 3/26/71. These first four sizes determined by time-specified roads were reached and burn patterns left in the vegetation.

Fire size and shape at 1636 hours, 3/26/71. Wind direction changes not handled well in this procedure.

Fire size and shape at 1745 hours, 3/26/71. Fuels became wetter as fire moved northeast toward Croatan Sound.

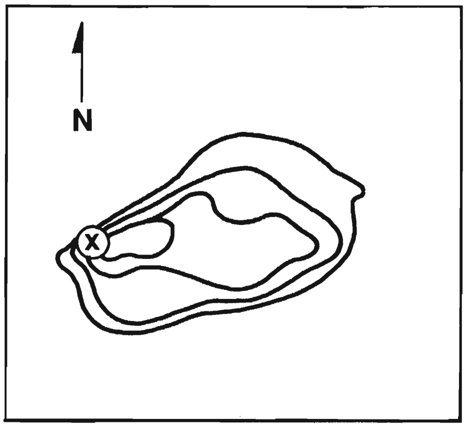
Figure 9.—Air Force Bomb Range Fire, March 26, 1971, in North Carolina; changes in size and shape.

Example 2:

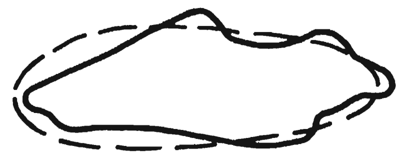
The Hellgate Fire of April 18, 1965, as reported by Taylor and Williams (1967), burned in forest cover of pine and oak with heavy litter and slash. Rapid spread with crowning and spotting occurred from 1350 to 1500. Maximum rate of spread was from 1400 to 1430 at 110 chains/h to the east. Wind shifts started to occur after 1430. The wind reduction was 0.332 for the double ellipse ℓ/w ratio to match field observations. These suggest the fire growth was controlled by the surface fire even though there was crowning and spotting. The wind reduction factor of 0.332 for 1430, 1500, and 1600 matches Albini and Baughman's (1979) values for open-stocked, intolerant young to mature species, 40 to 100 ft (12.2 to 30.5 m) tall. The fit of the double ellipse shape is shown in figure 10.

Example 2. The Hellgate Fire in Virginia was detected at 1335 on April 18, 1965, in an area with heavy litter and slash on the surface. The heavy surface fuels contributed to the fire quickly crowning out in the pine and oak overstory.

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	1400.0 hours			
Area	40.0 acres	40	39.5	40
Perimeter	1.0 mile	1	1	1.0
Distance	.4 mile	.4	.4	.4
Windspeed	SW 15-20.0 mi/h		6.6	7.7
ℓ/w	2.5:1	2.2:1	2.3:1	2.5:1
Time	1430.0			
Area	243.0	243	235	243
Perimeter	2.8	2.8	2.7	2.7
Distance	1.1	1.3	1.1	1.1
Windspeed	SW 30-50.0		10.0	9.5
ℓ/w	3:1	3.3:1	3.2:1	3:1
Time	1500			
Area	485	485	481	485
Perimeter	3.3	3.3	3.4	3.4
Distance	1.2	1.3	1.2	1.2
Windspeed	SW 15-20.0		5.8	5.5
ℓ/w	2.1:1	1.8:1	2.1:1	2.1:1
Time	1600			
Area	756	756	700	756
Perimeter	4.0	4.0	4.1	4.1
Distance	1.4	1.4	1.4	1.3
Windspeed	SW 15		5.0	3.6
ℓ/w	1.8:1	1.6:1	2:1	1.8:1



Fire size and shape at 1400 hours, 4/18/65.
Fan shape suggests some wind variability.
Measured fire size is 40 acres.



Fire size and shape at 1430 hours, 4/18/65.
Measured fire size is 243 acres.

Fire size and shape at 1500 hours.
Measured fire size is 485 acres.
Fastest spread rates have occurred.

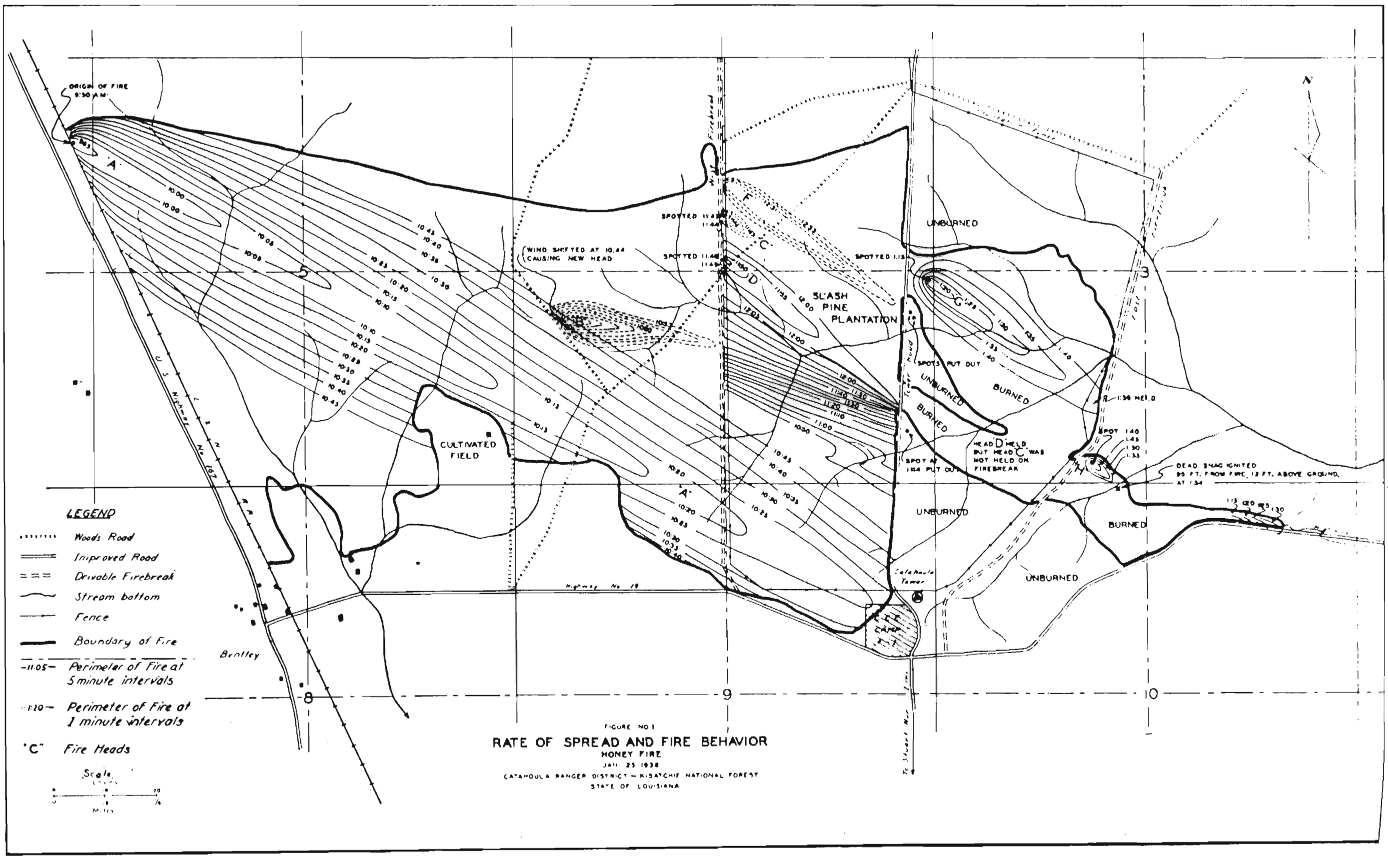
Fire size and shape at 1600 hours.
Measured fire size is 756 acres.

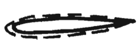
Figure 10.—The Hellgate Fire exhibited high spread rates with crowning and spotting. Passage of weather fronts after 1600 hours caused spread in several directions, eliminating further use of the fire shape model, April 18, 1965. Dotted fire shapes are computer estimates and solid lines are observations.

Example 3:
The Honey Fire of January 25, 1938, was documented by Olsen (1941) with detailed plotting of the perimeter during the first hour. The fire burned predominantly in broomsedge (*Andropogan* sp.) and other grasses to provide a uniform, extremely dense fuel bed. Wind measurements were made at 3.5 ft (1.1 m) above the ground and indicated a maximum wind of 9.9 mi/h (15.8 km/h). However, the ℓ/w ratios for the period of 1005 to 1025 indicate windspeeds on the fire of 19 to 20 mi/h (30.4 to 32.0 km/h) were present. The difference could be due to variability in the wind or may be due to the fuels having a larger surface area to volume ratio than the ponderosa pine needles fuel bed used by Fons. The fire shapes in figure 11 were closely matched by the double ellipse equations. Note in figure 7 that the fire accelerated during the first 10 minutes, and then stabilized at a nearly constant ℓ/w ratio. Spot fires later in the burn period show similar fire shapes. Spot fire "F" that burned just after 1230 had a ℓ/w ratio at 1233 of 6.1:1, which from figure 6, or equation 17, corresponds to an average wind on the fire of about 16 mi/h (25.6 km/h). This is within 2 mi/h (3.2 km/h) of the maximum wind between 1220 and 1233 hours. An hour later spot fire "G" developed a shape with a ℓ/w ratio of 3.5:1, which indicates a wind decrease to about 11 mi/h (17.6 km/h). The narrative indicates these spot fires in the eastern portion of the burned area were in blackjack oak (*Quercus marilandica*) stand with less fire-carrying fuel. The fire was contained in this area at 1443 hours.

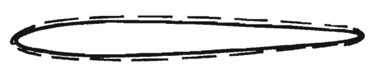
Example 3. The Honey Fire of Louisiana burned through broomsedge (*Andropogon* sp.) and other grasses on January 25, 1983.

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	0955 hours			
Area	.9 acres	.9	1.4	.9
Perimeter	.2 miles	.2	.2	.2
Distance	.1 miles	.1	.1	.1
Windspeed	6.7 mi/h		6.7	8.4
ℓ/w	2.7:1	3.4:1	2.3:1	2.7:1
Time	1000			
Area	10.2	10.2	31.3	10.2
Perimeter	.9	.9	1.0	.8
Distance	.4	.4	.4	.4
Windspeed	9.9		9.9	19
ℓ/w	8.4:1	9.3:1	3.1:1	8.4:1
Time	1005			
Area	27	27	96	27
Perimeter	1.5	1.5	1.7	1.5
Distance	.7	.8	.7	.7
Windspeed	9.9		9.9	21
ℓ/w	10.5:1	10.5:1	3.1:1	10.5:1
Time	1010			
Area	60.5	60.5	254	60.5
Perimeter	2.4	2.4	2.8	2.3
Distance	1.2	1.2	1.2	1.1
Windspeed	9.9		9.9	21.1
ℓ/w	10.6:1	12.4:1	3.1:1	10.6:1
Time	1015			
Area	109	109	462	109
Perimeter	3.3	3.3	3.8	3.1
Distance	1.6	1.6	1.6	1.5
Windspeed	9.9		9.9	21.2
ℓ/w	10.7:1	12.4:1	3.1:1	10.7:1
Time	1020.0			
Area	167.0	167	640	167
Perimeter	3.9	3.9	4.4	3.6
Distance	1.9	1.9	1.9	1.8
Windspeed	9.9		9.9	20.3
ℓ/w	9.7:1	11.3:1	3.1:1	9.7:1
Time	1025			
Area	250.8	250.8	911.6	250.8
Perimeter	4.6	4.6	5.3	4.4
Distance	2.2	2.3	2.2	2.2
Windspeed	9.9		9.9	20.2
ℓ/w	9.6:1	10.5:1	3.1:1	9.6:1

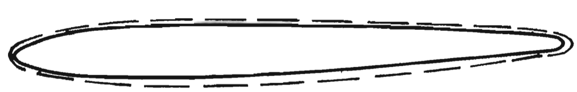




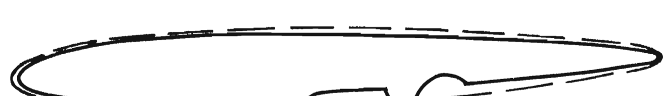
Fire size and shape ten minutes, 1000 hrs., after fire start. Size is just over 10 acres and l/w ratio is above 8:1.



Fire size and shape twenty minutes, 1010 hrs., after fire start. Size is just over 60 acres and l/w ratio over 10:1.



Fire size and shape thirty minutes, 1020 hrs., after fire start. Size is just over 167 acres and l/w ratio is under 10:1.



Fire size and shape thirty-five minutes, 1025 hrs., after fire start. Size is just over 250 acres and the l/w ratio is under 10:1.

—— **ACTUAL FIRELINE**

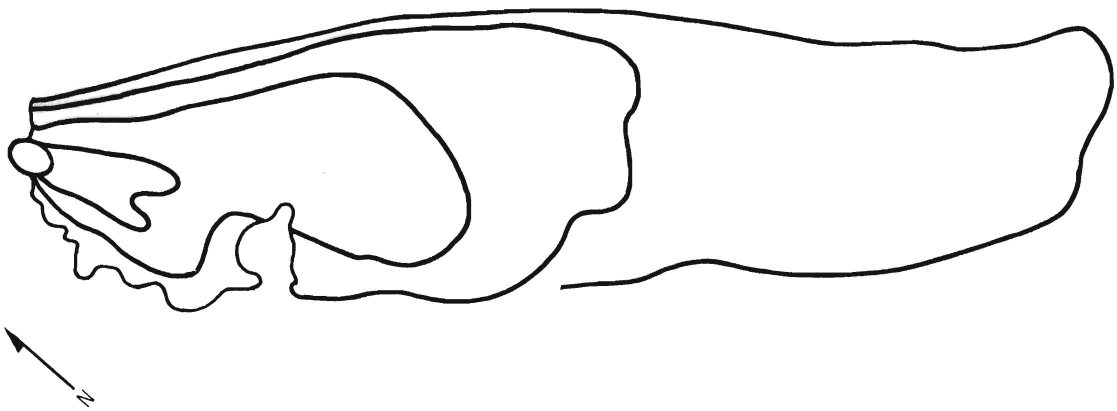
— — **MODEL OUTPUT**

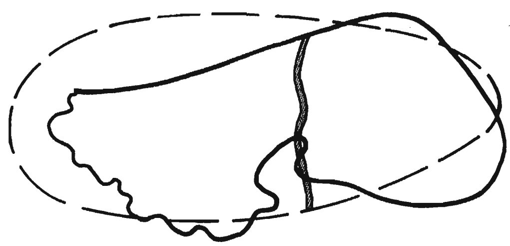
Figure 11.—The Honey Fire, taken from "An analysis of the Honey Fire" by C. F. Olsen, Fire Control Notes, vol. 5, No. 4, October 1941.

Example 4:
The Wandilo Fire of April 5, 1958, in South Australia near Mt. Gambier was documented by McArthur and others (1966). A "fire storm" developed and caused the death of eight firefighters. The fire started in tea tree (*Leptospermum* spp.) scrub as a surface fire with no crowning, but entered an unthinned, unpruned cluster pine (*Pinus pinaster*) plantation about 1230 and started crowning and spotting. The wind reduction was from about 20 mi/h (32.0 km/h) at 33 ft (10 m) to 7.6 mi/h (12.2 km/h). This reduction suggests the fire was predominantly a scrub fire, which is indicated in the narrative. The fire moved into a Monterey pine (*Pinus radiata*) stand and proceeded at a somewhat slower rate with occasional crowning. The fire area and perimeter at this time suggest a slower growth rate with winds on the fire of 6 to 7 mi/h (9.6 to 11.2 km/h). The wind at 33 ft (10 m) was averaging 22 mi/h (35.2 km/h) so the reduction factor was 0.31. The general area of the fire storm contained stands of die-back timber and heavier fuel accumulation that facilitated crowning. This allowed crown fires to develop, and downwind spotting caused almost an area ignition. It is difficult to say whether the fire advanced by spotting or crowning, but the fire shape by the double ellipse model fits reasonably well with a wind on the fire of about 12.5 mi/h (20.0 km/h). The reduction factor for 23 mi/h (36.8 km/h) to 12.5 mi/h (20.0 km/h) is 0.54, which agrees with what would be expected just above a vegetation layer as compared to the wind 33 ft (10 m) above the layer. The elliptical fire shapes for 1330, 1500, and 1530 hours are presented in figure 12.

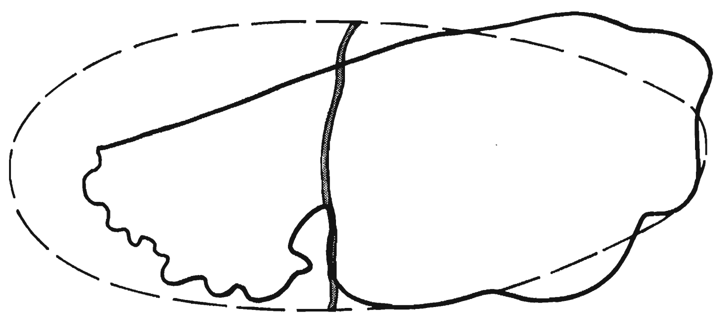
Example 4. The Wandilo Fire of April 5, 1958, in South Australia started in tea tree scrub as a surface fire, but after entering unthinned, unpruned pine plantations it became a crown fire.

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	1140 hours			
Area	8.0 acres	8	13.5	8
Perimeter	.3 miles	.3	.5	.5
Distance	.2 miles	.1	.1	.2
Windspeed	NNW 17.0 mi/h		1.0	7.75
ℓ/w	2.6:1	1.3:1	1.5:1	2.6:1
Time	1230			
Area	114	114	144	114
Perimeter	2.2	2.2	2.3	1.8
Distance	1.0	1.0	1.0	.7
Windspeed	NWN 20		12.3	8.8
ℓ/w	2.8:1	5:1	4:1	2.8:1
Time	1330			
Area	381.	381	381	381
Perimeter	3.9	3.9	4.0	3.2
Distance	1.5	1.8	1.8	1.2
Windspeed	NW 17-22		13.8	7.6
ℓ/w	2.5:1	4.4:1	4.7:1	2.5:1
Time	1500			
Area	900	900	986	900
Perimeter	5.9	5.9	6.2	4.8
Distance	2.0	2.8	2.8	1.8
Windspeed	NW 21-23		12.8	6.8
ℓ/w	2.3:1	4.2:1	4.2:1	2.3:1
Time	1530			
Area	1,547	1,547	3,016	1,547
Perimeter	8.4	8.4	9.7	7.6
Distance	3.4	4.0	4.0	3.4
Windspeed	NW 23		10	12.4
ℓ/w	4.1:1	5.3:1	3.2:1	4.1:1
Time	2230.0			
Area	3,383.0	3,383	3,383	—
Perimeter	14.5	14.5	9.5	—
Distance	4.6	7.1	3.7	—
Windspeed	14.0		7.7	—
ℓ/w	2.5:1	7.5:1	2.5:1	—





Fire size and shape at 1330 hours with over 380 acres burned and a l/w ratio of 2.5 :1.



Fire size and shape at 1500 hours with 900 acres burned and a l/w ratio of 2.3 :1.

Fire size and shape at 1530 hours with 1547 acres burned and a l/w ratio of 4.1 :1.

Figure 12.—The Wandilo Fire in South Australia on April 5, 1958, produced severe spotting that phased properly with the winds to initiate a "fire-storm" shortly after 1500 hours.

Example 5:
The Sundance Fire of September 2, 1967, was reported by Anderson (1968) and illustrates a wind-driven fire moving from a fire line 3 to 4 mi (6.4 to 9.6 km) wide. The fire size and shape were examined at 1500, 1700, 1900, 2100, and after 2300 hours (fig. 13). The fire shapes do not fit well because the fire on this day began its spread from a line rather than a point. Spotting began some time near 1500 hours and continued through at least 2000 hours. Crowning started after 1500 and played a significant role after 1800 hours. Midflame winds on the fire front began exceeding 12 mi/h (19.3 km/h) at about 1800 hours and appear to have been near 16 to 17 mi/h (27.4 km/h) until after 2300 hours. Up through 1700 hours the fire was generally a surface and shrub fire and the wind reduction coefficient was 0.18, indicating overstory material was slowing the wind's movement. After 1700 the wind reduction was less because the fire spread was more through the shrub and tree crown material. The earlier fire advance to the west is not included.

Even though the double ellipse model doesn't match a line fire during its intermediate growth stages, a projection of the final size and shape after an extended run appears possible. Figure 13 shows this in the projection of the size after 2300 on September 1, 1967. The average wind on the flame used to estimate a total run, must consider the windspeed variation over time. It also must consider how the free-stream windspeed above the vegetation surface is reduced as the location of the flame front is reached. In this case the average windspeed was 11.5 mi/h (18.5 km/h). For fires with wide fire fronts, it is probably better to represent each edge of the fire as a point source, project the fire advance from these points, and inscribe the combined area.

Other considerations that can be made with the material developed on fire size and shape include estimation of the backing and flanking rates of spread, interpreting the change in size and shape over time, and using the quadratic equation to determine any one of the three properties defining size and shape knowing the other two.

In appendix II, the Freeman Lake Fire in Idaho illustrates a fast moving crown fire that covered 20,000 acres (8 094 ha) in 12.5 hours (example 8). Jemison (1932) reports that by the morning of August 4, 1931, the fire had covered an area 5 mi wide and 11.5 mi long (8.0 km by 18.5 km), with some spot fires 15 mi (24.1 km) from the origin. Use of the double ellipse model and the wind reduction concepts suggests this fire had a ℓ/w ratio of 2.3:1 for an average wind on the fire of 6.8 mi/h (10.9 km/h). The wind measured at the 150-ft (45.7-m) level at Priest River Experiment Forest was an average of 14.9 mi/h (23.8 km/h), so the wind reduction factor was 0.46, which is reasonable for the upper surface of the vegetation layer or tree crowns. Solving the quadratic equation for perimeter yielded a value of 1,800 chains (27.3 mi or 43.7 km), which agreed with the double ellipse solution for an area of 20,000 acres (8 094 ha). Fires with similar rapid spread and growth have occurred in various regions of the United States. Jim Miller[5] notes that several fires in Wisconsin had the same features—the Brockway and Five Mile Tower Fires of 1977 and the Oak Lake Fire of 1980. The Mack Lake Fire in Michigan[6] has features of fire behavior that are like those of the above fires. Records of these types of fires will help evaluate the model of fire shape, (examples 6 and 7).

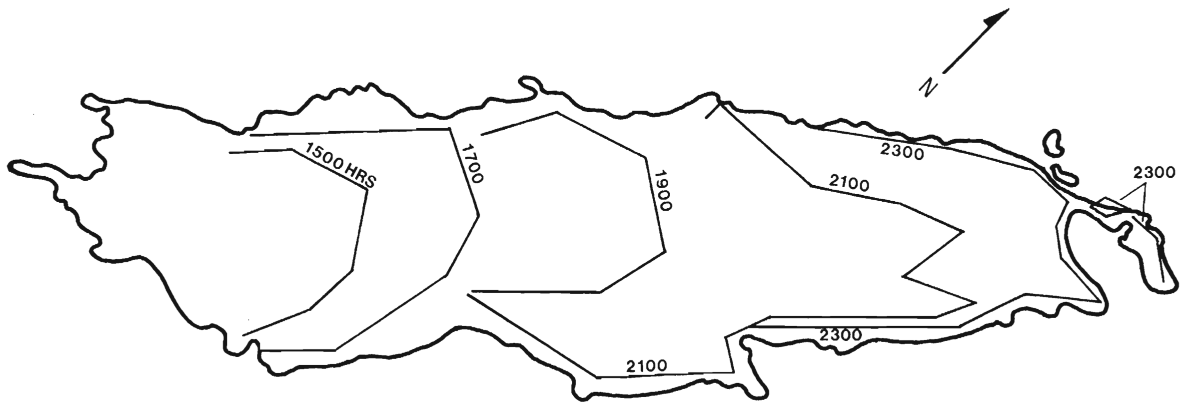
The Big Scrub Fire of 1935 on the Ocala National Forest in Florida— provides a data point at the high ℓ/w ratios shown in figure 7. This fire traveled 18 mi (29.0 km) in 3 hours and had an estimated area of 10,000 acres (4 048 ha). A wind shift resulted in another 25,000 acres (10 120 ha) burning before rains put it out. Winds were reported to be 60 mi/h (96.5 km/h) from the southeast, but the ℓ/w ratio computed from the quadratic equation, if the perimeter is estimated at 2 times the spread distance, was found to be 16:1. This corresponds to an average wind on the fire of 25 mi/h (40.2 km/h). The fire was reported as a crown fire in sand pine, *P. clausa*. The calculated wind reduction factor of 0.42 indicates the average wind was exerted at some point near the upper surfaces of the tree canopy, according to Albini and Baughman's (1979) presentation on estimating windspeed, Big Scrub Fire is given in example 9, Appendix II.

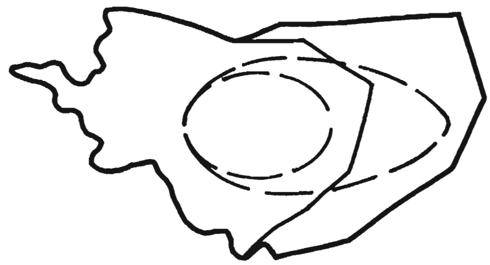
Interestingly, the windspeed of 25 mi/h (40.2 km/h) is essentially the windspeed McArthur (1966) found associated with the maximum rate of spread in grassland fuels. The above windspeed at the 33-ft (10-m) height above the vegetation was found to be associated with fire shapes having ℓ/w ratios of 6:1. If the grass is 1 ft (0.3 m) deep and the flame height is 1 to 1.5 ft (0.3 to 0.5 m) above the upper surface of the grass, the average wind on the flame is computed to be between 15 and 17 mi/h (24.1 and 27.4 km/h). This ℓ/w ratio and windspeed match closely equation 17 results (fig. 6).

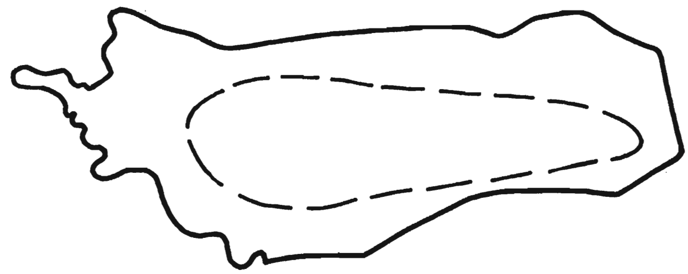
[5]Jim Miller, personal correspondence of October 26, 1981, on file at Northern Forest Fire Laboratory.
[6]"The Mack Lake Fire," by Al Simard and others, in preparation.
[7]From notes by Ocala National Forest Ranger John W. Cooper.

Example 5. The Sundance Fire of September 1, 1967, in Idaho had burned over 6,000 acres before starting its major run on this date. The fire burned through slash and understory shrub material initially. It became a running crown fire in the late afternoon and continued until nearly midnight.

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	1300.0 hours			
Area	6,202.0 acres	6,202	—	—
Perimeter	16.2 miles	16..2	—	—
Distance	— miles	7.7	—	—
Windspeed	SW 20.0 mi/h	—	—	—
ℓ/w	1:3.1	4.8:1	—	—
Time	1500			
Area	9,496	9,496	10,564	1,510
Perimeter	18.4	18.4	19.5	5.8
Distance	1.9	8.6	8.6	1.9
Windspeed	SW 24	—	11.9	4
ℓ/w	1.8:1	3.9:1	3.9:1	1.8:1
Time	1700			
Area	15,052	15,052	16,903	5,589
Perimeter	22.7	22.7	24.1	11.5
Distance	4	10.5	10.5	4
Windspeed	SW 29		11.4	5.2
ℓ/w	2.0:1	3.7:1	3.7:1	2.0:1
Time	1900			
Area	22,145	22,145	24,118	6,627
Perimeter	29.6	29.6	31.0	16.5
Distance	7.5	14.0	14.0	7.5
Windspeed	SW 37	—	13.2	13.6
ℓ/w	4.6:1	4.4:1	4.4:1	4.6:1
Time	2100			
Area	35,039	35,039	36,848	15,191
Perimeter	42.7	42.7	43.9	28.0
Distance	13.2	20.7	20.7	13.2
Windspeed	SW 45	—	16.2	16.1
ℓ/w	6.1:1	6.2:1	6.2:1	6.1:1
Time	After 2300			
Area	53,227	53,227	55,025	22,581
Perimeter	54.9	54.9	56.1	35.5
Distance	16.8	26.8	26.8	16.9
Windspeed	SW 49-52		17.1	16.9
ℓ/w	6.6:1	6.8:1	6.8:1	6.6:1

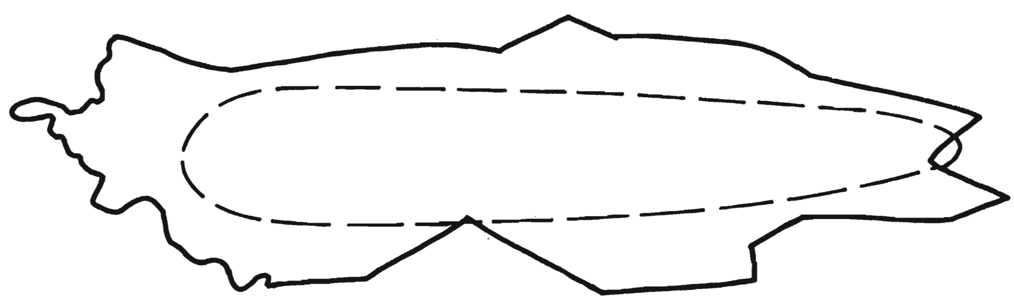




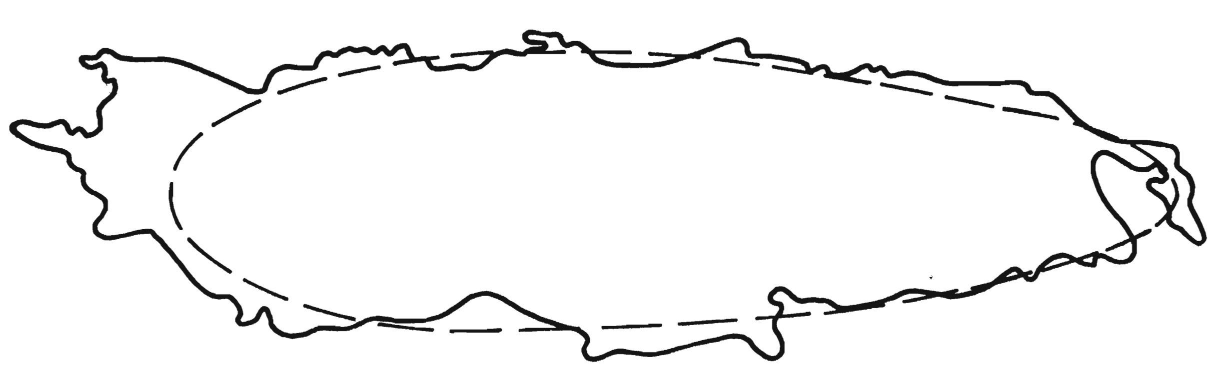


Fire size and shape at 1500 hours, just under 9500 acres. At 1700 hours, just over 15,000 acres.

Fire size and shape at 1900 hours, approximately 22,145 acres.



Fire size and shape at 2100 hours with area of over 35,000 acres.



Fire size and shape after 2300 hours with area near 53,000 acres.

Figure 13.—The Sundance Fire of September 1, 1967, started its run on a wide front such that projection from a single point appears too narrow. However, using the total spread distance and an average wind speed of 11.5 mi/h (18.5 km/h), shows a good fit to fire size after 2300 hours.

CONCLUSIONS

The double ellipse formulation developed from Fons' wind tunnel data is providing useful estimates of fire size, shape, and other physical dimensions for field use. The development allows the fire size and shape to be estimated from the downwind distance traveled in a specified time and the average wind influencing the fire. Equations are provided that can express the backing and flanking fire rates of spread so fires that have grown from a spot fire to the line fire or to an irregular-shaped area fire can be projected. This allows the opportunity for projecting fire growth from existing fire lines.

The accuracy of the equations for area and perimeter is within 10 percent of the area and perimeter determined graphically for Fons' fire sizes and shapes. The greatest uncertainty is in selecting the windspeed and the forward rate of spread. Since upper winds and terrain effects must be considered along with the vegetative cover to assess wind, estimates of windspeed will have considerable uncertainty about them. In addition, wind is an input to predicting the rate of spread of a fire. However, the use of historical fire data may help determine the resolution that is possible for field situations. If we assume that the model is accurate, working backward from fire size and spread distances, the average winds on the fire can be estimated. Then fuel models and fire spread mathematical equations can be exercised to provide comparisons to field data. This way confirmation of developed models can be accomplished and correlations developed to allow updating assumptions made in the formulations of equations. Thus, fire size and shape equations may be useful research tools as well as operational aids.

Other uses have been evaluated, including use of the model with historical fire, fuel, and weather records to establish the rate of spread and wind necessary to have produced what is documented. This allows an examination of the wind reduction model (Albini and Baughman 1979) by establishing the wind at midflame height and an estimate of the free-stream winds 20 ft (6.1 m) or more above the vegetation cover. These values can be compared to predicted or observed National Weather Service windspeeds and winds measured at the fire.

The rate of spread necessary to produce the size and shape of the fire can be tested against fire spread models and the various fuel models to determine if any of the fuel models produce predicted values similar to those measured. If none of the fuel models provides a rate of spread as fast as the observed/recorded field documentation, the threshold where spotting is contributing to fire growth can be established. If one or more fuel models equal or exceed the observed rate of spread, fuel model representativeness should be examined.

Either a double ellipse or a simple ellipse fire shape can be used with the equations, and little difference in fire size (acres), perimeter, or fire shape is apparent. However, the most realistic representation seems to be the double ellipse. With either model there will be an error if a backing fire is not possible. The model assumes there is a backing portion to the fire and would overestimate the area and perimeter.

Historical fire data and maps are being assembled to more thoroughly analyze the double ellipse fire shape model; these will be reported later. Weather and fuel data will be acquired so other models can also be tested. Crowning situations can be defined by the wind reduction coefficient needed to match the observed behavior. Investigations on these will complement other work that is addressing the problem of modeling crown fires.

PUBLICATIONS CITED

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; 1976a. 92 p.

Albini, Frank A. Computer-based models of wild land fire behavior: a user's manual. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1976b. 68 p.

Albini, Frank A.; Baughman, R. G. Estimating windspeeds for predicting wild land fire behavior. Res. Pap. INT-221. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 12 p.

Albini, Frank A.; Chase, Carolyn H. Fire containment equations for pocket calculators. Res. Note INT-268. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 17 p.

Albini, Frank A.; Korovin, G. N.; Goravaya, E. H. Mathematical analysis of forest fire suppression. Res. Pap. INT-207. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1978. 19 p.

Anderson, Hal E. Sundance Fire: an analysis of fire phenomena. Res. Pap. INT-56. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1968. 39 p.

Banks, Wayne G. A table for checking the reasonableness of entries on fire report forms. Fire Control Notes 24(3): 76–80; 1963.

Bauneister, Theodore, ed. Mark's mechanical engineer's handbook, 6th ed. New York: McGraw-Hill; 1958. Bratten, Frederick W. Containment tables for initial attack on forest fires. Fire Tech. 14(4): 297–303; 1978.

Brown, A. A. Guides to the judgment in estimating the size of a fire suppression job. Fire Control Notes 5(2): 89–92; 1941.

Brown, A. A.; Davis, Kenneth P. Forest fire: control and use, 2d ed. New York: 1973. 686 p.

Cargill, Gary E. Table speeds fire spread estimates. Fire Control Notes 31(2): 16; 1970.

Cheney, N. P.; Bary, G. A. V. The propagation of mass conflagrations in a standing eucalypt forest by the spotting process. In: Proceedings, 1969 mass fire symposium; Canberra, Australia. Maribyrnong, Victoria, Australia: Defense Standards Laboratory; 1969. 18 p.

Curry, J. R.; Fons, W. L. Rate of spread of surface fires in the ponderosa pine type of California. J. Agric. Res. 57(4): 239–267; 1938.

Fons, Wallace T. Analysis of fire spread in light forest fuels. J. Agric. Res. 72(3): 93–121; 1946.

Hanson, E. Arnold. Man-hours of work required to construct varying lengths of line under different resistance-to-control classes. Fire Control Notes 5(2): 84–88; 1941.

Hawley, Ralph C.; Stickel, Paul W. Forest protection. New York: John Wiley and Sons, Inc.; 1948. 355 p.

Hirsch, Stanley N. Project Fire Scan—summary of 5 years' progress in borne infrared fire detection. In: Proceedings, 1968 5th symposium on remote sensing of environment. Ann Arbor, MI: University of Michigan; 1968: 447–457.

Hirsch, Stanley N.; Bjornsen, Robert L.; Madden, Forrest H.; Wilson, Ralph A. Project Fire Scan fire mapping. Final report, April 1962 to December 1966. Res. Pap. INT-49. Ogden, UT:
U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1968. 49 p.

Hornby, L. G. Fire control planning in the Northern Rocky Mountain region. Progress Report No. 1. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1936. 179 p.

Jemison, George M. Meteorological conditions affecting the Freeman Lake (Idaho) fire. Monthly Weather Rev. 60(1): 1–2; 1932.

Klukas, Richard W. Control burn activities in Everglade National Park. In: Proc. Tall Timbers Fire Ecol. Conf. 12: 397–425; 1972.

McArthur, A. G. Weather and grassland fire behavior. Leafl. No. 100, P.D.C. 431.1–431.6. Canberra, Australia: Forest Research Institute; 1966. 21 p.

McArthur, A. G.; Douglas, D. R.; Mitchell, L. R. The Wandilo Fire, April 5, 1958. Fire behavior and associated meteorological and fuel conditions. Leafl. No. 98. Canberra, Australia: Forest Research Institute, Forestry and Timber Bureau; 1966. 32 p.

Mitchell, J. A. Rule of thumb for determining rate of spread. Fire Control Notes 20: 395–396; 1937.

Olson, C. F. An analysis of the Honey Fire. Fire Control Notes 5(4): 161–178; 1941.

Peet, G. B. The shape of mild fires in Jarrah forest. Austr. For. 31(2): 121–127; 1967.

Pirsko, Arthur R. Alinement chart for perimeter increase of fires. Fire Control Notes 22(1): 1–4; 1961.

Puckett, John V.; Johnston, Cameron M.; Albini, Frank A.; Brown, James K.; Bunnell, David L.; Fischer, William C.; Snell, J. A. Kendall. User's guide to debris prediction and hazard appraisal, revised. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region; 1979.

Rothermel, Richard C. A mathematical model for predicting fire spread in wild land fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972. 40 p.

Simard, A.; Young, A. AIRPRO, an airtanker productivity computer simulation model, the equations (documentation). Inf. Rep. FF-X-66. Ottawa, Ontario: Department of Fisheries and the Environment, Canadian Forestry Service, Forest Fire Research Institute; 1978.

Storey, Theodore G. FOCUS: a computer simulation model for fire control planning. Fire Technology 8(2): 91–103; 1972. Boston, MA: National Fire Protection Association.

Taylor, Dee F.; Williams, Dansy T. Meteorological conditions of the Hellgate Fire. Res. Pap. SE-29. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1967. 12 p.

Van Gelder, Randall J. A fire potential assessment model for brush and grass fuels. Fire Management Notes, Summer 1976: 14–16.

Van Wagner, C. E. A simple fire-growth model. For. Chron. 4(2): 103–104. 1969.

Wade, Dale D.; Ward, Darold E. An analysis of the Air Force Bomb Range Fire. Res. Pap. SE-105. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1973. 38 p.

APPENDIX I.

Tabulation of Area and Perimeter Estimates with the Ellipse Model Prepared by Williams and Duft for the S-390 Fire Behavior Training Package

Area Estimations for Point Source Fires:

Spread distance chains	Effective windspeed, mi/h									
	1	3	5	7	9	11	13	15	17	19
	Acres									
1	.1	.1	.1	00	00	00	00	00	00	00
2	.5	.3	.3	.3	.2	.1	.1	.1	.1	00
3	1.1	.8	.6	.4	.3	.3	.2	.2	.1	.1
4	1.9	1.4	1	.8	.6	.5	.4	.3	.2	.2
5	2	2	1.6	1.2	.9	.7	.6	.5	.4	.3
6	4	3	2	1.7	1.3	1.1	.8	.7	.5	.4
7	5	4	3	2	1.8	1.4	1.1	.9	.7	.6
8	7	5	4	3	2	1.9	1.5	1.2	.9	.7
9	9	6	5	3	3	2	1.9	1.5	1.2	.9
10	11	8	6	4	3	2	2	1.8	1.5	1.2
11	14	10	7	5	4	3	2	2	1.8	1.4
12	17	12	9	6	5	4	3	2	2	1.7
13	20	14	10	8	6	4	3	3	2	2
14	23	16	12	9	7	5	4	3	2	2
15	26	19	14	10	8	6	5	4	3	2
16	30	21	16	12	9	7	5	4	3	2
17	34	24	18	14	10	8	6	5	4	3
18	38	27	20	15	12	9	7	5	4	3
19	42	30	23	17	13	10	8	6	5	4
20	27	34	25	19	14	11	9	7	5	4
21	52	37	28	21	16	12	10	8	6	5
22	57	41	30	23	18	14	11	8	7	5
23	62	45	33	25	19	15	12	9	7	6
24	68	49	36	27	21	16	13	10	8	6
25	74	53	39	30	23	18	14	11	9	7
26	80	57	43	32	25	19	15	12	9	7
28	92	67	50	38	29	22	18	14	11	9
30	106	77	57	43	33	26	20	16	13	10
32	121	87	65	49	38	29	23	18	14	11
34	137	99	73	56	43	33	20	21	16	13
36	153	111	82	62	48	37	29	23	18	14
38	171	123	92	70	54	42	33	26	20	16
40	189	137	102	77	59	46	36	29	23	18
42	209	151	112	85	66	51	40	32	25	20
44	229	166	123	93	72	56	44	35	28	22
46	250	181	135	102	79	61	48	38	30	24
48	273	197	147	111	86	67	53	42	33	26
50	296	214	159	121	93	73	57	45	36	28
52	320	231	172	131	101	79	62	49	39	31
54	345	250	186	141	109	85	67	53	42	33
56	371	269	200	152	117	91	72	57	45	36
58	398	288	214	163	125	93	77	61	48	38
60	426	308	229	174	134	105	82	65	52	41
62	455	329	245	186	143	112	88	70	55	44
64	485	351	261	198	153	119	94	74	59	47
66	516	373	277	211	163	127	100	79	63	50
68	548	396	295	224	173	135	106	84	67	53
70	580	420	312	237	183	143	112	89	71	56

Area Estimations for Point Source Fires (continued):

Spread distance chains	Effective windspeed, mi/h									
	1	3	5	7	9	11	13	15	17	19
	Acres									
72	614	444	330	251	194	151	119	94	75	59
74	649	469	349	265	205	160	126	99	79	63
76	684	495	368	280	216	169	133	105	83	66
78	721	521	388	295	227	178	140	111	88	70
80	758	549	408	310	239	187	147	116	92	73
82	797	576	429	326	251	196	154	122	97	77
84	836	605	450	342	264	206	162	128	102	81
86	876	634	471	358	276	216	170	135	107	85
88	917	664	494	375	290	226	178	141	112	89
90	960	694	516	392	303	237	186	147	117	93
92	1003	726	540	410	316	247	195	154	122	97
94	1047	758	563	428	330	258	203	161	128	102
96	1092	790	588	446	345	269	212	168	133	106
98	1138	823	612	465	359	281	221	175	139	110
100	1185	857	638	484	374	292	230	182	145	115
105	1306	945	703	534	412	322	254	201	159	127
110	1434	1038	772	586	453	354	278	220	175	139
115	1567	1134	843	641	495	386	304	241	191	152
120	1706	1235	918	698	539	421	331	262	208	166
125	1852	1340	997	757	585	457	360	285	226	180
130	2003	1449	1078	819	632	494	389	308	245	195
135	2160	1563	1163	883	682	533	420	332	264	210
140	2323	1681	1250	950	734	573	451	357	284	226
145	2492	1803	1341	1019	787	615	484	383	304	242
150	2667	1930	1435	1091	842	658	518	410	326	259
155	2847	2061	1533	1165	899	703	553	438	348	277
160	3034	2196	1633	1241	958	749	590	467	371	295
165	3227	2335	1737	1320	1019	796	627	496	394	314
170	3425	2479	1844	1401	1082	845	666	527	419	333
175	3630	2627	1954	1485	1146	896	705	559	444	353
180	3840	2779	2067	1571	1213	948	746	591	470	374
185	4057	2936	2184	1659	1281	1001	788	624	496	395
190	4279	3097	2303	1750	1352	1056	832	658	523	417
195	4507	3262	2426	1844	1424	1112	876	694	551	439
200	4741	3431	2552	1939	1498	1170	921	730	580	462
210	5227	3783	2814	2138	1651	1290	1016	804	639	509
220	5737	4152	3086	2347	1812	1416	1115	883	702	559
230	6720	4538	3375	2565	1981	1547	1219	965	767	611
240	6827	4941	3675	2793	2157	1685	1327	1051	835	665
250	7408	5362	3986	3031	2340	1828	1440	1140	906	722
260	8013	5799	4313	3278	2531	1978	1558	1233	980	780
270	8641	6254	4652	3535	2730	2133	1680	1330	1057	842
280	9293	6726	5003	3802	2936	2294	1807	1431	1137	905
290	9969	7215	5366	4078	3149	2460	1938	1535	1219	971
300	10668	7721	5743	4364	3370	2633	2074	1642	1305	1039

NOTE; Interpolations will become less accurate at the lower end of this table due to the greater spans between spread distance values and the non-linear equations used to produce the table. Your interpolated values may differ somewhat from those given by the TI-59 calculator with CROM.

APPENDIX I, continued.

Perimeter Estimations for Point Source Fires:

Spread distance chains	Effective windspeed, mi/h 1	3	5	7	9	11	13	15	17	19
	Acres									
1	3	3	3	2	2	2	2	2	2	2
2	7	6	6	5	5	5	4	4	4	4
3	11	10	9	8	7	7	7	7	6	6
4	15	13	12	11	10	10	9	9	9	9
5	19	17	15	14	13	12	12	11	11	11
6	23	20	18	16	15	15	14	14	13	13
7	27	23	21	19	18	17	17	16	16	16
8	31	27	24	22	21	20	19	19	18	18
9	35	30	27	25	23	22	21	21	20	20
10	39	34	30	28	26	25	24	23	23	23
11	43	37	33	31	29	27	26	26	25	25
12	47	41	36	33	31	30	29	28	27	27
13	50	44	39	36	34	32	31	30	30	29
14	54	47	43	39	37	35	34	33	32	32
15	58	51	46	42	39	37	36	35	34	34
16	62	54	49	45	42	40	39	38	37	36
17	66	58	52	48	45	42	41	40	39	39
18	70	61	55	50	47	45	43	42	41	41
19	74	65	58	58	50	47	46	45	44	43
20	78	68	61	56	52	50	48	47	46	46
21	82	71	64	59	55	53	51	49	48	48
22	86	75	67	62	58	55	53	52	51	50
23	90	78	70	64	60	58	56	54	53	52
24	94	82	73	67	63	60	58	57	55	55
25	98	85	76	70	66	63	60	59	58	57
26	101	88	79	73	68	65	63	61	60	59
28	109	95	86	79	74	70	68	66	65	64
30	117	102	92	84	79	75	73	71	69	69
32	125	109	98	90	84	80	78	76	74	73
34	133	116	104	96	90	85	82	80	79	78
36	141	123	110	101	95	90	87	85	83	82
38	148	130	116	107	100	95	92	90	88	87
40	156	136	122	112	105	101	97	95	93	92
42	164	143	129	118	111	106	102	99	97	96
44	172	150	135	124	116	111	107	104	102	101
46	180	157	141	129	121	116	112	109	107	105
48	188	164	147	135	127	121	117	114	111	110
50	196	171	153	141	132	126	121	118	116	115
52	203	177	159	146	137	131	126	123	121	119
54	211	184	165	152	143	136	131	128	125	124
56	219	191	172	158	148	141	136	133	130	128
58	227	198	178	163	153	146	141	137	135	133
60	235	205	184	169	158	151	146	142	139	138
62	243	212	190	175	164	156	151	147	144	142
64	250	219	196	160	169	161	156	152	149	147
66	258	225	202	186	174	166	160	156	153	151
68	266	232	208	192	180	171	165	161	158	156
70	274	239	215	197	185	176	170	166	163	161

Perimeter Estimations for Point Source Fires (continued):

Spread distance chains	Effective windspeed, mi/h 1	3	5	7	9	11	13	15	17	19
	Acres									
72	282	246	221	203	190	181	175	171	167	165
74	290	253	227	209	196	186	180	175	172	170
76	297	260	233	214	201	191	185	180	177	174
78	305	266	239	220	206	197	190	185	181	179
80	313	273	245	225	211	202	195	190	186	184
82	321	280	251	231	217	207	199	194	191	188
84	329	287	258	237	222	212	204	199	195	193
86	337	294	264	242	227	217	209	204	200	197
88	344	301	270	248	233	222	214	209	205	202
90	352	308	276	254	238	227	219	213	209	207
92	360	314	282	259	243	232	224	218	214	211
94	368	321	288	265	249	237	229	223	219	216
96	376	328	294	271	254	242	234	228	223	220
98	384	335	301	276	259	247	289	232	228	225
100	392	342	307	282	264	252	243	237	233	230
105	411	359	322	296	278	265	256	249	244	241
110	431	376	337	310	291	277	268	261	256	253
115	450	393	353	324	304	290	280	273	268	264
120	470	410	368	338	317	303	295	285	279	276
125	490	427	383	353	331	315	304	297	291	287
130	509	444	399	367	344	328	317	308	303	299
135	529	462	414	381	357	341	329	320	314	310
140	548	479	430	395	370	353	341	332	326	322
145	568	496	445	409	384	366	353	344	338	333
150	588	513	460	423	397	378	365	356	349	345
155	607	530	476	437	410	391	378	368	361	356
160	627	547	491	451	423	404	390	380	373	368
165	646	564	506	466	437	416	402	392	384	379
170	666	581	522	480	450	429	414	404	396	391
175	686	599	537	494	363	442	426	415	408	402
180	705	616	552	508	476	454	439	427	419	414
185	725	633	568	522	490	467	451	439	431	425
190	744	650	583	536	503	479	463	451	443	437
195	764	667	599	550	516	492	475	463	454	448
200	784	684	614	564	529	505	487	475	466	460
210	823	718	645	593	556	530	512	499	489	483
220	862	753	675	621	582	555	536	522	513	506
230	901	787	706	649	609	581	560	546	536	529
240	940	821	737	677	635	606	585	570	559	552
250	980	855	767	706	662	631	609	594	583	575
260	1019	889	798	734	688	656	634	617	606	598
270	1058	924	829	762	715	682	658	641	629	621
280	1097	958	860	790	741	707	682	665	653	644
290	1136	992	890	819	768	732	707	689	676	667
300	1176	1026	921	847	794	757	731	713	699	690

NOTE: Interpolations will become less accurate at the lower end of this table due to the greater spans between spread distance values and the non-linear equations used to produce the table. Your interpolated values may differ somewhat from those given by the TI-59 calculator with CROM.

APPENDIX II

Notes

The five example fires cited previously (pages 8 through 19) and the four here (examples 6 through 9) have their critical values tabulated and compared to values computed for a simple ellipse using the quadratic equation approach, and for the double ellipse model using equations 2 through 9. The documented values of column 1 are obtained from reports and tables or transcribed from maps of fire growth. The perimeter, if not available, is estimated as 2.5 times the spread distance.

The simple ellipse column uses the area and perimeter values of column one in the quadratic equation (equation 13) to determine the major and minor semiaxes, a and b, of the ellipse. The total major axis dimension, 2a, is entered as the spread distance. The ration, a/b, is entered as the ℓ/w ratio.

The third column, for the double ellipse model, uses the spread distance of column 1 and applies the wind reduction factors (Albini and Baughman 1979) to the wind at 20 ft (6.1 m) to compute the average wind on the fire. These values are used with equations 2 through 9 to calculate the area, perimeter, and ℓ/w ratio values that are listed. The wind reduction factors are derived using descriptions of the fire behavior to estimate where the fire is burning into the fuel complex—surface, understory, or overstory, and from descriptions of vegetation types to determine the resistance to air movement.

The adjusted double ellipse of column 4 shows the best fit the model can make to the documented data. The ℓ/w ratio that is documented is used with figure 7 to estimate the average wind over the fire. This, along with the spread distance, is used to compute the area and perimeter of the fire. Minor adjustments to windspeed and/or spread distance may be made to improve the match to column one. This is an iterative process to try to provide insights to where the greatest uncertainties exist.

The dimensions used in the table are for spread distance in miles, windspeed in miles per hour, perimeter in miles, and area in acres. If figure 6 is used, area has to be expressed as the square of the unit used to measure the spread distance—for instance, if miles for distance, then square miles for area. Perimeter and spread distance must be measured in the same units.

Example 6. Wisconsin Fire Suppression Handbook Example, No Control. Time of event is 3 hours from start of fire. Fire is a crown fire moving over forested land, probably jack pine (*P. banksiana*).

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	3.0 hours			
Area	5,320.0 acres	5,320	5,969	5,320
Perimeter	14.0 miles	14.0	14.7	12.3
Distance	5.5 miles	6.6	6.6	5.0
Windspeed	— mi/h		12.5	8.7
ℓ/w	2.8:1	4.1:1	4.1:1	2.8:1
Time	4.0			
Area	11,200	11,200	12,560	11,200
Perimeter	20	20	21.2	18.1
Distance	7.8	9.3	9.3	7.4
Windspeed			11.9	9.1
ℓ/w	2.9:1	3.9:1	3.9:1	2.9:1

Example 7. Wisconsin Fire Suppression Handbook Example, Good Control. Time of event is 1 hour after fire start. Fire is a crown fire moving over forested land, probably jack pine (*P. banksiana*).

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	1.0 hours			
Area	460.0 acres	460	588	460
Perimeter	3.5 miles	3.5	4.6	3.4
Distance	1.4 miles	1.5	1.5	1.2
Windspeed	— mi/h		7.6	5.9
ℓ/w	2.2:1	2.6:1	2.5:1	2.2:1
Time	2.0			
Area	1,300.0	1,300	1,396	1,300
Perimeter	7.5	7.5	7.8	7.5
Distance	3.2		3.6	3.4
Windspeed			14.2	14.0
ℓ/w	4.9:1	5.0:1	4.9:1	4.9:1
Time	3.0			
Area	1,900.0	1,900	1,993	1,900
Perimeter	10.0	10	10.3	10.5
Distance	4.5	4.9	4.9	5.0
Windspeed	—		16.3	17.2
ℓ/w	6.9:1	6.2:1	6.2:1	6.9:1
Time	4.0			
Area	2,200	2,200	2,291	2,200
Perimeter	12.0	12	12.2	12.3
Distance	5.6	5.9	5.9	6.0
Windspeed			18.5	19.0
ℓ/w	8.4:1	7.9:1	7.9:1	8.4:1

Example 8. The Freeman Lake Fire in northern Idaho on August 3, 1931, started in a stand of young Douglas-fir interspersed with patches of brush and grass. All dead fuels were very dry with duff and slash moisture contents under 10 percent and as low as 4 to 5 percent.

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	1030.0 to 2300.0 hours			
Area	20,000.0 acres	20,000	34,000	20,005
Perimeter	N/A miles	22.5	29.4	22.6
Distance	11.5 miles	9	11	8.4
Windspeed	14.9 mi/h	—	6.8	6.8
ℓ/w	2.3:1	2.3:1	2.3:1	2.3:1

Example 9. The Big Scrub Fire occurred in the spring of 1935 in Florida from a burning stump on muck land, but moved quickly into the crowns of the sand pine (*P. clausa*).

Variable	Documented values	Simple ellipse values	Double ellipse values	Double ellipse adj. values
Time	N/A hours			
Area	10,000.0 acres	10,000	Winds	10,000
Perimeter	36.0 miles	36	exeed	36.1
Distance	18.0 miles	18.1	range of	18.0
Windspeed	SW 60.0 mi/h		model	2.5
ℓ/w	N/A	16:1		16.5

☆ U.S. GOVERNMENT PRINTING OFFICE: 1983—676-032/45 REGION No. 8

Anderson, Hal E. Predicting wind-driven wild land fire size and shape. Res. Pap. INT-305. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 26 p.

Documents the analysis of wind tunnel experiments on fire spread that produced a double ellipse concept of fire area growth. This provides ways of estimating size (area), shape (perimeter), and length to width ratio of a wind-driven wild land fire. The only inputs needed are estimates of the windspeed and the expected fire spread distance. Equations are available to estimate flank and backing fire rates of spread. Graphs show the relationship of wind to fire size and shape properties. Fire growth in terms of perimeter and area is available to aid fire management activities involving treatment or suppression.

KEYWORDS: fire growth, modeling, fire behavior

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)