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FIRE BEHAVIOUR AND FIRE SUPPRESSION IN AN ELEVATED FUEL TYPE IN EAST GIPPSLAND: PATROL TRACK WILDFIRE, FEBRUARY 1991

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SUMMARY

A wildfire occurred at Patrol Track, 35 km east of Orbost, East Gippsland on 9 February 1991 and provided an opportunity to study fire behaviour and fire suppression in an elevated fuel type in open forest under conditions of moderate to high, but decreasing, fire danger. This study was limited to a spot fire which developed following the passage of a south-westerly wind change over the wildfire area. The total fine fuel load adjacent to the area burnt by this spot fire was a mean of 14 t/ha, which comprised a mean of a very low 4 t/ha of litterbed fuel, 7 t/ha of living shrub fuel and 3 t/ha of elevated dead fuel. The mean shrub height was 1.0 m. Both the bark and shrub fuel hazards were assessed as 'Very High' and the overall fuel rating for the site was classified as 'Very High'.

For the 'Very High' hazard rating, the range of fire danger index proposed by Wilson (1993) of 12 to 24 where a Reference First Attack will be successful was compared to the actual fire behaviour and suppression at the spot fire. For the combination of fuel hazards at this site, success is probable in the range of fire danger index from 12 to 18.

The rate of spread of the observed spot fire under the conditions of decreasing fire danger and increasing fuel moisture content was a mean of between 225 and 255 m/h and the fireline intensity was a mean of between 1400 and 1600 kW/m. This rate of spread was greater than the rate of spread predicted by the McArthur Mk5 Forest Fire Danger Meter but, under the prevailing conditions of wind speed of 12 to 19 km/h, the meter provided a reasonable estimate of fire behaviour upon which to base decisions on fire suppression. The observed rate of spread was also greater than the rate of spread predicted by the fire behaviour guide for southern Jarrah forest.

Parallel attack with a D6 class bulldozer, at a rate of control line construction of about 675 m/h, was effective in suppressing this observed spot fire. However, prior to the checking of the forward spread of the head fire, a sudden increase in wind speed to about 45 km/h for two to three minutes dramatically increased the fire behaviour and endangered the safety of the suppression crew. Based on the suppression action and fire behaviour at this fire, the threshold of effective suppression in elevated fuel is considered to be less than in litter fuel and to be about 2000 kW/m. Although fire bombing by a Beaver fixed wing aircraft, which delivered Phoschek fire retardant at a rate of 1960 l/h, was not completely successful at this fire, it is strongly recommended that air support under the direction of an Air Attack Supervisor by either fixed or rotary wing aircraft be used at wildfires burning at similar intensities to the fire studied.

Subject to the qualifications discussed, the actual spotting distance of 300 to 400 m was within the range predicted by the McArthur Forest Fire Danger Meter, but the meter's indication of fuel availability, as shown by the drought factor, did not closely match the actual conditions of fuel moisture content. Review of the drought factor function is recommended.

Based on the observations at this wildfire and those at the 1991 Heywood wildfire, the wind speed function of the McArthur Mk5 Forest Fire Danger Meter may underestimate significantly the effect of wind speed on rate of spread for fires burning in elevated fuels in open forest above a threshold wind speed of about 15 to 20 km/h. On-going research into fire behaviour in elevated fuels is recommended.

INTRODUCTION

Fire behaviour in Victorian forests is predicted using the McArthur Mk5 Forest Fire Danger Meter (McArthur 1973). This model of fire behaviour was developed for fires burning in commercial, dry sclerophyll eucalypt forest with a predominantly litter fuel type. However, the use of this model has been widely extended to forests with a developed shrub layer.

Elevated shrub fuels increase flame heights and reduce the visibility of suppression forces (National Bushfire Research Unit 1987). Compared with litter fuels, elevated, fine, evenly distributed and moderately spaced fuel particles will also facilitate easier ignition and faster rates of burning (and hence faster rates of spread) (Wilson 1992a). The combined impact of scrub flammability and the percentage of dead scrub material on rate of spread is accounted for in Western Australian forests by applying a scrub flammability weighting factor of between 0.5 and 5 to the dry weight of shrub fuel components (Sneeuwjagt and Peet, 1985). Recent research by Cheney *et al.* (1992) in the shrub dominated fuels of the regrowth forests of south-east New South Wales identifies a significant relationship between the height of this shrub fuel layer and rate of spread.

The most dynamic meteorological force which affects fire behaviour is wind speed, but it is also one of the most difficult to measure and relate to fire behaviour in the field (Cheney 1981). The McArthur Mk5 Forest Fire Danger Meter is designed for use in well stocked forests with a dominant height of 20 m or more (Luke and McArthur 1978) and uses a definition of average wind speed measured at a height of 10 m above ground level at an open, flat locality. However, stand height and density will affect the actual wind speed at the flame front and consequently, fire behaviour predictions will be adversely affected in forests which are structurally different from this standard. The actual location between ridge and gully (Cheney *et al.* 1992) and the height and density of the understorey (Cheney 1981, Burrows and Sneeuwjagt 1991 and Cheney *et al.* 1992) are further factors which affect wind speed at 1.5 or 2 m above ground level in the forest relative to the wind speed at 10 m in the open.

Following analysis of predicted and observed behaviour of a wildfire in open forest with elevated fuel types of heath, Wiregrass or Bracken and grass under conditions of moderate fire danger, Wouters (1993) cautioned that the McArthur Mk5 Forest Fire Danger Meter can under-predict rate of spread in elevated fuels by a factor of between 3.5 and 5. Further data from wildfires and from experimental and operational burning programs conducted in these fuel types are needed to add to these important observations and also to assist in improving the fuel and wind functions which enable fire behaviour to be predicted.

A wildfire occurred, as shown on Figure 1, at Patrol Track, 35 km east of Orbost, East Gippsland on 9 February 1991. This fire (Orbost Fire Number 33) provided an opportunity to study fire behaviour and fire suppression in an elevated fuel type in open forest under conditions of moderate to high, but decreasing, fire danger. The location of the main fire and of a spot fire which originated following the passage of a south-westerly wind change across the fire area are shown in Figure 2. The aims of this report are to document the fire behaviour of this spot fire, to document the suppression action taken to control this spot fire, to compare the observed rate of spread of this spot fire with the rates predicted by the McArthur Mk5 Forest Fire Danger Meter and the fire behaviour guide for southern Jarrah forest (Sneeuwjagt and Peet 1985) and, for the fuel hazard at the site of the spot fire, to check the fuel rating classification proposed by Wilson (1993).

Figure 1. General location of the Patrol Track wildfire of 9 February 1991.

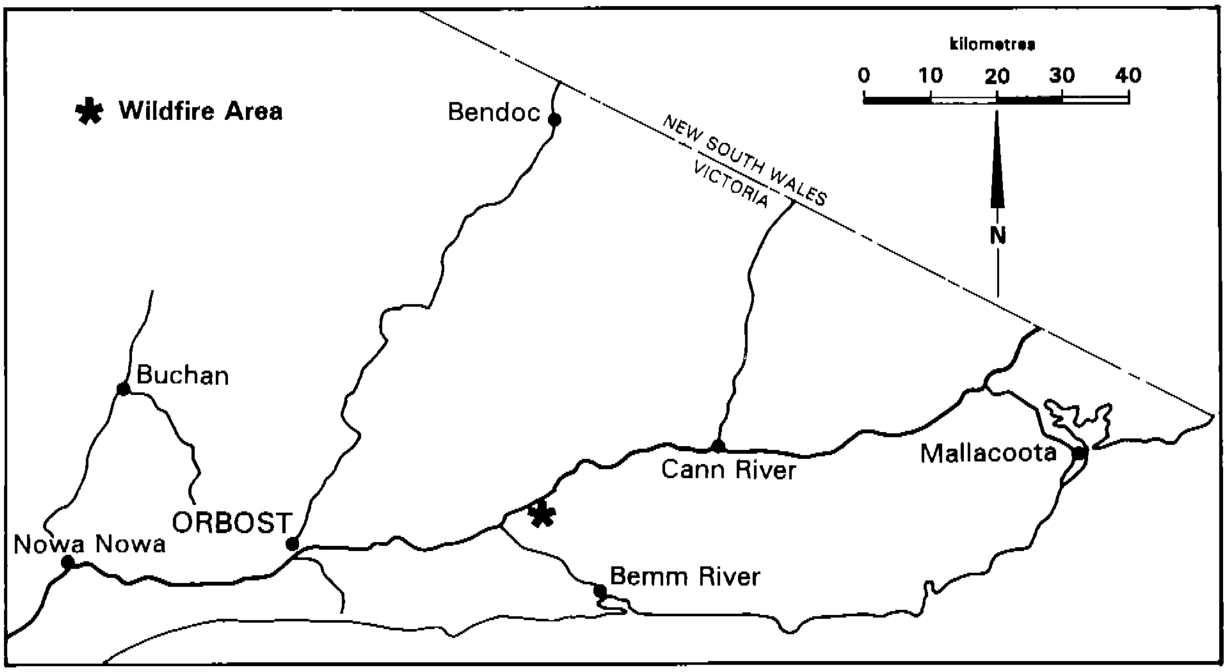
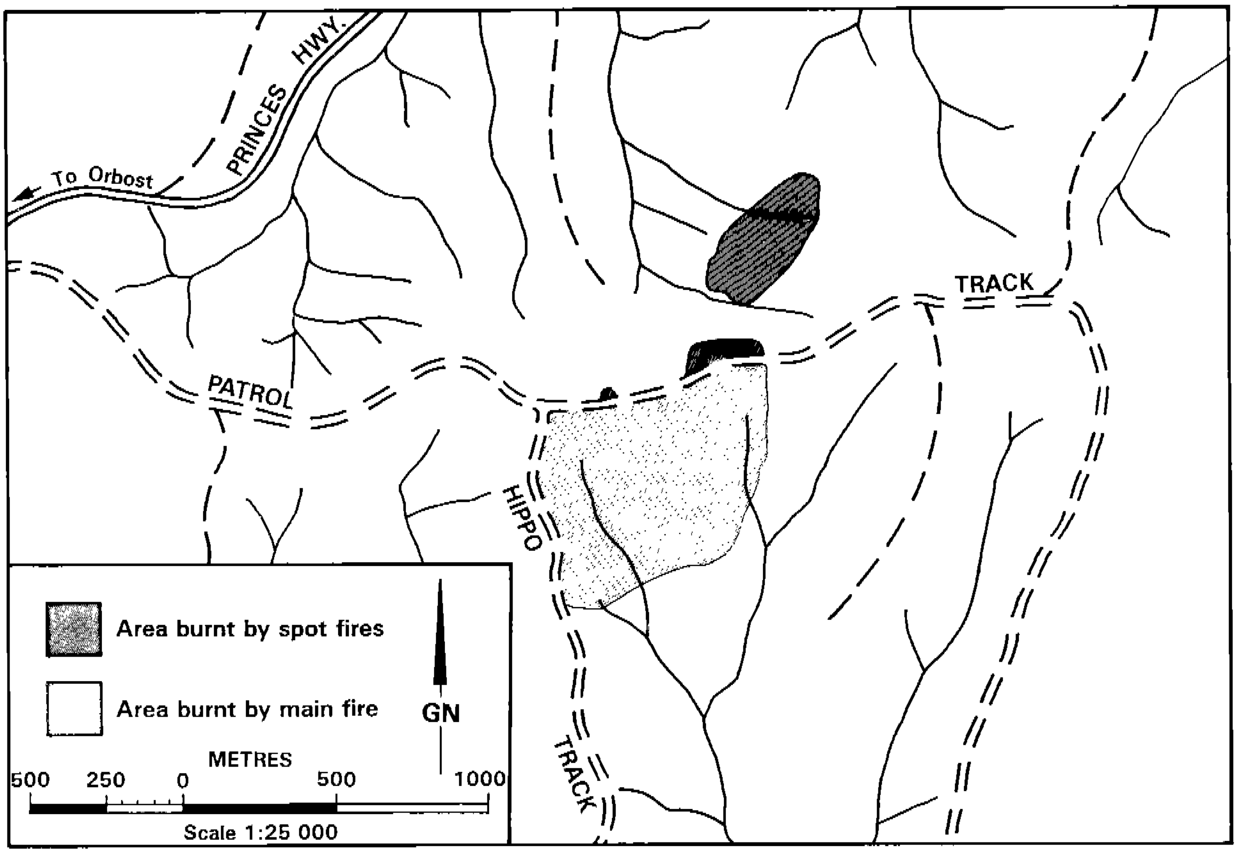


Figure 2. Location of the Patrol Track wildfire and of the spot fire where fire spread and fire suppression were observed.



METHODS

Forest type and stand characteristics

The forest type which covered the area burnt by the spot fire where fire behaviour was observed is classified as Lowland Sclerophyll Forest (1) (Forbes, *et al.* 1981). *Eucalyptus consideniana* (Yertchuk), *Eucalyptus globoidea* (White stringybark) and *Eucalyptus baxteri* (Brown Stringybark) were the dominant tree species in this older growth forest. *Banksia serrata* (Saw Banksia) was common and the dominant shrub species, as illustrated in Photos 1 and 2, included *Pteridium esculentum* (Austral Bracken), *Gahnia spp.* (Saw-sedge), *Gleichenia dicarpa* (Pouched Coral-fern), *Platylobium formosum* (Handsome Flat-pea) and various heath species. *Tetrarrhena juncea* (Forest Wire-grass) was present but did not dominate the fuel complex. Tree stocking was much lower than it was in the forest that was burnt by the main wildfire.

The forest type which covered the area burnt by the main wildfire is classified as Lowland Sclerophyll Forest (2) (Forbes, *et al.* 1981) and occurred as stands of predominantly even-aged regrowth, established in 1957, 1962 and 1967, and as mixed-age forest. The dominant tree species were *Eucalyptus sieberi* (Silvertop) and *Eucalyptus globoidea* (White Stringybark). Dominant shrub species included *Hakea sericea* (Bushy Hakea), *Acacia terminalis* (Sunshine Wattle), *Tetrarrhena juncea* (Forest Wire-grass), *Pteridium esculentum* (Austral Bracken), *Platylobium formosum* (Handsome Flat-pea), and *Gahnia spp.* (Saw-sedge) and is collectively referred to as the Wiregrass fuel type (Buckley 1992, 1993 and Fogarty 1993).

Fuels

The areas burnt by both the spot fire and the main wildfire had been burnt 23 years previously in 1968. The fuel load and arrangement of fuels adjacent to the area that was burnt by the spot fire were subsequently assessed during January 1992. The following classes of fine fuel (fuel less than 6 mm in thickness) were defined:

Litterbed fuel:	Dead fine fuel, including surface fuel and fuel lower in the fuel profile. Those fuels such as eucalypt capsules and charcoal which do not ignite or burn readily were excluded.
Elevated dead fuel:	Dead fine fuel forming part of, or being suspended in, the shrub layer.
Living shrub fuel:	Living understorey fuel less than 2 m above ground level.

Fine fuel load was assessed by destructively sampling eleven square plots, each of area 0.37 m^2. These plots were systematically located to the west and south west of the boundary of the spot fire. The plots were located 10, 15 or 20 m apart (depending on the occurrence of bull ant nests) and the sampling frame was subjectively placed at each sampling point to be representative of the fuels at that point.

The height of the shrub layer at each sample plot was measured and the density of the shrub layer in the immediate vicinity of each plot was assessed on a subjective scale of 1 (sparse) to 5 (dense). Fuels were sorted into each fuel class and then removed to the laboratory for air drying and weighing. A sub sample of air dried fuel from each fuel class from each plot was oven dried to constant weight at 105^{o}C to enable the weight of each fuel sample to be adjusted for moisture content.

Photo 1 and 2. **The elevated shrub fuel type that was burnt by the observed spot fire (height pole = 2 m with 10 cm markings).**

The hazard level of bark and shrub fuels was also assessed using the guides developed for this purpose by Wilson (1992b) and (1993). Using the classification system proposed by Wilson (1993), these hazard levels were then combined with the litter fuel load to determine an overall fuel rating and the actual suppression difficulty was then compared to the suppression limit for a Reference First Attack[1] as described in the classification.

Fuel moisture content

The moisture content of the fine fuel on the day of the wildfire was determined by collecting fuel samples in air-tight jars for subsequent oven drying and weighing. Replicated fuel samples were collected from four fuel classes in the Wiregrass fuel type from sites adjacent to the main wildfire. The type of sample collected as representative of each fuel class was:

Elevated dead fuel (EDFMC): Dead eucalypt leaves suspended in the shrub layer at about waist height.

Exposed surface litter (ESLMC): Dead fine fuel (mainly leaves and petioles) found in the top 1.0 cm of the litter bed and exposed to the weather elements of sun and wind in the gaps between clumps of Wiregrass.

Shaded surface litter (SSLMC): Dead fine fuel (mainly leaves and petioles) found in the top 1.0 cm of the litter bed and shaded from the weather elements below clumps of Wiregrass and shrub fuels.

Profile litter (PLMC): Dead fine fuel situated *below* the surface litter in the litter bed and collected from fuels shaded by clumps of Wiregrass (Note that a different definition of profile litter moisture content was adopted for the "Wiregrass Prescribed Burning Guide for Regrowth Forests in East Gippsland' (Buckley 1993)).

The moisture content of the fine fuel in the Bracken and heath fuel type where the spot fire burnt was not measured but was assumed to be similar to that measured in the Wiregrass fuel type. No sampling was conducted prior to the passage of the wind change over the fire area.

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[1] A Reference First Attack is defined as being: direct attack by a 50 kW bulldozer (D3 class) and a small tanker (400 l capacity) and crew, within 30 minutes of detection of a single fire burning on level terrain with good access, when the drought factor is 10 and the wind speed at a height of 10 m in the open is 20 km/h.

Weather

Weather variables were independently measured on-site by two observers. Dry and wet bulb temperatures were measured using an Assman psychrometer[1] and a Bacharrah sling psychrometer[2]. Wind speed at canopy level, which was assumed to equal wind speed at 10 m in the open, was estimated using the Beaufort Scale (Bureau of Meteorology 1984) modified for use in forests by incorporating specifications of tree movement (Rothermel and Rinehart 1983)[1]. The wind speed at 1.5 m above ground level in the forest was measured using a Dwyer hand-held anemometer[2] and the mid point of these data was subsequently converted to the wind speed at 10 m in the open (Beaufort Scale class) using the function developed by McArthur (1962) for a well stocked stand, 21 to 30 m tall. These wind speed data were not electronically measured by anemometers correctly located at 10 m in the open or at 1.5 or 2.0 m in the forest. Consequently, an exact 10 minute average wind speed cannot be stated, although the confidence that the wind speed was estimated to be in the correct Beaufort Scale class was high. Rainfall was measured at Orbost and the metric Byram Keetch Drought Index (Keetch and Byram 1968) was calculated from rainfall and temperature data that were recorded at Orbost. The equations developed by Noble *et al.* (1980) were used to calculate the McArthur forest fire danger index (Luke and McArthur 1978) using the Orbost and on-site data.

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[1] Author

[2] John McDonald, Regional Fire Management Officer, CNR, Orbost

Fire behaviour and development

The fire behaviour and development discussed in this report is restricted to the spot fire which developed from a point or points about 300 m north of the boundary of the main fire at Patrol Track (see Figure 2). This spot was initially reported by the observer at the Mt Bemm fire tower, 10 km east of the fire, and was observed from the air at 1530 hours. The observations and records of Andrew Buckley[1] (Fire Research Officer), Butch Healy[2] (Fireline Supervisor), Peter Geary[3] (Fireline Boss) and Mike Timpano[4] (Air Attack Supervisor) were pooled to determine and verify the details of the fire behaviour and development.

The perimeter of the spot fire is described in terms of three zones; the head fire, flank fires and back fire (Burrows 1984) and the final perimeter was measured by a 'chain and compass' survey after the fire event. The ground slope on the central axis of the fire was measured at intervals of 50 m or less to enable an overall or average slope factor (McArthur 1962) to be calculated. The rate of spread of this fire was calculated from the distance travelled from when the fire was about one hectare in size at 1530 hours, and hence was considered to have passed through the acceleration phase (Luke and McArthur 1978), to 1650 hours, when the fire 'blew up' for two to three minutes. The actual rate of spread is presented as a range, as there was uncertainty as to where the head fire was actually burning when the fire was initially observed.

The actual rate of spread and fuel quantity data were used to calculate the quantitative expression of fire behaviour, fireline intensity[5]. A measure of fire shape, the length to breadth ratio, was also calculated. The length of the fire was measured on the longest axis of fire spread from the back fire to the head fire and the breadth was measured perpendicular to this axis where the distance between the flanks was greatest.

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[1] Author

[2] Butch Healy, Technical Officer, CNR, Orbost (former)

[3] Peter Geary, Research Scientist, CNR, Orbost

[4] Mike Timpano, Operations Area Supervisor, CNR Orbost

[5] Fireline intensity was devised by Byram (1959) as a measure of fire behaviour. It is the rate of energy release per unit length of fire front and is defined by the equation $I = Hwr$. I denotes the fireline intensity (kW/m), H denotes the heat yield of fuel (kJ/kg), assumed to be 16,000 kJ/kg for forest fuels (Luke and McArthur 1978), W denotes the dry weight of fuel consumed (kg/m^2) (mean total less mean unburnt fine fuel load) and r denotes the forward rate of spread (m/s). An unburnt fine fuel load of 0.4 t/ha was assumed in the calculations.

Predicted fire spread

The rate of spread predicted by the McArthur Mk5 Forest Fire Danger Meter of the spot fire was calculated using the equation developed by Noble *et al.* (1980) which relates rate of spread to fire danger index and fine fuel load. The fine fuel load used in calculations was the sum of the litter bed, living shrub and elevated dead fuel classes. However, to obtain a realistic measure of fire danger index to calculate rate of spread when weather conditions were moderating, current wind speed data was combined with temperature and relative humidity data that had been measured at or about one-and-a-half hours earlier. This was because moisture content uptake by eucalypt litter under moisture adsorption conditions of decreasing temperature and increasing relative humidity is delayed by between one and two hours (Luke and McArthur 1978). This assumption was tested by comparing actual fuel moisture content data with the moisture content of surface litter predicted by McArthur (1967) for each pair of temperature and relative humidity readings. Also, separate calculations were performed using each of two values of drought factor, one based on Orbost rainfall data and one based on the actual conditions of fuel moisture content at the fire. The predicted rate of spread was calculated as an average of the separate predictions at 1530 and 1650 hours (using the wind speed estimated at 1640 hours) and was corrected for slope using the average slope factor.

The fire behaviour model for southern Jarrah forest (Sneeuwjagt and Peet 1985) was selected for additional comparison because it had been developed for a forest type that is described as usually carrying a low (1 m), dense, understorey scrub layer and hence, appears to be structurally similar to the fuel type that was burnt by this fire. Fuel moisture content and wind speed were required as direct inputs to this model. However, separate measurements of fuel moisture content at 1530 and 1640 hours were not available, so the rate of spread predicted by this model was based on the measured surface fuel moisture content at 1600 hours (the approximate mid-point between 1530 and 1640 hours) and, based on the wind speed data collected, an average wind speed of 13 to 17 km/h and also 18 to 21 km/h.

Spotting distance

The spotting distances predicted by the McArthur Forest Fire Danger Meter under conditions of fire danger index from 10 to 20 were compared to the actual spotting distance observed.

Suppression

Fire suppression actions and outcomes were obtained by pooling the observations and records of the staff of the Department of Conservation and Natural Resources (CNR) previously mentioned and of Lawson Willoughby[1] (Air Base Manager). To avoid possible confusion, the fire organisation titles used during 1990/91 are again used in this report. However, all fires attended by CNR are now managed under the Incident Command System (ICS) of the Australian Inter-service Incident Management System (AIIMS) (AARFA 1992). Consequently, some of the terminology of the former systems of fire organisation are no longer current.

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[1] Lawson Willoughby, Fisheries and Wildlife Planning Officer, CNR, Orbost

RESULTS

Fuels

The data on fine fuel load, which are summarised in Table 1, show a total fine fuel load of mean 14 t/ha, comprising a mean of a very low 4 t/ha of litter bed fuel, 7 t/ha of living shrub fuel and 3 t/ha of elevated dead fuel. The mean shrub height was 1.0 m. The bark hazard was assessed as 'Very High', the shrub fuel hazard was assessed as 'Very High' and the overall fuel rating was classified as 'Very High'.

Table 1. Fine fuel load, shrub density class and shrub height data for the fuel type burnt by the observed spot fire.

Plot number	Shrub height (m)	Shrub density class (1-5)	Fine fuel load (t/ha)				
			Litter bed fuel	Living shrub fuel	Elevated dead fuel	Total shrub fuel	Total fine fuel
1	1.3	5	6.8	3.8	5.0	8.8	15.6
2	1.4	5	4.5	5.4	3.7	9.1	13.6
3	1.2	5	3.3	5.1	3.3	8.4	11.7
4	1.0	4	4.1	7.8	2.9	10.7	14.8
5	0.8	5	3.8	6.1	1.9	8.0	11.8
6	1.0	5	5.7	6.0	1.9	7.9	13.6
7	1.5	5	5.9	3.8	4.0	7.8	13.7
8	1.1	5	4.5	17.9	4.5	22.4	26.9
9	0.8	5	4.9	8.0	1.4	9.4	14.3
10	0.4	5	1.7	5.2	1.7	6.9	8.6
11	0.8	5	2.1	9.2	2.9	12.1	14.2
Mean	1.0	5	4.3	7.1	3.0	10.1	14.4
s.d.[1]	0.3	-	1.6	4.0	1.2	4.3	4.6

[1]standard deviation

Fuel moisture content

Fuel moisture content data for the afternoon of 9 February 1991 are shown in Table 2. At 1600 hours, the moisture content of elevated dead fuel was 9%, of exposed surface litter was 6%, of shaded surface litter was 10% and of profile litter was 13%. The moisture content of each of the sampled fuel classes increased during the following two and a half hours. These data indicate that virtually all the fuel was available for burning and hence the appropriate drought factor to use when predicting fire behaviour was 10.

Table 2. Fine fuel moisture content of fuels on 9 February 1991.

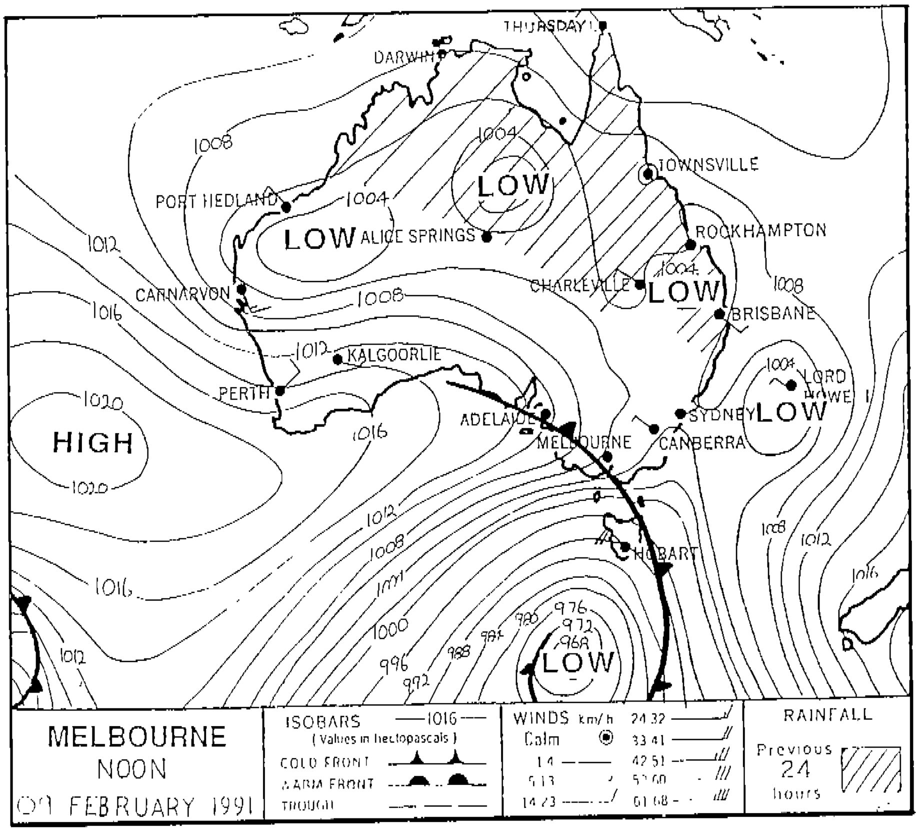
Time (hrs)	Fine fuel moisture content (% ODW)			
	Elevated dead fuel	Exposed surface litter	Shaded surface litter	Profile litter
1545 - 1600	9.4 (0.6)[1]	5.8 (0.3)	10.4 (0.6)	12.5 (1.1)
1715 - 1720	9.7 (0.3)	8.3 (1.0)		
1820 - 1825	12.3 (0.6)	10.2 (0.1)		

[1] Mean and standard deviation

Weather

The synoptic situation on 9 February 1991 is shown on Figure 3. A cold front was crossing the Great Australian Bight with an associated deep low well to the south of the continent. High pressure systems were located near New Zealand and to the south-west of Perth. The cold front was predicted to cross Victoria during the day and establish a cooler south-westerly airstream in its wake. The forecast for Orbost, issued at 0630 hours, was for a maximum temperature of 28°C, minimum relative humidity of 35% and west-north-westerly winds of 15 km/h which were predicted to change to south-westerly winds of 35 km/h following the passage of the front late in the afternoon.

Figure 3. The synoptic situation at 12 noon on 9 February 1991. (Source: Bureau of Meteorology)



The Byram Keetch Drought Index at Orbost on 9 February 1993 was 44 and 14.2 mm of rain had fallen 12 days previously. Consequently, the drought factor indicated by the Forest Fire Danger Meter was 7. Weather observations taken at the wildfire and fire danger indices are shown in Table 4. The maximum temperature of 34°C and the minimum relative humidity of 30% were recorded at 1400 hours, although the wind direction had been observed to change direction from north-west to south-west at about 1340 hours. Wind strength following the change varied considerably, with a maximum wind speed of Beaufort Scale class 5 (29 - 38 km/h) occurring from about 1430 to 1500 hours. From about 1530 hours, wind speed was mainly in Beaufort Scale class 3 (12 - 19 km/h), although conditions remained gusty and the strength of one particularly strong gust at 1650 hours was estimated to be 45 km/h. The maximum forest fire danger index before wind speed increased following the change was 12 at 1400 hours.

Table 4. **Weather observations and fire danger indices at the wildfire area on 9 February 1993 (with observations between 1530 and 1650 hours highlighted).**

Time (hrs)	Temperature (°C)	Relative humidity (%)	Wind speed at 1.5 m (km/h)	Wind speed at canopy[4] (km/h)	Gust wind speed at canopy (km/h)	Wind direction	Fire danger index[5]
1315[2]	31	31	0-5 (2.5)	6-11	gusty	NW	10
1340[2]						SW	
1400[2]	34	30	0-5 (2.5)	6-11		SW	12
1430[2]	34	48	5-10 (7.5)	29-38		W-SW	12
1500[2]	26	54	5-10 (7.5)	29-38		W-SW	7
1530[1]	25.0	54	-	12-19	30	SW	5
1610[2]	26	58	0-5 (2.5)	6-11		SW	4
1640[1]	23.0	62	-	12-19		SW	3
1650[3]					45	SW	
1730[1]	23.2	60	-	1-5		SW	3
1830[1]	21.5	67	-	1-5		SW	2

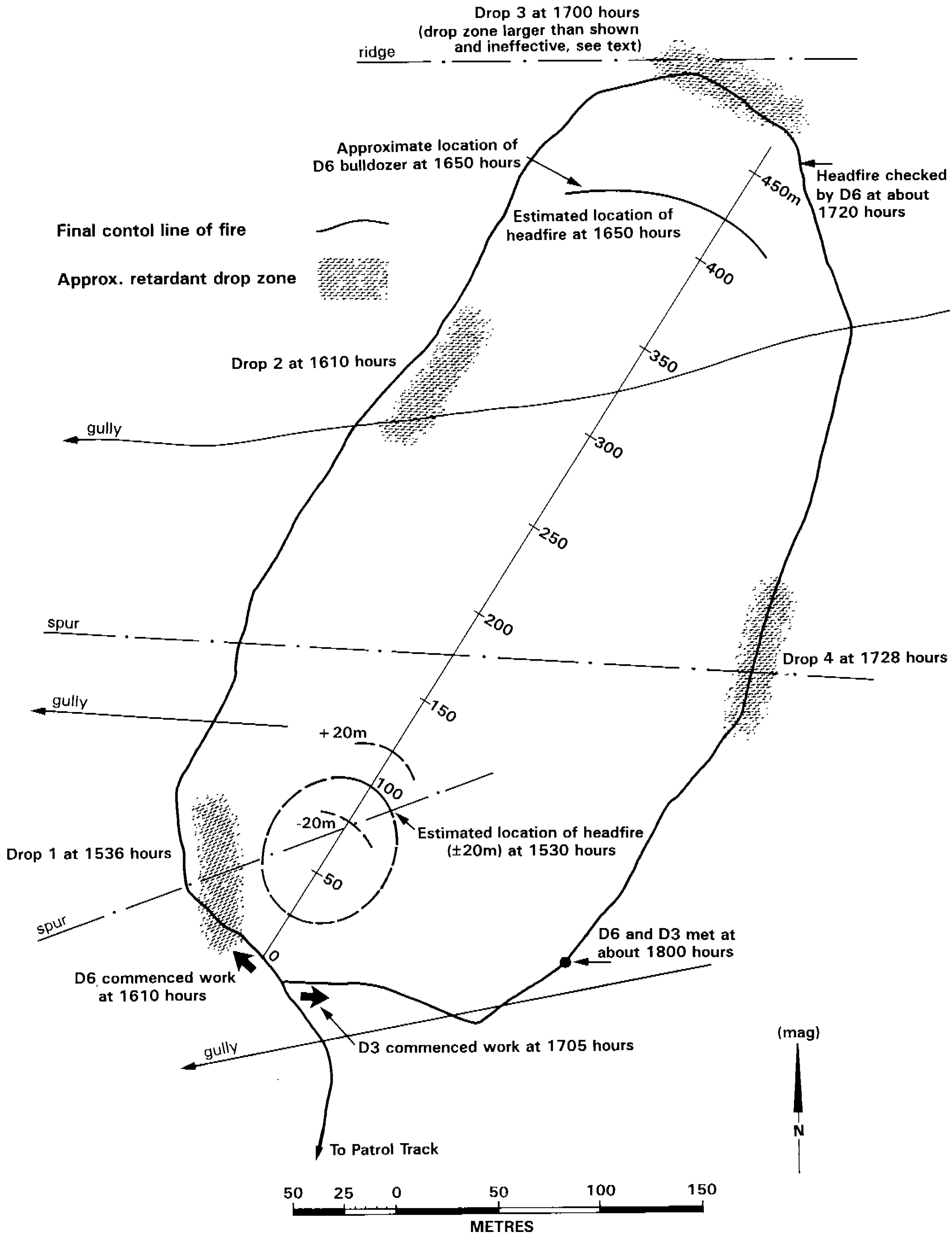
[1] Author
[2] John McDonald
[3] Butch Healy
[4] Assumed to equal the wind speed at 10 m in the open
[5] Calculations of FDI from 1430 hours underestimate fire danger; see Table 6

Observed fire behaviour and development

The spread and final boundary of the spot fire are shown in Figure 4. The spot fire burnt a distance of between 300 and 340 m between 1530 hours, when the spot fire was initially observed from the air to be about one hectare in size, and 1650 hours, when the fire 'blew up' for two to three minutes. This corresponds to a forward rate of spread of between 225 and 255 m/h and a fireline intensity of between 1400 and 1600 kW/m. The flame height of the headfire was not closely observed during this time. However, the flame height on the western flank was observed, and was estimated to vary, depending on wind speed and slope factors, from between 1 and 2 m to between 4 and 5 m. The length to breadth ratio of this fire was 2:1.

At 1650 hours, wind speed was observed to gust to about 45 km/h for two to three minutes. The head fire 'blew up' over this short time interval, with flame height of about 10 to 12 m which ignited the upper crowns of trees ahead of the fire. A distance of between 20 and 30 m was burnt before the wind speed and fire behaviour decreased. Assuming that a distance of 30 m was burnt in 3 minutes, this corresponded to a rate of spread of 600 m/h and a fireline intensity of 3,700 kW/m.

Figure 4. **Fire spread, final fire boundary and details of the suppression action taken at the observed spot fire.**



Predicted fire behaviour

Slopes on the central axis of the spot fire were mainly in the range of - 1° to + 4°, although the slope adjacent to and north-east of the gully (see Figure 4) was + 12° to + 7°. The vertical rise on the central axis over a horizontal distance of 368 m was 17 m. Hence, the average slope was + 3° and the slope factor was 1·2.

The predicted and observed values of the moisture content of exposed surface litter, as shown in Table 5, were very similar. They indicate that the time interval of one-and-a half hours that was selected to represent the 'lag' in moisture content response of surface litter appears reasonable.

Table 5. Predicted and observed values of the moisture content of exposed surface litter.

Actual time (T1) (hrs)	T1 less 1.5 hours (T2) (hrs)	Temperature at T2 (°C)	Relative humidity at T2 (%)	Predicted moisture content of exposed surface litter (% ODW)	Observed moisture content of exposed surface litter (% ODW)
1530	1400	34	30	4.5	-
1600	1430	34	48	6	6
1715	1545	25	54	8	8
1820	1650	23	62	9	10

The data that were used to calculate the predicted rate of spread of the spot fire using the McArthur Forest Fire Danger Meter are shown in Table 6. The maximum forest fire danger index during the prediction period, calculated using a drought factor of 7 and considering the 'lag' effect in moisture content response, was 14 at 1530 hours (compared to an index of 5 when actual time data was used as shown in Table 4). The predicted rate of spread for an average slope of +3° at 1530 hours was 282 m/h, at 1650 hours was 101 m/h and hence the average rate of spread over this 80 minute time interval was 187 m/h. The observed rate of spread of between 225 and 255 m/h was greater than this predicted rate.

Table 6. Details of weather, adjusted fire danger indices (calculated using a drought factor of 7), fuel load and rates of spread predicted by the McArthur Forest Fire Danger Meter.

Actual time (T1) (hrs)	Wind speed at canopy at T1 (km/h)	T1 less 1.5 hours (T2) (hrs)	Temp-erature at T2 (°C)	Relative humidity at T2 (%)	Adjusted fire danger index at T1	Fuel load (t/ha)	Predicted rate of spread at zero slope (m/h)	Predicted rate of spread at 3° slope (m/h)
1530	12-19 (15.5)	1400	34	30	14	14	235	282
1650	12-19 (15.5)	1520	25	54	5	14	76	91
Mean								187

However, when calculations of fire danger index were made using a drought factor of 10, as is shown in Table 7, the maximum forest fire danger index during the prediction period was 20 at 1530 hours. Consequently, the average rate of spread over the 80 minute time interval between 1530 hours and 1650 hours was 266 m/h. Although the observed rate of spread of between 225 and 255 m/h was less than this predicted rate, the use of the adjusted drought factor improved the rate of spread prediction.

Table 7. Details of weather, adjusted fire danger indices (calculated using a drought factor of 10), fuel load and rates of spread predicted by the McArthur Forest Fire Danger Meter.

Actual time (T1) (hrs)	Wind speed at canopy at T1 (km/h)	T1 less 1.5 hours (T2) (hrs)	Temp-erature at T2 (°C)	Relative humidity at T2 (%)	Adjusted fire danger index at T1	Fuel load (t/ha)	Predicted rate of spread at zero slope (m/h)	Predicted rate of spread at 3° slope (m/h)
1530	12-19 (15.5)	1400	34	30	20	14	334	401
1650	12-19 (15.5)	1520	25	54	6	14	108	130
Mean								266

Calculations of the predicted rate of spread for the southern Jarrah fuel type at 1610 hours are shown in Table 8. For a wind speed of 13 to 17 km/h, the predicted rate of spread for a 3° slope was 118 m/h and for a wind speed of 18 to 21 km/h, the predicted rate of spread was 176 m/h. Both these predictions were less than the observed rate of spread.

Table 8. Calculations of predicted rate of spread for the southern Jarrah fuel type at 1610 hours.

Step number	Explanation		
1	Select wind speed (Table 6.12) (tower wind speed = wind speed at 10 m in the open)	13-17 km/h	18-21 km/h
2	Select surface fuel moisture content	6%	6%
3	Determine the rate of spread index for 15-19 t/ha of available fuel (Table 6.12)	70	105
4	Determine the total fuel quantity		
4(a)	Litter	4.3 t/ha	4.3 t/ha
4(b)	Scrub fuel (living)	7.1 t/ha	7.1 t/ha
4(c)	Determine the scrub flammability factor (Table 7.4.2); scrub flammability = high, scrub foliage = 20-50% dead fuel	3.0	3.0
4(d)	Calculate the scrub fuel loading (scrub fuel weight x scrub flammability factor)	21.3 t/ha	21.3 t/ha
4(e)	Calculate total fuel quantity (litter + scrub fuel loading)	25.6 t/ha	25.6 t/ha
5	Correct total fuel quantity for surface fuel moisture content (Table 6.13)	1.4	1.4
6	Adjust the rate of spread index for fuel quantity (rate of spread index x fuel correction factor)	98	147
7	Determine the slope factor	1.2	1.2
8	Calculate the predicted rate of spread (adjusted rate of spread index x slope factor)	118	176

Spotting distance

The spot fire which ignited at about 300 m north of Patrol Track probably originated from a point in the north-east corner of the main fire area (see Figure 2). The spotting distance was probably in the range between 300 and 400 m. The average spotting distance predicted by the McArthur Forest Fire Danger Meter for a fire burning in a fuel quantity of 15 t/ha at a fire danger index of 10 was 200 m and at a fire danger index of 20 was 900 m.

Suppression

Details of the suppression action taken are shown in Figure 4. One D6 class bulldozer, operated by Fred Jonkers and supervised by Butch Healy, but not supported by any tanker or slip-on units, commenced a parallel flank attack (Luke and McArthur 1978) at the south west corner of the fire at 1610 hours. Over the next 40 minutes, this bulldozer constructed 450 m of control line adjacent to the western flank of the fire, which was equivalent to a rate of line construction of about 675 m/h.

At 1650 hours, the bulldozer had commenced to construct a control line ahead of the head fire (north west edge) and to 'pinch off' the head. However, the wind speed increased dramatically for two to three minutes, to an estimated strength of about 45 km/h, causing the fire behaviour also to dramatically increase. Flames burnt over and through the bulldozer, singing the hairs on the arms of the operator. Selecting third gear, the operator drove 'blind' in the dense smoke ahead of the fire and then returned to the safety of the flank. Butch Healy, who was on foot, had to run back to the flank to escape the flames.

Following the subsequent decrease in wind strength and fire behaviour, the bulldozer was able to check the head fire and, by about 1710 hours, had commenced constructing a control line on the north east flank. At about 1720 hours, the D6 had to return to the head fire area to control a subsequent spot fire.

A D3 class bulldozer commenced a parallel flank attack at the south east corner of the fire at about 1705 hours and constructed about 150 m of control line in heavy shrub fuels in and adjacent to a gully before meeting up with the D6 at about 1800 hours. This was equivalent to a rate of line construction of about 150 m/h.

A Beaver fixed wing fire bomber of capacity 900 l was deployed to this spot fire and made four drops of Phoschek[1] fire retardant. Refilling was at Noorinbee Phoschek base, 29 km north-east of the wildfire and the location of each drop zone is shown on Figure 4. In the absence of instructions from CNR personnel, the initial drop was poorly placed at the rear of the fire, although the second drop was placed correctly on the north west edge of the head fire. The third drop was placed under the direction of Mike Timpano, Air Attack Supervisor, across the head fire, but was ineffective due to a malfunction with the dump door. A fourth drop was made on the eastern flank after the head fire had been checked. The turn around time between drops varied from 26 to 31 minutes and the rate of retardant delivery was 1960 l/hour.

[1] Registered trademark of Monsanto Company

DISCUSSION

The combined effect of the relatively low crown coverage in the Lowland Sclerophyll Forest (1) and the intercepting and suspending of leaf and twig litter by the layer of dense shrubs explain the very low litter fuel load measured adjacent to the area burnt by the spot fire. Despite this low litter fuel load, the important fuel hazard components of shrub and bark combine to result in an overall 'Very High' rating for the site. Wilson (1993) classifies a 'Very High' hazard as one where a Reference First Attack will fail at a fire danger index in the range of 12 to 24. In comparing this classification to the actual events, the following factors are relevant:

- the adjusted fire danger index at 1530 hours was 20.
- the adjusted fire danger index at 1650 hours (prior to the wind gust) was 6.
- the spot fire was about 1 ha in area at 1530 hours and had probably been burning for greater than 30 minutes and possibly up to an hour.
- the rate of line construction of the D3 bulldozer was about 150 m/h.

Although the defined Reference First Attack conditions are not equivalent to the suppression action taken at this fire, a comparison indicates that such an attack would have failed under the conditions of fire danger at 1530 hours. However, if a Reference First Attack was commenced within 30 minutes of ignition, it is probable that the attack would be successful in the range of fire danger index from 12 to 18. The study of future wildfires will further assist in verifying this classification.

Under the moisture adsorption conditions following the south-west change at the fire area, the measured values of moisture content of the elevated dead fuel were higher than those of the exposed surface litter. During the afternoon of a normal diurnal cycle during autumn, the moisture content of the elevated dead fuel is normally lower than that of the exposed surface litter because of greater exposure of the elevated fuel to the weather elements (Buckley 1993). Under dry summer conditions, the moisture content during the afternoon of the two fuel classes is probably similar. The actual situation measured at this fire presumably reflects the faster response of the elevated dead fuel to the moisture adsorption conditions of decreasing temperature and increasing relative humidity.

Effective suppression of wildfires that are burning in forest fuels at rates of spread of up to 200 m/h using parallel attack is normally possible (Luke and McArthur 1978). The fireline is constructed parallel to and just far enough from the fire edge to allow men and equipment to work safely and effectively away from the radiant heat of the fire. The strip of fuel between the fire and the control line is then normally burnt out as soon as possible. A fireline intensity of about 3,000 kW/m is considered by Loane and Gould (1985) to be the limit above which suppression is rarely successful in forest fuels, even with heavy machinery and retardant drops. The observed spot fire was suppressed with a D6 class bulldozer whilst burning at a rate of spread of average 225 to 255 m/h and fireline intensity of average 1400 kW/m to 1600 kW/m. Based on the suppression action and fire behaviour at this fire, a threshold of effective suppression in elevated fuel appears to be less than in litter fuel and is probably about 2,000 kW/m.

A sudden increase in fire behaviour, such as occurred at this fire, is a characteristic of fire behaviour associated with fatalities and near misses. A study of United States Forest Service records of fatalities and near misses at 125 wildland fires (Anon. 1982) showed that just over 50% of the incidents involved a sudden increase in fire intensity or other changes in fire behaviour associated with a fire moving rapidly upslope or with a sudden wind shift (increased fire spread). Consequently, suppression crews working close to fires such as the one in this study must be able to quickly return to burnt ground if fire behaviour increases suddenly. Support from fire bombing aircraft is also highly desirable in these circumstances to assist in reducing the intensity of the burning head fire, to assist in controlling spot fires and to assist ground crews if their safety is threatened.

The effectiveness of the Beaver fire bomber at this fire was limited as the initial load of retardant was located inappropriately and because of the mechanical failure of the dump door during the third drop. Experienced fire bombing pilots are to be preferred for the often difficult flying procedures involved in fire bombing and, in order to facilitate fire behaviour observation, direction of drop location and communication with ground crews, the role of Air Attack Supervisor should be filled during fire bombing operations.

The rate of fireline construction of about 675 m/h by the D6 bulldozer at this fire was similar to the rate of 700 m/h predicted for this class of bulldozer in the southern Jarrah forest type by Sneeuwjagt and Peet (1985). However, as can be seen by the much lower rate of fireline construction by the D3, bulldozer size, the presence of dense scrub fuels or old log material, slope and the need to side cut will each affect the rate at which fireline can be constructed. Tables which predict the rate of fireline construction must therefore be interpreted according to actual site conditions.

Predicting fire behaviour can be a difficult task, even when a suitable fire behaviour model for the specific fuel type is available, because of the dynamic nature of the weather, fuel and topographical variables which determine fire spread. In this study, conditions of an elevated fuel type, of increasing fuel moisture content and of wind speed which was often gusty complicated the comparison of the observed with the predicted fire behaviour.

The drought factor in the McArthur Forest Fire Danger Meter is a broad measure of fuel availability as determined by seasonal severity and recent rain effects (McArthur 1973). However, the drying characteristics of litter fuel will vary with increasing shrub quantity and coverage as well as with daily weather and stand height and density. Low litter fuel loads are a further complicating factor. Based on fire behaviour studies in the Wombat State Forest, Tolhurst, *et al.* (1992) recommend that the calculation of drought factor be modified because of the poor relationship that was derived in their study between the drought factor and the actual percentage of the total fuel burnt. Results from the current study support this recommendation.

Providing that the dry weight of shrub fuel is added to the dry weight of litter fuel to determine fuel quantity and that the technique described for accounting for the lag in moisture content response were used in calculations, the McArthur Forest Fire Danger Meter provided a reasonable estimate of the rate of spread under the prevailing conditions upon which to base fire suppression decisions. This estimated rate of spread did under-predict the observed rate of spread but the error was small compared to the error factor of between 3.5 and 5 observed by Wouters (1993) at the 1991 Heywood wildfire. The wind speed during the above prediction period at the Heywood wildfire was 28 km/h compared to the lower wind speed during the prediction period at the Patrol Track wildfire of generally 12 to 19 km/h. Although only relatively small, this difference in wind speed may be particularly significant. The fire behaviour model for southern Jarrah is for an elevated fuel type and as shown by the rate of spread calculated in this study, a small increase in wind speed from the class 13 to 17 km/h to the class 18 to 21 km/h resulted in a 49% increase in the predicted rate of spread. Also, the divergence between the effect of wind speed on rate of spread between this model and the Forest Fire Danger Meter continues to increase with increasing wind speed (Cheney 1981). Based on these limited observations and for fires burning in elevated fuels in open forests, the wind speed function of the Forest Fire Danger Meter may significantly underestimate the effect of wind speed on rate of spread above a threshold of wind speed of about 15 to 20 km/h.

Comparing the spotting distance observed at this fire with the distance predicted by the McArthur Forest Fire Danger Meter is not strictly valid because, at the time of the spotting, the head of the main fire was burning across the slope south of Patrol Track and Patrol Track was checking the northern spread of the fire. Hence, the main fire was not behaving as a freely burning fire under the prevailing conditions of fire danger. Nevertheless, the actual spotting distance was within the range predicted by the meter. This distance of between 300 m and 400 m and the subsequent behaviour of the spot fire emphasizes the importance of the spotting process as a characteristic of fire behaviour and as a limiting factor in suppressing fires in eucalypt forest.

Predictions of wildfire behaviour which significantly underestimate actual fire behaviour can result in inappropriate suppression strategies being adopted and in suppression crews being endangered. As heath and other elevated fuels contribute significantly to the fire hazard on over 50% of the public lands in Victoria (Wouters 1993), on-going research[1] into fire behaviour which validates the hazard classification system proposed by Wilson (1993) and which improves the existing models of fire behaviour or develops new models in these elevated fuel types is clearly warranted.

CONCLUSIONS

Despite low levels of litter fuel at the site of the observed spot fire, the important fuel hazard components of shrub and bark combine to result in an overall 'Very High' rating for the site. For the fuel hazard classification proposed by Wilson (1993) and based on the fire behaviour and suppression action at this fire, a Reference First Attack will probably be successful in the combination of fuel hazards at this site in the range of fire danger index from 12 to 18.

Based on the fire behaviour of the observed spot fire, parallel attack with a D6 class bulldozer is effective on fires burning in open forest with an elevated fuel type with a rate of spread of average 225 to 255 m/h and a fireline intensity of average 1400 to 1600 kW/m. However, any significant increase in fire behaviour will most likely result in the parallel attack failing and, if the suppression crew is working in front of the head fire, will probably endanger their safety. The threshold of effective suppression in elevated fuel appears to be less than in litter fuel and is probably about 2000 kW/m. Air support by either fixed or rotary wing fire bombing aircraft is highly desirable under the conditions of fire danger of this study and, during fire bombing operations, the role of Air Attack Supervisor should be filled.

Provided that the dry weight of shrub fuel is added to the dry weight of litter fuel to determine fuel quantity and that the technique described for accounting for the lag in moisture content response were used in calculations, the Forest Fire Danger Meter provided a reasonable estimate of the rate of spread under the prevailing conditions upon which decisions on fire suppression could be based. However, the drought factor function needs review and the wind speed function of this meter may significantly underestimate the effect of wind speed on rate of spread of fires burning in elevated fuels in open forests above a threshold of wind speed of about 15 to 20 km/h. On-going research into fire behaviour in elevated fuels is clearly warranted.

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[1] The type and standard of data that should be collected by Fire Research Officers at wildfires is listed and briefly discussed in Appendix 1.

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APPENDIX A Collecting fire research data at wildfires.

The value of fuel, weather, fire behaviour and suppression data collected at wildfires is determined by the type and standard of that data, as well as by the subsequent analysis. Fuel load and arrangement data can often be collected from adjacent unburnt forest after the fire event, but weather, fuel moisture content and fire behaviour data must be collected, measured or estimated at regular intervals during the fire. Aspects of wild fire behaviour of particular interest include fire behaviour in elevated fuels, crown fire development, the effects of spotting on fire behaviour and fire behaviour at conditions of Very high or Extreme fire danger.

For fire researchers, temperature and relative humidity should be measured with an Assman psychrometer, wind speed at 1.5 m above ground level in the forest should be measured with a hand held anemometer, wind speed at 10 m in the open should be estimated using the Beaufort Scale (Bureau of Meteorology 1984, Rothermel and Rinehart 1983) and ideally, wind speed at 2 m in the open should be measured using an electronic anemometer and data logger. Data should be collected hourly, or more frequently during significant changes in weather. Fuel strata, for example surface, elevated or profile fuel, should be carefully defined before sampling for later determination of fuel moisture content. A minimum of two replicated samples of each strata should be collected at time intervals which correspond with the fire spread data being collected. Because of the difficulty of predicting fire behaviour following a significant weather change, moisture content data that are collected before and following such a change are particularly useful, as are data collected during periods of maximum fire behaviour.

Any fire behaviour observation is potentially useful, but the most important observations which are preferably made at hourly time intervals are spread distance, spotting distance and flame height. Quality data can and should be collected from the ground but aerial observers and the infra-red scanner (Wouters 1993) can considerably increase data availability. Also, the accuracy of data, particularly spread distances, should be estimated to enable more effective analysis and comparison. Observing the type and effectiveness and measuring the rate of progress of suppression actions are further subjects of interest where valuable data can be collected. Date and time imprinted 35 mm photography and the careful noting of the actual timing of weather, fire behaviour and suppression events will greatly assist later analysis.

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