DESCRIBING FOREST FIRES IN WESTERN AUSTRALIA

A GUIDE FOR FIRE MANAGERS

by N.D. Burrows

FORESTS DEPARTMENT OF WESTERN AUSTRALIA

TECHNICAL PAPER NO. 9

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Forests Department of W.A.
P.J. McNamara
Acting Conservator of Forests
1984

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SUMMARY

In addition to traditional fire prevention and suppression activities, forest fire managers must be able to describe and evaluate the role of fire and fire regimes in relation to land management objectives. An important part of this is communicating with other fire organizations, and land managers who may not be familiar with fire. It is also necessary to be able to describe and quantify aspects of fire behaviour which affect land management. This paper presents common definitions of the many aspects of fire behaviour, and outlines techniques for quantifying fire behaviour. This information should be used with existing fire behaviour models, manuals, and texts to further aid fire planners, fire controllers and fire researchers.

INTRODUCTION

The role of fire, and its impact on forest resources has always been of significance to land managers. As our understanding of forest fire behaviour and fire effects increases, this knowledge will become an increasingly important tool in the development of future land management strategies.

The Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet, 1976), also called the "Red Book", are useful guides for forecasting forest fire danger, fire behaviour, and for evaluating fire suppression strategies. The "Red Book" can be used to predict the likely head fire rates of spread for fires burning under various fuel, weather and topographical conditions.

However, rate of spread may enable us to predict the location of a fire after a time interval, but it does not fully describe the fire's suppression difficulty, nor its potential to damage vegetation.

It is generally recognized that five primary factors must be specified before the possible effects of fire on an ecosystem can be examined. These are:

- (i) fire frequency;
- (ii) fire intensity and duration;
- (iii) fuel bed characteristics;
- (iv) soil and vegetation characteristics;
- (v) season of burn.

In the past fires have been described with subjective terms such as: "cool", "hot", "fast", or "slow". These terms are not always adequate for developing a clear picture of fire effects.

The purpose of this paper is to provide standardized techniques and terminology for describing forest fire behaviour in Western Australian forests. It is intended that this should complement the Forest Fire Behaviour Tables for Western Australia, and other guides used by forest fire managers, and supplement comprehensive fire texts such as "Bushfires in Australia" (Luke and McArthur, 1978) and "Fire and the Australian Biota" (Gill, A.M. *et al*, 1981).

1 DESCRIBING AND QUANTIFYING FIRE BEHAVIOUR

MEASURES OF FIRE GROWTH

Viewed from above, fires which have developed from a spot, or point source, are roughly elliptical or egg-shaped (Peet, 1967). Initially, fires may be circular, but wind, slope, or fuels will change the fire shape. Under constant conditions, the fire width - to - length ratio (or flank fire to head fire rate of spread ratio) is governed by wind and slope. Figure 1 below illustrates this, and shows idealized fire shapes associated with various forest windspeeds (measured at 1.5 metres above the ground, and in the forest). A conversion to approximate tower windspeed (windspeed at 10 m above the ground, and in the open) is also given.

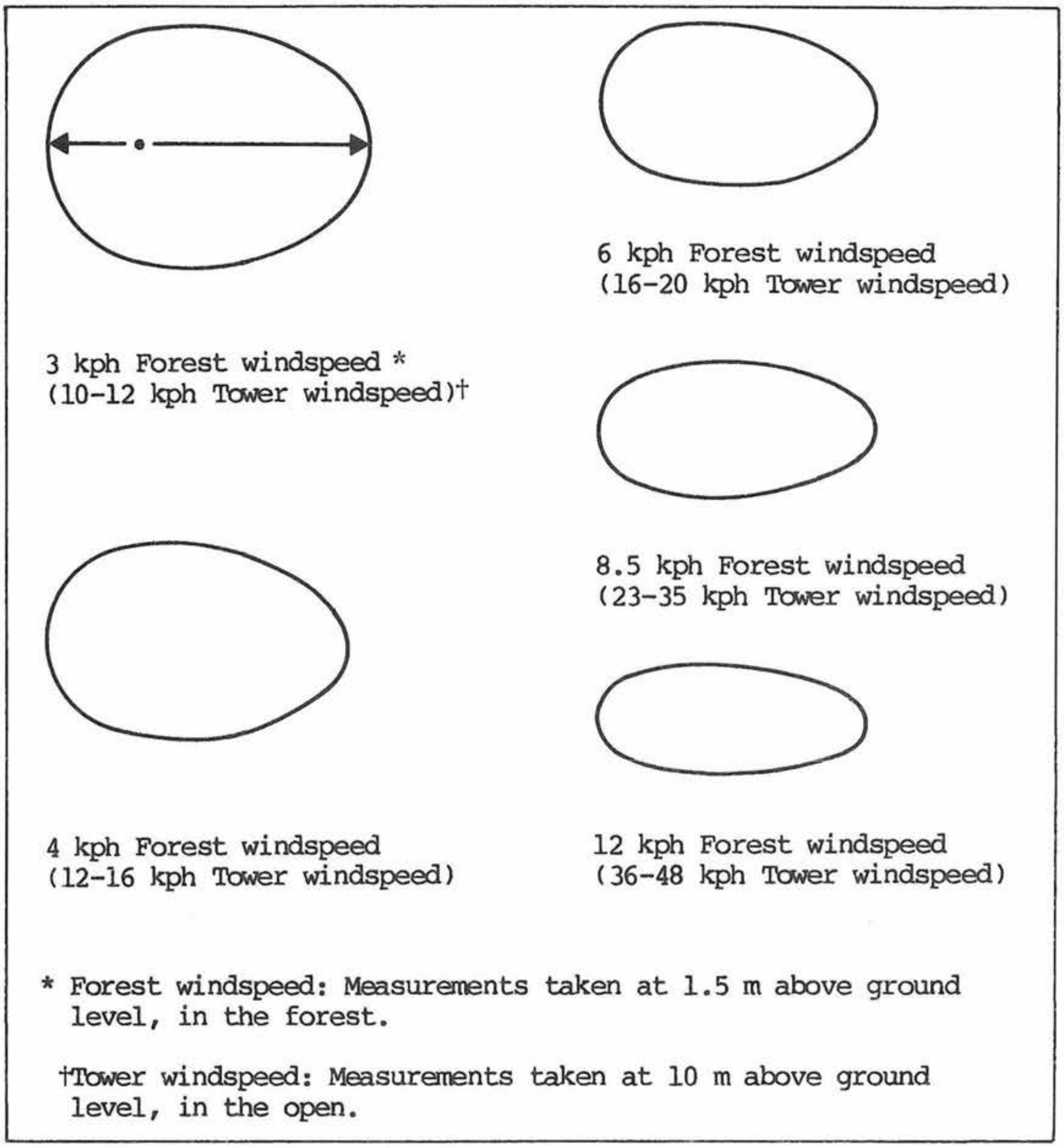


FIGURE 1 : Idealized fire shapes for various windspeeds.

FIRE SECTORS

Fire behaviour varies around the perimeter of a fire burning with a roughly elliptical shape. This variation depends largely on fuel, weather, topographical conditions, and the shape of the fire. There are three main sectors or zones of a fire. These are the head fire, flank fire, and back fire.

Head Fire

The head fire is the section of the fire moving in the same direction as the wind or the slope. Head fire flames lean in the direction of the wind or slope and lean over the unburnt fuel (Fig. 2). The head fire is further characterized by being the most intense part of the fire; where flame height, flame length, flame depth, and rate of spread are greatest. An arbitrary zone of head fire is shown in Figure 2. Head fire rate of spread, or the rate of advance of the head fire, is the distance travelled by the head fire along the central axis (Fig. 2) over time. Head fire rate of spread can be measured by using a stop-watch and estimating the distance travelled. Other techniques are discussed later. Rate of fire spread is usually expressed in metres per second ($m\ s^{-1}$) or metres per hour ($m\ hr^{-1}$). In severe forest fires and grassland fires kilometers per hour (kph) are sometimes used to express rate of spread.

Flank Fire

Flames on the flanks of a fire move in the general direction of wind or slope but at an acute angle to wind or slope (see Fig. 2). For a fire driven by a strong wind, the flank fire can make up most of the fire perimeter, so flank fire rate of spread will vary at different points along the perimeter. Flank fire rate of spread increases as the flank moves closer to the head fire zone. In determining lighting techniques for mild hazard reduction burns, flank fire rate of spread is

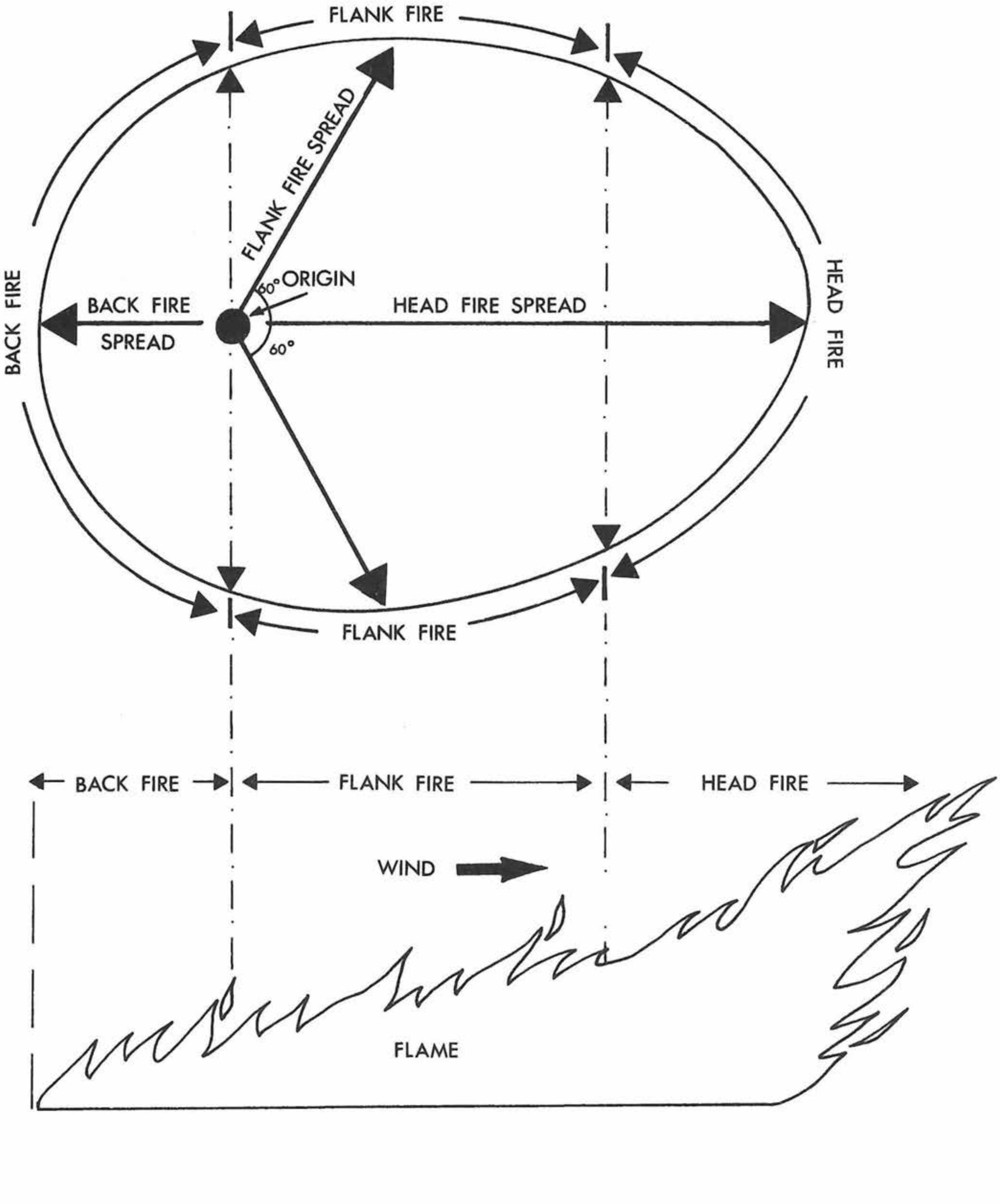


FIGURE 2: Head, flank, and back fire zones and relative flame sizes for a typical mild fire.

taken as the mean distance the fire travels along axes at 60 degrees to the central axis (Peet, 1967) (Fig. 2). Flank fire intensity, flame height, and rates of spread are lower than those of the head fire. Units for expressing flank fire rate of spread are the same as for the head fire. The length of the flank fire will influence the severity of control problems resulting when a wind shift causes the flank fire to become the new head fire.

Back Fire

The back, or tail, of the fire is the part of the fire where the flames are moving against the wind, or are moving downslope against the wind. Back fire flames are short (0.1 - 0.5 m), lean towards the head fire, and hence lean over burnt fuel. It is the least intense, slowest moving, and most constant part of the fire, and by far the least damaging and easiest to control. Units for expressing back fire rate of spread are the same as for head fire. Back fires in forest situations rarely spread at rates above 10 - 30 m hr^{-1}, even when the head fire is travelling very fast.

FIRE PERIMETER

Fire perimeter is the distance around the fire encircling the head, both flanks, and the back of the fire. Perimeter is usually expressed in metres (m) for small fires, and kilometres (km) for large fires. Increase in fire perimeter is expressed in m hr^{-1} or kph, depending on the fire size. So long as conditions remain unchanged, the perimeter will increase linearly with time. The Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt & Peet, 1976) provide guides for calculating fire perimeter. It is necessary to know the perimeter of wildfires so that the appropriate suppression strategies and resource allocations can be made. Usually, large wildfires are divided into sectors or portions of the fire's perimeter. A sector boss and suppression crew are responsible for controlling and containing a sector.

FIRE AREA

Fire area is the area burnt by the fire. This is the area enclosed by the fire perimeter and is usually expressed in hectares (ha). For constant conditions, including constant fuels, fire area will increase quadratically with time, according to the expression:

$$A = \frac{\frac{x}{2} (v + W)\ ut^2}{10\ 000} \quad \text{(Van Wagner, 1972)}$$

where : A = fire area (ha)

v = head fire rate of spread (m hr^{-1})

u = flank fire rate of spread (m hr^{-1})

w = back fire rate of spread (m hr^{-1})

t = time since ignition (hrs)

Figure 3 is a guide to estimating fire area for fires burning with an elliptical shape. This formula can be used to forecast fire area increases with time after ignition, or over any time interval. To use Figure 3, multiply the fire's length in km (back fire to head fire) by its width in km (across the flanks) and divide by two. Select this figure on the horizontal axis in Figure 3 and read off fire area on the vertical axis (note the logarithmic scale).

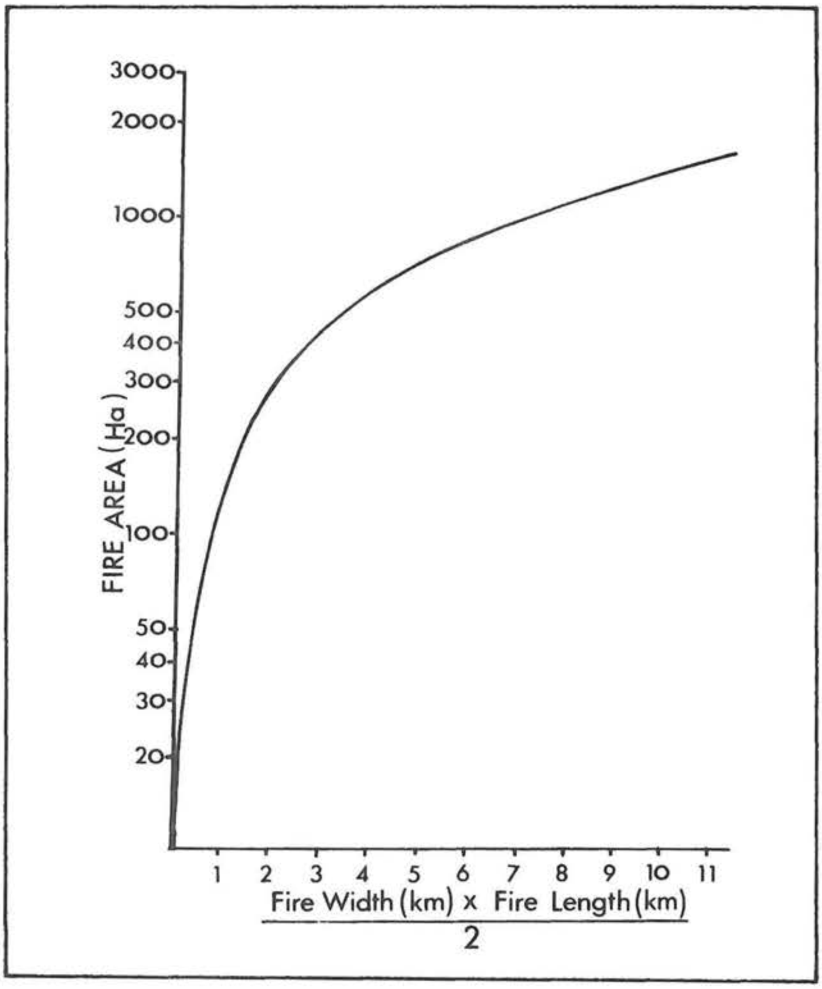


FIGURE 3: Fire area (ha) derived from fire length and fire width for roughly elliptical fire shapes.

2 MAPPING RUNNING FIRES

The easiest and safest way of mapping forest fires is from the air. This can be accomplished in two main ways (Cheney *et al*, 1968):

OBSERVATION FROM THE AIR

The observer simply plots the visible fire edge onto a scaled map of the area. The fire's position in relation to roads, creeks, ridges, property and other values, recently burnt areas, etc. is noted. Map scale used and the altitude from which the plot is made will depend on fire size, accuracy requirements, flying conditions and purpose of the fire plot. Fire plots are mostly used to aid ground crews in suppression and mop-up operations, and to enable controllers to calculate the area burnt and the fire perimeter. Information can also be provided on rates of spread, flame heights, hot spots requiring mop-up or further attention, hop-overs, and potential danger areas. The observer plotting fire perimeters and gathering information about the fire must have a good knowledge of the country and of fire behaviour.

INFRA-RED TECHNIQUES

Visual mapping of fire perimeters from the air is difficult when smoke obscures the fire, or rough flying conditions are encountered. Infra-red instruments allow the fire to be observed and even photographed through smoke. The quality of the imagery and depth of penetration through smoke varies with the sophistication of the instrument. Instruments range from relatively cheap, hand held viewers to expensive and sophisticated line scanners. The latter can map fire edges very accurately and through dense smoke. Fire behaviour, fire size, and fire perimeter can be readily determined by plotting the fire perimeter at frequent intervals. An added advantage of infra-red techniques is that hot spots, hop-overs, and long distance spotting can be detected through dense smoke which would obscure visual detection. The main disadvantages of infra-red scanners are their high cost and poor terrain detail. Figure 4 shows the infra-red imagery of an experimental fire.

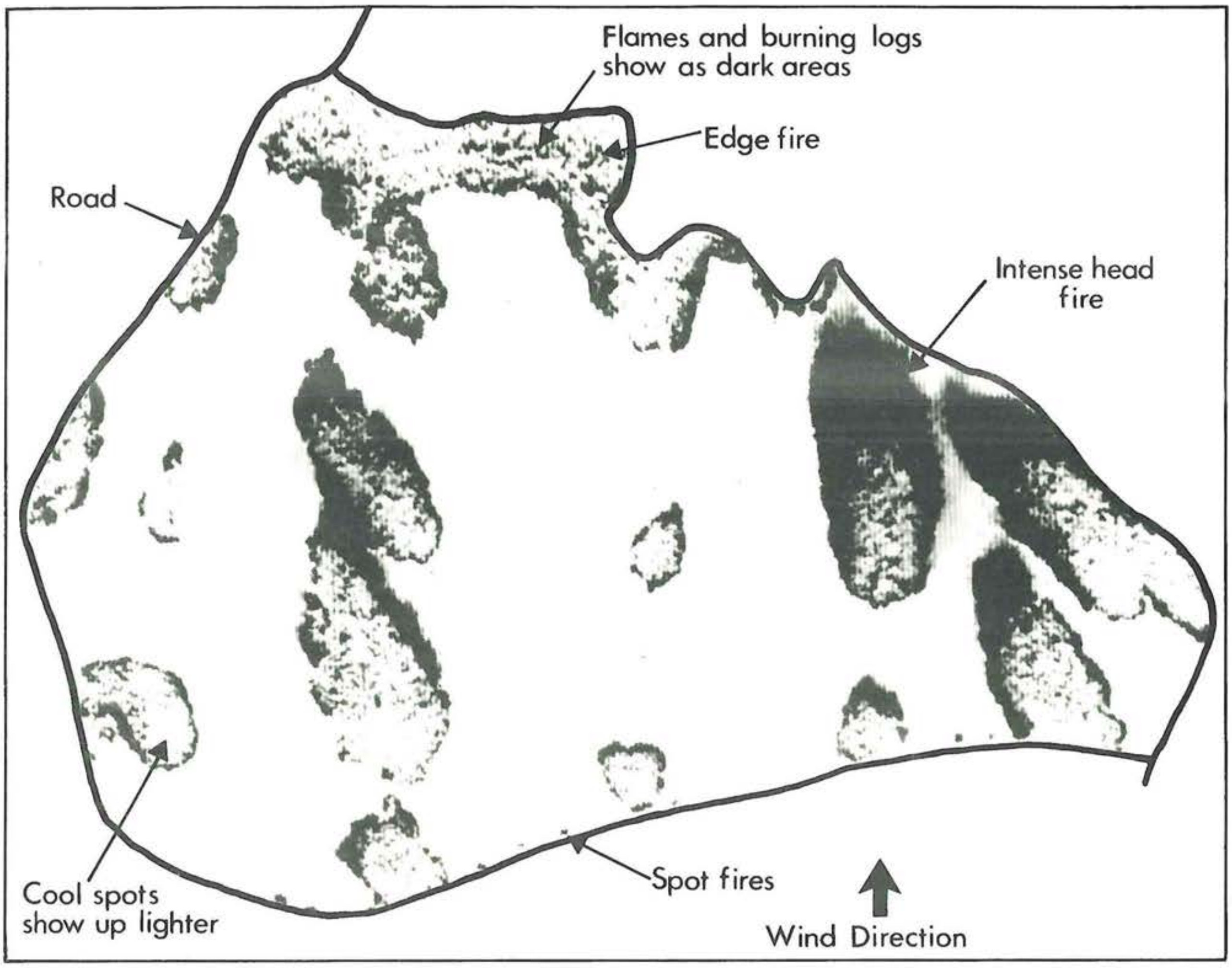


FIGURE 4: Infra-red line scan of an experimental mass ignition fire. Much information about fire behaviour can be interpreted from these scans taken through dense smoke.

3 DESCRIBING FLAMES

Flame dimensions are used to estimate fire behaviour and fire intensity. Therefore, flame descriptions can provide information about the likely damage to vegetation and the suppression difficulty of the fire. The most common flame dimensions used are flame length, flame height, flame depth and flame angle.

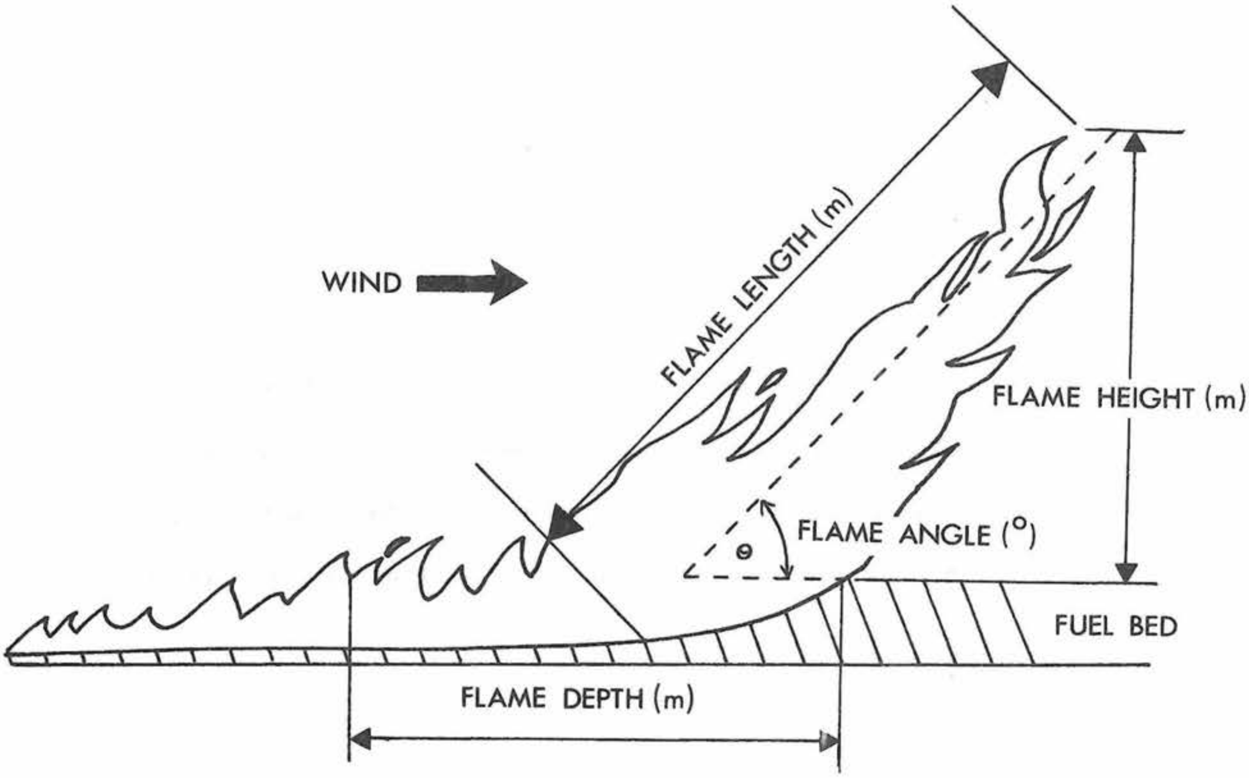


FIGURE 5: Flame dimensions for a wind driven fire.

FLAME LENGTH

Flame length is the distance between the top of the flame, and the ground (or fuel bed) midway through the zone of active flaming (Rothermel and Deeming, 1980) (Fig. 5). Flame length can be estimated visually in the field and with a reasonable degree of accuracy for low intensity fires (< 350 kW m^{-1}).

However, under severe burning conditions, flames become more buoyant, randomized and diffuse. Visual estimates are less reliable, and difficult to obtain safely. In the forest there are many features which can be used to provide a scale, such as scrub height, the height of small trees including *Banksia spp.*, *Persoonia spp.* and others. In extreme situations, the overstorey canopy can also be used as a scale.
Flame length can also be calculated from measurements of flame height and flame angle (See below). Flame length is usually expressed in metres (m).

FLAME HEIGHT

Flame height (Fig. 5) is the vertical distance between the tip of the flame and the ground or fuel bed. Like flame length, it is estimated using a simple visual scale, and is expressed in metres (m). Flame height is usually less than flame length, but may be the same for fires burning on flat terrain under very low wind speeds.

Post-burn Estimations of Fire Behaviour

In the absence of observations made during the fire, approximate flame heights can be estimated soon after the fire by (i) measuring the height to which vegetation has been defoliated, or (ii) measuring the height of stem charring on non-fibrous barked plants such as *Banksia grandis*. Stem charring will be considerably higher on the leeward side of the stem due to the "chimney" effect. This is very pronounced under strong winds and dry conditions. More reliable estimates from stem char can be obtained from the windward or downhill side. The "chimney" effect can reveal wind direction and can be used as a coarse measure of wind strength; the higher the leeward-to-windward char ratio, generally, the stronger the wind. The direction of head fire travel can be determined from stem char. Another useful post burn technique for determining wind and head fire direction is "freeze" direction. Heat from the fire often makes the stems and twigs of living vegetation very supple. After the fire passes and the sap has cooled, stems and twigs remaining will be "frozen" in this wind-bent position.

FLAME DEPTH

Flame depth (Fig. 5) is the distance at the base of the flame from the leading edge to the rear of the flame. Flame depth does not include the after-burn of twigs and logs. It is probably the most difficult flame dimension to measure, especially for severe fires, because of the indefinite trailing edge. Flame depth is expressed in metres (m).

FLAME ANGLE

Flame angle (Fig. 5) is defined as the angle formed between the flame front and the unburnt fuel bed.

4 USING FLAME DESCRIPTIONS

ESTIMATING RATE OF SPREAD FROM FLAME DIMENSIONS

Observations of flame dimensions provide information about a fire's behaviour, and its likely effects. Figure 6 is a guide to estimating fire rate of spread from flame height for typical upland jarrah (*Eucalyptus marginata* Sm) litter fuels. As windspeed increases, flames tend to become lower and longer for a given rate of spread. The windspeeds shown in Figure 6 assume a 4:1 ratio between windspeed measured at 10 m above ground level in the open (Tower windspeed), and windspeed measured at 1.5 m above ground level in the forest (Forest windspeed).

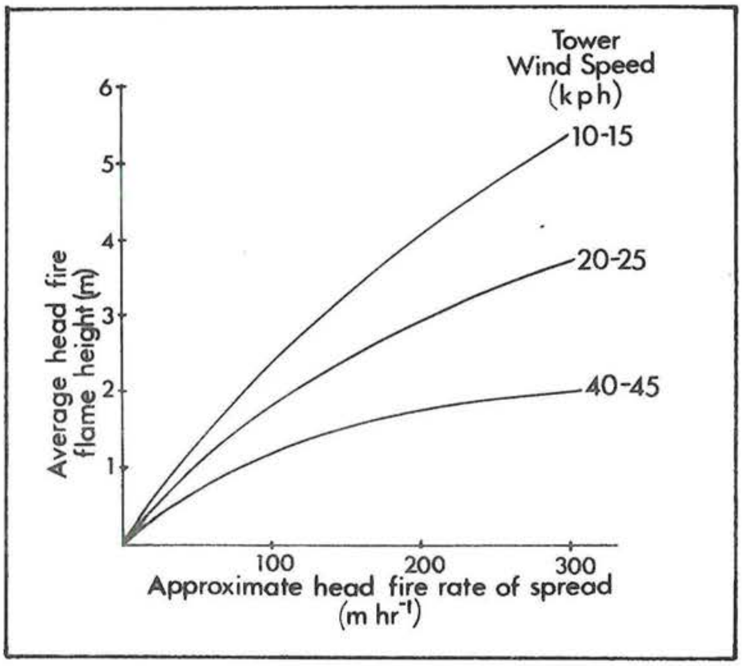


FIGURE 6: Approximate head fire spread rates from average flame heights for fires burning in a typical upland jarrah litter fuel of 8 - 9 tonnes per hectare (t ha^{-1}).

ESTIMATING SCORCH HEIGHT FROM FLAME HEIGHT

The Forest Fire Behaviour Tables (Sneeuwjagt & Peet, 1976) provide guidelines for estimating scorch heights for given fuel conditions, and rates of spread. Head fire flame height can be used to estimate scorch for a given set of conditions. Figure 7 illustrates the likely scorch height from fires burning in 5-7 year old jarrah litter fuels under dry summer or autumn conditions.

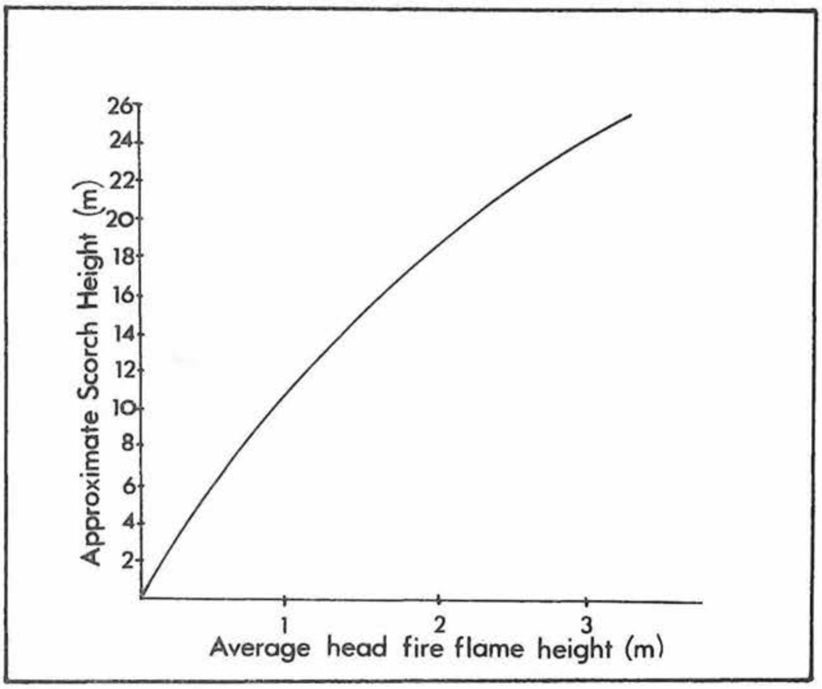


FIGURE 7: Head fire flame height, and approximate scorch height for fires burning under warm, dry conditions with a windspeed of 10-15 kph.

ESTIMATING INTENSITY FROM FLAME DIMENSIONS

Byram (1959) related the length of flames at the fire front to fire intensity by the formula:

$$I = 258F_L^{2.17}$$

where: I = fire intensity (kW m^{-1})

F_L = flame length (m)

The difficulty of using flame length to estimate fire intensity in the field is in measuring flame length, especially for high (<1,200 kW m^{-1}) intensity fires. It is often easier to use flame angle and flame height to calculate flame length, and then determine fire intensity. The relationships between flame length, flame angle, and flame height are shown in Figure 9, and can be used with Figure 8 to determine fire intensity.

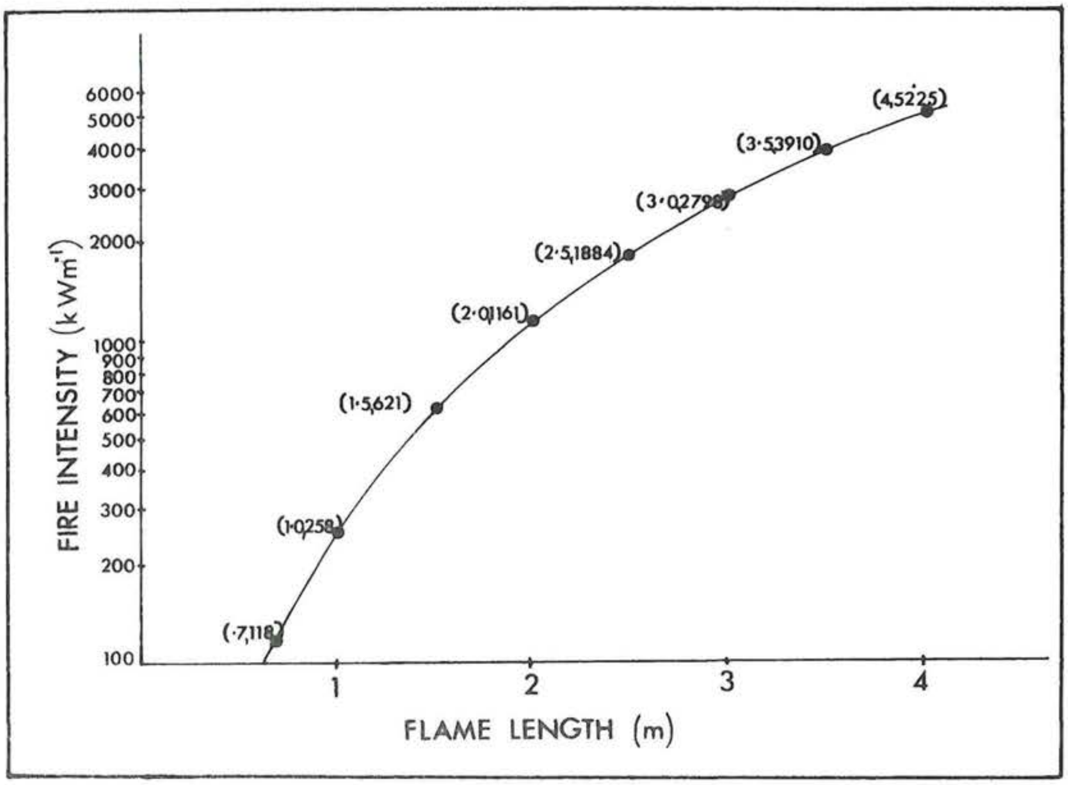
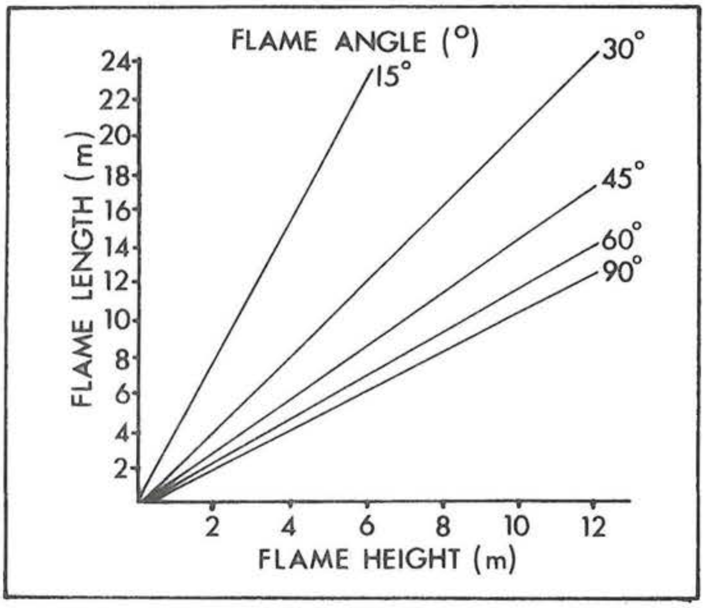


FIGURE 8: Estimating Fire Intensity from Flame length.



$$\text{flame length (m)} = \frac{\text{flame height (m)}}{\text{sine flame angle } (^{\circ})}$$

FIGURE 9: Flame length (m) from flame height (m) and flame angle (degrees).

As flame length and fire intensity are related, flame length can be used to estimate scorch height, bole damage and suppression difficulty.

5 FIRE INTENSITY

The frontal, or head fire intensity derived by Byram (1959) is an acceptable measure of forest fire behaviour and its potential to damage vegetation. Numerically, it is equal to the product of nett heat of combustion, quantity of fuel consumed in the active combustion or flaming zone (i.e. does not include large fuel particles such as logs) and a rate of linear spread.

i.e. $I = H W R$

where I = fire intensity in kilowatts per metre ($kW\ m^{-1}$)

H = fuel heat yield which is 18,600 kilojoules per kilogram of fuel for most forest fuels ($kJ\ kg^{-1}$)

W = fuel weight in kilograms per square metre ($kg\ m^{-2}$)

R = linear rate of advance (rate of spread) in metres per second ($m\ s^{-1}$)

so: $$I = \frac{kJ}{kg} \times \frac{kg}{m^2} \times \frac{m}{s} = kJ\ m\ s^{-1}$$

now $kJ\ m\ s^{-1} = kW\ m^{-1}$

$\therefore\ I = kW\ m^{-1}$ or $kJ\ m\ s^{-1}$

Simple and quick methods for estimating fire intensity are:

(i) use the flame length relationship as discussed earlier.

(ii) $I \approx \frac{\text{rate of spread (m hr}^{-1}\text{) x fuel consumed (tonnes/ha)}}{2}$

(iii) consult the relationship graphed in Figure 10 below.

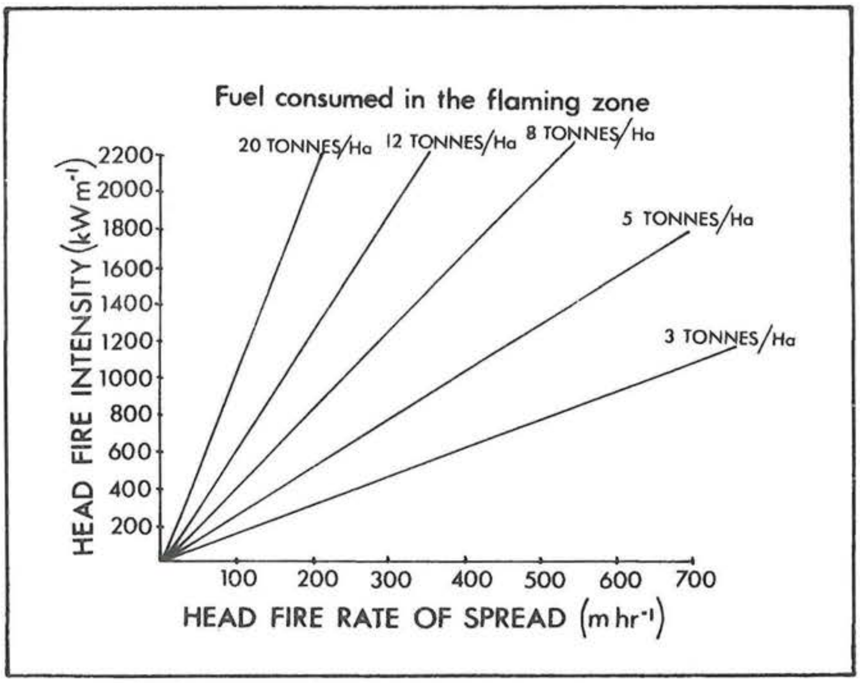


FIGURE 10: Head fire intensity from head fire rate of spread and fuel consumed in the flaming zone.

USING FIRE INTENSITY

Qualitative descriptions of forest fire cannot be used to accurately predict or compare the damage potential, the suppression difficulty, or the ecological effects of forest fires. Cheney (1981) classified fire intensity as low, moderate, high and very high. In addition to these classifications, Table 1 contains common descriptions of forest fire intensity. An aid to understanding the concept of "kilowatts per metre" is to compare the measurement with the heat energy output of a typical domestic radiator, which is usually one kilowatt.

TABLE 1

General classification of forest fires by flame length and fire intensity.

FLAME LENGTH (m)	FIRE INTENSITY ($kW\ m^{-1}$)	CLASSIFICATION
<1.5m	<350	Cool, mild, low intensity.
1.5- 4.4	350-1,200	Warm, moderate intensity.
1.5- 6.2	1,200-2,000	Hot, moderate - high intensity.
6.2-12.0	2,000-5,000	Hot, high intensity.
>12.0	>5,000	Very hot, very high intensity.

Fire intensity varies in space and time as fuel, weather and topographical conditions change. All other factors being unchanged fire intensity varies around the perimeter of a fire with the head of the fire being the most intense.

Figure 11 and Table 2 are further aids to interpreting forest fire intensity.

TABLE 2
Flame length and fire intensity as guides to suppression difficulty and some fire effects.

FLAME LENGTH (m)	FIRE INTENSITY (kW m^{-1})	INTERPRETATION	
		SUPPRESSION DIFFICULTY	SOME LIKELY EFFECTS
<1.5	<350	Fires can generally be attacked at the head and flanks using hand tools. Hand constructed breaks should hold fire.	Ideal fuel reduction burning range. Little or no damage to forest trees, although most scrub species will be killed to ground. Small eucalypts (<10 m) may be killed to ground or deformed by intensities near 350 kW m^{-1}.
1.5-6.2	351-2,000	Fires too intense for attack with hand tools. Dozers and heavy duty water tankers with retardent can be effective on flanks, and possibly on the head. Fire may jump dozer breaks.	Small trees (<10 cm diameter at breast height over bark, [d.b.h.o.b.]) will be killed to ground or severely damaged. Damage to growing tips and canopy may result in dog-legging or forking. Larger trees may suffer slight bole damage.
6.2-12.0	2,001-5,000	Fires may present serious control problems. There may be crowning and long distance spotting. Head fire attack will probably fail and could endanger fire fighters. Fires may display erratic behaviour.	Physical damage to bole and crown of eucalypts with some timber degrade. Small eucalypts (20 cm d.b.h.o.b.) may be killed to ground. Mature *Pinus radiata* will probably be killed.
>12	>5,000	Crowning, long distance spotting, whirlwinds and highly erratic behaviour are likely. Control efforts at head of fire will fail. Mass spotting and erratic behaviour can endanger the lives of fire fighters many km downwind of the fire.	Considerable damage may occur to crowns and boles. Mature pines will be killed. Considerable damage to soil structure may result. Rootstock species may be killed.

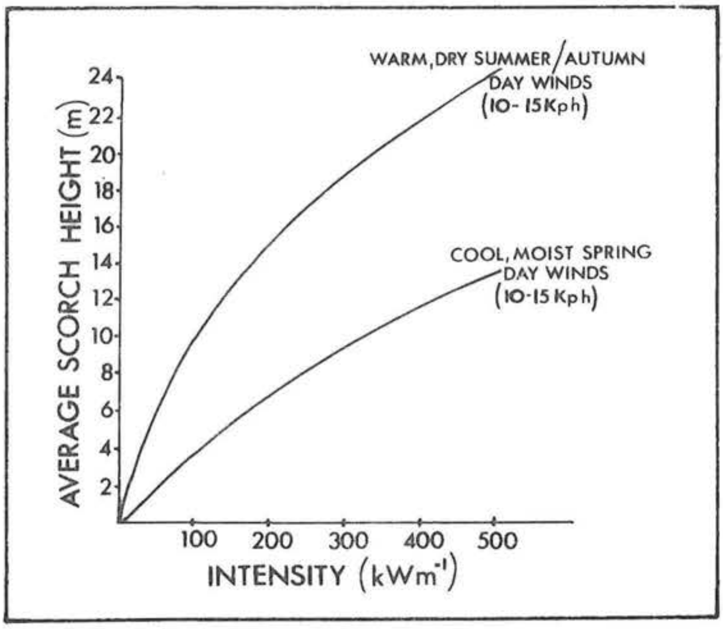


FIGURE 11: Average scorch height vs fire intensity for different burning seasons.

6 OTHER FIRE DESCRIPTORS

HEAT PER UNIT AREA

The heat per unit area generated by a fire can be calculated from fire intensity simply by dividing intensity by the fire rate of spread.

i.e. $$H_A = \frac{3.600I}{R}$$

where H_A = heat per unit area (kilojoules per square metre, kJ m^{-2}).

I = fire intensity (kW m^{-1})

R = fire rate of spread (m hr^{-1})

The 3 600 is required to correct units since I utilizes seconds and R utilizes hours.

Interpreting H_A

For a constant fire intensity (I), the faster the spread, the less heat will be released. Conversely, slow moving fires with the same fire intensity, will concentrate considerable heat on site. Andrews and Rothermel (1982) developed a fire characteristics chart (Fig. 12) which visually displays four basic fire characteristics: rate of spread; heat per unit area; flame length, and fire intensity; as a single point on the chart. If heat released per unit area is taken as a measure of fire severity, then fires that plot further to the right (such as a slash burn) are more severe. If rate of spread is used as a measure of severity, then fires which plot towards the top, such as grass fires, will be more severe. If intensity, or flame length, is the measure, then fires that plot in bands of equal flame length successively further from the origin, are more severe. The fire characteristics chart can be used for site specific fire management objectives.

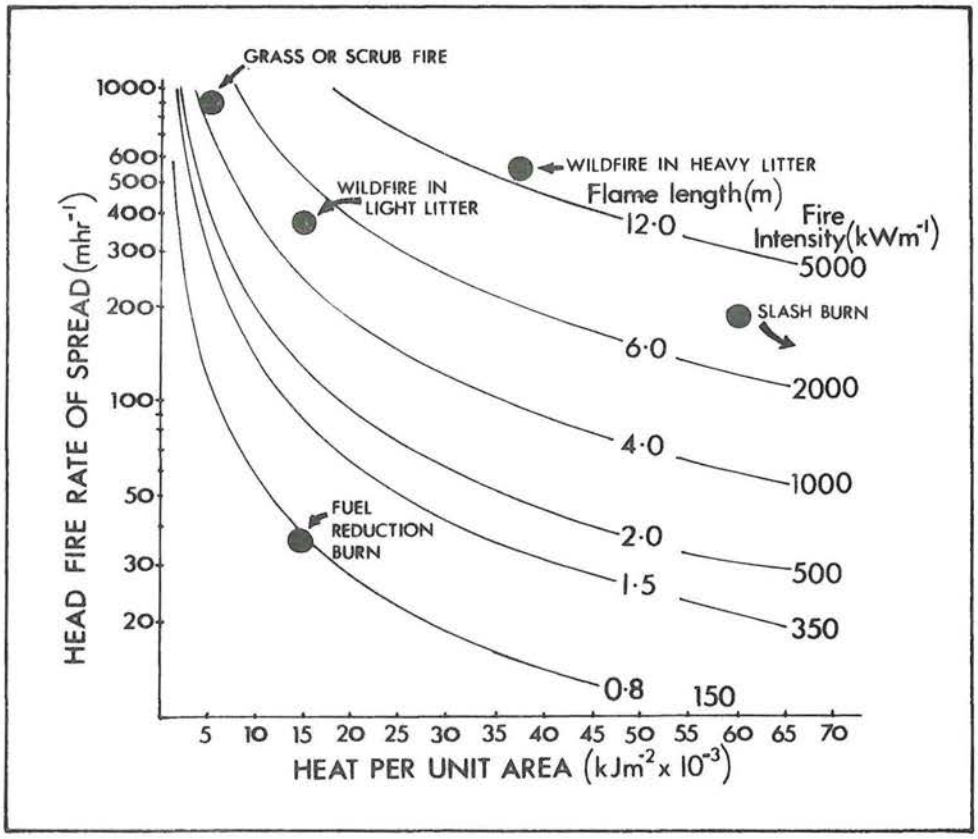


FIGURE 12: Fire characteristics chart showing intensity, rate of spread, flame length (locally developed for jarrah litter) and heat per unit area. (after Andrews and Rothermel).

TOTAL FIRE ENERGY

The total energy or heat released from a fire can be estimated by multiplying the heat per unit area (H_A) for the fire, by the area of the fire that produced it. This may be useful in estimation of particulate emmission (Rothermel and Deeming, 1980) or in smoke management. Fire energy is expressed in kJ.

RESIDENCE TIME

Residence Time is the length of time it takes for the fire front to pass a given point. Damage to living vegetation, and the heat penetration into the soil from a fire, are related to Residence Time. This measurement can be difficult because of the indefinite trailing edge of the flame.

Residence Time can be estimated using the equation:

$$T_R = \frac{D}{R}$$

where T_R = residence time (minutes)

D = flame depth (m)

R = spread rate (m min.$^{-1}$)

This equation does not account for the burnout of larger fuels such as logs.

SMOKE COLOUR

Smoke colour can provide a crude indication of fire behaviour. It is affected by burning conditions such as fuel moisture content, and wind. A guide to the relationship between smoke colour and fire behaviour is given in Table 3.

TABLE 3

Smoke colour as a visual approximation of forest fire behaviour.

Smoke Colour	Approximate Fuel Condition and Fire Behaviour
Dense White	Very moist fuels, mild behaviour.
Grey	Moist fuels, mild - moderate fire behaviour.
Black	Dry fuels, high fire behaviour.
Copper-Bronze	Very dry fuels, high to severe fire behaviour.

SMOKE PLUME HEIGHT

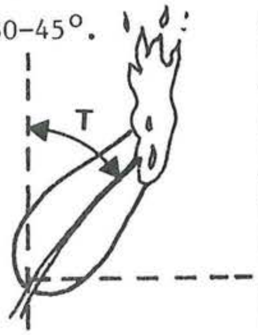
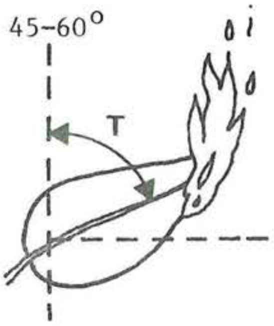
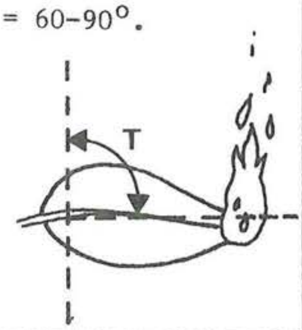
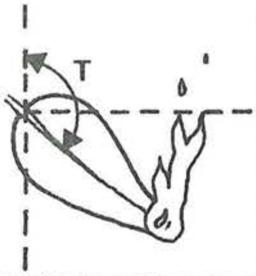
The height to which smoke plumes rise is related to fire intensity (Norum, 1974). Atmospheric stability was shown by Norum to be inadequate for describing the ultimate level of smoke rise from high intensity fires. Towering convection columns topped with a white condensation cap are derived from intense ground fires.

7 ESTIMATING LEAF LITTER MOISTURE CONTENT IN THE FIELD

Several instruments (e.g. the Marconi moisture meter and the Speedy moisture meter) enable the field determination of fine fuel (i.e. leaf litter) moisture content. The accuracy of these instruments varies with fuel moisture content, but is acceptable within the range of burning conditions most frequently encountered. If such instruments are available, they should be used. A cruder technique requires only a cigarette lighter, or a fusee match, and some judgement. The burning rate of a match is increased by tilting it so that the flame burns up towards the fingers, and reduced by holding the match vertical with the flame at the top. The angle to which a burning leaf is tilted so that combustion is just sustained will depend largely on the moisture content of the leaf. In a spot sheltered from the wind (such as behind a tree) ignite the tip of a cured but not decomposed leaf selected from the surface of the litter bed. Move the leaf slowly through 180 ^{o} until the point at which the flame is just sustained is reached. This can be repeated with several leaves to obtain a good average. Note the approximate angle of tilt of the leaf, from the vertical. Table 4 below shows tilt and approximate moisture contents of jarrah leaves.

TABLE 4

Crude estimation of fine fuel moisture content from the angle of leaf tilt.

Angle at which combustion is just sustained (°).	Approximate moisture content (%) and burning conditions.
$T = 30-45°$. 	Leaf is very dry (4-6%). Fire behaviour could be severe. Too dry for fuel reduction burn.
$T = 45-60°$ 	Leaf is dry (6-10%). Conditions may not be suitable for fuel reduction burn.
$T = 60-90°$. 	Leaf is moist (10-15%). Conditions may suit mild intensity fuel reduction burn.
$T = 90-120°$. 	Leaf is damp (15-20%). Low intensity fuel reduction burn could be patchy.

CONCLUSIONS

Forest fire means different things to different people. To a biologist, fire may be only a binary event - the forest burnt or it did not. To early foresters fire was good, or bad, depending on whether or not it scorched the tree canopy, or scarred the bole of the tree. Modern approaches to fire management recognize the importance of fire in forest land management, either to protect or to enhance forest resources. In this paper, I have outlined a standardized approach to describing forest fires. It is hoped that this will help managers with the many ecological and suppression aspects of forest fires.

ACKNOWLEDGEMENTS

I thank Roger Underwood, George Peet, Rick Sneeuwjagt and Paul Jones for their useful comments on this manuscript.

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