The sudden increase to gale force wind speeds occurred in the fire area at 1125 hours, approximately one hour 30 minutes later than at East Sale. The west to south west wind change reached a location two kilometres north of the Bemm River township at 1530 hours, again approximately one hour 30 minutes later than at East Sale, although a further hour passed before the change reached the inland location of Manorina (see Figure 2). In this report, a time adjustment of one hour 30 minutes is therefore applied to wind data between East Sale and the fire area.

Wind speed at the fire area was assessed using the Beaufort Scale (Bureau of Meteorology 1984). A "Force 10 storm or whole gale", which corresponds to an average wind speed of 89 to 102 km/h, characterised the initial two hours of the wildfire. Observations of maximum gust wind speed made on a Dwyer anemometer at the Orbost DCE office during this time ranged between 120 and 130 km/h. Higher wind damage levels in the Orbost area compared to the Sale area support the higher average wind speed assessed at the wildfire area. The wind uprooted trees, snapped off branches and tree trunks and caused structural damage to buildings and utilities; winds of such strength are rarely experienced inland.

Wind speed at the fire area during the two hour period prior to the wind change decreased to a Force 8 to 9 on the Beaufort Scale, which corresponds to an average wind speed of between 62 to 88 km/h (gale to strong gale). The extent of the decrease in wind speed recorded at East Sale did not occur in the wildfire area. Wind speed following the wind change continued at gale force strength for at least one-and-a-half hours before moderating late on the Friday afternoon.

Temperature and relative humidity data derived from a thermo-hydrograph trace at Orbost are shown in Table 5. Temperature and relative humidity data collected at Hippo Track, near the point of fire ignition, are shown in Table 6. The data in Tables 5 and 6 correspond closely; although a lag of between half and one hour in the increase in relative humidity at Hippo Track is apparent. A maximum temperature of 30^{o}C and an estimated minimum relative humidity of 26% occurred in the wildfire area between 1115 and 1145 hours, which illustrates that extremes of temperature or relative humidity are not features of this wildfire.

Table 5. Temperature and relative humidity data, Orbost, 14 October 1988.

TIME (hours)	TEMPERATURE (^{o}C)	RELATIVE HUMIDITY (%)
0900	24	33
1000	27	32
1100	29.5	26
1200	28	27
1300	25	30
1400	24	37
1500	24	45
1600	24	45
1700	17	84
1800	15	62
1900	14.5	65
2000	14	70

Table 6. Temperature and relative humidity data, Hippo Track, 14 October 1988.

TIME (hours)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
1100	28.5	-
1115-1145 (approx)	30	-
1500	25	37
1530	23	45

The metric Byram Keetch Drought Index (Keetch and Byram 1968) at Orbost for Friday, 14 October 1988 was a relatively low 29. The following rainfall data were collected at Hippo Track prior to the wildfire: two days since 0.2 mm, three days since 1 mm and five days since a cumulative 8.5 mm. The combination of the drought index and recent rainfall data by the McArthur Mk 5 Forest Fire Danger Meter to give a drought factor of 7 indicates that 70% of the fuel was theoretically available for consumption.

An integrated measure of fire weather conditions is provided by the fire danger index which is calculated using the McArthur Mk 5 Forest Fire Danger Meter. This index is directly related to the chance of a fire starting, and the fire's rate of spread, intensity and difficulty of suppression, and has been widely used in Australia for fire danger forecasting and as a guide to fire behaviour (Luke and McArthur 1978). For the Bemm River wildfire, calculations of the index are shown in Table 7. These calculations are based on the McArthur equations described by Noble *et al.* (1980) which allow the input of wind speed data greater than the maximum figure of 70 km/h found on the McArthur meter. The fire danger index peaked at 82 when the temperature was 28°C, relative humidity 27% and average wind speed 95 km/h. Values of fire danger index greater than 50 are classified as "extreme".

Table 7. Fire danger index for 14 October 1988, based on temperature, relative humidity and wind speed data at Orbost.

TIME (hour)	TEMP. (°C)	RELATIVE HUMIDITY (%)	AVERAGE WIND SPEED (km/h)	FIRE DANGER INDEX
1000	27	32	20	11
1100	29.5	26	40	24
1200	28	27	95	82
1400	24	37	75	32
1530	24	45	75	23

Table 6. Temperature and relative humidity data, Hippo Track, 14 October 1988.

TIME (hours)	TEMPERATURE (^{o}C)	RELATIVE HUMIDITY (%)
1100	28.5	-
1115-1145 (approx)	30	-
1500	25	37
1530	23	45

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1000	27	32	20	11
1100	29.5	26	40	24
1200	28	27	95	82
1400	24	37	75	32
1530	24	45	75	23

FIRE BEHAVIOUR AND DEVELOPMENT

The Bemm River wildfire started at Hippo Track (see Figure 5) at 1130 hours on Friday, 14 October 1988. The source of the wildfire was a burning *Eucalyptus sieberi*, located within the control lines of a fire which had been alight the previous day. The crew of a tanker had almost completed "blacking out" the previous fire when the wind speed increased dramatically. Despite the presence of this tanker crew, two spot fires became uncontrollable within minutes. Flames completely scorched the forest canopy within 15 m of the point of ignition. Gale force winds not only fanned the spot fires but blew numerous branches, 30 year old regrowth trees and dead old growth trees (known as stags) to the ground. The situation was life threatening and the crew was withdrawn.

Details of the subsequent fire development are shown on Figure 5, and the fire behaviour is summarised in Table 8. In the 15 minutes following ignition, the fire front travelled 100 m, which corresponds to a forward rate of spread of 0.4 km/h. Short distance spotting of up to 40 m was well established, even at this early stage. The author estimated the location of the fire front at 1330 hours (from the Bemm River Road, prior to the wildfire crossing the road) to be between 3.5 and 4.5 km from the point of ignition, which corresponds to a forward rate of spread of between 2.0 and 2.6 km/h. A large spot fire was observed at 1330 hours to be burning intensely near Patrol Track, which indicates long distance spotting of at least 3 km.

During the period 1330 to 1530 hours, the fire progressed between 7.0 and 8.0 km through Open Forest, Woodland and Heathland fuels, at a calculated rate of spread of between 3.5 and 4.0 km/h. At 1500 hours aerial reconnaissance detected spot fires burning east of Bemm River and south of River Road, which had resulted from long distance spotting. The position of the headfire was not accurately located by the reconnaissance flight because of the dense smoke and the necessity for the aircraft to fly at 9,000 ft due to severe atmospheric instability. The steeply angled convection column of the main fire at this stage was approximately 12,000 ft in height.

The fire behaviour prior to the wind change can be expressed quantitatively in terms of fire intensity*, as is shown in Table 8. The maximum average fire intensity (assuming an average value of heat yield for forest fuels of 16,000 kJ/kg (Luke and McArthur 1978) and an estimated dry weight of fuel consumed of 20 tonnes/ha) was between 31,200 and 35,600 kW/m.

Table 8. Summary of fire behaviour of the Bemm River fire on 14 October 1988, prior to the wind change. (Possible range in spread distance, and hence forward rate of spread and fire intensity, is shown in brackets).

TIME (hours)	SPREAD DISTANCE (km)	AVERAGE FORWARD RATE OF SPREAD (km/h)	AVERAGE FIRE INTENSITY (kW/m)
1130-1145	0.1	0.4	3,600
1145-1330	4.0 (3.5-4.5)	2.3 (2.0-2.6)	20,500 (17,800-23,200)
1330-1530	7.5 (7.0-8.0)	3.8 (3.5-4.0)	33,900 (31,200-35,600)
1130-1530	11.5	2.9	25,800

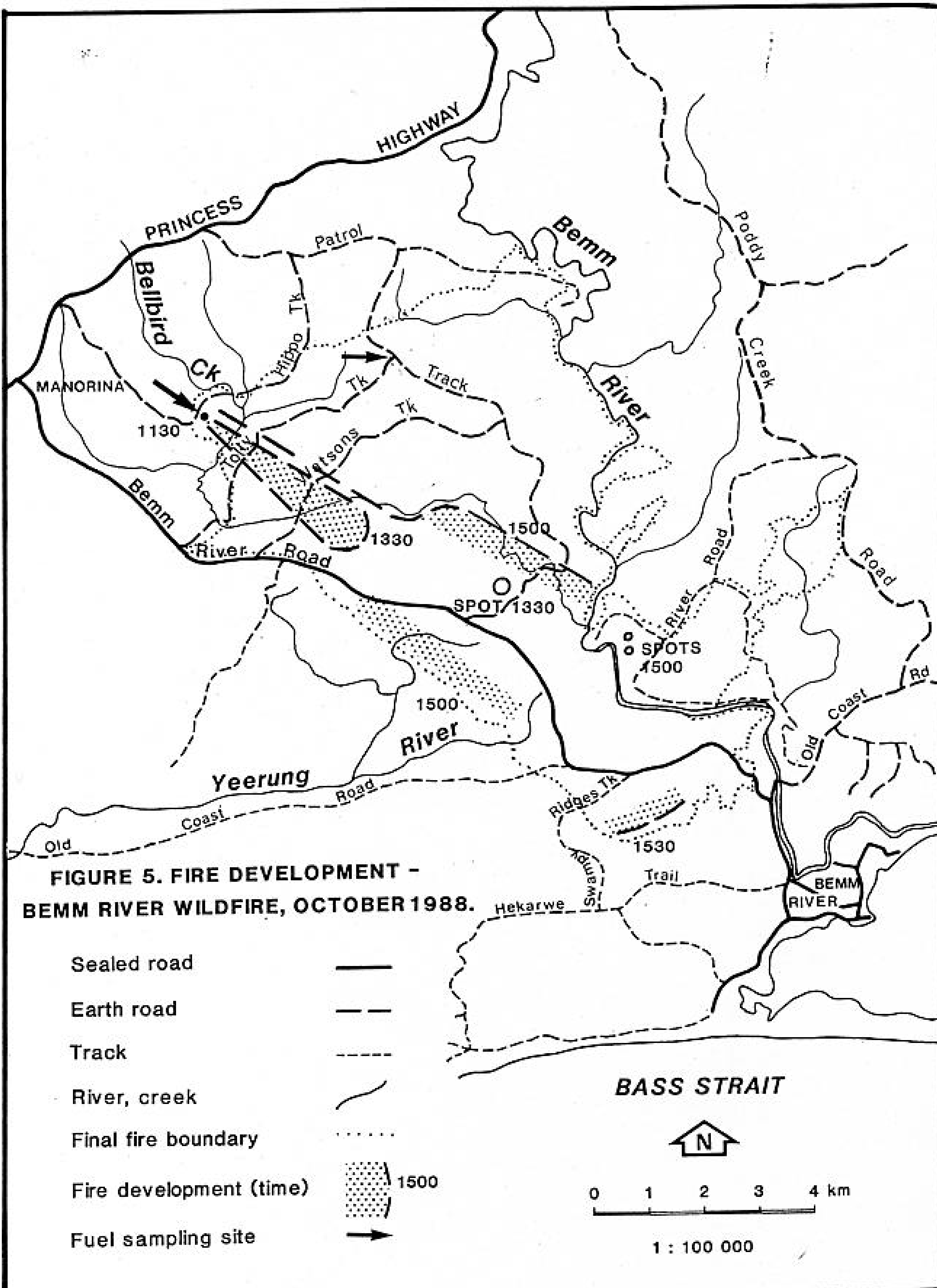

FIGURE 5. FIRE DEVELOPMENT – BEMM RIVER WILDFIRE, OCTOBER 1988.

Following the south west wind change, the north eastern flank became the headfire which burnt intensely on a wide front until weather conditions moderated late in the afternoon. The Bemm River and adjacent Warm Temperate Rainforest vegetation provided a natural boundary to the development of the fire. However, three separate fire areas developed on the eastern side of Bemm River as a result of spot fires which had ignited both before and after the wind change. The final fire area was 5,670 ha with a perimeter of 80 km.

The intense fire behaviour of the Bemm River wildfire resulted in complete crown scorch of most of the forest burnt by the main run of the fire. Interpretation of scorch classes from large scale colour aerial photographs flown four months after the fire is shown on Figure 6 with a corresponding area statement in Table 9. The scorch classes are defined on the basis of complete crown scorch**. While about half of the total fire area was classified as scorch class 1, only insignificant areas of forest were completely defoliated by this fire.

Table 9. Area statement of crown scorch classes.

CROWN SCORCH CLASS	AREA (ha)	% OF TOTAL
Scorch class 1	3,185	56%
Scorch class 2	556	10%
Scorch class 3	1,318	23%
Unburnt	276	5%
Heathland	335	6%
TOTAL	5,670	100%

An informal inspection of tree damage conducted 15 months after the wildfire found that leader shoots had been lost from some of the 20 to 30 year old regrowth stems, but that there was only limited evidence of butt scarring, as indicated by the absence of bark splitting.

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* Fire 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:

$$I = Hwr$$

Where I denotes the fire intensity (kW/m), H denotes the heat yield of fuel (kJ/kg), W denotes the dry weight of fine fuel consumed (kg/m^2) and r denotes the forward rate of spread (m/s).

** Scorch class 1 : complete crown scorch of 50-100% of crowns
Scorch class 2 : complete crown scorch of less than 50% of crowns
Scorch class 3 : minimal complete crown scorch (includes lower crown scorch)
Heathland : heathland burnt by the wildfire
Unburnt : unburnt area within the fire boundary

The observed average rate of spread over each of two intervals of two hours prior to the wind change is compared in Table 10 with rates of spread predicted by the McArthur Mk 5 Forest Fire Danger Meter. The predictions are based on the fire danger indices tabulated in Table 7, on a fuel quantity of 20 tonnes/ha and on zero slope*. The predicted rate of spread of 2.0 km/h during the first time period when the fire danger index peaked at 82 compares favourably with the observed rate of spread of between 2.0 to 2.6 km/h. However, despite a substantial decrease in fire danger index to 32 during the second time period and hence a decrease in the predicted rate of spread to 0.8 km/h, the fire increased its rate of spread to between 3.5 and 4.0 km/h.

Table 10. Comparison of predicted and observed rates of spread using weather conditions at 1200 and 1400 hours.

TIME (hours)	AVERAGE WIND SPEED (km/h)	FIRE DANGER INDEX (ORBOST)	PREDICTED RATE OF SPREAD (km/h)	OBSERVED RATE OF SPREAD (km/h)
1200	95	82	2.0	2.0-2.6
1400	75	32	0.8	3.5-4.0

Suppression action against the head fire and north eastern flank was effectively impossible during the main run of the fire. However, effective suppression action was implemented prior to the south west wind change on the south western flank of the fire. Two D6 class bulldozers commenced a direct flank attack on the fire edge south east of the Bemm River Road at about 1500 hours, "checking" the flank later in the afternoon. Subsequent suppression action involved direct attack with bulldozers which "checked" the southern, western and much of the northern edge during the later afternoon and night of the first day. However, the total wildfire was not declared "checked" until 0900 hours on the fourth day. Strong wind conditions persisted into the second and third days of the wildfire which increased suppression difficulty on the fire areas east of Bemm River. "Control" was declared at 0900 hours on the fifth day of the fire.

* The effects of slope can be virtually disregarded when considering large fire behaviour under forest conditions (Luke and McArthur 1978).

DISCUSSION

"Very high intensity" fires are defined as having fire intensities greater than 7,000 kW/m (Cheney 1981), and severe forest fires can have intensities as high as 60,000 kW/m (Luke and McArthur 1978) or, based on the Ash Wednesday fires, even higher (Cheney 1983). The Bemm River wildfire, with an estimated average intensity in the range 31,200 to 35,600 kW/m over a two hour period, was clearly an extremely severe wildfire.

The wildfire completely defoliated only small areas of forest, despite the high intensity and rates of spread. This means that a crown fire was not maintained during the main run of the wildfire. Cheney (1981) states that crown fires can develop in most forest types, particularly those with rough barked eucalypts, at intensities of 7,000 kW/m or less. The present wildfire, with a much higher intensity, appears to be unusual in this regard and may be similar to the Daylesford wildfire of the 16 January 1962 (McArthur 1968) and the devastating southern Tasmanian wildfires of the 7 February 1967 (Luke and McArthur 1978). The Daylesford wildfire burnt under "very high" and the southern Tasmanian wildfires burnt under "extreme" fire danger conditions, yet crown fire development was limited in both cases. High wind speed was a feature of both wildfires, averaging 45 km/h at the Daylesford wildfire and 55 km/h with gusts to 110 km/h at Hobart. Luke and McArthur (1978) suggest that at high wind speeds the flame angle becomes very acute and flames are prevented from remaining in the crowns.

The 10% moisture content of exposed surface and elevated eucalypt litter at mid afternoon on the first day of the Bemm River wildfire is moderate in comparison to a level of 7% or less which is considered dangerous (Luke and McArthur 1978). The profile moisture content of litter bed fuels, measured on the day prior to the wildfire, varied widely but was generally well above 20%, the level above which fuels are considered not to sustain combustion (Luke and McArthur 1978). Despite this, the rate of spread was very high, which suggests that fire behaviour was independent of a substantial part of the fuel profile. The profile fuels were consumed, but would have generated considerably less heat radiation (Vines 1981) than if the whole fuel complex had been dry. This implied reduction in "effective" fuel load is consistent with the lack of stem damage and the finding by Knight (1981) that heat absorbed by stems during a fire is correlated with fuel load rather than rate of spread. The only fuels which appear to have had a significant bearing on fire behaviour or fire damage are those which were elevated or on the litter bed surface.

The apparent underprediction of rate of spread by the McArthur Mk 5 Forest Fire Danger Meter for the second two hour period of the main run of the fire raises the question of possible errors in the inputs to the equation. For example, the fuel load may have been 5 tonnes/ha higher than that measured and the moisture content of the fine fuels may have been lower than that predicted by the McArthur Meter using the Orbost temperature and relative humidity data because of a lag in moisture content uptake (Luke and McArthur 1978) and the time delay in the rise in relative humidity at the fire area compared to Orbost. However, the wind speed had definitely decreased and, even if it had not, accounting for each of the above possible sources of error in combination still leaves an underprediction of a factor of about one half.

The aerated arrangement of the fuel type may have contributed to this discrepancy between the observed and predicted rate of spread, but this possibility is inconsistent with the comparable prediction of the initial two hour period. Luke and McArthur (1978) state that under severe burning conditions all fire behaviour characteristics tend to accelerate with time, with the rate of spread increasing in a series of steps, due largely to the progressive involvement of different fuel components, development of a convection column and initiation of the spotting process. The 1962 Daylesford wildfire exhibited similar acceleration to the Bemm River fire over a three hour period, with the average rate of spread of 3.2 km/h three times higher than that predicted by the McArthur Meter. McArthur (1967) attributes this to the dramatic effect of concentrated spotting from a stringybark eucalypt fuel type. A similar effect may have equally applied to the Bemm River wildfire but there was a reduced number of ignitions ahead of this wildfire prior to the wind change compared to the Daylesford wildfire. Unfortunately, the lack of a complete pattern of spot fire ignition and development prevents a conclusive statement. A further possibility is that a combination of high wind speed, spotting and the aerated fuel type may have resulted in a "large fire effect" and hence the observed increase in rate of spread of the fire front.

Underprediction of rates of spread by the McArthur Meter has been documented by Rawson *et al.* (1983), who report that for the devastating Deans Marsh-Lorne fire on Ash Wednesday, the rate of spread of 10.8 km/h before the wind change was almost three times greater than the rate predicted. Cheney (1983) concludes that the observed rates of spread for established wildfires burning under extreme conditions appear to be at least three times higher than those predicted by the McArthur Meter. The documentation of future severe wildfire behaviour should increase the knowledge of this important subject and allow the improvement of the predictive capacity of the McArthur Meter under "extreme" fire danger conditions.

Intense wildfires can cause loss of life and property, damage to eucalypts (for example see Appendix 1) and adverse affects on other forest values. The losses can be reduced by a rapid and effective suppression capability matched to an extensive access network and efficient detection system. However, the constraint facing forest fire control organizations in Australia is that direct attack on forest fires is generally effective only on wildfires of intensity less than 4,000 kW/m (Luke and McArthur 1978), which is within the lower range of intensity experienced in Australian conditions.

The Bemm River wildfire illustrates that even immediate on-site response to a wildfire can be ineffective. Additional protection from wildfire can be achieved by prescribed burning or fuel reduction burning. This is undertaken with the aim of reducing fuel hazards and is achieved (NBRU 1987) by reducing the total weight of fuels and hence the rate of spread and intensity, by reducing the height of the fuel bed hence reducing flame heights and by removing the fire brand material (stringybark or gum bark) from the trees and hence greatly reducing the potential of fires to generate spot fires ahead of the main fire.

The effectiveness of fuel reduction burning in modifying the fire behaviour of the Bemm River wildfire is shown by comparing the six burning units illustrated on the fire history map (Figure 2) with the crown scorch assessment map (Figure 6).

Available fuel and fire behaviour data for Area 1 are insufficient to enable interpretation of the scorch class assessment of the separate fire areas east of Bemm River. However, the level of fuel reduction achieved was insufficient to prevent the spread of the fires.

The main run of the wildfire prior to the wind change burnt intensely in Area 2. Fuel reduction operations conducted six months and one-and-a-half years prior to the wildfire, assessed as having covered the lower end of the 20-50% range, did not significantly alter the intense fire behaviour prior to the wind change but did reduce the extent of crown scorch to less than 50% (scorch class 2) in areas burnt after the wind change.

The main run of the wildfire crossed Area 3 while burning under extreme fire danger conditions, and resulted in complete crown scorch and some limited defoliation. The wildfire subsequently burnt in a north easterly direction after the wind change and caused measurably less damage within Area 3 than to adjacent forest. The crown scorch within Area 3 (scorch class 3) provides a clear comparison to the complete scorch affecting 50 to 100% of crowns (scorch class 1) in adjacent forest. The height of stem char was also significantly reduced within Area 3. Fire intensity under conditions of "high" fire danger was clearly reduced within the fuels that had accumulated over the seven years since fuel reduction, due probably to a sustained reduction in the amount of bark on the stringybark trees and a persistent change to the shrub fuel arrangement.

At the time of the wind change the north east flank of the wildfire was approximately 1.5 km from Area 4 and 2.5 km from Area 5. No data are available to enable the rate of spread to be calculated after the wind change, except to say that the decrease in wind speed and increase in relative humidity would have progressively decreased the rate of spread from the pre-change level. The fire which approached Areas 4 and 5 was of unknown intensity but fully scorched the crowns in adjacent forest and is likely to have been uncontrollable by direct attack. Both the six month old burn and the two-and-a-half year old burn prevented the spread of the fire within those areas.

The impact of fuel reduction burning which had achieved broad coverage on the main run of the wildfire can be seen in Area 6. The fire front approached Area 6 from the north west. Key areas of scorch are highlighted on Figure 6 with the notation 6a-6e. Area 6a was burnt intensely with full crown scorch (scorch class 1). However, a large reduction in fire intensity is apparent in Area 6b, downwind of Area 6a, with only the lower crowns scorched (scorch class 3). Intense fire behaviour redeveloped in Area 6c (scorch class 1) but Area 6d* was largely unburnt, which consequently halved the width of the fire front.. The fuel reduction effect in Area 6e was apparently insufficient to prevent the redevelopment of intense fire behaviour as evidenced by the scorch class 2 classification. Overall, a one-and-a-half year old fuel reduction burn that had covered greater than 50% of the area caused a major reduction of both headfire intensity and fire front width of an extremely severe wildfire.

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* Areas burnt in the Autumn 1987 fuel reduction burn and scorch class 3 areas which resulted from the wildfire are not separated by the scorch class interpretation. As a consequence, some areas not burnt by the wildfire in Area 6 are incorrectly shown as scorch class 3 rather than as unburnt.