ESTIMATING THE LENGTH-TO-BREADTH RATIO OF ELLIPTICAL FOREST FIRE PATTERNS[1]

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ABSTRACT.--An empirical relationship was derived between the ratio of total length to maximum width or breadth (L/B) of wind-driven forest fires on level terrain originating from a point source ignition and the international standard 10-m open wind (W). The relation is based on the wind component of the relative spread index in the Canadian fire-danger rating system. The resulting equation, a nonlinear regression exhibiting a rising curve of increasing slope ($L/B = 1.0 + 0.00120 W^{2.154}$), yields L/B equal to 1.0 at zero wind and $\gtrsim$ 6.5 at 50 km/h, the upper limit of application. Wind direction is assumed to remain fairly constant. Comparisons of predicted L/B values with actual observations extracted from experimental fires and well-documented wildfires in a variety of coniferous forests (n = 18) by and large show good agreement (r = 0.865). The L/B versus surface wind speed function is suitable for use inconjunction with a simple fire growth model for calculating the approximate size (area and perimeter length) of free-burning elliptical-shaped surface and crown fires spreading through fuel types with an overstory tree canopy, given the time elapsed and forward spread rate.

INTRODUCTION

The growth pattern of a forest fire developing from a single ignition source is governed largely by surface wind velocity. Provided that wind direction remains fairly constant, the general outline of wind-driven fires resemble an ellipse (fig. 1), or nearly so depending on fuel and terrain conditions. Assuming a roughly elliptical shape, it is possible to forecast approximate fire sizes, in very practical terms, on the basis of (1) the predicted forward rate of fire spread, (2) the lapsed time involved in the projection period, and (3) an estimate of the probable ratio of the fire's length to breadth (the shape factor) or elliptical eccentricity.

The primary purpose of this paper is to document the derivation and evaluation of the mathematical function for estimating the elliptical 'shape factor' of point ignition fires in standing timber fuel types contained in the 1984 interim edition of the Canadian Forest Fire Behavior Prediction (FBP) System (Lawson et al. 1985); the relation was used in a simple fire growth model to compute area and perimeter length. Also included is a summary of supporting/related background information and a review of other similar work.

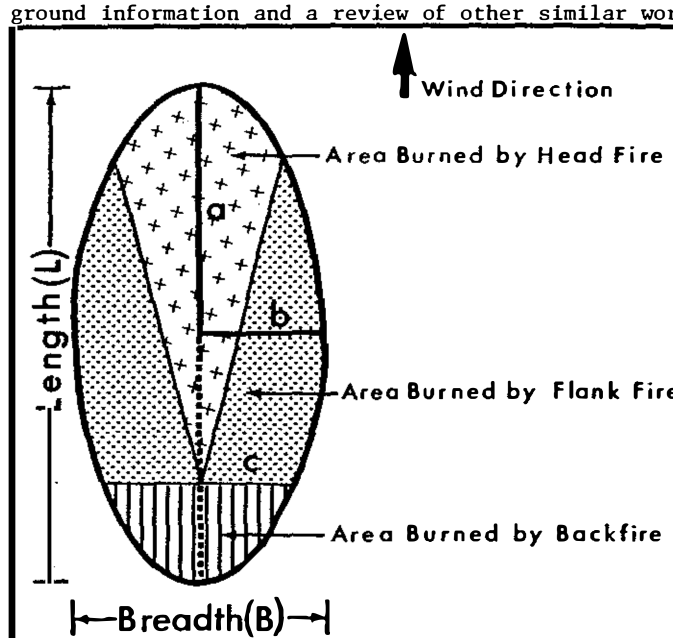

FIGURE 1.--Schematic diagram of a simple elliptical fire growth model (after Van Wagner 1969). The point of ignition is at the junction of the four area growth zones. For a definition of length-to-breadth ratio (L/B) refer to the text on the following page.

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A couple of preliminaries are in order before proceeding. The first concerns the fundamental properties of an elliptic fire shape. The two basic dimensions of an elliptical fire outline are its length and breadth (fig. 1). The 'shape factor' mentioned earlier is more commonly referred to as the length-to-breadth ratio or L/B. The term and corresponding symbol follow the usage found in the Australian rural fire literature (McArthur 1966, Luke and McArthur 1978, Cheney 1981, McArthur et al. 1982). The L/B is a ratio quantity determined by dividing the total fire length by the maximum fire width or breadth. For example, the fire ellipse illustrated in figure 1 has an L/B of about 2.0:1 or a 2.0 to 1 ratio. In this paper it would be simply stated as L/B = 2.0. This means that the elliptical-shaped fire is twice as long as it is wide. Note that ellipse with a ratio of unity (i.e., L/B = 1.0) is a circle (fig. 2). L/B is synonymous with "length-to-width" or "length/width" ratio (L/W, 1/w, or ℓ/ω), which is used almost exclusively in the United States (e.g., Sanderlin and Van Gelder 1977, Bunton 1980, Bratten et al. 1981, Anderson 1983, 1984, Simard et al. 1983). It does however differ from the "head-to-flank ratio" (h/f) used by Potter et al. (1981), which represents only about one-half of an ellipse (e.g., h/f ~ 4:1 $\simeq$ L/B ~ 2.0). Finally, the term "free-burning" used in this paper refers to a fire on which no work has been done to hinder or stop its spread. In other words, the suppression action, if any, has not restricted the fire's growth significantly below its free-burning potential size (Douglas 1966, McArthur et al. 1982).

FIRE GROWTH FROM A POINT IGNITION

The simplest fire pattern is that of a single ignition source, on flat terrain and under calm conditions, spreading out at an equal rate in all directions from its starting point in a more or less circular fashion, with the origin at approximately the center of the burned/burning area (fig. 2). As the elapsed time increases, the shape resembles less and less the circular form characteristic of an initiating fire without any wind or slope (e.g., Curry and Fons 1940, Valendik et al. 1978, de Mestre 1981). As wind and slope or their joint effects start to influence the fire's growth, it gradually assumes a roughly elliptical shape provided wind direction remains fairly steady. The description of the initial run made by the 1971 Little Sioux Fire in northeastern Minnesota represents a pertinent example (from Sando and Haines 1972):

> *The fire moved in a north-northeastern direction, and at approximately 1800 aerial observers reported that the burning area had the typical cigar shape of a fast-moving fire in flat topography ...*

In fire growth modeling, it has generally been assumed that directional variation in wind normally decreases with increasing speed (Stade 1967, Van Wagner 1969). Thus, the stronger the wind, the more narrow and elongated the elliptic fire shape (fig. 2). A perusal of the wind velocity literature (Baughman

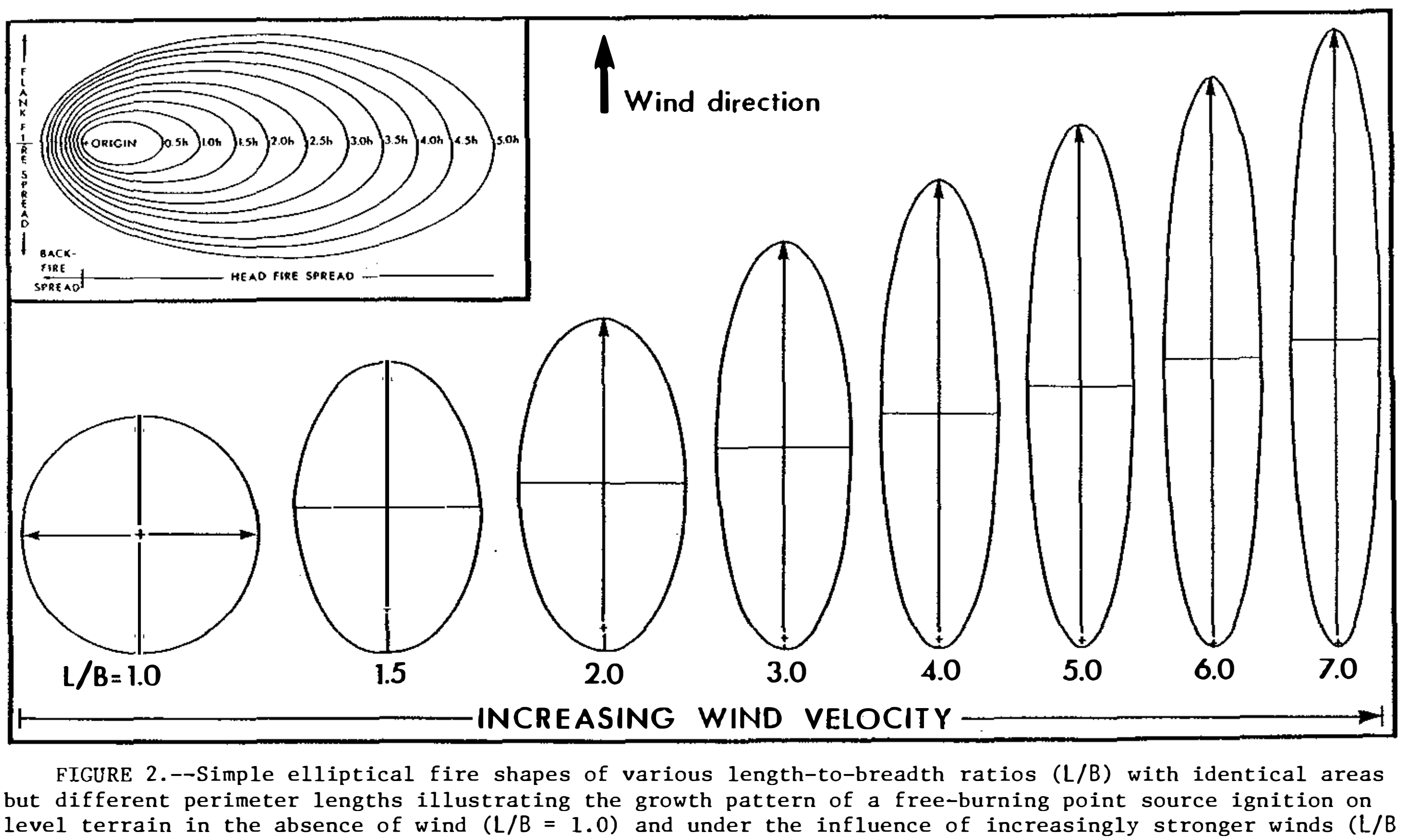

FIGURE 2.--Simple elliptical fire shapes of various length-to-breadth ratios (L/B) with identical areas but different perimeter lengths illustrating the growth pattern of a free-burning point source ignition on level terrain in the absence of wind (L/B = 1.0) and under the influence of increasingly stronger winds (L/B = 1.5 - 7.0). The cross (+) on each ellipse denotes the fire's origin or start. Note that the head fire and backfire spread distance has been scaled, as determined by the L/B, along each ellipse's major axis of length. Insert: A series of "nested" ellipses illustrating the area and perimeter of an idealized free-burning elliptical shaped wildland fire, at one-half hour intervals, spreading at a constant rate following an initial period of time required after ignition to achieve an equilibrium steady-state for the prevailing burning conditions.

1981) indicates that this assumption is basically valid; the standard deviation of wind direction is considered to decrease with an increase in wind speed, depending on atmospheric stability and height above ground (e.g., Smith and Abbott 1961, Takeuchi 1963, Lumley and Panofsky 1964, Swanson and Cramer 1965, Munn and Reimer 1968, Skibin 1974, Kristensen and Panofsky 1976).

Many wildland fire researchers have assumed that the basic shape of a free-burning point source fire is that of the simple ellipse variety like the ones illustrated in figures 1 and 2 (e.g., McArthur 1966, Van Wagner 1969, Walker 1971b, Quintilio and Anderson 1976, Sanderlin and Van Gelder 1977, Simard and Young 1978, Bunton 1980, Bratten et al. 1981, Davis and Lyon 1981, Potter et al. 1981, Anderson et al. 1981, Catchpole et al. 1982, McArthur et al. 1982, Anderson 1984, Martell et al. 1984). Changes in wind, heterogeneity in the fuel type mosaic, and topographic differences no doubt distort this simplistic picture except when there are strong winds on the fire front. Near-perfect ellipses are formed when fires, with the ignition point lying on or very close to the major axis of length, spread freely through uniform, continuous fuels and across homogeneous topography under the influence of a constant, unidirectional wind. Two excellent examples of this scenario, illustrated with color photos, include the cover of Johansen's (1984) publication and figure 32 in Wade et al. (1980, p. 38). Assuming level terrain, and as long as the wind direction remains reasonably constant, the L/B of an elliptical-shaped fire will depend solely on wind speed as illustrated in figure 2, for a given fuel type. No doubt differences exist among fuel complexes.

Deviations from the simple ellipse shape have generally been assumed to arise because of a spatially nonuniform fire environment -- especially in slope conditions and wind direction. Green's (1983) simulation modeling of fire growth patterns implies that the combination of fuel distribution or patchiness, wind speed and fire spread mechanism can combine to produce many different possible fire shapes. Three of the most common fire shapes, exhibiting bilateral symmetry about their long major axis, that have been documented and/or suggested in the literature include the (1) double ellipse, (2) ovoid, and (3) lemniscate (fig. 3). The double ellipse assumes that the overall shape can be represented by two semiellipses, one for

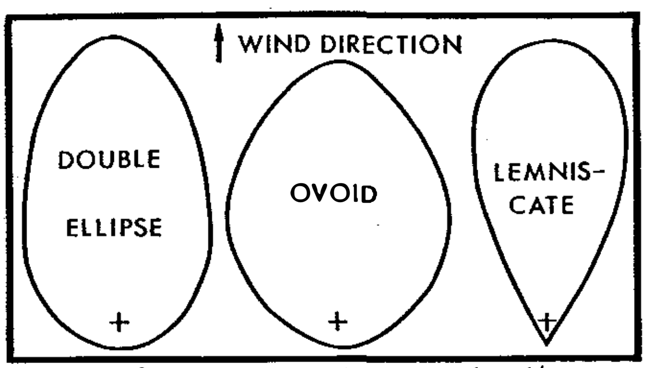

FIGURE 3.--Three commonly proposed and/or observed alternate shapes to the simple ellipse form for the growth pattern of free-burning wildland fires originating from a point source ignition. The cross (+) denotes the ignition point.

head fire spread and the other for the backfire (Anderson 1983), which share a common minor axis (represented by the entire length of line C in figure 1 if the ellipse were of the double rather than the simple variety). Anderson[3] feels that the simple ellipse provides a reasonable estimate of fire shape and size up to initial attack or a change in burning conditions. He feels that the double ellipse is a little more accurate for wind-blown spot fires, but not enough to require its use (Anderson 1984). The simple ellipse is currently used in the BEHAVE interactive computer program system (Andrews and Latham 1984). Peet (1967) considered the ovoid or "egg-shape" to be the most appropriate shape for low-intensity surface fires in the native hardwood forests of Western Australia. The "pennantlike" or "fanlike" pattern of fire spread that Brown and Davis (1973) considered as typical lies somewhere between the double ellipse and ovoid shapes. Both the double ellipse and ovoid seek to accommodate varying head fire and backfire spread rates (Green 1983). Although fires may resemble ovoids during the incipient phase of fire growth, they tend to become more nearly elliptical in shape as time passes and they increase in size (Green et al. 1983) and/or intensity (Green 1983). The lemniscate shape has generally been assumed to result from fluctuating wind direction, but the simulation results of Green (1983) suggest that it could also occur as a natural consequence of high wind speed and very patchy fuel.

The perimeter, and corresponding burned area, of an elliptical-shaped fire consists of four recognized components or sectors that are characterized on the basis of their progress with respect to the prevailing wind direction or slope -- i.e., with (downwind spread), into or against (upwind spread) and parallel to (lateral spread). These individual segements are the head, back, and two 'sides' or flanks connecting the front and heel or base of the fire, respectively (fig. 1). The exact boundaries of each sector cannot be precisely delineated. The percentage of perimeter occupied by each sector varies according to the L/B. When L/B = 1.0, then each component should theoretically constitute 25% of the total perimeter. As wind speed, and L/B in turn, increases, the two flanks make up an increasingly greater proportion of the total perimeter.

The most commonly accepted relationships between the three linear rates of fire spread and wind speed are illustrated in figure 4. The relative differences between the individual spread rates are supported by numerous studies in a variety of fuel types (e.g., Peet 1967, 1980, Korovin 1973, Barney et al. 1978, Valendik et al. 1978, de Mestre 1981). The fact that the head fire or forward rate of spread characteristically increases in roughly an exponential manner as wind increases is well-substantiated in the literature (Van Wagner 1974, Cheney 1981).

Backfire spread is normally considered to be essentially constant throughout a change in wind speed. However, some investigators have reported that backfire rate of spread actually increases with increas-

[3]Personal communication with H.E. Anderson, Supervisory Research Physicist, USDA Forest Service, Intermountain Fire Sciences Laboratory, Missoula, Mont., 14 January 1985.

ing wind speed (e.g., Murphy et al. 1966). Some of these conclusions are based on uncontrolled fuel moisture levels. The overwhelming evidence obtained from experimental test fires conducted under laboratory conditions (e.g., Beaufait 1965) and in outdoor field situations (e.g., Korovin 1973) indicates that backing fires spread at virtually the same rate as fires under still air conditions for a given level of fuel moisture. Backing fires seldom exceed a certain maximum value (Peet 1967, Burrows 1984). In fact, Potter et al. (1981) have assumed a constant backfire spread rate of 1.0 m/min in their elliptical fire growth model, which probably represents nearly an absolute upper limit for most fuel types. Wade et al. (1980) have observed that neither point ignitions or line source fires are able to "back" in the sawgrass fuel type of south Florida when standing water is present.

According to figure 4, the flank fire or lateral rate of advance is similar to backing fires at low wind speeds but gradually increases at the higher levels, though at a considerably lower rate than heading fires. The ratio of forward to lateral spread increases in a linear fashion with wind speed (de Mestre 1981, Anderson et al. 1982). It has been observed in some small-scale laboratory test fires that the spread rate under zero wind conditions was in some cases closer to the lateral spread rate than the backfire spread spread rate (de Mestre 1981). This observation was attributed to the fact that the wind is less likely to alter the flame angle at a flanking vs. backing position, which would in turn influence the propagation. There appears to be general agreement that the flanks of an elliptical-shaped fire's perimeter are aligned roughly parallel to the prevailing wind or main direction of fire spread. However, opinions do seem to vary on the angle and location of the measurement with respect to determining flank fire rate of spread. Brown and Davis (1973) have stated that the flanking fire represents the spread roughly at right angles or obliquely to the direction taken by the head fire. Some investigators have apparently favored measuring from the midpoint and perpendicular to the elliptical-shaped fire's major axis of length (e.g., Korovin 1973). Peet (1967) considered flank fire spread, taken from the origin, to be at an acute angle (60°) to the central axis of a fire's forward position.

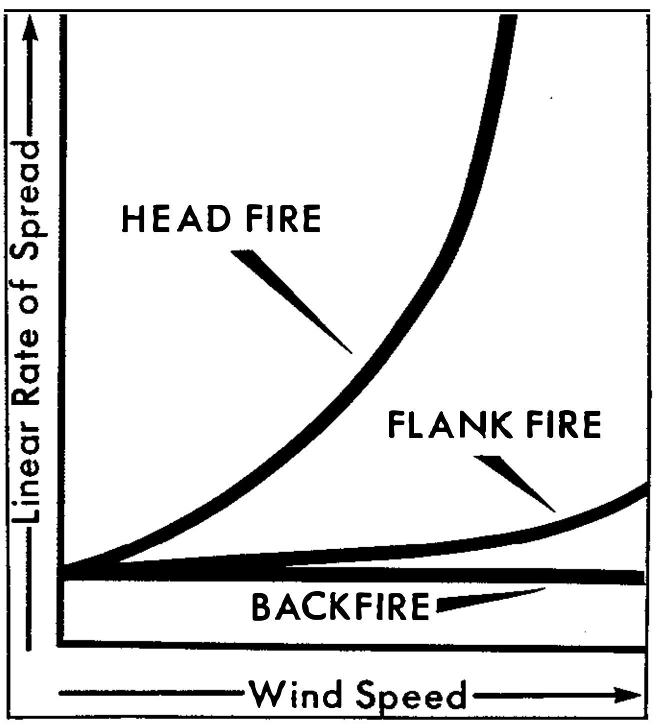

FIGURE 4.--Relative effect of wind on the spread rate of the three main segments associated with the perimeter of a free-burning elliptical shaped wildland fire (after Barney et al. 1978). Observe the shape, slope, and position of each stylized curve as wind speed increases. Fuel characteristics (load, moisture content, etc.) and % slope are considered constant.

It's already been pointed out that the portion of a fire's perimeter immediately downwind of its point of inception advances the most rapidly and that the remainder of the perimeter moves more slowly in other directions at a diminishing rate from the head to flank to rear. Associated with these differences in rate of spread are strong differences in fire intensity. The variation in intensity around the perimeter, as determined by the linear rate of spread at any given point, gradually increases from a maximum at the forward position to a minimum at the rear or tail of the elliptic fire front (Catchpole et al. 1982). Thus, the head fire region represents the most intense zone but as wind speed and L/B increase, it in turn represents an increasingly smaller proportion of the whole perimeter.

FIRE AREA AND PERIMETER LENGTH COMPUTATIONS

The standard mathematical formulae required to calculate the area (A) of an ellipse and its length of perimeter (P) are as follows (cf. Franklin and Moshos 1978):

$$[1] \quad A = \pi ab$$

$$[2] \quad P = \pi(a + b)\left(1 + \frac{M^2}{4} + \frac{M^4}{64} + \frac{M^6}{256} + \ldots\right)$$

where, $\pi \simeq 3.14159$, a = long semiaxis of the ellipse (fig. 1), b = short semiaxis of the ellipse (fig. 1), and $M = (a - b)/(a + b)$. The series in M equals 1.03 when $b = a/2$ (i.e., L/B = 2.0) and increases as L/B increases, becoming 1.15 when L/B = 7.0. The major and minor axis of the ellipse are equal to 2a and 2b, respectively. Note that the following expression for the approximate perimeter length or circumference (C) of an ellipse (cf. Selby 1975) has also been applied to forest fire problems in the past (e.g., Walker 1971b, Davis and Lyon 1981):

$$[3] \quad C \simeq 2\pi\sqrt{(a^2 + b^2)/2}$$

In terms of forest fire spread and growth, the long and short semiaxes of the ellipse can be defined as follows (after Van Wagner 1969):

$$[4] \quad a = [(v + w)t)]/2$$

$$[5] \quad b = (2ut)/2 = ut$$

where, v = head fire rate of spread, w = backfire rate of spread, u = flank fire rate of spread, and t = time since ignition. Van Wagner (1969) notes that the short semiaxis b is not so plainly equal to ut but is more exactly represented by one half of line C in figure 1. However, he does state that the mathematical advantage of the elliptical shape makes this approximation worthwhile for practical purposes. According to Van Wagner (1969), the area and perimeter length of an elliptical-shaped fire can be determined from the following equations:

$$[6] \quad A = \frac{\pi}{2}(v + w)ut^2$$

$$[7] \quad P = \pi t\left(\frac{v + w}{2} + u\right)\left(1 + \frac{M^2}{4}\right)$$

Note that the terms after M^2 in Equation [2] have been omitted for practical purposes, with less than one percent loss in accuracy (Anderson 1983). Fire area is normally quoted in SI units of hectares (ha), as recommended by Van Wagner (1978) for general usage. Any system of units can be used in Equation [6]. However, internal consistency demands that the square of the unit of length be the unit of area. For example, if the linear rates of spread (v, u, and w) are in metres per hour (m/h) then time t must be in hours, and then division by 10 000 converts m^2 to ha. Fire perimeter length and spread distance can be quoted in either metres (m) or kilometres (km). The former unit is better suited to a small-scale mental image whereas the latter is more suitable for a large-scale impression (Van Wagner 1978).

Burrows (1984) has used Equation [6] to develop a graphical aid for estimating area (ha) of free-burning elliptical shaped fires based on the fire's total length (head fire + backfire spread) and maximum width (km). Van Wagner (1969) indicated that Equation [6] can be simplified if necessary and offers two examples for L/B = 1.0 and 2.0. The following equation represents yet a further simplification that offers considerably more flexibility in terms of field application (after Bunton 1980, McArthur et al. 1982):

$$[8] \quad A = \frac{\pi}{4(L/B)}(vt + wt)^2$$

The above equation does alleviate the task of having to make an estimate or prediction of the flank fire spread.

The length of fire perimeter represents the distance around the head, both flanks, and back. Several general rules of thumb do exist for calculating the perimeter of an elliptical-shaped fire in lieu of Equation [7], provided the total length of the fire is known or an estimate is available. These consist simply of a standard multiplier such as 2.5 (McArthur 1966, Anderson 1983) or 3.0 (Van Wagner 1965a, McArthur 1967, Anderson 1984) for a fire with a length about twice its breadth. Sneeuwjagt and Peet (1979) used values that varied from 3.0 to 2.3 for corresponding fire lengths of 50 - 10 000 m. In general terms, these factors would actually vary from 2π ($\simeq$6.3) for circular fires to about 2 for long, narrow fires. The following equation, based on the area enclosed by the fire perimeter, can also be used to calculate perimeter length, at least for fires with a L/B = 2.0 (after Walker 1971b):

$$[9] \quad P = 0.3962\sqrt{A}$$

where, P = length of fire perimeter (km) and A = fire area (ha). To obtain P in units of m rather than km, change the coefficient to 396.2.

It's worth noting that the rate of area growth does remain constant with time; rather, it increases in direct proportion to time. Provided suppression action is ineffective in restricting fire growth and rate of spread remains constant, total area burned increases as the square of the time since ignition (McArthur 1968, Van Wagner 1969). For example, the fire area 2 hours after ignition will be four times the area after 1 hour. Rate of area growth can be quoted as area per unit time (e.g., ha/h), provided this understood to apply to the current moment only. In constrast to rate of area growth, the rate of perimeter growth or increase does remain constant with time provided burning conditions do not change (Van Wagner 1965a).

The simple ellipse was adopted as the standard shape of 'point ignition' fires in the 1984 interim edition of the FBP System. The following simplified formula was given for manually calculating the approximate area of a free-burning elliptical-shaped fire:

$$[10] \quad A = K_A (ROS \times T)^2$$

where, A = probable fire area after time T (m^2 or km^2), K_A = area shape factor, ROS = head fire rate of spread (m/min or km/h), and T = elapsed time since ignition (min or h). The units for ROS and T used in Equation [10] must be compatible (i.e., m/min and min or km/h and h). To convert area to ha, divide m^2 by 10 000 and multiply the km^2 by 100. The area shape factors, given in tabular format verus 10-m open wind speed by substituting for L/B, were determined as follows:

$$[11] \quad K_A = \frac{\pi}{4(L/B)}$$

For estimating the perimeter length of a free-burning elliptical-shaped fire, the following simple computation was offered:

$$[12] \quad P = K_P D$$

where, P = probable fire perimeter length after time T (m or km), K_P = perimeter shape factor, and D = fire spread distance (m or km). The latter quantity was specified as being numerically equal to the product of head fire rate of spread (ROS) multiplied by the elapsed time since ignition (T). Perimeter shape factors were formulated on the basis of Equation [3] and then the following empirical function linking K_P to the L/B of a simple ellipse was derived to satisfy the computerized use of Equation [12]:

$$[13] \quad K_P = \frac{L/B}{-0.14145 + 0.47034(L/B)} \quad ,1.1 \leq L/B \leq 7.0$$

The resulting K_P values, which were presented in tabular format versus L/B, vary from 2.93 at L/B = 1.1 to 2.22 at L/B = 7.0 (K_P was set = 3.14 at L/B = 1.0). The actual length of the perimeter tends to be underestimated by the above procedure because natural irregularities in the fire edge are not considered in Equations [12] and [13], but rather a smooth outline is presumed.

Two simplifying assumptions were made in developing the above fire size calculations: (1) the fire attains a steady-state condition in a homogeneous fire environment a short time after ignition (fig. 2), and (2) the backfire spread is, for practical purposes, negligible. The latter assumption implies that backfire spread is set equal to zero and that the head fire spread accounts for all of the major axis of length. This does result in a problem at low wind speeds (i.e., L/B $\simeq$ 1.0 to 2.0). The nature of the problem is that, as the L/B approaches 1.0, the backfire rate of spread actually approaches the head fire rate of spread, and the point of origin should eventually be at the center of a circular fire. Thus, the assumption of negligible backfire spread over the whole range of L/B results in underprediction of area and perimeter at low wind speed conditions. At moderate to high wind speeds, it was considered an acceptable simplification in order to avoid the requirement of the user to make a separate estimation for backfire spread. This would involve, according to the FBP System, computing the total spread distance by accounting for the backfire contribution on the basis of a rate of spread prediction with the wind speed set = 0, as illustrated in the practical example given by Lawson et al. (1985). This represents a trivial matter in terms of computer calculation but seems unnecessarily complex for field users.

Fuglem[4] has suggested a means of indirectly incorporating backfire spread into the area and perimeter length computations that would avoid the inconvenience of an additional distance estimate and also correct the present problem with the simple elliptical fire growth model at low L/B situations. It's based on the fact that an ellipse has two foci that are located on, but near the opposite ends of the major axis. The distance between the midpoint of the major axis and either focus is equal to $\sqrt{a^2 - b^2}$. Further details are available elsewhere (e.g., Selby 1975, Franklin and Moshos 1978). Thus, a fire's point of origin is assumed to be at one focus of the ellipse. The ellipse's major axis of length is portioned, the split being dependent on the L/B (fig. 5), between the head fire and backfire spread according to the following equations:

[14] $vt = a + \sqrt{a^2 - b^2}$

[15] $wt = a - \sqrt{a^2 - b^2}$

The curve of head fire/backfire spread ratio (H/B) versus L/B depicted in figure 5 is based on the following equation (see tabulation in Appendix I):

[16] $H/B = [(L/B) + \sqrt{(L/B)^2 - 1}]/[(L/B) - \sqrt{(L/B)^2 - 1}]$

The focus method does offer the advantage of incorporating both head fire and backfire spread . If it were accepted, revised area and perimeter shape factors would be worked out on the basis of the following formulae (fig. 6):

[17] $K_A = \pi\ (Ra)^2\ Rb$

[18] $K_p = \pi\ (Ra + Rb)\ (1 + \frac{[(Ra - Rb)/(Ra + Rb)]^2}{4})$

where, $Ra = 1/(1 + \sqrt{1 - (Rb)^2}\ )$ and $Rb = 1/(L/B)$

[4]Personal communication with P.J. Fuglem, Planning and Devlopment Analyst, British Columbia Ministry of Forests, Forest Protection Branch, Victoria, B.C., 20 August 1984.

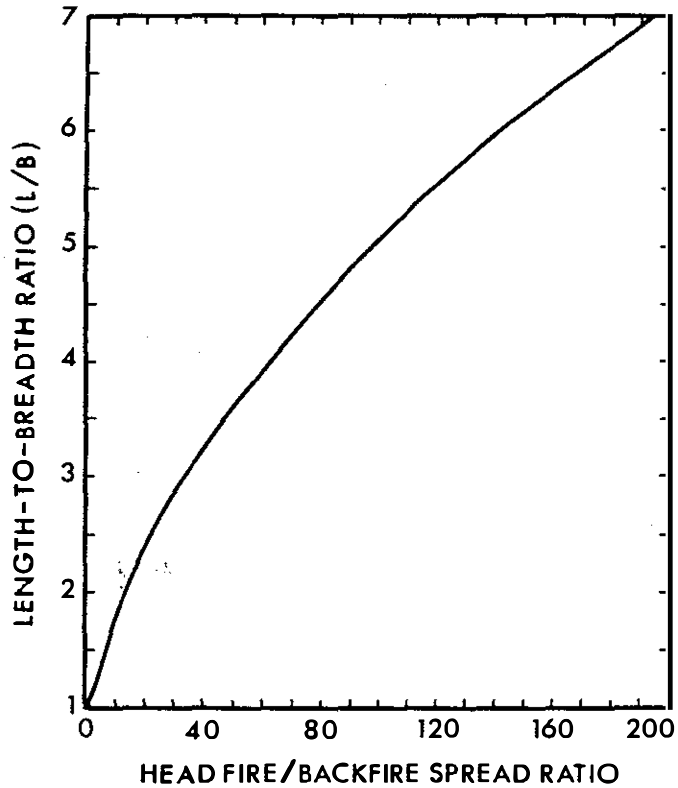

FIGURE 5.--Relationship between ratio of head fire to backfire spread and the length-to-breadth ratio (L/B) of a free-burning elliptical-shaped wildland fire. The former quantity represents the ratio of the distance from the focus, which is presumed to be the point of origin, to the forward and backward edges of the ellipse along the major axis of length.

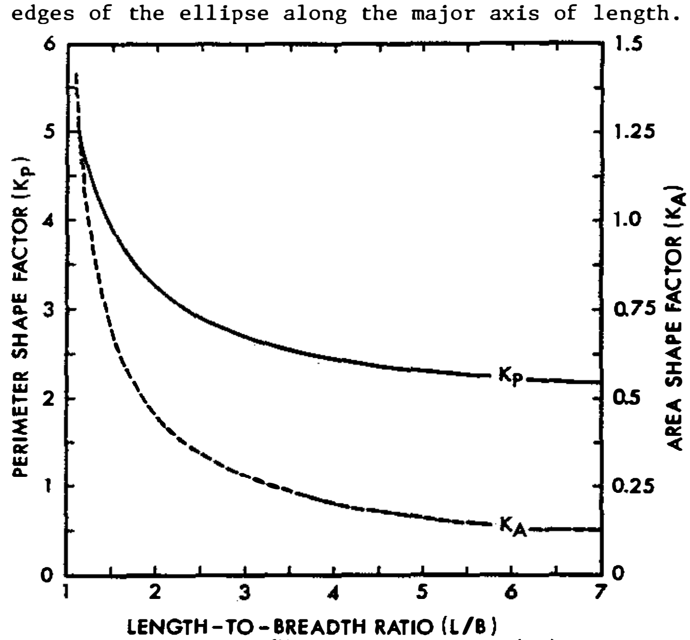

FIGURE 6.--Area (K_A) and perimeter (K_p) shape factors as a function of the length-to-breadth ratio (L/B) for use with the product of head fire rate of spread and elapsed time since ignition in computing the approximate size of free-burning elliptical-shaped wildland fires. Backfire spread has been indirectly considered. K_A = 3.14 and K_p = 6.28 when L/B = 1.0.

for the sake of simplicity in the presentation of the above equations. The resulting values (see Appendices II and III) start to become remarkably close to those produced by Equations [11] and [13] beginning above an L/B $\simeq$ 2.0.

The focus concept has apparently been applied to elliptical fire growth models by others (e.g., Bratten et al. 1981). Several fire modelers have recently pointed out that placing the ignition point at a focus of the ellipse may actually be inappropriate since they do not necessarily coincide (Catchpole et al. 1982, Green 1983, Green et al. 1983). In addition, these same authors have suggested that the focus of an ellipse generally tends to be somehwat downwind of the ignition point. This observation has been confirmed in a general way by comparing backfire spread projections based on the focus approach with those produced by using a zero wind; the former gave consistently larger but not necessarily significantly higher values. Nevertheless, the focus scheme does provide an automatic estimate of backfire spread once the head fire spread and L/B are specified. The credibility of the estimate depends in large part on the L/B prediction.

REVIEW OF EXISTING MATHEMATICAL RELATIONSHIPS

Some user-oriented guides for estimating L/B such as that given in table 1 do exist. In addition, schematic diagrams depicting relative elliptical fire shapes for various wind speed regimes (e.g., Burrows 1984) have been produced. However, only three mathematical models for predicting L/B have been devloped to date. A brief review of their technical basis, applicability, etc. is given below. Each model is graphically illustrated in figure 7 for 10-m open wind speeds up to a limit of 50 km/h. Individual L/B values for winds between 0 and 50 km/h are listed in Appendix IV.

TABLE 1.--General guidelines for estimating the length-to-breadth ratio (L/B) of free-burning elliptical-shaped wildland fires (after Bunton 1980).

L/B	Associated fire characteristics and/or environmental conditions
1.0	Expected only for very small, slowly spreading fires.
2.0 & 3.0	Normal fire shape on flat to moderate ground.
4.0 & 5.0	Normal fire shape on steep slope or with moderate winds.
6.0	Very windy or very steep terrain.

McArthur (1966) related the L/B grassland fires to wind speed in Australia, presumably on the basis of 21 experimental fire observations and three sustained wildfire runs with associated 10-m open winds up to 40 km/h; a metric version of his graph appears in Luke and McArthur (1978) for 10-m open winds up to 56 km/h. It is not entirely clear whether McArthur's model, a rising curve with decreasing slope (fig. 7a), is based on a free-hand fit of the data or is the result of regression analyses. In any event, the following equation has been offered as a mathematical reflection of McArthur's original work (after Cheney 1981, McArthur et al. 1982):

$$[19] \quad L/B = 1.1\ W^{0.464} \qquad ,W \geq 1$$

where, W = 10-m open wind speed (km/h). Cheney (1981) indicated that the above model was valid for winds up to 40 km/h but McArthur et al. (1982) indicated no such restriction. The McArthur (1966) curve for grass fires given in figure 7a is based on the above equation. Comparison of observed versus predicted L/B values from well-documented wildfires (e.g., Country Fire Authority of Victoria 1983) generally show good agreement.

Simard (1969) worked out L/B values versus wind speed on the basis of the Initial Spread Index (ISI) table in the 1969 provisional version of the Canadian Forest Fire Weather Index (FWI) System in a manner very similar to that used in the present study that is discussed in the next section. An empirical function relating L/B to wind speed for elliptical wildland fire shapes was derived by Simard and Young (1978), using the data published earlier in Simard (1969). The resulting equation is as follows (after Simard and Young 1978, Simard et al. 1977):

$$[20] \quad L/B = 1/[(e^{-0.0162\ W^{1.2}}) + (0.000194\ \sigma_A)\ W]$$

where, W = 10-m open wind speed (km/h) and σ_A = standard deviation of wind direction (deg.). Equation [20] gives a rising curve with increasing slope as illustrated in figure 7b. The above model includes a consideration of wind direction variability on L/B. No information is given on the derivation of the σ_A variable coefficient. Simard and Young (1978) somewhat arbitrarily recommended a value of 10^o be used for σ_A, regardless of the wind speed. If the σ_A variable is disregarded (i.e., $\sigma_A = 0^o$), then Equation [20] can be rewritten as simply:

$$[21] \quad L/B = e^{0.0162\ W^{1.2}}$$

Simard and Young's (1978) graphical representation of Equation [20] for $\sigma_A = 0^o$, 10^o, and 20^o (fig. 7b) suggests that the model is valid to wind speeds of 80 km/h or extreme L/B values of 23.1, 5.0, and 2.8, respectively.

Anderson (1983) developed the following model deemed applicable to any fuel complex:

$$[22] \quad \ell/\omega = 0.936e^{0.1147\ U} + 0.461e^{-0.0692\ U}$$

where, ℓ/ω = length-to-width ratio and U = wind at midflame height (mi/h). The above equation is based on an analysis of 198 unpublished experimental fires conducted in a low velocity wind tunnel by W.L. Fons during 1939. A brief overview of this work can be found in Fons (1946). The fuel beds consisted of ponderosa pine needles 5.1 cm deep, 0.91 m wide, and 2.44 or 3.66 m long. The fires were ignited from a point source, allowed to grow until they reached a width of approximately 46 cm, and were then immediately extinquished with water in order to preserve their shape. Wind speed, measured at 0.3 m above the fuel bed, varied between 3.2 and 19.3 km/h during the tests. Application of Anderson's model to daily operational use normally depends on the selection of

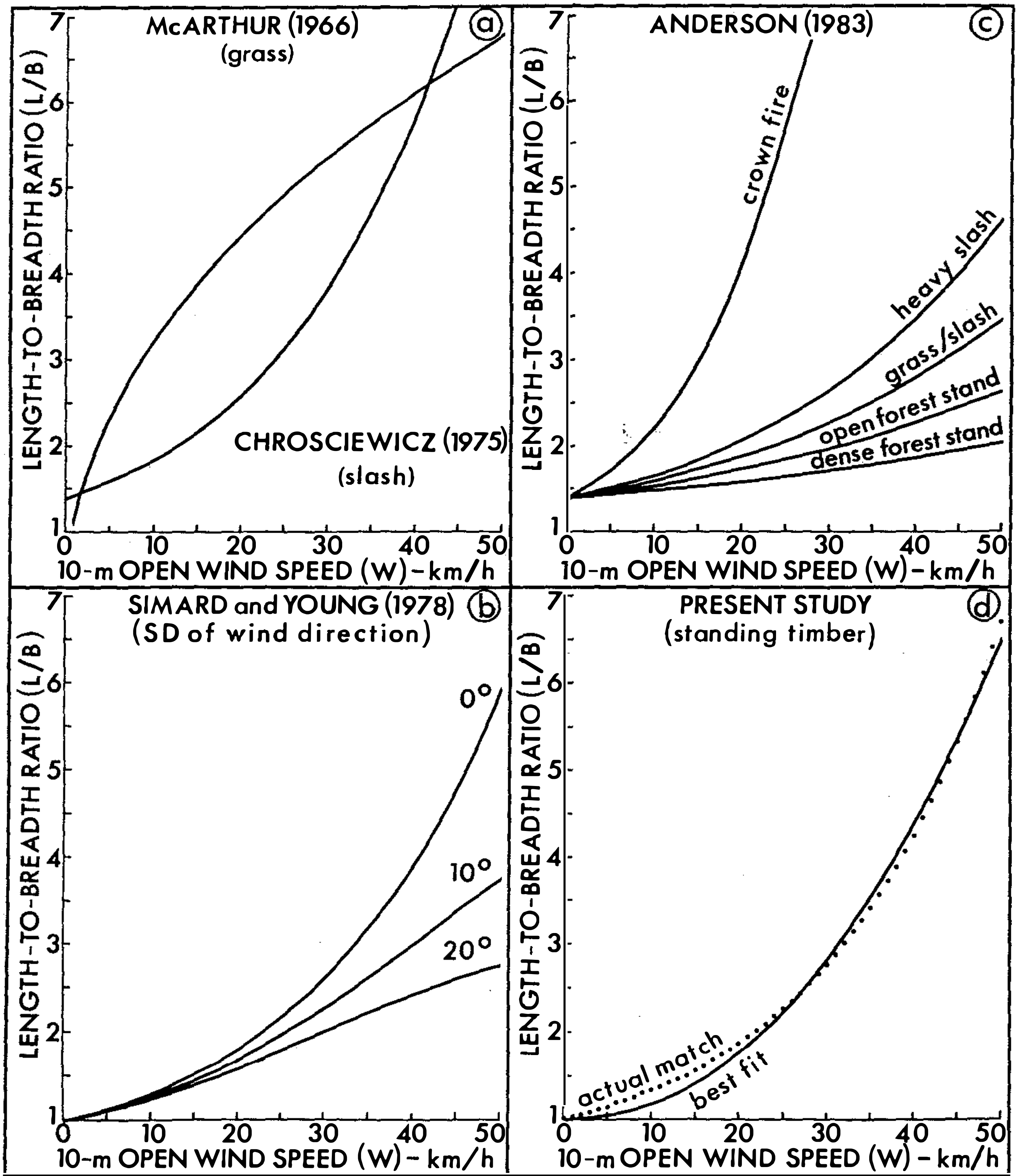

FIGURE 7.--Relationship between the length-to-breadth ratio (L/B) of elliptical wildland fire patterns and wind speed, determined for the international standard height and exposure of 10 m in the open on level terrain, according to four different mathematical models: (a) McArthur (1966) - Equation [19] (and Chrosciewicz (1975) - Equation [28] -- this latter relation for slash fires represents a simple extension of Anderson's (1983) model); (b) Simard and Young (1978) - Equation [20] -- standard deviation (SD) of wind direction is given in degrees (°); (c) Anderson (1983) - Equation [23] to [27] -- open and dense forest stand curves refer to surface fires only; and (d) Present Study - Equation [35] -- best fit and Equation [36] -- actual match.

factors to adjust wind speed at a height of 20 ft or 6.1 m in the open to a midflame height on the basis of the anticipated fire behavior (i.e., surface or crown fire spread) and/or specific fuel complex (table 2). The 20-ft open wind has traditionally been used in the United States for fire-danger rating and fire behavior prediction purposes (Fischer and Hardy 1976). In Canada, the international standard 10-m open wind was adopted with the introduction of the FWI System in 1970 (Van Wagner 1974, Turner and Lawson 1978). A good estimate of the 10-m open wind can be obtained by multiplying the 20-ft or 6.1-m value by 1.15 (Turner and Lawson 1978).

TABLE 2.--A list of 20-ft or 6.1-m open to midflame height (U/U_{20}) and 1.2-m above ground to 10-m open ($W/W_{1.2}$) wind speed adjustment factors referred to in the text.

Fire type and/or fuel complex	U/U_{20}	$W/W_{1.2}$	Ref.[1]
Crown fire - forest stand	1.0	1.0	-
Heavy logging slash	0.5	2.30	1
Short & tall grass, light & medium logging slash, and leafless hardwood stands	0.4	2.88	1
Surface fire - open forest stand	0.3	3.83	1
Surface fire - dense forest stand	0.2	5.75	1
Clear-cut logging slash (Sask.)	0.72	1.6	2
Jack pine stand (Petawawa, Ont.)	0.23	5.0	3
Tussock tundra (Alaska)	0.75	1.53	4

[1]Reference: 1 - Rothermel (1983); 2 - Chrosciewicz (1975); 3 - Van Wagner (1974); and 4 - Norum (1983).

The following equations for specific fire/fuel situations have been produced on the basis of Anderson's (1983) generalized model (fig. 7c). The first four are based on several of the U/U_{20} values given by Rothermel (1983). The final is based on the assumption that the 10-m open wind is equivalent to the midflame height value in the case of an active crown fire in a coniferous forest stand. In all five equations, W = 10-m open wind speed (km/h):

Surface fire - dense forest stand

$$[23] \quad L/B = 0.936e^{0.01240\,W} + 0.461e^{-0.00748\,W}$$

Surface fire - open forest stand

$$[24] \quad L/B = 0.936e^{0.01859\,W} + 0.461e^{-0.0112\,W}$$

Short & tall grass, light & medium logging slash, and leafless hardwood stands

$$[25] \quad L/B = 0.936e^{0.02479\,W} + 0.461e^{-0.0149\,W}$$

Heavy logging slash

$$[26] \quad L/B = 0.936e^{0.03099\,W} + 0.461e^{-0.0187\,W}$$

Crown fire - forest stand

$$[27] \quad L/B = 0.936e^{0.07127\,W} + 0.461e^{-0.0430\,W}$$

To illustrate further the versatility of Anderson's (1983) model, a $W/W_{1.2}$ value for clear-cut logging slash in central Saskatchewan derived by Chrosciewicz (1975) gave the following result (fig. 7a):

$$[28] \quad L/B = 0.936e^{0.04455\,W} + 0.461e^{-0.0269\,W}$$

where, W = 10-m open wind speed (km/h). In the above case, the wind speed at a height of 1.2 m above ground was equated to the midflame value required by Anderson's model. Note the conversion of $W/W_{1.2}$ to U/U_{20} values (example based on Wagner 1974 in table 2):

$$1 \div [(1 \div 1.15) \times 5.0)] = 0.23$$

Equations [23] to [27] were developed by simply modifying the coefficients 0.1147 and -0.0692 in Equation [22]. The modifications involved consideration of the specific U/U_{20} value (table 2), allowance for the 10-m open wind rather than the 20-ft or 6.1-m open wind (1.15 multiplier), and the unit conversion factor for mi/h to km/h (1.6093). Consider the following example for the Alaskan tussock tundra fuel complex in table 2:

$$0.75 \times (1 \div 1.15) \times (0.1147 \div 1.6093) = 0.04648$$

$$0.75 \times (1 \div 1.15) \times (-0.0692 \div 1.6093) = -0.0280$$

The above computations would in turn result in the following equation:

$$[29] \quad L/B = 0.936e^{0.04648\,W} + 0.461e^{-0.0280\,W}$$

where, W = 10-m open wind speed (km/h).

PRESENT STUDY

Development of the L/B model in the present study represents a continuation and refinement of the work originally begun by Simard (1969). He computed the ratio of forward plus rear fire spread to lateral fire spread on the basis of the Initial Spread Index (ISI) component of the Canadian Forest Fire Weather Index (FWI) System. Conceptually, the basic L/B model, utilizing the ISI is as follows:

$$[30] \quad L/B = \frac{\overbrace{(\text{ISI } \textit{at Given Wind})}^{\text{HEAD FIRE SPREAD}} + \overbrace{(\text{ISI } \textit{at Zero Wind})}^{\text{BACKFIRE SPREAD}}}{\underbrace{2(\text{ISI } \textit{at Zero Wind})}_{\text{FLANK FIRE SPREAD}}}$$

In the formulation of the above model, flank fire spread was regarding as advancing perpendicular to the direction of prevailing wind and is therefore considered to be independent of wind speed (i.e., zero wind condition). This simplifying assumption has bee used by others (e.g., Quintilio and Anderson 1976, Potter et al. 1981, Martell et al. 1984). A Brief account of the structure of the ISI is given below as background to the derivation of the actual equation(s) based on the simple conceptual model presented above.

The technical derivation of the ISI is described by Van Wagner (1974). In simplistic terms, the ISI represents a relative numerical rating that combines the effects of wind velocity and moisture content of litter and other cured fine fuels, represented by the Fine Fuel Moisture Code (FFMC), on the expected rate of fire spread without the influence of variable quantities of fuel (Canadian Forestry Service 1984). Mathematically, the ISI is merely the product of wind and fine fuel moisture functions, together with a constant (from Wagner 1974, Van Wagner and Pickett 1985):

[31] $R = 0.208\ f(W)\ f(F)$

where, R = Initial Spread Index (ISI), f(W) = wind function, and f(F) = fine fuel moisture function. The ISI wind function was developed after examining various kinds of evidence, including the several published accounts ow wind effects on fire spread in the literature and the available experimental field evidence at the time. The chosen wind effect, a simple exponential relation, was in the final analysis a matter of judgment (Van Wagner 1974). The current metric version is (from Wagner and Pickett 1985):

[32] $f(W) = e^{0.05039\ W}$

where, W = 10-m open wind speed (km/h). Van Wagner (1974) notes that the above function is essentially empirical, and at very high wind speeds (i.e., > 50 km/h) its validity is uncertain. In fact, wind speed in the ISI table (Canadian Forestry Service 1984) has a limit of 50 km/h. The ISI fine fuel moisture function is empirical in nature as well. It is based to a very large extent on the culmination of three decades of field research associated with test fire behavior studies by the Canadian Forestry Service (Van Wagner 1974). The current metric version is (from Van Wagner and Pickett 1985):

[33] $f(F) = 91.9e^{-0.1386\ m}\ [1 + m^{5.31}/(4.93 \times 10^{7})]$

where, m = fine fuel moisture content (%) which is further defined as (from Van Wagner and Pickett 1985):

[34] $m = 147.2(101 - F)/(59.5 + F)$

where, F = Fine Fuel Moisture Code (FFMC). At any given level of the FFMC, the ISI doubles in value for every 13 km/h increase in wind (Van Wagner 1974, Turner and Lawson 1978).

L/B values were computed for 10-m open wind speeds between 0 and 50 km/h using the ISI equations (Van Wagner and Pickett 1985) as described above rather than the ISI Table (Canadian Forestry Service 1984) from the 1984 version of the FWI System and the basic conceptual model given by Equation [30]. The resulting ratios were plotted over the 10-m open wind speed (fig. 7d) and then subjectively fitted to the equation form of $Y = aX^{b}$ so that L/B = 1.0 when wind = 0 km/h. Particular attention was paid to obtaining a close fit between an L/B of 2.0 and 6.0. After much trial and error the following equation was selected as exemplifying the best overall fit (fig. 7d):

[35] $L/B = 1.0 + 0.00120\ W^{2.154}$,$W \leq 50$

where, W = 10-m open wind speed (km/h). The difference between an actual perfect match and the best possible fit selected was $\pm$ 0.10 on the average, with a range of -0.23 to +0.14 (see Appendix IV). Equation [35] was cast into graph and tabular formats[5] for practical field use such as map plotting of projected fire areas.

The L/B values computed by the basic conceptual model are identical, at a given wind speed, for any FFMC level provided the ISI equations are used; minor differences between FFMC columns of the ISI Table (Canadian Forestry Service 1984) would be evident due to rounding associated with table construction. Thus, Equations [30] and [32] can be reduced to the following expression (fig. 7d):

[36] $L/B = 0.5 + 0.5e^{0.05039\ W}$,$W \leq 50$

where, W = 10-m open wind speed (km/h). The above equation represents an actual perfect match of the data points for the present study as given in figure 7d and also yields L/B = 1.0 when W = 0 km/h.

Equations [35] and [36] are both applicable to standing timber fuel types (i.e., those with an overstory tree canopy). A preliminary evaluation of the L/B versus 10-m open wind speed relationship represented by Equation [35] was undertaken during the final stages of preparation of the 1984 interim edition user guide to the FBP System. Since that time additional published and unpublished validation data have been obtained through a thorough literature search and actively soliciting by personal contacts. The scope of the evaluation included mainly coniferous plantations and natural forests and natural forests in Canada, the United States, and Australia. Data for fires in logging slash were also sought. Information on each wildfire was normally documented in a case history or study report of some sort. The results of these efforts, involving 30 wildland fires, are summarized in table 3 and include both surface and crown fires. The number of fires by major fuel complexes is as follows: standing timber - 19; logging slash - 5; cutover/forest stand - 2; and grassland - 4. This represents a reasonably exhaustive account of the data that might normally be available in published form. Table 3 also includes data on a few representative grassland fires, although there was never any intention to evaluate McArthur's (1966) relationship rigorously. Data on the low end of the L/B scale came chiefly from experimental fire observations. For the most part, the wildfires selected for inclusion in table 3 are: (1) believed to be relatively unaffected by any suppression action that might have restricted lateral growth, and (2) were either mapped at or near the end of the run on which the L/B determination is based or did not exhibit any major increase in area following the run. A few explanatory notes regarding table 3 are appropriate here. First, the description of fuel type is the best characterization possible given the space limitations. The fire size quoted generally coincides with L/B determination and therefore does not necessarily correspond to the final area burned. The 10-m open wind speed value represents the best possible estimate after consulting all applicable sources. In

[5]Alexander, M.E., B.D. Lawson, B.J. Stocks, and C.E. Van Wagner. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Interim edition. Can. For. Serv. Fire Danger Group. 73 p. + Supplements.

TABLE 3.--Validation data and background information obtained from the literature and personal correspondence regarding the length-to-breadth ratio (L/B) vs. 10-m open wind speed relationship for wildland fires.

Reference	Fire name	Location	Date	Fuel type	Fire size (ha)	10-m wind (km/h)	L/B
Curry & Fons (1938)	JRC/WLF Experimental	California, USA	-	Ponderosa pine	<0.1	2	1.0[1]
McArthur (1971)[2]	AGM Experimental	Fiji Islands	14.01.71	Carribbean pine	<0.1	11	1.4
Thomson (1979)	Carrolls Rd. Plot 29	Vic., Australia	??.??.76	Radiata pine	<0.1	10	1.5
Curry & Fons (1938)	JRC/WLF Experimental	California, USA	-	Ponderosa pine	<0.1	10	1.5
Williams (1955)	DEW Experimental	Manitoba, Canada	25.08.49	Jack pine slash	0.1	13	1.7
Watson et al. (1983)	Bright Plantation	Vic., Australia	24.11.82	Radiata pine slash	4	10	1.7
Walker & Stocks (1972)	Thackeray	Ontario, Canada	01.06.71	Logging slash	324	11	1.8
Kiil (1975)	ADK Experimental	Alberta, Canada	13.07.72	Black spruce	0.2	19	1.9
Curry & Fons (1938)	JRC/WLF Experimental	California, USA	-	Ponderosa pine	<0.1	19	2.1
Williams (1968)[3]	Fletcher Road	Michigan, USA	08.05.68	Jack pine	1882	24	2.2
E. & W. Catchpole (1983)	NPC Experimental 1	N.T., Australia	08.08.72	Grassland	2	6	2.4
Brotak (1977)	Bass River	New Jersey, USA	22.07.77	Pitch pine	931	25	2.5
Van Wagner (1965b)	Gwatkin Lake	Ontario, Canada	07.05.64	Pine/aspen	152	26	2.5
Walker (1971b)	Geraldton 9-70	Ontario, Canada	06.06.70	Cutover/Jack pine	435	16	2.5
Stocks & Street (1981)[4]	Fort Frances 9-81	Ontario, Canada	20.05.81	Logging slash	900	21	2.6
Simard et al. (1983)	Mack Lake	Michigan, USA	05.05.80	Jack pine	1214	28	2.7
Anderson et al. (1982)	NPC Experimental 53	N.T., Australia	31.07.73[5]	Grassland	6	5[5]	2.8[5]
Stocks & Street (1981)[4]	Fort Frances 9-81	Ontario, Canada	21.05.81	Pine/spruce	9554	32	3.4
Sando & Haines (1972)	Little Sioux	Minnesota, USA	14.05.71	Cutover/spruce-fir	3552	31	3.5
McArthur et al. (1966)	Wandilo	South Australia	05.04.58	Radiata pine	626	35	3.7
Alexander et al. (1983)	DND-4-80	Alberta, Canada	02.05.80	Pine/spruce	7500	36	3.9
Pratt (1985)[5]	Kongorong	South Australia	29.03.71	Radiata pine slash	11	32	4.1
Alexander (1983)	Lesser Slave Lake	Alberta, Canada	23.05.68	Pine/spruce	60 700	46	4.9
Wade & Ward (1973)	Air Force Bomb Range	N. Carolina, USA	22.03.71	Pond pine	1204	32	5.0
Geddes & Pfeiffer (1981)	Caroline	South Australia	02.02.79	Radiata pine	2679	43	5.3
Stocks & Walker (1973)	Garden Lake	Ontario, Canada	02.06.30	Spruce/pine/fir	67 000	48	6.2
Stocks (1975)	Red Lake 31-74	Ontario, Canada	13.07.74	Pine/spruce	2966	32	6.4
Keeves & Douglas (1983)	Narraweena	South Australia	16.02.83	Grassland	48 750	45	6.5
McArthur et al. (1982)	Penshurst	Vic., Australia	12.02.77	Grassland	1650	41	6.7
Stocks & Walker (1973)	Red Lake 35-61	Ontario, Canada	01.07.61	Jack pine	5672	64	7.1

[1]The actual value was L/B = 1.02.

[2]McArthur, A.G. 1971. Aspects of fire control in the P. caribaea and P. elliottii plantations of north western Viti Levu, Fiji Islands. Commonw. Aust., Dep. Natl. Develop., For. and Timber Bureau, For. Res. Inst., Canberra, A.C.T. Report to Fiji Pine Commission. 38 p. + Appendices. (unpublished).

[3]Williams, E.B. 1968. Fletcher-Billman Road Fires - May 8, 1968. U.S. Dep. Comm., Environ. Sci. Serv. Admin., Weather Bureau, Cent. Reg., Kansas City, Mo. Proj. Fire Weather Rep. 29 p. (unpublished).

[4]Stocks, B.J., and R.B. Street. 1981. Fire weather factors associated with Fort Frances Fire #9/81. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont. File Rep. 12 p. (unpublished).

[5]N.J. de Mestre, University of New South Wales, Royal Military College, Faculty of Military Studies, Department of Mathematics, Duntroon, A.C.T., personal communication, 24 May 1985.

[6]J. Pratt, Senior Forester, Woods & Forests Department, Regional Office, Mt. Gambier, South Australia, personal communication, 27 February 1985. Refer to Ollerenshaw and Douglas (1971) as well.

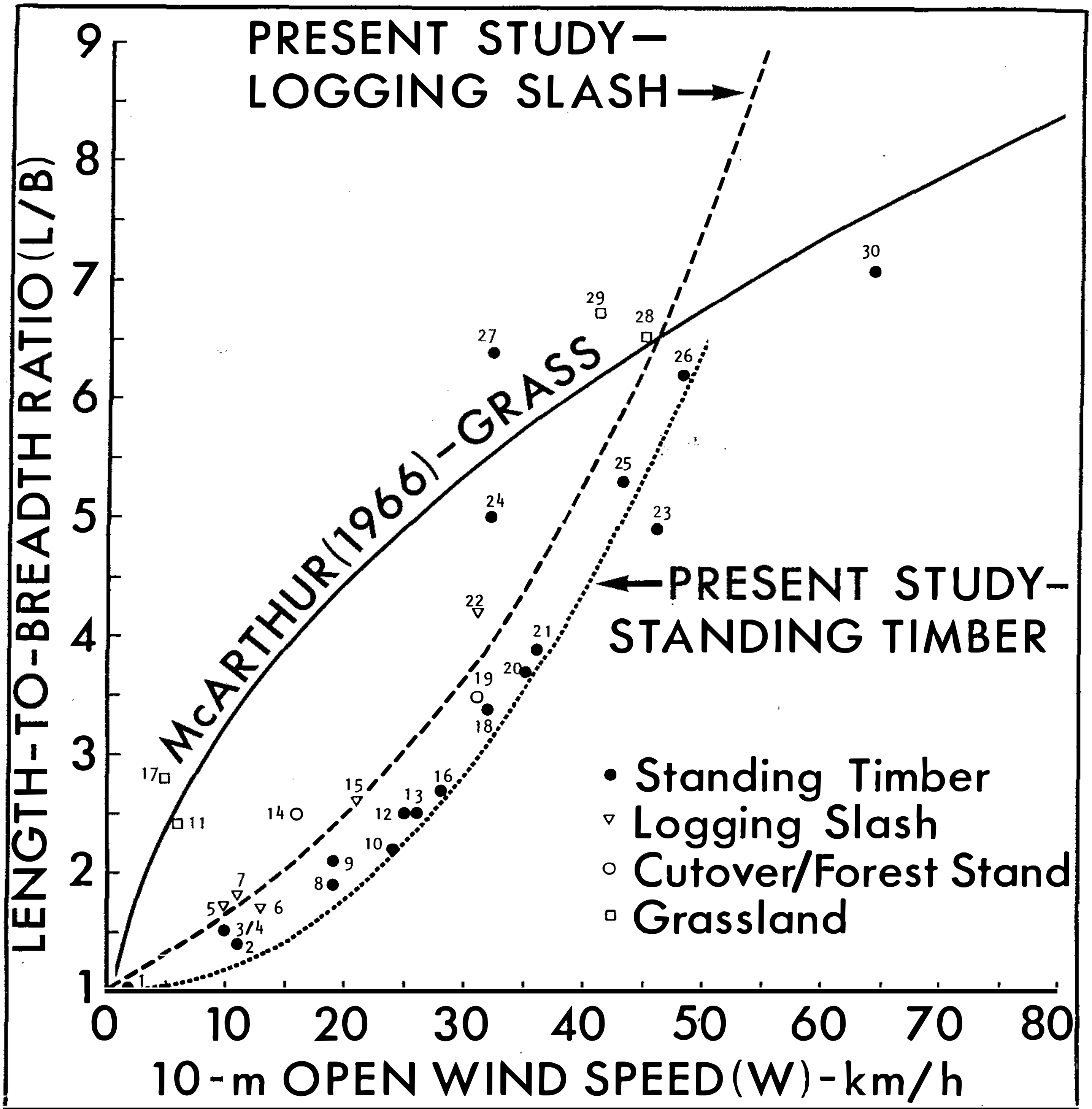

FIGURE 8.--Comparison of actual length-to-breadth ratios (L/B) obtained from experimental fire observations and well-documented wildfires with the L/B vs. 10-m open wind speed relationship developed for standing timber fuel types in the present study and for logging slash as a result of the evaluation work associated with the present study. McArthur's (1966) curve for grass fires is recommended, on an interim basis, for logging slash and standing timber fuel types when wind speeds exceed 45 km/h and 50 km/h, respectively. The number adjacent to each data point in the illustration above refers to a fire listed in table 3:

1 - JRC/WLF Experimental (L/B = 1.02); 2 - AGM Experimental; 3 - Carrolls Rd. Plot 29; 4 - JRC/WLF Experimental (L/B = 1.5); 5 - DEW Experimental; 6 - Bright Plantation; 7 - Thackeray; 8 - ADK Experimental; 9 JRC/WLF Experimental (L/B = 2.1); 10 - Fletcher Road; 11 - NPC Experimental 1; 12 - Bass River; 13 - Gwatkin Lake; 14 - Geraldton 9-70; 15 - Fort Frances 9-81 (L/B = 2.6); 16 - Mack Lake; 17 - NPC Experimental 53; 18 - Fort Frances 9-81 (L/B = 3.4); 19 - Little Sioux; 20 - Wandilo; 21 - DND-4-80; 22 - Kongorong; 23 - Lesser Slave Lake; 24 - Air Force Bomb Range; 25 - Caroline; 26 - Garden Lake; 27 - Red Lake 31-74; 28 - Narraweena; 29 - Penshurst; and 30 - Red Lake 31-61.

some cases, the determination of the L/B required considerable judgment on the part of the author. Readers should consult the reference given for further details, information, etc.

The data listed in table 3 are dispalyed in figure 8 in relation to three predictive relationships. The general impression of the present study curve for standing timber fuel types is one of good agreement up to nearly 50 km/h; few observations are available beyond this point. The almost consistent tendency at underprediction is noticeable, especially at winds less than 20 km/h. It would appear that Equation [36] is perhaps more suitable over the whole practical L/B range (refer to figure 7d). Not included in table 3 or figure 7 are four generalized L/B observations based on a prescribed fire behavior study in Georgia slash pine plantations reported on by Johansen (1984). According to the information contained in the text and the data in tables 1 and 2 of that publication, the spot fires resulting from the plots ignited on a square-spaced grid exhibited L/B values of approximately 1.01 and 1.32. Predicted L/B values would range from 1.02 to 1.21, according to Equation [35] based on 10-m open winds estimated to be 4-11 km/h during the experimental trials. The sole overprediction in figure 8 is the 1968 Lesser Slave Lake Fire (# 23) which advanced 65 km in 10 hours. However, it spread downwind from an active perimeter source of unknown width rather than a point during its major run. The wide fire front was therefore responsible for the slight underprediction. This situation is analogous to the one described by Anderson (1983) for the 1967 Sundance Fire.

Figure 8 also includes two extreme outliers. These are the 1971 Air Force Bomb Range Fire (# 24) and the Red Lake 31-74 Fire (# 27). The most plausible explanation for the former case of severe underprediction would appear to be that the high water table at the time inhibited the lateral development of the fire (Wade et al. 1973). The very high L/B associated with the Red Lake 31-74 Fire remains somewhat of a mystery. In addition to the winds reported by Stocks (1975) for Red Lake, Ontario, at 45 km east of the fire area, the hourly observations at Bissett, Manitoba, at 90 km directly west of the fire, were also examined and turned out be very similar. It is possible that the combination of low-level jet winds (Street 1979), the alignment of lakes in relation to the wind direction, and a relatively high level of fuel moisture in the duff layer (as reflected by the Buildup Index (BUI) of the FWI System) were responsible for the extreme L/B value and corresponding underprediction.

At the time when the fire size calculation section of the 1984 interim edition user guide to the FBP System was prepared, it was felt that broad differences in L/B versus wind speed existed among major fuel complexes (i.e., timber vs. slash vs. grass). McArthur's (1966) relationship was tentatively applied to all noncanopied or non-forested fuel groups. This included the open fuel types (i.e., grass) and, at least on an interim basis, the slash fuel types as well. Sufficient data have not become available as a result of the evaluation process, to propose a separate L/B vs. wind function based on the five slash fires given in table 3:

[37] $L/B = e^{0.068234\, W^{0.86559}}$ $, W \leq 45$

where, W = 10-m open wind speed (km/h). The above equation parallels and is distinctly higher than Equation [35] for the standing timber fuel types.

Both the standing timber and logging slash L/B versus wind speed relationships were not intended to be extrapolated to very high wind speeds. The 50 km/h limit for Equation [35] was based on the cautionary note in Van Wagner (1974). The 45 km/h limit specified for Equation [37] was somewhat subjectively established to mesh with McArthur's (1966) relation. In the 1984 interim edition of the FBP System, McArthur's relationship was recommended for use at wind speeds greater than 50 km/h regardless of the fuel type. This procedure basically still remains valid, although its use as a leveling-off function is largely speculative. The Big Henry Fire in the Florida peninsula (year unknown) documented by Brown and Folweiler (1953) provides a possible data point at a very high L/B level. This fire traveled 31.5 km in 5 hours over level to rolling topography and left a roughly elliptical burn pattern estimated at 8900 ha. It occurred at the peak of the spring fire season (March 12) and was reported to have advanced as a crown fire through longleaf pine and scrub pine stands for the final three-quarters of its run. The maximum width near the midpoint of the fire varied from 1.6 to 6.3 km. This corresponds to L/B values of 5.0 and 19.7. How much expansion in the perimeter took place after the major run is unknown as only the final area burned map is available and little information is available in the written account by the authors. The map does give the position of the fire's head on six different occasions during the run, which leads one to believe that the actual breadth lies somewhere between the two extremes quoted earlier. A simple average based on the minimum and maximum widths yields an L/B of 8.0. Using Equation [8], the L/B based on an area of 8900 ha and a total spread distance of 31.5 km is 8.8. The predicted L/B based on Equation [19] for a 10-m open wind of 75 km/h is 8.2.

The comparisons of predicted versus observed L/B values for each major fuel complex are shown in figure 9. The simple correlation coefficient (r) for the standing timber fuel type observations was 0.865, indicating that a strong relationship exists. The tendency to underpredict L/B is again evident. This means that Equation [35] is estimating slightly "fatter" fires.

As a matter of possible future interest, here are the U.S. wind standard versions of Equations [35], [36], [37], and [19] in English units, respectively:

[38] $L/B = 1.0 + 0.00452\, U_{20}^{2.154}$ $, U_{20} \leq 27$

[39] $L/B = 0.5 + 0.5e^{0.09326\, U_{20}}$ $, U_{20} \leq 27$

[40] $L/B = e^{0.11626\, U_{20}^{0.86559}}$ $, U_{20} \leq 25$

[41] $L/B = 1.46\, U_{20}^{0.464}$ $, U_{20} \geq 1$

where, U_{20} = 20-ft or 6.1-m open wind speed (mi/h). Equation [41] is currently recommended for use above the limits specified in the three previous equations.

CONCLUDING REMARKS

The L/B versus 10-m open wind relationship derived in the present study, represented by Equation [35] (or [36]), can probably be regarded as a digest of current knowledge and information about the effect of wind on the elliptical shaped pattern of free-burning fires in standing timber fuel types. Improvements will no doubt come from more field observations of wildfires such as the DND-4-80 Fire (Alexander et al. 1983, Lawson et al. 1985) and further experimental fire studies. The present model is a very simplistic one. A single equation can be applied with considerable confidence to forested or tree canopied fuel types based on a measure of wind speed that is commonly recorded at fire weather network stations and included with fire weather forecasts on a daily basis in Canada. Any numerical L/B model has two two pertinent properties: strength and shape. Equation [35] (or [36]) yields 1.0 when is zero, which is considered a necessary condition, and it compares favorably with actual surface and crown fires in a fairly wide variety of coniferous forests over a realistic range in wind speed. The function will tend to underestimate L/B and result in overestimates of fire size (e.g., Lawson et al. 1985), a situation which can probably be tolerated.

The necessity of a separate relationship for logging slash fuel types appears justified on the basis of readily available observational evidence. Additional L/B data are needed to refine the existing relation or to refute the requirement altogether. The peculiar shape of McArthur's (1966) curve would also suggest further investigation of grassland fires is desirable in view of the general nature of the other L/B models.

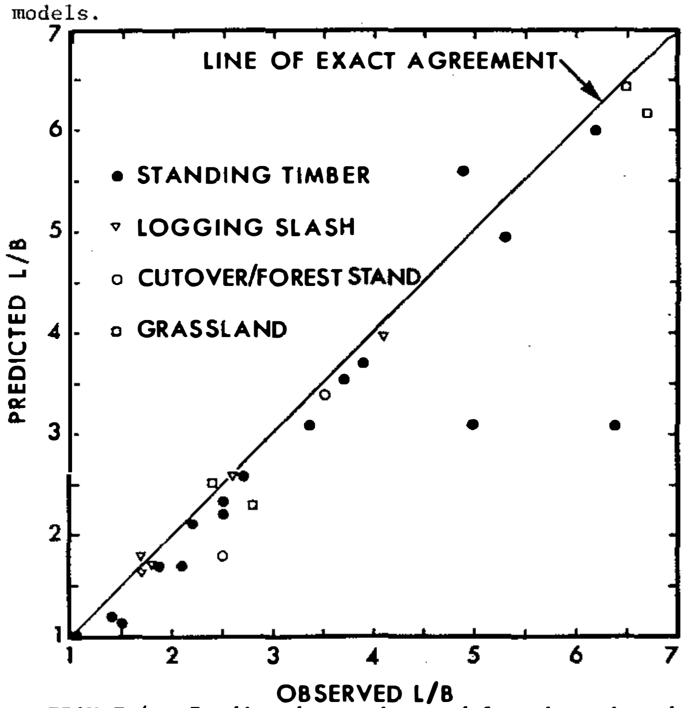

FIGURE 4.--Predicted vs. observed length-to-breadth ratios (L/B) for four distinct fuel complexes: (i) standing timber - Present Study, Equation [35]; (ii) logging slash - Present Study, Equation [37]; (iii) cutover/forest stand - theoretically, the midpoint of (i) and (ii); and (iv) grassland - McArthur (1966), Equation [19].

Simard et al. (1983) have pointed out that wind diretion variability would decrease the L/B. All existing models, including the ones developed in the present study, assume a constant wind direction, except for the model proposed by Simard and Young (1978). A constant adjustment factor would appear inappropriate, but development of a more rigorous calculation does not appear to be justified. Simard et al. (1983) have also noted that horizontal roll vortices (HRV) (Haines 1982, Haines and Smith 1983) would increase observed lateral fire spread beyond what would normally be expected, thereby descreasing the ratio as well. The 1956 Dudley Lake Fire in northern Arizona (Schaefer 1957, Dieterich 1976) represents a possible case in point. That fire is documented as having displayed HRV activity (Haines 1982). The fire made a major run of more than 16 km on June 14 through a mature ponderosa pine forest, eventually burning over an area of approximately 8656 ha under the influence of strong, fairly constant southwest winds measured at 56-80 km/h. The computed L/B based on the map contained in Schaefer (1957) was only 3.2. The reported winds and photos of the wind-driven smoke plume in Dieterich (1976) and Haines (1982) would have suggested a very narrow fire front. It is not known how wide a front was established prior to the fire run or how much expansion in the perimeter took place after the run. Given our imperfect knowledge about the exact environmental conditions and fire characteristics under which HRV's occur, consideration of this factor doesn't seem warranted at this time. Besides, one has to suspect that wind direction variability and HRV activity effects are in most cases at least partially compensated for by fuel moisture conditions, natural and man-made barriers constricting fire growth, low-level jets, and possible other hitherto unknown factors.

This paper has so far dealt exclusively with the influence of the surface wind speed on L/B. How could 'slope + wind' and 'slope + no wind' situations be easily handled? In terms of rate of spread (ROS), it has traditionally been assumed (e.g., Cheney 1981), for reasons of expediency, that no interaction exists between wind and slope (i.e., the effects are additive). Applying this concept to the growth pattern of an elliptically shaped fire, or, in this case the L/B, we would determine the increase or equivalency in wind speed required to attain the corresponding increase in ROS between level ground and a given percent slope. The following example, based on Fuel Type C-3 (Mature Jack or Lodgepole Pine) in the 1984 interim edition of the FBP System (Lawson et al. 1985), will illustrate the above principles:

10-m wind (km/h)	ROS on 0% slope (m/min)	Ground slope (%)	Spread Factor (SF)	ROS adjusted for % slope (m/min)	L/B
23	6.3	0	1.00	6.3	2.03
23	6.3	38	3.02	19.0	3.10
0	0.3	38	3.02	0.9	1.15

The effect of slope on fire spread rate in the above example is based on the relation derived by Van Wagner (1977) for fires burning upslope, the practical output of which is a relative Spread Factor, a simple multiplier. The above situations refer to fires spreading directly upslope with or without any wind. This rerepresents a rather elementary case. More robust schemes involving manual computational vectoring procedures (e.g., Rothermel 1983) or large fire growth models requiring extensive fuel and terrain data bases (e.g., Kourtz et al. 1977, Sanderlin and Van Gelder 1977, Anderson et al. 1982, Kourtz 1984) are also available or under development for complex or "amoeba-like" fire situations.

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APPENDIX I: Tabulation of Head Fire/Backfire Spread Ratios (H/B) versus Length-to-Breadth Ratio (L/B) of Free-Burning Elliptical Shaped Wildland Fires.

L/B	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
					H/B					
1	1.00	2.43	3.47	4.54	5.66	6.86	8.12	9.46	10.9	12.4
2	13.9	15.6	17.3	19.1	21.0	23.0	25.0	27.1	29.3	31.6
3	34.0	36.4	38.9	41.6	44.2	47.0	49.8	52.7	55.7	58.8
4	62.0	65.2	68.6	71.9	75.4	79.0	82.6	86.3	90.2	94.0
5	98.0	102	106	110	115	119	123	128	133	137
6	142	147	152	157	162	167	172	178	183	188

__Note__: e.g., L/B = 2.0 and H/B = 13.9 or 13.9:1.

APPENDIX II: Tabulation of Area Shape Factors (K_A) versus Length-to-Breadth Ratio (L/B) for Free-Burning Elliptical Shaped Wildland Fires.

L/B	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
					K_A					
1	3.14	1.42	1.09	0.90	0.78	0.69	0.62	0.56	0.52	0.48
2	0.45	0.42	0.40	0.38	0.36	0.34	0.33	0.31	0.30	0.29
3	0.28	0.27	0.26	0.25	0.24	0.23	0.23	0.22	0.21	0.21
4	0.20	0.20	0.19	0.19	0.18	0.18	0.17	0.17	0.17	0.16
5	0.16	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14
6	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.12

__Note__: e.g., L/B = 2.0 and K_A = 0.45.

APPENDIX III: Tabulation of Perimeter Shape Factors (K_p) versus Length-to-Breadth Ratio (L/B) for Free-Burning Elliptical Shaped Wildland Fires.

L/B	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
					K_p					
1	6.28	5.09	4.66	4.35	4.10	3.90	3.73	3.59	3.46	3.35
2	3.26	3.17	3.09	3.03	2.96	2.91	2.86	2.81	2.77	2.73
3	2.69	2.66	2.63	2.60	2.58	2.55	2.53	2.51	2.49	2.47
4	2.45	2.43	2.42	2.40	2.39	2.38	2.36	2.35	2.34	2.33
5	2.32	2.31	2.30	2.29	2.28	2.27	2.27	2.26	2.25	2.24
6	2.24	2.23	2.23	2.22	2.21	2.21	2.20	2.20	2.19	2.19

__Note__: e.g., L/B = 2.0 and K_p = 3.26.

APPENDIX IV: Tabulation of Length-to-Breath Ratio (L/B) versus 10-m Open Wind Speed Relationships

10-m wind (km/h)	McArthur (1966) grass	Anderson (1983) forest stand dense[1]	Anderson (1983) forest stand open[2]	Anderson (1983) grass/ slash[3]	Anderson (1983) heavy slash[4]	Anderson (1983) crown fire[5]	Chrosciewicz (1975) slash[6]	Simard & Young (1978) SD of wind direction 0°	Simard & Young (1978) SD of wind direction 10°	Simard & Young (1978) SD of wind direction 20°	Present study Eq. [34]	Present study Eq. [35]	Present study Eq. [36]
	L/B												
0	1.00	1.40	1.40	1.40	1.40	1.40	1.40	1.00	1.00	1.00	1.00	1.00	1.00
1	1.10	1.41	1.41	1.41	1.42	1.45	1.43	1.02	1.01	1.01	1.00	1.03	1.07
2	1.52	1.41	1.42	1.43	1.44	1.50	1.46	1.04	1.03	1.03	1.01	1.05	1.13
3	1.83	1.42	1.44	1.45	1.46	1.56	1.50	1.06	1.06	1.05	1.01	1.08	1.19
4	2.09	1.43	1.45	1.47	1.49	1.63	1.53	1.09	1.08	1.07	1.02	1.11	1.25
5	2.32	1.44	1.46	1.49	1.51	1.71	1.57	1.12	1.11	1.09	1.04	1.14	1.32
6	2.53	1.45	1.48	1.51	1.54	1.79	1.62	1.15	1.13	1.12	1.06	1.18	1.38
7	2.71	1.46	1.49	1.53	1.57	1.88	1.66	1.18	1.16	1.15	1.08	1.21	1.44
8	2.89	1.47	1.51	1.55	1.60	1.98	1.71	1.22	1.19	1.17	1.11	1.25	1.51
9	3.05	1.48	1.52	1.57	1.63	2.09	1.76	1.25	1.23	1.20	1.14	1.29	1.58
10	3.20	1.49	1.54	1.60	1.66	2.21	1.81	1.29	1.26	1.23	1.17	1.33	1.65
11	3.35	1.50	1.56	1.62	1.69	2.34	1.87	1.33	1.30	1.26	1.21	1.37	1.72
12	3.48	1.51	1.57	1.65	1.73	2.48	1.93	1.38	1.33	1.29	1.25	1.42	1.80
13	3.62	1.52	1.59	1.67	1.76	2.63	2.00	1.42	1.37	1.33	1.30	1.46	1.87
14	3.74	1.53	1.61	1.70	1.80	2.79	2.06	1.47	1.41	1.36	1.35	1.51	1.95
15	3.86	1.54	1.63	1.73	1.84	2.97	2.13	1.52	1.45	1.40	1.41	1.56	2.04
16	3.98	1.55	1.65	1.75	1.88	3.16	2.21	1.57	1.50	1.43	1.47	1.62	2.12
17	4.10	1.56	1.66	1.78	1.92	3.37	2.29	1.63	1.54	1.47	1.54	1.68	2.21
18	4.21	1.57	1.68	1.81	1.96	3.59	2.37	1.68	1.59	1.51	1.61	1.74	2.30
19	4.31	1.58	1.71	1.85	2.01	3.83	2.46	1.74	1.64	1.54	1.68	1.80	2.39
20	4.42	1.60	1.73	1.88	2.06	4.09	2.55	1.80	1.69	1.58	1.76	1.87	2.49
21	4.52	1.61	1.75	1.91	2.11	4.37	2.65	1.87	1.74	1.62	1.85	1.94	2.59
22	4.62	1.62	1.77	1.95	2.16	4.67	2.75	1.94	1.79	1.66	1.93	2.02	2.69
23	4.71	1.63	1.79	1.98	2.21	4.99	2.86	2.01	1.84	1.70	2.03	2.09	2.80
24	4.81	1.65	1.81	2.02	2.26	5.34	2.97	2.09	1.90	1.75	2.13	2.18	2.91
25	4.90	1.66	1.84	2.06	2.32	5.72	3.09	2.16	1.96	1.79	2.23	2.26	3.02
26	4.99	1.67	1.86	2.10	2.38	6.12	3.21	2.25	2.02	1.83	2.34	2.35	3.14
27	5.08	1.68	1.89	2.14	2.44	6.56	3.34	2.33	2.08	1.87	2.45	2.45	3.26
28	5.16	1.70	1.91	2.18	2.50	7.02	3.48	2.42	2.14	1.92	2.57	2.55	3.39
29	5.25	1.71	1.94	2.22	2.57	7.53	3.62	2.51	2.20	1.96	2.70	2.66	3.52
30	5.33	1.73	1.96	2.26	2.63	8.07	3.77	2.61	2.27	2.00	2.82	2.77	3.65
31	5.41	1.74	1.99	2.31	2.70	8.65	3.92	2.72	2.33	2.05	2.96	2.88	3.79
32	5.49	1.75	2.02	2.35	2.78	9.27	4.09	2.82	2.40	2.09	3.10	3.01	3.94
33	5.57	1.77	2.05	2.40	2.85	9.94	4.26	2.94	2.47	2.13	3.24	3.14	4.09
34	5.65	1.78	2.08	2.45	2.93	10.67	4.44	3.05	2.54	2.18	3.39	3.27	4.24
35	5.73	1.80	2.11	2.50	3.01	11.44	4.63	3.18	2.61	2.22	3.54	3.42	4.40
36	5.80	1.81	2.14	2.55	3.09	12.28	4.83	3.30	2.69	2.26	3.70	3.57	4.56
37	5.88	1.83	2.17	2.61	3.18	13.17	5.04	3.44	2.76	2.30	3.86	3.73	4.73
38	5.95	1.85	2.20	2.66	3.27	14.13	5.25	3.58	2.83	2.34	4.03	3.89	4.90
39	6.02	1.86	2.23	2.72	3.36	15.17	5.48	3.73	2.91	2.38	4.21	4.07	5.09
40	6.09	1.88	2.26	2.78	3.45	16.28	5.72	3.88	2.98	2.42	4.39	4.25	5.27
41	6.16	1.90	2.30	2.84	3.55	17.47	5.97	4.04	3.06	2.46	4.57	4.45	5.46
42	6.23	1.91	2.33	2.90	3.65	18.75	6.23	4.21	3.14	2.50	4.76	4.65	5.66
43	6.30	1.93	2.37	2.96	3.75	20.13	6.50	4.39	3.21	2.53	4.96	4.87	5.87
44	6.37	1.95	2.40	3.02	3.86	21.61	6.79	4.58	3.29	2.57	5.16	5.09	6.08
45	6.43	1.96	2.44	3.09	3.97	23.19	7.09	4.77	3.37	2.60	5.37	5.33	6.30
46	6.50	1.98	2.48	3.16	4.09	24.90	7.40	4.97	3.45	2.64	5.58	5.58	6.53
47	6.57	2.00	2.51	3.23	4.21	26.73	7.73	5.19	3.52	2.67	5.80	5.84	6.76
48	6.63	2.02	2.55	3.30	4.33	28.70	8.07	5.41	3.60	2.70	6.02	6.12	7.00
49	6.69	2.04	2.59	3.38	4.46	30.81	8.43	5.64	3.67	2.72	6.25	6.41	7.25
50	6.76	2.06	2.63	3.45	4.59	33.08	8.80	5.89	3.75	2.75	6.48	6.71	7.51

[1] Fully sheltered fuel complexes using a 6.1-m or 20-ft open to midflame height wind speed adjustment factor (U/U_{20}) of 0.2 (Rothermel 1983). Based on Equation [23] in the text.

[2] Partially sheltered fuel complexes using U/U_{20} = 0.3 (Rothermel 1983). Based on Equation [24] in the text.

[3] Includes short and tall grass, light and medium logging slash, and leafless hardwood stands corresponding to Fuel Models 1, 3, 11, 12, and 7 in Anderson (1982). A U/U_{20} = 0.4 was used (Rothermel 1983). Based on Equation [25] in the text.

[4] Heavy logging slash corresponding to Fuel Model 13 in Anderson (1982). A U/U_{20} = 0.5 was used (Rothermel 1983). Based on Equation [26] in the text.

[5] Assumes that the 10-m open wind speed is equivalent to the midflame wind speed (i.e., U/U_{20} = 1.0). Based on Equation [27] in the text.

[6] Determined from Anderson's (1983) ℓ/ω vs. midflame wind speed relationship and Chrosciewicz's (1975) 1.2-m above ground to 10-m open wind speed adjustment factor of 1.6 (U/U_{20} = 0.72). Based on Equation [28] in the text.

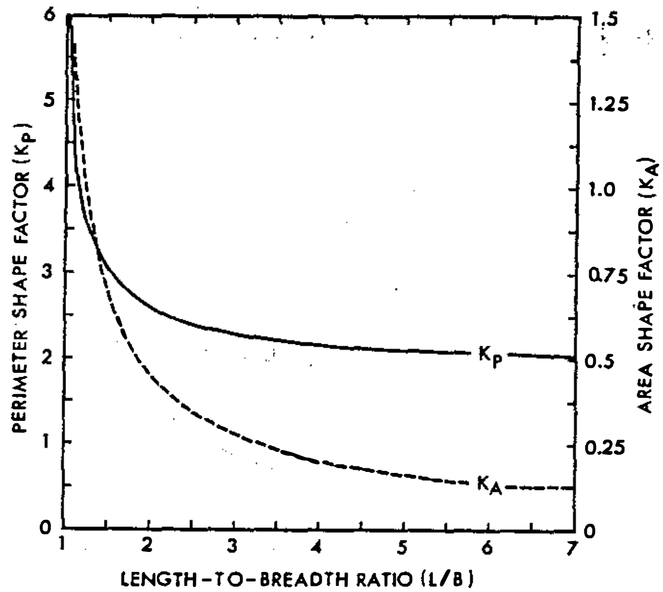
ERRATUM

Alexander, M.E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Pages 287-304 in Proceedings of the Eight Conference on Fire and Forest Meteorology (Apr. 29-May 2, Detroit, Mich.). Society of American Foresters, Bethesda, Maryland.

1. Page 292, Equation [18] should read:

$$[18] \quad K_p = \pi \left(\frac{1 + Rb}{1/Ra}\right) \left(1 + \frac{[(1 - Rb)/(1 + Rb)]^2}{4}\right)$$

2. Page 292, revised Figure 6:



3. Page 300, Figure 9 not 4.

4. Page 303, revised Appendix III:

L/B	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	K_p									
1	6.28	4.24	3.72	3.41	3.19	3.03	2.91	2.81	2.72	2.65
2	2.60	2.55	2.50	2.46	2.43	2.40	2.37	2.35	2.33	2.31
3	2.29	2.27	2.26	2.25	2.23	2.22	2.21	2.20	2.19	2.18
4	2.17	2.17	2.16	2.15	2.15	2.14	2.14	2.13	2.13	2.12
5	2.12	2.11	2.11	2.10	2.10	2.10	2.09	2.09	2.09	2.08
6	2.08	2.08	2.08	2.07	2.07	2.07	2.07	2.06	2.06	2.06

Note: e.g., L/B = 2.0 and Kp = 2.60.

5. Page 304, Appendix IV, last three columns refer to Eqs. [35], [36], and [37].

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