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THE WANDILO FIRE, 5 APRIL 1958

Fire behaviour and associated meteorological and fuel conditions

BY

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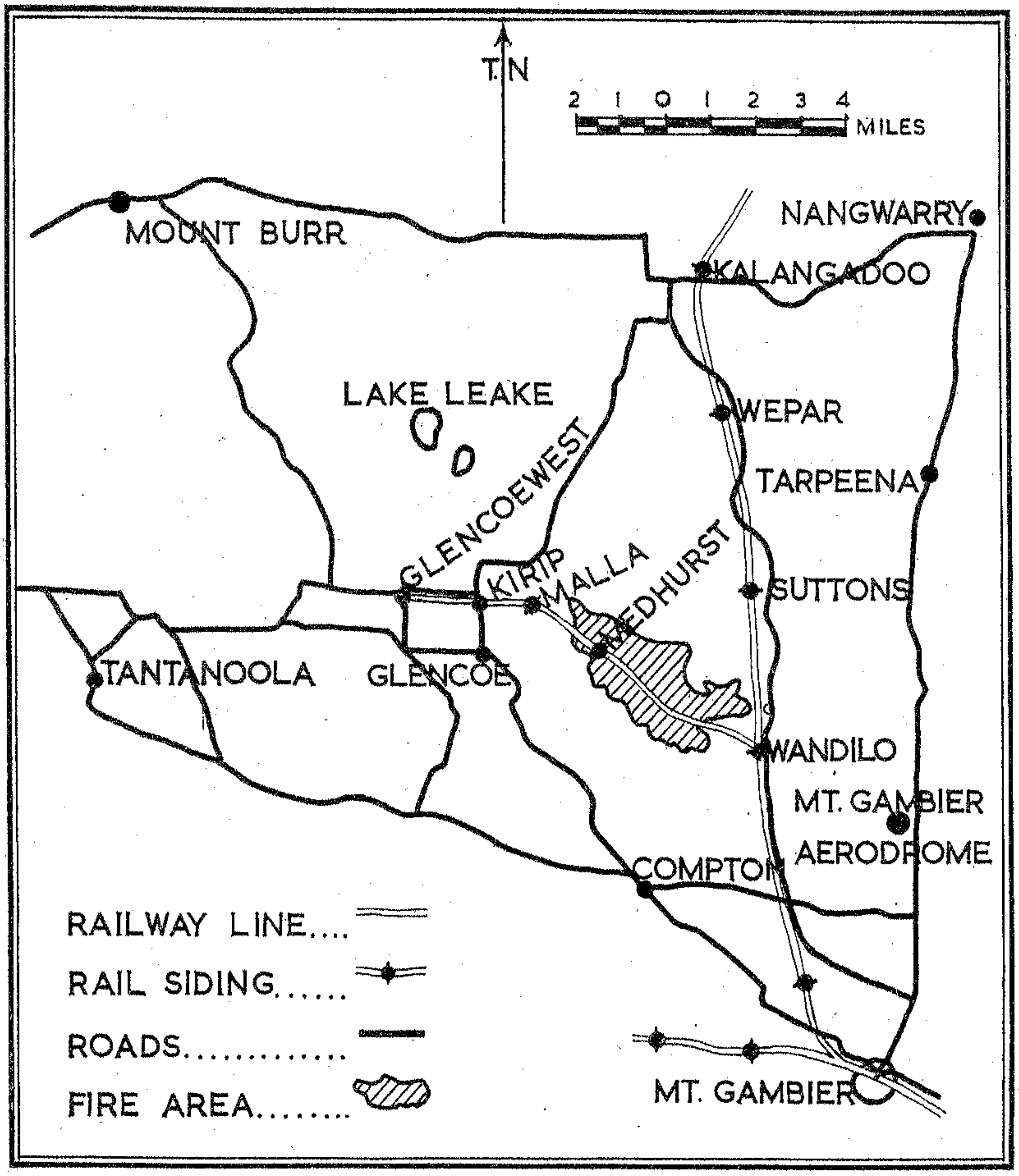
CONTENTS

SUMMARY

The fire which occurred at Mount Gambier Forest Reserve, South Australia, on 5 April 1958, has become widely known as 'The Wandilo Fire'. This fire is noteworthy because of the loss of eight fire-fighters and three fire fighting vehicles during a fire-storm which suddenly developed during the progress of the fire.

Meteorological and fuel conditions associated with the fire are presented, together with a detailed account of the progress of the fire as a whole, and the mechanics of the development of the fire-storm in particular.

Some conclusions concerning forest plantation layout and management, fire-fighting tactics, fire-fighting equipment, safety precautions for personnel, and fire weather forecasting which are directed towards lessening the likelihood of such losses in the future, are presented.



Location of the Wandilo Fire in the lower south-east of South Australia.

THE WANDILO FIRE, 5 APRIL 1958—FIRE BEHAVIOUR AND ASSOCIATED METEOROLOGICAL AND FUEL CONDITIONS

By A. G. McArthur and D. R. Douglas† (in collaboration with L. R. Mitchell‡ with respect to meteorological aspects)*

1. INTRODUCTION

Bearing in mind the number and size of its forest fires, Australia has a remarkably low record of loss of life of personnel engaged in fire fighting. Nevertheless fire control authorities can never afford to be complacent regarding the danger which is ever present in this activity, and must learn all possible lessons which can be gathered from the tragedies which do occur occasionally.

During a fire at Wandilo in the south-east of South Australia on Saturday, 5 April 1958, one of Australia's worst fire-fighting tragedies occurred. Of eleven men employed by the Woods and Forests Department, who were trapped by an unexpected 'blow-up', eight died and three survived.

The purpose of this paper is to discuss as fully as possible the interaction of the meteorological and fire behaviour aspects of this fire, and to indicate some methods by which silvicultural practice, fire equipment design, suppression tactics, and fire weather forecasting can perhaps lessen the likelihood of such losses of life in similar circumstances in the future.

The meteorological factors relevant to the fire have been derived from the Mount Gambier Meteorological Station, 9 miles east of the fire area, and from recordings made at Mount Burr Forest Reserve 17 miles to the west.

The fire behaviour details presented have been compiled very largely from personal interview made immediately after the fire with personnel engaged on the fire suppression action. The rate of spread maps were drawn from spot times supplied by officers and fire-fighting personnel engaged on the fire. Most time estimates were verified by at least two observers before being accepted.

Vertical aerial photographs taken before and after the fire, together with site quality plans of the burnt pine plantations, have been used to prepare fuel type and fire severity maps.

The interpretation of fire behaviour has been based on this verbal and photographic evidence and also upon certain experimental work in fire behaviour research carried out at the Forestry and Timber Bureau, Canberra, A.C.T.

2. DESCRIPTION OF THE AREA

The fire started in Section 346, Hundred of Young, County Grey, and initially spread in a south-easterly direction roughly parallel to, and on either side of, a new disused branch railway line. The fire was finally brought under control near the Wandilo Railway Siding.

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Physiographically, the area is divided into two distinct zones, separated by the old railway line. Sand dunes of the Mount Burr range system lie to the south-west of the railway line, while north of it the country is comparatively low lying with little relief.

Exotic pine plantations have been established on the dune country while natural eucalypt 'scrub', consisting of trees of *Eucalyptus baxteri, Eucalyptus huberiana,* over a shrubby understorey of tea-tree (*Leptospermum spp.*), bracken (*Pteridium spp.*) and yacca (*Xanthorrhoea spp.*) then occupied the low lying intermittently swampy country to the north which, in the years following the fire, has been partially cleared and sown to improve pasture.

3. FUEL TYPES

Four major fuel types are recognised in the fire area.

(a) natural forest;
(b) swamp vegetation;
(c) exotic pine plantations;
(d) improved pasture land.

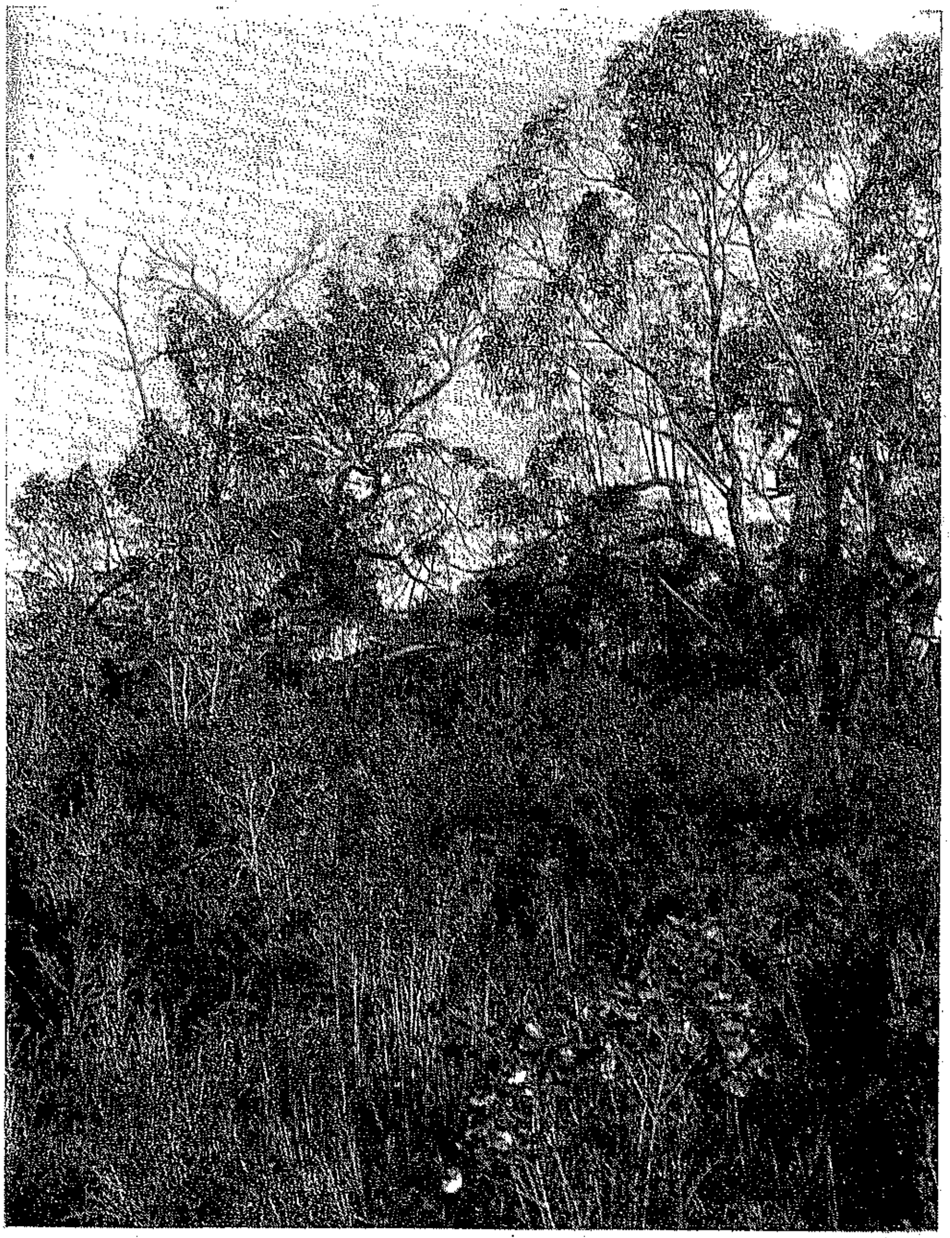

Figure 1. Eucalypt fuel type near railway line.

Figure 2. Eucalypt fuel type. Note: Very heavy understorey of *Leptospermum spp.* under *E. ovata*, north-eastern perimeter.

(a) Natural forest

As described above, this consists of various species of eucalypt over a shrubby understorey. The area covered by the fire was felled in the early 1930's and in consequence, the tree vegetation was a relatively open regrowth stand around 40-50 ft. high. Over the years, periodic patch burning as a hazard reduction measure had been carried out and the accumulation of fuel thus had been reduced from time to time. This work was mainly confined to the drier ridge tops. Typical eucalypt fuel types are shown in Figures 1 and 2. Ground fuel quantities are estimated to be of the order of 10-15 tons per acre in the long unburnt areas and 5-10 tons in the more frequently burnt patches.

(b) Swamp vegetation

Swamps occur mostly in the scrub area but one or two large ones either adjoin, or are in the middle of, the lower sand dune country and have been surrounded by pine plantations. Swamp vegetation in the forest area is nearly always dense tea-tree from 7-10 ft. high, but variations occur. Many swamps are under water for long periods and peat has formed in some. At the time of the fire all swamps were dry, following a very dry summer, and a below-average rainfall during the previous winter. Swamp areas outside the Forest Reserve are mostly cleared, and heavy grazing during the dry summer resulted in a very sparse grass cover which materially aided control of the fire along the north and north-eastern perimeter.

(c) Exotic pine plantations

These consist of two species, cluster pine (*P. pinaster*) and radiata pine (*P. radiata*). Fuel quantities and stand densities varied quite widely within the plantations; the *P. pinaster* however was less uneven than the *P. radiata.*

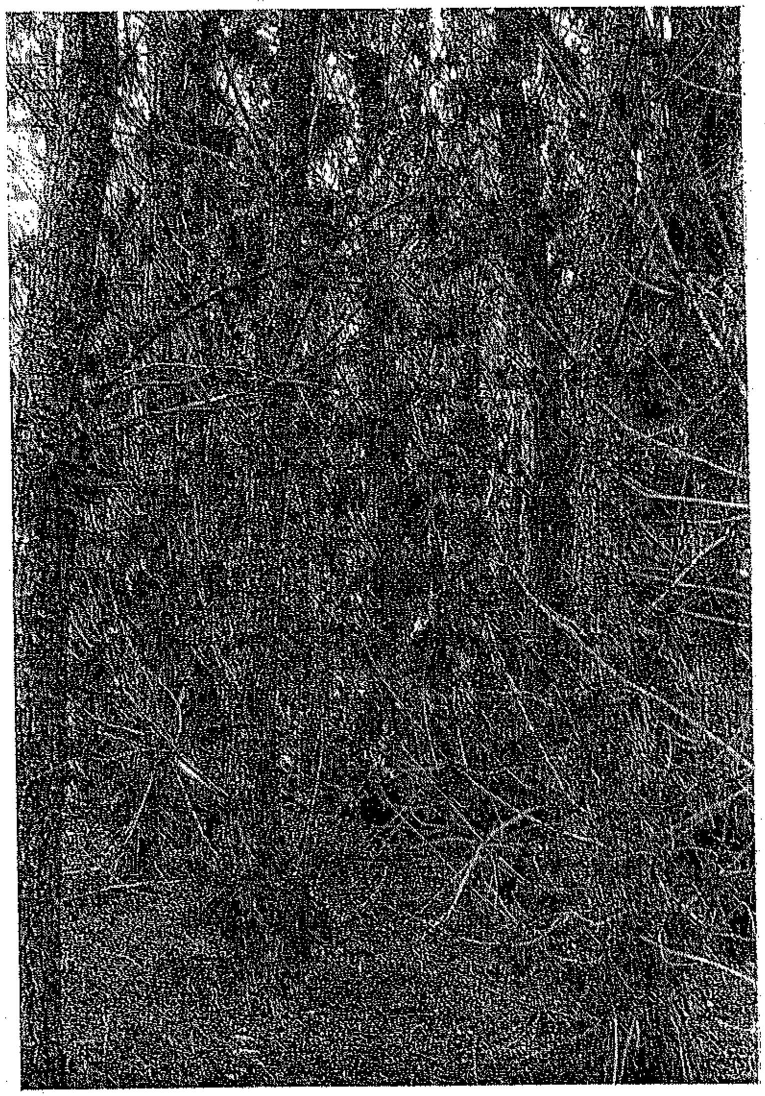

Figure 3. *Pinus pinaster* stand, unthinned and unpruned. Note: Heavy clusters of needles caught in the dead lower branches. The fire entered a similar stand at 1230 hours and crowned immediately.

(i) The *Pinus pinaster* plantations were 23 years old at the time of the fire with a mean height of approximately 35 feet. Canopy had been formed in most areas, but the original ground vegetation had not been entirely suppressed and patches of yacca and bracken were scattered throughout the stands.

A very deep compacted pine needle litter layer covered the floor and large bunches of needles were caught in the angle between branches and the trunk. The entire *Pinus pinaster* area was unthinned and unpruned.

Dead branches and needles extended to ground level as shown in Figures 3 and 4. The dead litter was estimated to represent a fuel weight of from 10-15 tons per acre.

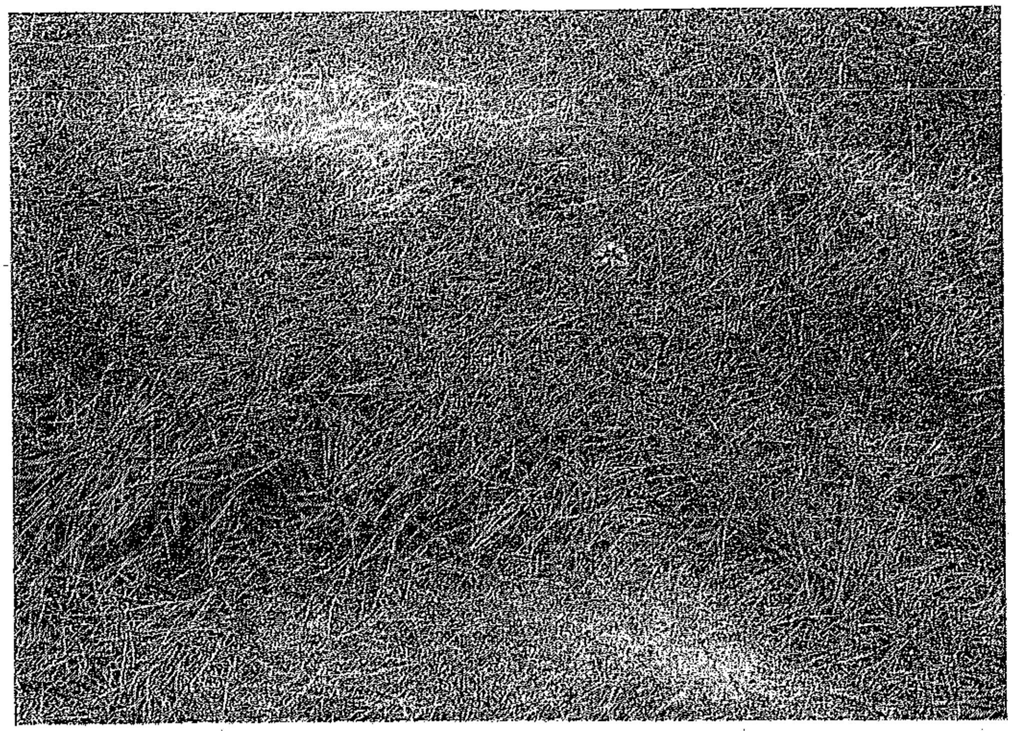

Figure 4. Surface litter under the *Pinus pinaster* stand shown in Figure 3. This quantity is estimated to be approximately 10 tons per acre, is loosely compacted and ideally distributed for rapid combustion.

(ii) The *Pinus radiata* area covered by the fire was nearly all 24 years of age although a small area to the north-west was 23 years. The stands were unpruned and varied in Site Quality from II (trees over 100 ft. high) to VII (trees about 60 ft. high). In addition, there were some 'spindle' stands 15-30 ft. high, and some areas of 'die-back'.

'Dieback' is a deficiency disease which manifests itself, when not corrected, in the repeated death of the leading shoot of the tree in its early years. The consequent stimulated growth of side branches gives the tree a very bushy appearance and, when occurring in clumps (as frequently happens), a distinct fuel type is created. Generally, there is a high rate of fire spread through such stands.

Portions of the *Pinus radiata* stands had been thinned prior to the fire and logging slash from 1 ft. to 3 ft. deep was left. The density of this slash was very variable but was greatest along the sides of log extraction routes which resulted from the removal of every ninth row of trees. The quantity of fuel represented by the litter and forest slash was estimated to range from 15-25 tons per acre.

The litter beneath the unthinned *Pinus radiata* and *Pinus pinaster* stand was a deep layer of undecomposed bracken and pine needles, underlain by a partially decomposed layer containing a mass of fungal hyphae. This layer was not always completely consumed even on the most severely burnt parts of the plantation. In the absence of recent logging slash, the quantity of surface needle litter is estimated to vary between 10-15 tons per acre in the *P. radiata* areas and up to 20 tons in the *P. pinaster* areas.

(d) **Improved pastures**

The area lying to the south-east of the fire area is mainly improved pasture land. Due to the preceding dry spring and summer, the major portion of this land had been heavily grazed and carried a very sparse cover of grass, averaging between ½ to 1 ton per acre. The fire almost extinguished itself in this sparse fuel.

4. METEOROLOGICAL CONDITIONS.

(a) Rainfall

The winter of 1957 was significantly drier than normal and, although spring rains were good, the rainfall of the ensuing summer and autumn was significantly below normal.

TABLE 1

MONTHLY RAINFALL—MOUNT GAMBIER AERODROME

Month	*Actual points*	*Average points (Town)*	*Month*	*Actual points*	*Average points (Town)*
May 1957	265	290	November 1957 ..	240	156
June 1957	155	355	December 1957 ..	132	145
July 1957	117	349	January 1958 ..	10	93
August 1957.. ..	256	344	February 1958 ..	82	122
September 1957 ..	417	291	March 1958 ..	86	117
October 1957 ..	253	210	April 1958	79	214

The dry conditions were reflected in the ground water tables which were lower than normal. Many swamps which usually carried water all the year were completely dry at the time of the fire.

In the period immediately preceding the fire, 76 points were recorded at Mount Gambier Aerodrome between 21 and 31 March in a series of very light to light falls, the largest being 26 points on 28 March.

(b) Synoptic Situation

The synoptic situation was one reasonably typical of bad fire weather in the south-east of the Continent. An anticyclone of central pressure 1026 mbs. was located in the Tasman Sea where it had remained for some days, with a ridge extending westwards over New South Wales to central Australia. Following the passage of several minor troughs of low pressure which weakened and passed south-east of Tasmania, an active and more intense one developed over the western part of the Great Australian Bight during the morning of 5 April and moved rapidly eastwards while at the same time deepening.

This resulted in the development of strong hot north to north-west winds ahead of the associated cold front. This front accelerated across the Bight and moved eastwards at 35-40 knots. The passage of the front caused a sharp change in wind direction, an increase in wind velocity, a decrease in temperature and a rise in relative humidity.

(c) Weather Conditions on 5 April 1958

(i) *Temperature and Relative Humidity*

Maximum temperatures throughout the State, except for a few isolated coastal stations, were in the mid to upper 90's with a few centuries. The maximum temperature of 92.40° F. at Mount Gambier Aerodrome was recorded at 1230 hours and the minimum relative humidity of 29 per cent. was reached at about the same time. This is shown in Figure 5. Conditions on the previous day were also fairly severe with the temperature rising to 86° F. and the relative humidity falling to 22 per cent. The relative humidity during the night of 4 April was low and little moisture gain would have occurred in the heavier fuel components. The air mass associated with the north to north-west air stream ahead of the cold front was not particularly 'dry'. Surface dew

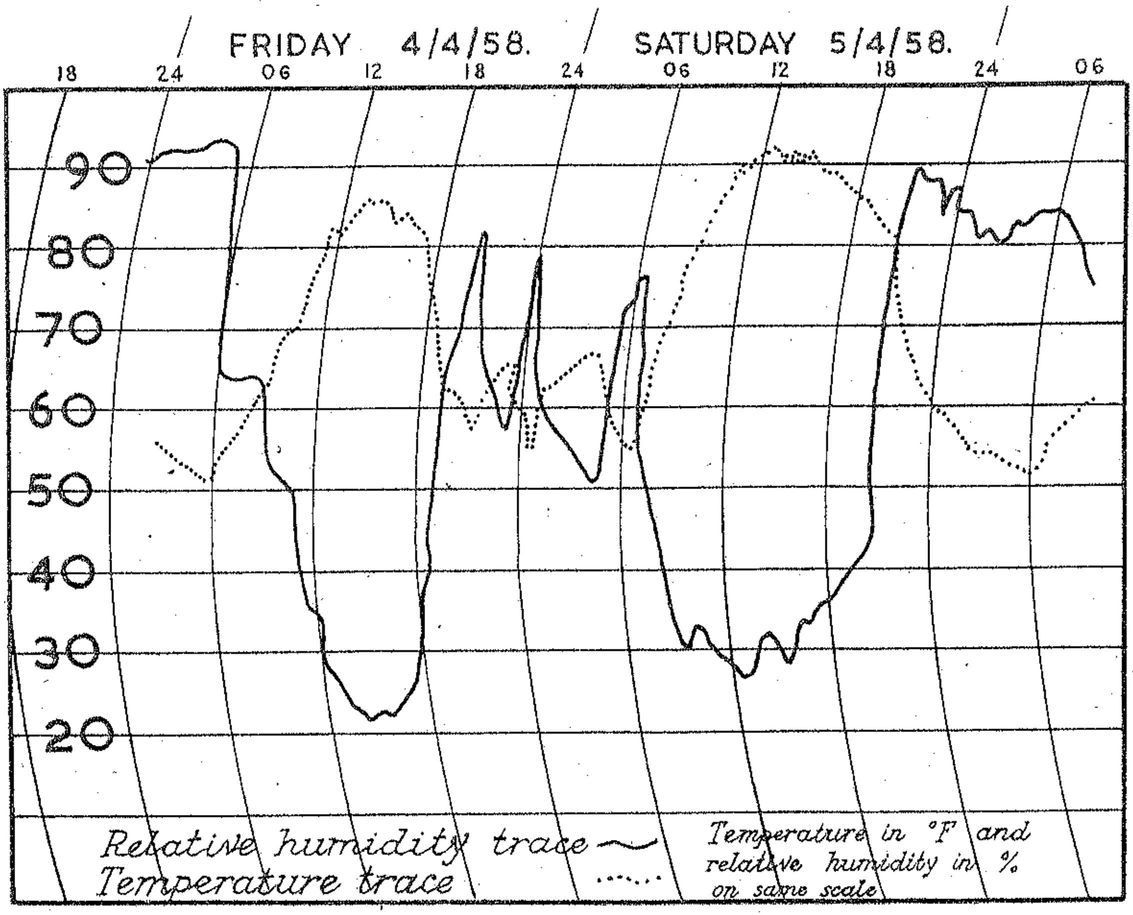

Figure 5. Relative humidity and air temperature recorded at Mount Gambier Aerodrome—4 and 5 April 1958.

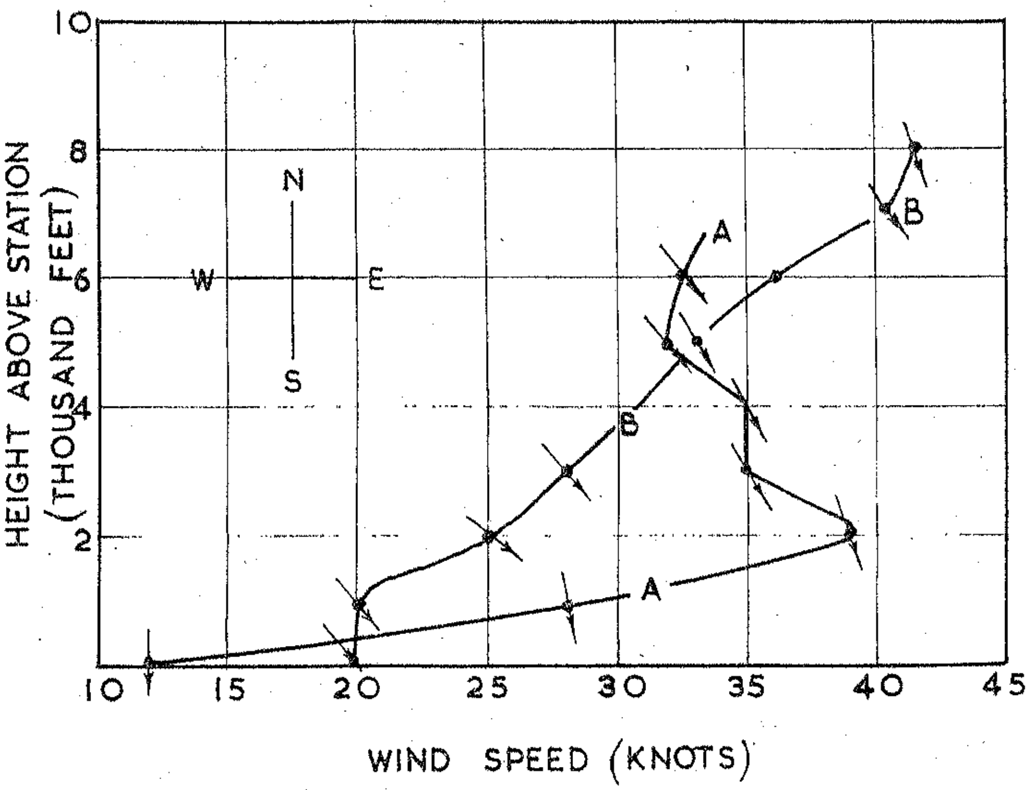

Figure 6. Upper wind profiles at (A) 0900 hours and (B) 1500 hours—recorded at Mount Gambier Aerodrome on 5 April 1958. (Derived from single balloon flight with assumed rate of ascent.)

points were generally above 40° F., above 50° F. in many areas, and exceeded 60° F. in some coastal stations. The minimum relative humidity at Mount Gambier could not be regarded as being exceptionally low as values of less than 20 per cent. occur with reasonable frequency in summer months. However, these conditions must certainly be regarded as being quite severe for April.

(ii) *Upper Winds*

The 0900 hours wind profile at Mount Gambier shows a sharp increase in wind speed from 12 knots at the surface to about 36 knots at the 2,000-3,000 ft. level, with a slight decrease to 32 knots at 6,000 ft. The direction backed from 360° at the surface to 320° at 6,000 ft. (Figure 6). This profile indicates that the surface wind velocities would be likely to increase considerably during the morning and early afternoon. The strong wind shear existing during the early morning hours would probably have inhibited strong convection but, as the surface wind speeds increased, the profile would have become increasingly conducive to convection column formation. The 1500 hour profile at Mount Gambier does not indicate that the energy conversion rate in the convection column would exceed the rate of flow of kinetic energy in the wind field (Byram 1959) under the rate of spread of the fire up to that time. However, because of the very rapid spread of the plantation fire induced by the open swamp (vide Chapter 6 (a) (i), and Figure 11), and the converging of the two headfires, the energy conversion rate in the convection column probably equalled or slightly exceeded that in the wind field. This would account for the well defined vertical structure of the convection column for at least the first 2,000-3,000 ft. The stronger winds aloft must have tended to fracture the column and certainly would have contributed to the spread of burning embers thrown down wind of the main fire (vide Chapter 6 (a) (vii)).

(iii) *Surface Winds*

Surface wind speeds and directions during the period 0900 to 2300 hours on 5 April are shown in Figure 7.

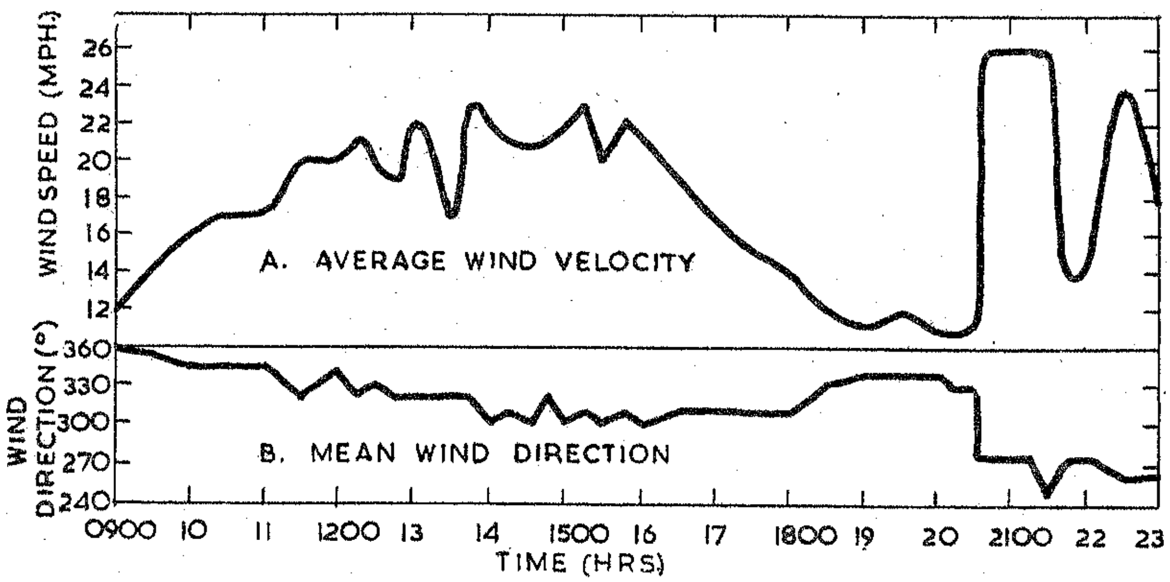

Figure 7. Surface wind speed and direction taken from a Dynes Anemometer trace recorded at Mount Gambier Aerodrome—5 April 1958.

Before the frontal passage, the highest average speeds of 23 m.p.h. occurred between 1345 and 1515 hours. After the change, the wind speed increased sharply to 26 m.p.h. for a short period. Mean wind directions remained approximately 300° to 330° for most of the period and the wind change associated with the passage of the front is clearly indicated.

(iv) *Fire Danger Measurement*

The Fire Danger Index as derived from the Forest Fire Danger Meter (McArthur 1963) and using the above meteorological data is computed as 33 on a 0-100 scale. This is a VERY HIGH classification.

(v) *Atmospheric Instability*

At the time of the fire, radiosonde had not been installed at Mount Gambier Aerodrome, nor was an 1100 G.M.T. flight then performed at Adelaide Airport. Hence the 2300 G.M.T. Adelaide radiosonde flight has been used to establish the possible air mass characteristics existing over the Wandilo area some 270 miles distant. This stability data must, then, be accepted in broad terms only.

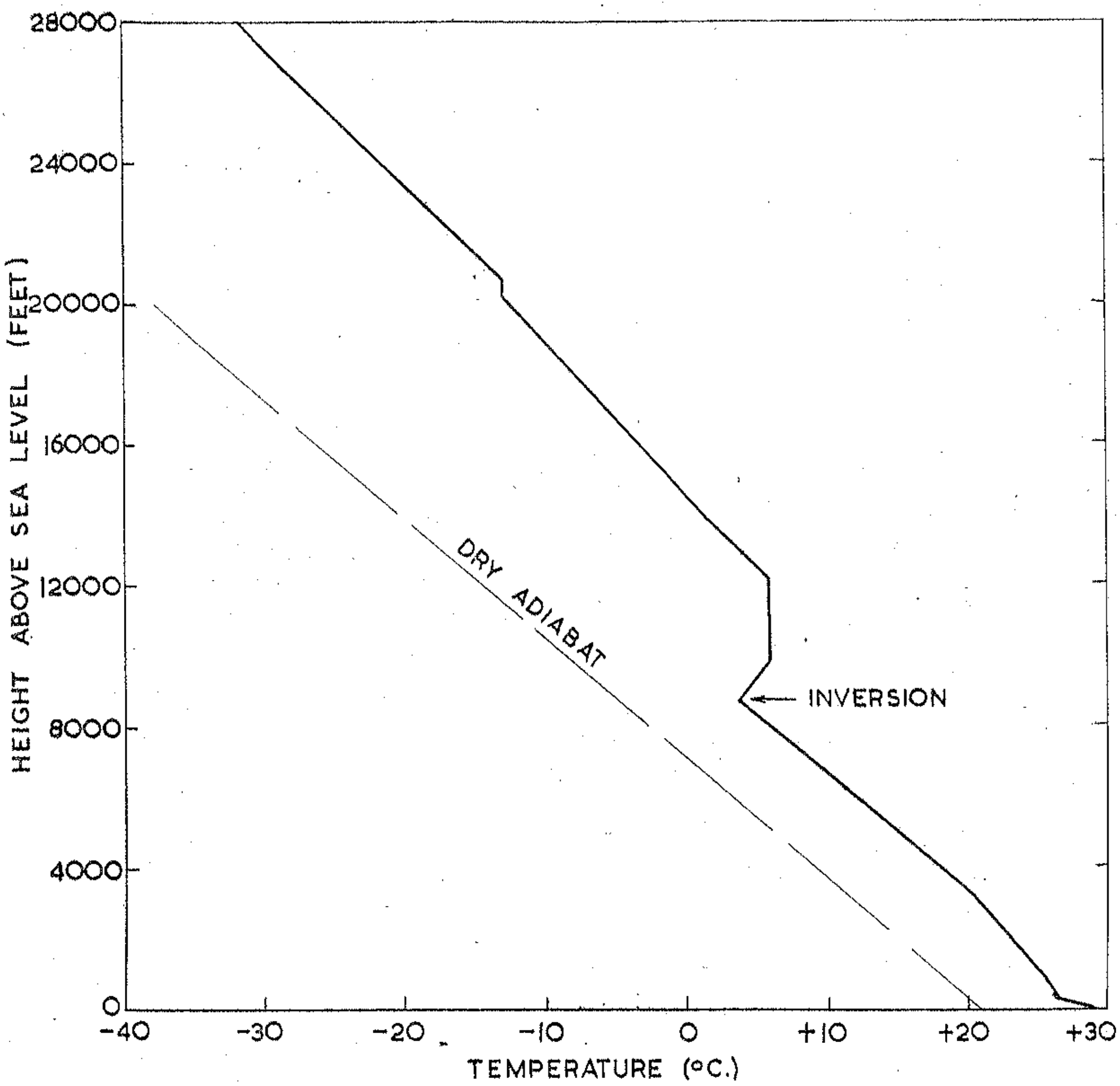

Figure 8. Radiosonde sounding at 0830 hours on 5 April 1958 taken at Adelaide Aerodrome.

The recorded ascent at 2300 G.M.T. is shown in Figure 8. The air mass at that time of day did not exhibit excessive instability and the following details provided an outline of the stability pattern up to about 28,000 feet.

TABLE 2

AIR MASS CHARACTERISTICS OF THE 2300 G.M.T. (0830 C.S.T.) RADIOSONDE FLIGHT, ADELAIDE, 5 APRIL 1958

Height (feet)	*Stability*
0– 420	Unstable
420– 9,200	Neutral
9,200–12,700	Stable
12,700–21,000	Neutral
21,000–21,800	Stable
21,800–28,000	Neutral
28,000 upwards	Stable
Showalter Index(a) + 6°C . .	Stable
Lifted Index(b) + 3°C . .	Stable

(*a*) *Showalter Index.* This is a simple parameter for determining atmospheric stability. The index is defined as the difference between the 500 mb. environmental temp. and that of an 850 mb. level parcel lifted dry adiabatically to saturation, and then by a saturated adiabatic process to the 500 mb. level.

A negative value indicates instability while a positive value indicates stability.

(*b*) *The Lifted Index.* This is defined as the difference between the 500 mb. environmental temp. and that of a parcel of air at the estimated maximum temp. with a dew point averaged for the layer from the surface to the 850 mb. level, and lifted dry adiabatically to saturation and then by a saturated adiabatic process to 500 mb. A positive value of LI indicates stability, and if LI SI-1° G, then instability is indicated, and severe convection can be forecast.

This sounding indicates absolute instability only in a shallow surface layer. However, as the rise in air temperature was very rapid (37° between 0700 and 1200 hours), it is reasonable to expect that unstable conditions intensified and extended to a greater height by early afternoon.

A 2° C inversion is shown to exist between 9,200 ft. and 12,700 ft., followed by isothermal conditions for the remainder. It is likely that this inversion would have been broken by midday due, once again, to the rapid surface heating and an adjusted Showalter Index for midday of + 2.5° C is indicative of convective activity. The deep layer from 420 ft. to 9,200 ft. was in a state of conditional stability during early morning hours, and any changes would have depended on whether the process involved was moist or dry adiabatic. The latter condition would appear far more probable in view of the wind regime in these levels during the period. This layer was so close to instability that it is quite conceivable that the heat source of the fire itself could have provided the small amount of energy necessary to bring this about. This possibility could explain the sudden increase of fire intensity at 1140 hours when a well developed convection column formed.

5. THE PROGRESS OF THE FIRE

The fire apparently started at about 0825 hours at which time some light smoke was first detected from the Bluff fire tower some eight miles distant. Other look-out towers could not see the smoke and cross bearings were thus unavailable. An early investigation by a fire unit failed to find the fire in the flat, thickly vegetated country.

From ground investigation it is reasonably certain that the fire started in a dry swamp some 70 chains north-west of the nearest pine plantation. This swamp consisted of dense tea-tree 7-10 ft. high between open areas of fairly green grass, and it appears likely that the fire trickled around in this area for some hours, sending occasional puffs of light smoke above tree-top level. Rapid combustion sufficient to give rise to a significant smoke column developed only after fuel moisture contents had decreased significantly.

At 1140 hours the fire began to spread rapidly and the smoke column was visible from all surrounding look-outs, bearings from which gave a close triangle of error.

From the assumed starting time of 0825 hours until 1140 hours, the fire may have travelled a maximum of 14-16 chains and burnt over an area of about 8 acres. The result of the light fire in the early stages is shown in Figure 9.

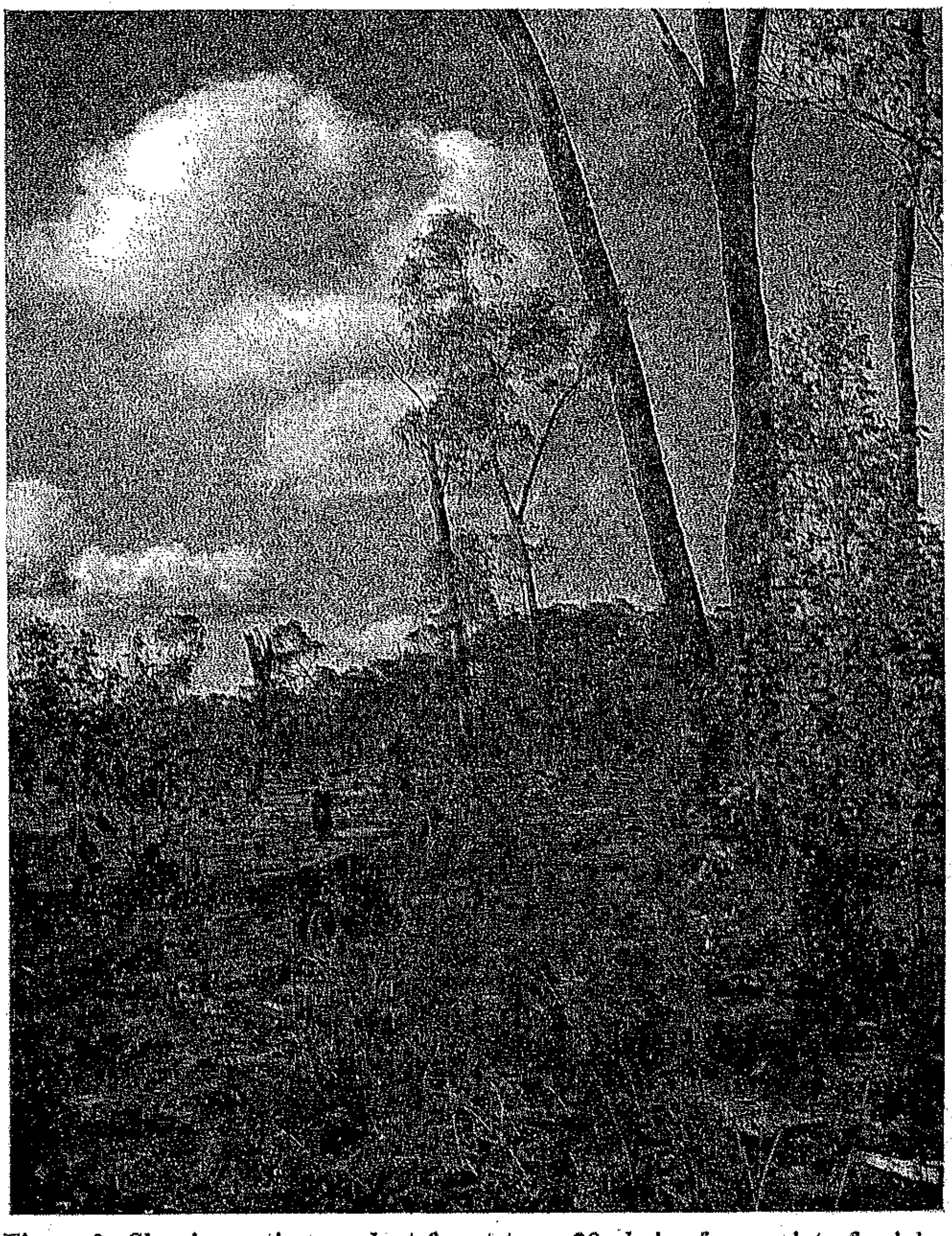

Figure 9. Showing native eucalypt forest type. 20 chains from point of origin. Flame height 6-8 ft. Little damage to tree crowns and ground vegetation not entirely consumed.

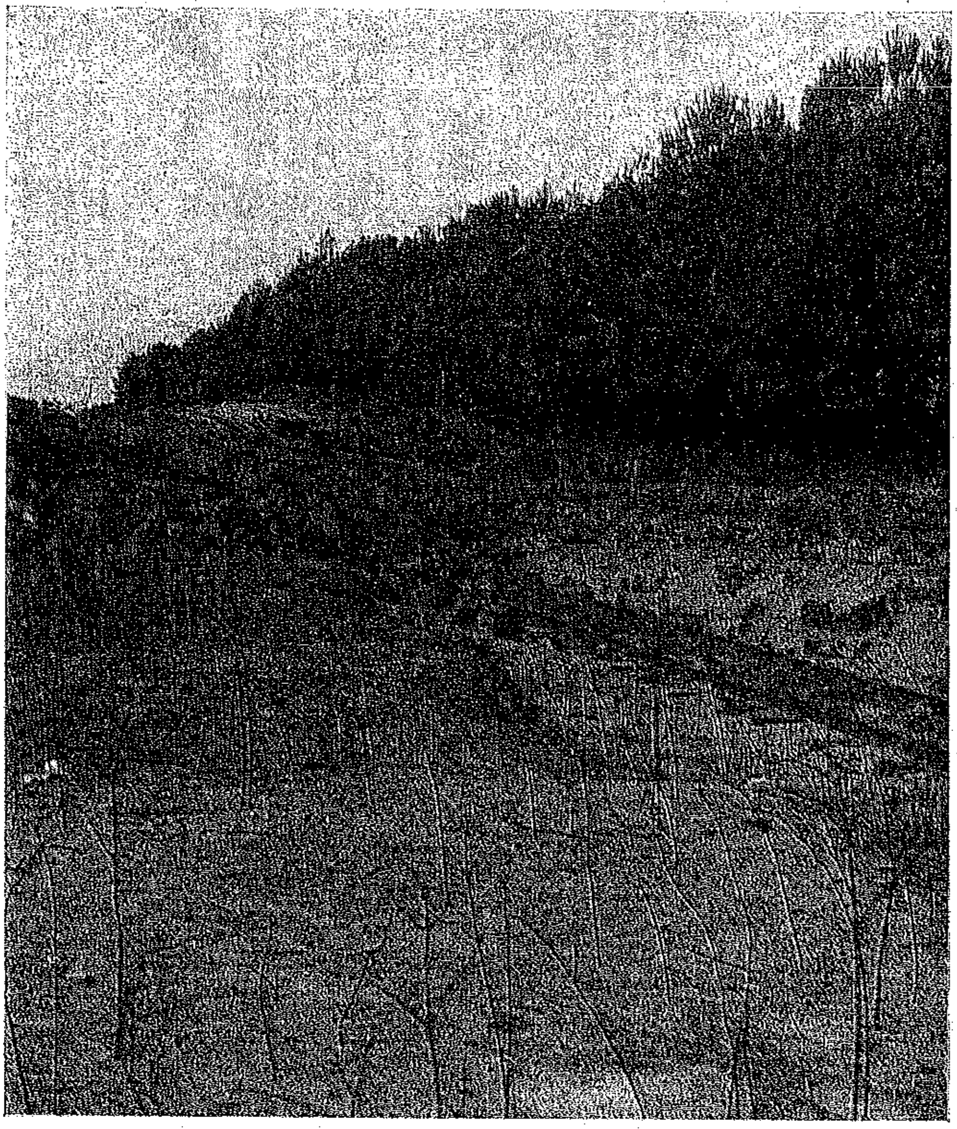

Figure 10. The fire first entered the *Pinus pinaster* on the rise seen in the top left hand corner of the photograph.

aged 23 years. (See Figure 10.) It entered on an upslope of 10° which extended into the pines for some 8-10 chains. Due to this slope and the heavy ground and aerial fuels (see Figures 3 and 4), the fire crowned on a narrow front and, reaching the top of the rise, threw 'spot fires' 20-30 chains further into the plantation. This resulted in intense crown fires ahead of the original head fire as the 'spot fires' coalesced.

It is estimated that this area was burnt out by 1330 hours.

By this time:

Total forward spread was 119 chains.
Total perimeter spread was 309 chains.
Total area burnt was 381 acres.

(iii) *Period* 1330 *to* 1500 *hours*

(Temperature 92°, R.H. 31%, Wind 300-320°/21-23 m.p.h.)

After the intense crown fire resulting from the extensive pattern of spot fires in the *Pinus pinaster* area, the fire continued more quietly as a ground fire spreading through 24-year-old *Pinus radiata* with only isolated areas of 'crowning'. In this fuel type the rate of forward progress slowed considerably.

The plantation was unpruned and partly thinned some 6 months previously. During this period the rate of forward spread was 26 chains per hour, the rate of perimeter spread was 107 chains per hour. By 1500 hours the total area burnt was 900 acres.

Several observers undertaking a reconnaissance of the fire just before 1500 hours, individually commented upon the quiet nature of the fire and the very light wind prevailing inside the plantation. As a result of this reconnaissance it was deemed safe to move men and equipment across the head of the fire in order to strengthen the attack on the western flank.

(iv) *Period* 1500-1530 *hours*

(Temperature 91°, R.H. 31%, Wind 300-310°/20-23 m.p.h.)

At the beginning of this period the fire 'blew-up' and developed fire-storm characteristics which resulted in the group of men and equipment then moving to the western flank being trapped. Eight men died and three fire-fighting vehicles were gutted.

The mechanics of this fire-storm are discussed in Section 6.

As a result of the fire-storm, a shower of spot fires were initiated for almost 1½ miles down wind of the fire-storm and some 600 acres of *Pinus radiata* plantation was burnt by crown fire within 15-20 minutes.

By 1530 hours the total forward progress was 273 chains, the perimeter 675 chains and the burnt area 1,547 acres and the head of the fire, having reached heavily grazed grassland, virtually extinguished itself.

(v) *Period* 1530-2040 *hours*

By 2000 hours the air temperature had dropped to 82° F., the relative humidity increased to 40 per cent. and the wind speed decreased to 11 m.p.h. During this period the fire perimeter was relatively quiet and effective suppression action was possible along the southern flank, and at the head, where the fire had spotted into a compartment of young pines. The whole of the north-eastern flank was spreading slowly in the hardwood area and little suppression action had been initiated in this section. At 2040 hours the total forward spread was 320 chains, the perimeter 810 chains and the area burnt 2,415 acres.

(vi) *Period* 2040-2230 *hours*

At 2040 hours a cold front reached the fire area. The wind backed from 340° to 280° and the speed increased from 11 to 26 m.p.h. The whole of the north-eastern flank broke away and spread rapidly under the influence of the strong wind. The rate of forward spread during the first 30 minutes after the wind change was approximately 2 m.p.h. and an intense burn resulted (see Figure 11). Some isolated 'spotting' occurred where the head fire entered some poor quality pine stands. After the change the relative humidity rose rapidly and some rain fell after 2130 hours, 4 points being recorded at the Mount Gambier Aerodrome.

However, competent observers in the fire area considered the fall there to be approximately 10 points. The surface fuels were thoroughly wetted and suppression action became relatively simple. By 2230 hours the forward spread was halted and mopping up of the north-eastern perimeter proceeded with mechanical equipment.

The final perimeter of the fire was 1,160 chains and the total area burnt was 3,383 acres, including a gross plantation area of 1,020 acres.

Figure 11. Hardwood area burnt after passage of the cold front at 2040 hours. A fairly severe fire with a flame height of 25-30 ft, but not a crown fire.

6. THE ERRATIC FIRE BEHAVIOUR

Up to 1500 hours, the fire can be described as being a fairly normal fast-moving high-intensity fire, which conformed closely to the fire behaviour pattern expected under the prevailing fuel and meteorological conditions.

The rate of forward progress for eucalypt forest carrying 10 tons per acre of inflammable ground fuels for a Forest Fire Danger Rating of 30 is computed to be 44 chains per hour (McArthur 1963). However, the open nature of the re-growth forest in this case would allow a much greater wind movement close to ground level than in a fully stocked forest. This difference is estimated to be the equivalent of raising the rating to an index of 50 which would give a rate of spread of 75 chains per hour. This agrees closely with the measured rate between 1140 and 1230 hours of 73 chains per hour.

For a Fire Danger Rating of 30, the rate of forward spread of a *ground fire* in a medium-aged *Pinus radiata* stand is computed to be 28 chains per hour (McArthur, unpublished data). This compares favourably with the actual rates of 23 chains per hour between 1330 and 1430 hours, and 32 chains per hour between 1430 and 1530 hours.

The only tangible warning sign up to 1500 hours that fuel and meteorological conditions were perhaps conducive to erratic fire behaviour was the 'spotting' and subsequent crown fire development in the *Pinus pinaster* area at about 1230 hours. Apart from this there was, to those at the scene, no obvious warning of the impending holocaust which suddenly developed at 1500 hours. Within 15 minutes the fire suddenly assumed fire storm characteristics. Eight experienced firefighters in three specially-equipped vehicles had perished, and the fire area had dramatically increased.

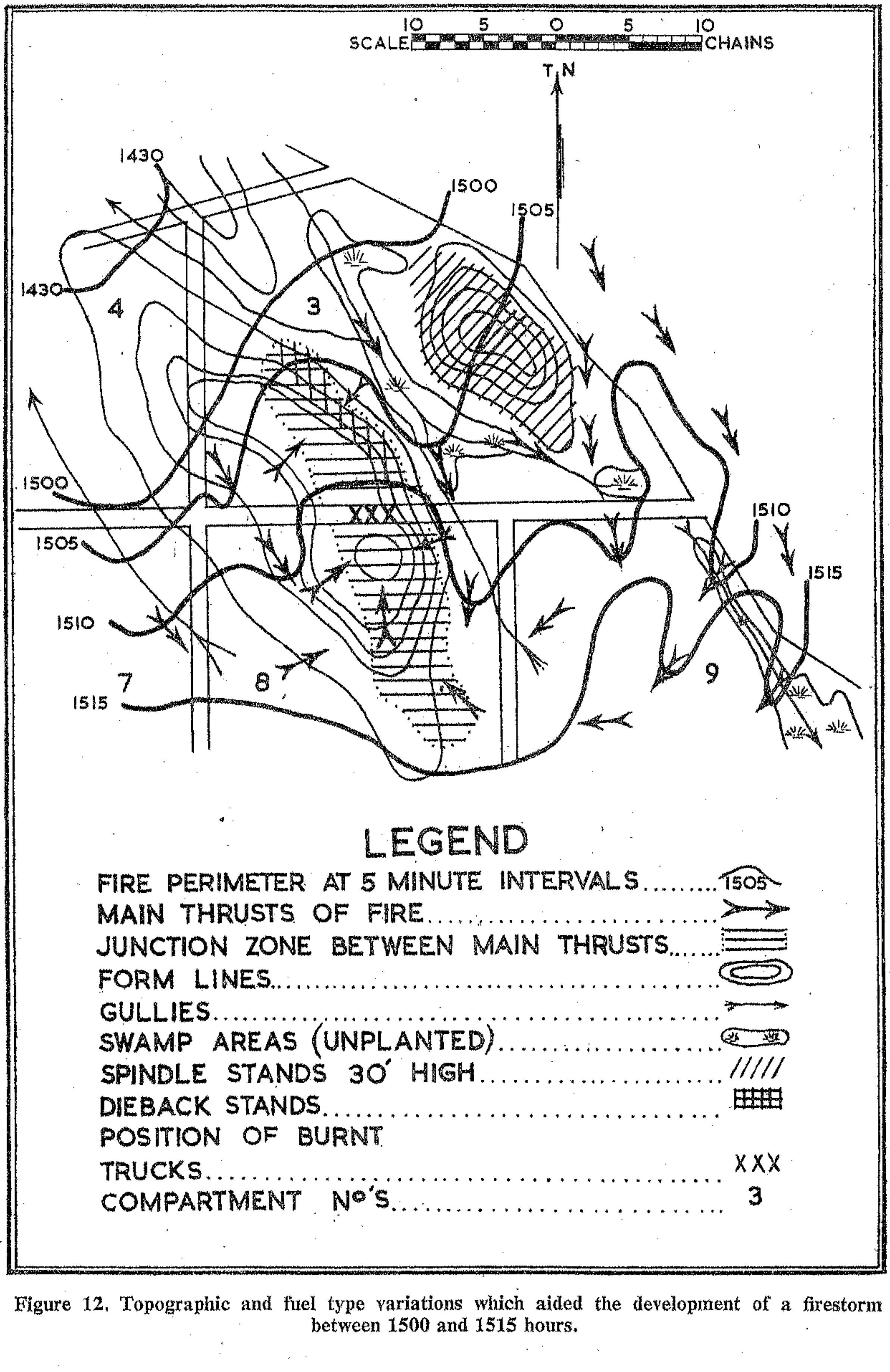

Figure 12. Topographic and fuel type variations which aided the development of a firestorm between 1500 and 1515 hours.

(a) The Mechanics of the Fire Storm

The formation of the firestorm as deduced from field observations after the fire and from evidence of personnel engaged can best be followed with the aid of Figure 12. The following sequence of events is believed to have occurred:

(i) At 1500 hours the fire perimeter was to the west and north of what came to be known as 'the tragedy area'. The eastern edge of the perimeter in the pine plantation had just entered the northern end of the long treeless swamp in Compartment 3, which is aligned in a NNW-SSE direction.

(ii) To the *west* of this open swamp, dense patches of 'dieback'-affected *Pinus radiata* provided an exceptionally heavy fuel accumulation on rising ground. To the *east* of the swamp a distinct knoll carried a poor 'spindle' stand of pine and intermixed eucalypt coppice and heavy ground vegetation. This 'valley', being roughly orientated with the gradient wind direction, allowed the formation of a strong wind-funnel effect which accelerated the spread of the fire through the swamp. The fast moving headfire which developed soon crossed the break between Compartments 3 and 8.

(iii) The rapid spread through the open swamp induced a severe crown fire in the fringing spindle and dieback stands, and the intense fire created a strong convectional indraught which drew in the previously quiet main fire to the north and west in Compartment 4. Another head-fire prong was thus formed and this also crossed the break between compartments 3 and 8 some 10-15 chains to the west of the first head-fire.

(iv) These two headfires, each on either side of a distinct sand dune, converged and formed a junction zone at about 1512 hours reaching its greatest intensity at the head of the knoll in Compartment 8. The vehicles and trapped fire-fighters were located directly in this junction zone only 2-3 chains north of the knoll. Vide Figure 13.

(v) The effect of the strong convectional indraught, caused by the crown fire on the area fringing the swamp and the two accelerating head-fires, extended also to the previously quiet fire perimeter in the hard-wood area. This then spread rapidly in a south-easterly direction along the pine edge and, a little later, was drawn towards the developing storm centre, entered the pines in Compartment 9 and was soon a vigorous crown fire.

(vi) The energy released by these converging crown fires caused a very strong convection column to form. This was closely observed by the weather observer at the Mount Gambier Aerodrome who being an amateur glider pilot, remarked particularly upon the strongly developed updraughts exhibited in the column.

(vii) The strong convection draught and the strong winds aloft initiated immediate and heavy 'spotting' over a wide area south-east of the storm centre for a distance of some 110 chains and resulted in the almost simultaneous ignition of approximately 600 acres of *Pinus radiata.* This area was practically burnt out by 1530 hours. A view of this area is shown in Figure 14.

(b) Factors which aided the initiation of the fire-storm

It is now generally agreed by most fire research personnel that the most significant factors influencing such extreme fire behaviour are:

(i) the fuel moisture content;
(ii) the surface wind speed;
(iii) the nature of the upper wind profile;
(iv) atmospheric instability;
(v) the quantity, size and arrangement of the fuel.

Unfavourable values of some or all of these factors are required to create erratic fire behaviour. It is clear that the circumstances at Wandilo on 5 April 1958, were such that several of the factors were poised close to critical values and comparatively small changes were sufficient to convert a difficult but manageable situation into an impossible and very dangerous one in a matter of minutes.

McArthur (unpublished data) has found a definite relationship between the moisture content of surface fuels, fuel quantity and crown fire development. In eucalypt fuels of moderate to heavy fuel quantity (5-7 tons/acre) crown fire development does not occur until the fuel moisture content falls below 4 per cent. In heavier fuels ranging up to 10 tons per acre, crown fire development can occur when the moisture falls below 5½ per cent. However, when two or more fires draw together, crown fires may occur in the junction zones at higher moisture contents than those quoted above.

The critical level of moisture content for eucalypt fuels can be accepted as 5 per cent. in heavy fuel concentrations. Below this level erratic fire behaviour is a distinct possibility if the values of other factors also become significant.

If these same figures can be accepted for pine fuels (information for which is as yet very limited) it appears that critical moisture values of the litter beneath the pine canopy were reached between 1200 and 1600 hours.

TABLE 3

CALCULATED FUEL MOISTURE CONTENTS UNDER FULL CANOPY USING MOUNT GAMBIER METEOROLOGICAL DATA

Time (hours)	0700	0900	1200	1300	1400	1500	1600
Calculated fuel MC% under canopy	11.0	8.0	5.4	4.9	4.6	4.6	5.3

It has been indicated earlier that the surface wind speed was estimated to be very light beneath the pine canopy and, with the wind speed in the open averaging 23 m.p.h., it is certain that winds inside the canopy rarely exceeded 3-5 m.p.h.

A break in the canopy, such as the swamp in Compartment 3, allowed increased wind strength to reach the fuel bed and thus provide additional oxygen for an increased rate of combustion.

It has been stated earlier (Section 4 (c)) that the wind profile was clearly one in which erratic fire behaviour could be expected.

The changes in the nature and distribution of the fuels due to the spindle stands and dieback areas clearly affected the fire and these aspects have already been commented upon. Recent logging slash was also a significant component on the fuel complex in the blow-up area.

It will be noted then, that while not one of the factors instrumental in contributing to the fire-storm was at such a dangerous level as to be obviously responsible for the initiation of the 'blow-up', a combination of several factors at near critical values was able to do so.

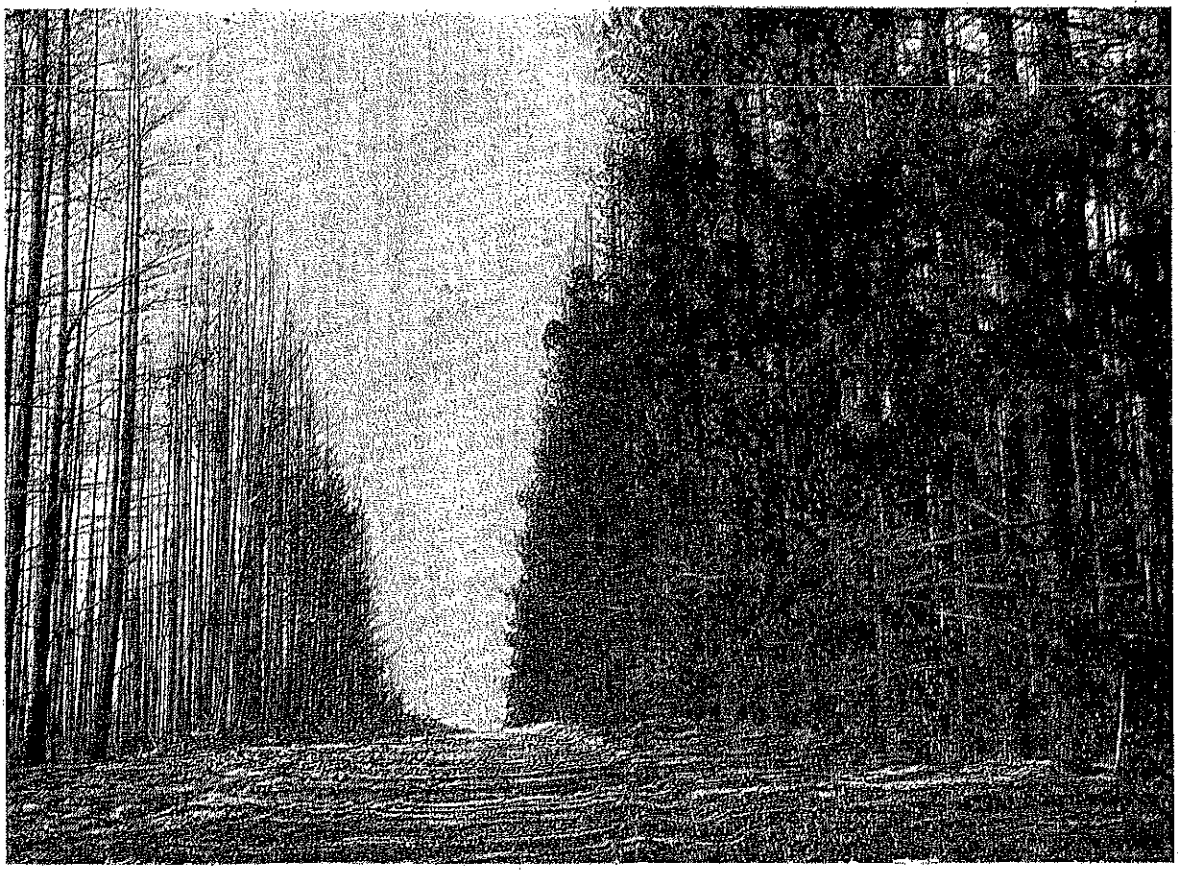

Figure 13. Looking east along the firebreak between Compartments 3 and 8. The trucks and men were trapped on this slope. The knoll in Compartment 8 is located some 2-3 chains to the right of the photograph.

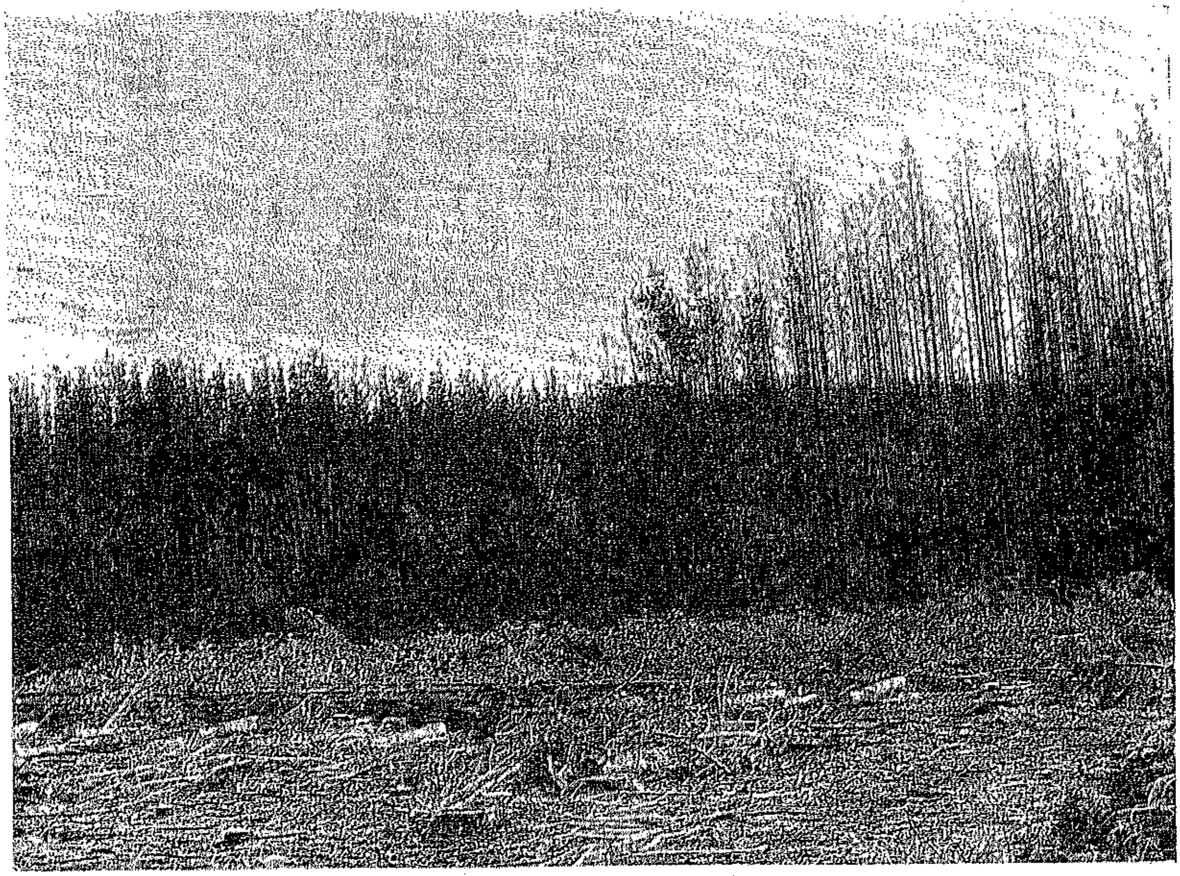

Figure 14. Looking into swamp area in Compartment 9. This is the edge of the fire-storm area. Salvage logging operations have already commenced in the foreground.

7. CONCLUSIONS

Large fires inevitably lead to the questioning of the bases and practices of the fire protection organisation, any weaknesses of which being invariably pinpointed by the severe strain to which it has been subjected. Fire protection should always benefit in some way from its failures, and aspects of forest plantation lay-out and management, fire-fighting tactics, fire-fighting equipment, safety precautions for personnel and fire-weather forecasting, relative to this fire are accordingly commented upon.

(a) Plantation Lay-out and Management

(i) *Species differences*

Because of specific differences in fuel characteristics, various pine species affect fire behaviour in different ways. In this fire, the rapid combustion of the *Pinus pinaster* was an important factor in spreading the fire in the early stages.

Pinus pinaster stands almost invariably accumulate a much greater quantity of loosely compacted needles at ground level than do stands of *Pinus radiata*. Fuel quantities in excess of 20 tons per acre have been measured in 30 year old stands on the coastal plain of Western Australia. It would appear also that the decomposition rate of the coarser *Pinus pinaster* needles is much slower than the finer *Pinus radiata* needles. Having plantations of this species in vulnerable locations, such as adjacent to external boundaries, is a risk which at least must be recognized if not avoided.

(ii) *Pruning*

Unpruned stands almost always increase the likelihood of crown fire formation because of the continuous vertical distribution of flammable fuel provided by dead branches and entangled fallen needles, etc. Pruning provides an air barrier between ground fuels and the tree crown and, provided the volume of ground fuels is not too great in relation to the pruned height, can decidedly inhibit crown fire formation. Although partly pruned stands are a fire protection advantage in providing better visibility and access through the stand, the remaining unpruned stems can stimulate crown fire formation. It is certain that unpruned stands contributed to the severity of the plantation fire on 5 April. Pruning on fire protection grounds alone may frequently be too costly for general wide-area application. Complete pruning of sufficiently wide areas in specific vulnerable zones and near possible ignition sources is considered, however, to be a justifiable fire protection expense. The retention of all the green external limbs of edge trees of pine plantations is a distinct advantage for limiting the number of wind-borne fire-brands which can fall on needle litter beneath the trees. The lower external limbs of the trees of the *P. pinaster* compartment where the fire entered the plantations (Figure 10) were dead and leafless and provided no screen to reduce the number of fire-brands able to ignite successfully at the plantation edge. This particular circumstance could not be avoided, but conscious pruning of external limbs of edge trees is certainly an undesirable fire protection practice.

(iii) *Firebreaks*

Firebreaks of one chain width were generally sufficient to hold flank fires during the course of this fire. It is considered, however, that breaks of ½ chain width would also have serve adequately, and thus it is felt that internal firebreaks, which define compartment boundaries, need be no wider than is sufficient to provide adequate access for all forest management purposes. In some instances, side limbs of the edge trees require pruning to ensure that suitably equipped personnel can shelter safely should they be trapped in a sudden crown fire development.

(iv) *Breaks in forest canopy*

Distinct breaks in the forest canopy, such as those caused by swamps of large enough area, can clearly increase the severity of fires in the immediately adjacent forest. It is essential then, that all fire control personnel be aware of the possible danger associated with significant canopy openings. In the cases of swamps, stony outcrops and other unplantable areas, such open areas cannot be avoided and, on other occasions, breaks in the canopy are a management necessity (e.g. clear-felling of rotation age stands). Firebreaks of two or more chains are sometimes located through plantation areas and these also may cause unpredictable wind effects.

(v) *Control burning of eucalypt scrub*

Areas control burnt in September 1957 were very effective in stopping fire spread in the eucalypt scrub area (See Figure 15). In this particular scrub,

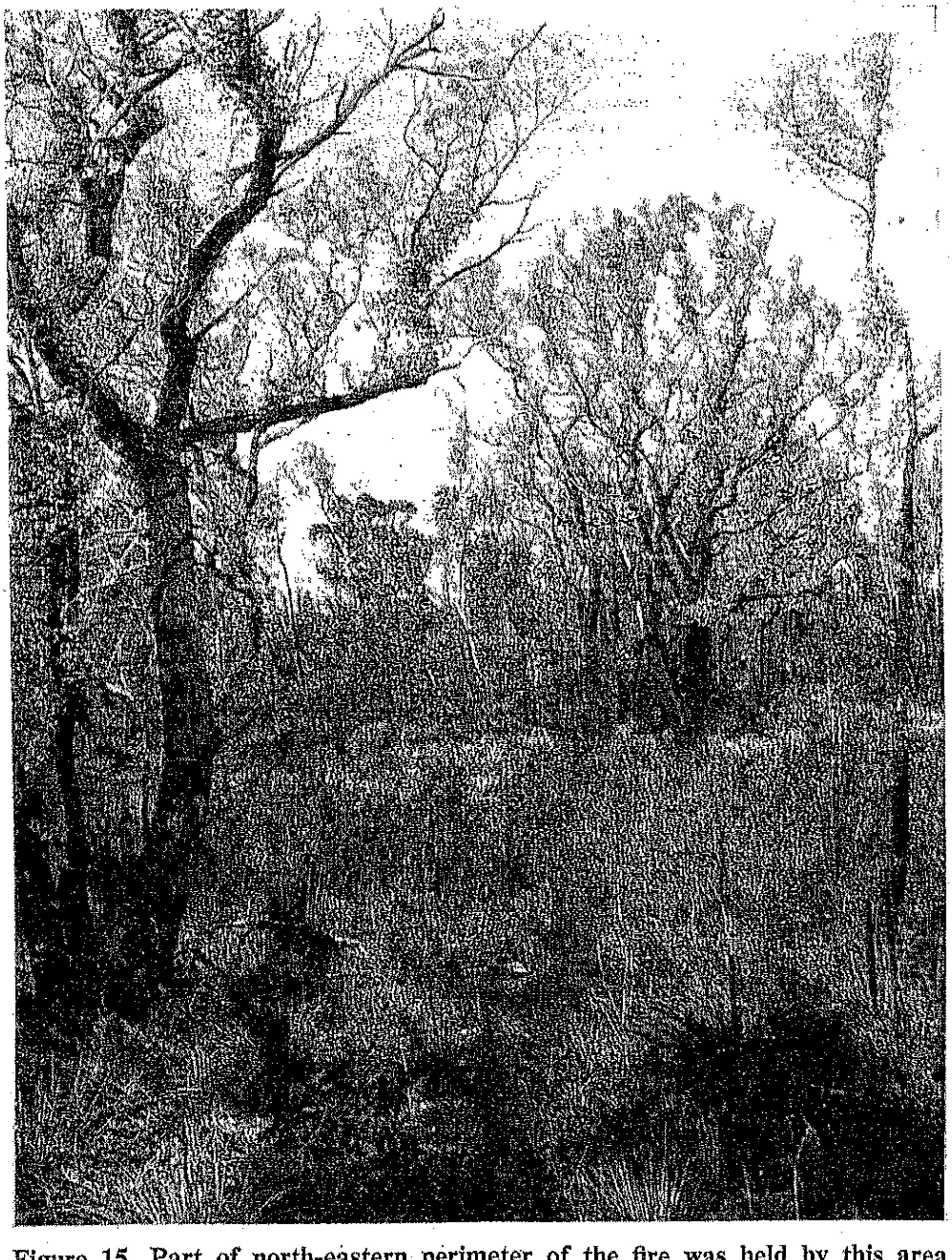

Figure 15. Part of north-eastern perimeter of the fire was held by this area which was controlled burnt in September 1957.

control burning on a broad area basis cannot always be carried out because of high seasonal water tables and patch burning during Spring has to be resorted to. There is no doubt, however, that regular area control burning of poor quality eucalypt scrub on plantation boundaries greatly enhances their protection. Frequently the adjoining eucalypt forest is a non-commercial stand and the normal standards of prescribed burning can be relaxed so as to provide a hot clean burn.

(b) **Fire-fighting Tactics**

The suppression tactics to be employed on any individual fire are usually determined by the local fuel, meteorological and topographical conditions and by the number and quality of the men and equipment available for the suppression job. The large number of possible combinations of these factors make it impossible to lay down hard and fast tactical rules. Generally the man on the spot is the only person who can best sum up these factors.

Under most circumstances, the period between 1300 and 1500 hours is very frequently that most dangerous to fire-fighters. During this period, fuel moisture contents often reach critical values, temperature and wind speeds their maxima and atmospheric instability is strongly developed. As the borderline between a surface fire and a crown fire can be such a delicate balance, a slight change in one of the key variables at this time of the day may trigger a quiet, normal surface fire into an erratic high intensity crown fire.

With the potential dangers of this period in mind, it is important to emphasise that an all out suppression effort is necessary to contain fires starting during morning hours before the onset of this dangerous period. When quick control is not achieved, fire suppression crews must obviously proceed very cautiously if working anywhere near the head of the fire. Efficient flank attack, giving preference to that flank likely to become a head as the wind changes, will almost invariably be a practicable and safe operation and will keep the burnt area to a minimum until such time as the head fire can be attacked with safety.

(c) **Fire-fighting equipment**

In heavy fuels, such as those in pine plantations, water is an effective suppression agent if it is available on the fire edge in sufficiently large quantities. Because of the limited access inherent in unthinned or lightly thinned plantations, adequate water supplies are only obtained by long hose lays backed up by a well organised system of wheeled water transport to maintain continuous supplies on the fire edge.

At the time of this fire, the equipment required for this was not available, and attempts at direct water attack were restricted to locations where adequate vehicular access was available.

Small bulldozers (D4 and smaller) can sometimes operate effectively in thinned plantations, but their mobility is very much hampered by stockings as high as those of the burnt plantations. Generally, sufficient mobility for safety purposes cannot be ensured with stockings above about 200 trees per acre. It is thus felt that their use in this case would not have been practicable.

(d) **Safety precautions for men and equipment**

As mentioned in the Introduction, three men, of the eleven trapped, survived. Two remained in the cabin of a truck to shelter from the worst of the fire-storm, and only left this cover when the vehicle was well alight and the petrol tank about to explode. The third man sheltered in a deep wheel rut in the soft sand of the firebreak, with his coat over his face, during the peak of the conflagration.

It would appear almost certain then that safe refuge for men caught in circumstances such as those at Wandilo could be provided by:

(a) Properly protected vehicle cabins; OR

(b) The use of survival tents for fire fighters developed by King (1965).

Immediately following this fire, asbestos-lined cabins have been provided on fire-fighting vehicles in South Australia and cabin accommodation enlarged to accommodate all crew members of the vehicle. King (1965) has since indicated, however, that radiant heat is the chief danger. Consequently asbestos-lining is probably unnecessary and it would appear that better and cheaper protection for truck cabins could be provided by a 'throw-over' blanket of aluminium foil, of a suitable design which allowed quick and sure anchoring.

One of the trapped vehicles was apparently forced to stop because of a fuel vapour lock. To avoid this occurrence it is now considered that each fire-fighting vehicle should be fitted with dual fuel pumps operating on the same fuel line. In addition to the usual mechanical pump located alongside the engine, an electrical pump is located adjacent to the fuel tank. This latter pump is operated as soon as the vehicle enters the fire area. Vapour locks are virtually eliminated as cool fuel is always pumped. A further safety measure to ensure that the fuel remains cool is to lag the fuel line.

Petrol tanks on two of the trapped vehicles exploded. The tank of the third truck was protected from external physical damage by a ¼ in. plate shield and this protection was apparently also sufficient to prevent the tank exploding. It is now considered wise to enclose the petrol tank within the water tank or, when this is not possible, to provide a shield of ¼ in. plate as well as some form of insulation.

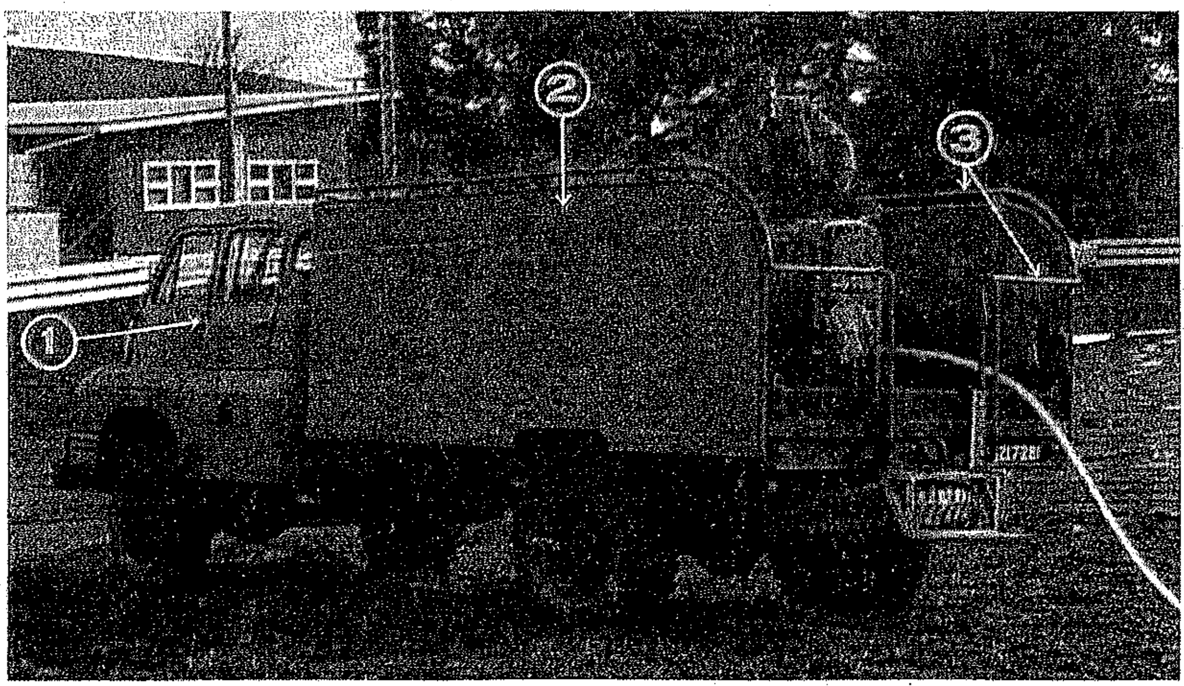

Figure 16. Fire-fighting truck designed as result of conditions experienced in this fire.

1. Asbestos-lined cabin accommodation for 6-7 men.
2. High sides to protect deck crew from occasional flashes of radiant heat.
3. Water sprays to protect deck crew and the vehicle.

Unshown: Fuel tank inside water tank, dual fuel pumps and lagged fuel lines.

(e) Fire Weather Forecasts

As has been indicated, the erratic behaviour of this fire is attributed to the combining of several factors (in themselves not at critical levels) to transform suddenly a relatively quiescent situation into a very dangerous one. One such factor was *atmospheric stability.* It would seem, then, that the routine inclusion in fire weather forecasts of a guide to atmospheric stability for at least the first few thousand feet is warranted. This could be simplified to a statement of stable, unstable or conditionally stable layers, or may be better conveyed as an estimate of a suitable stability index. After initial instruction, fire control officers could be expected to become familiar with the concept and their burden of having to make many subjective decisions would be eased in at least one important aspect.

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3. McArthur, A. G. (1963): Forest Fire Danger Meter.
4. King, A. R. (1965): A Prototype Survival Tent for Forest Fire-fighters.

SOURCES OF DATA

1. An aerial photograph of the fire taken a few days after 5 April 1958.
2. Evidence given by witnesses and personnel involved.
3. Weather data by courtesy of the Director, Commonwealth Bureau of Meteorology.

APPENDIX No. I

APPENDIX No. I

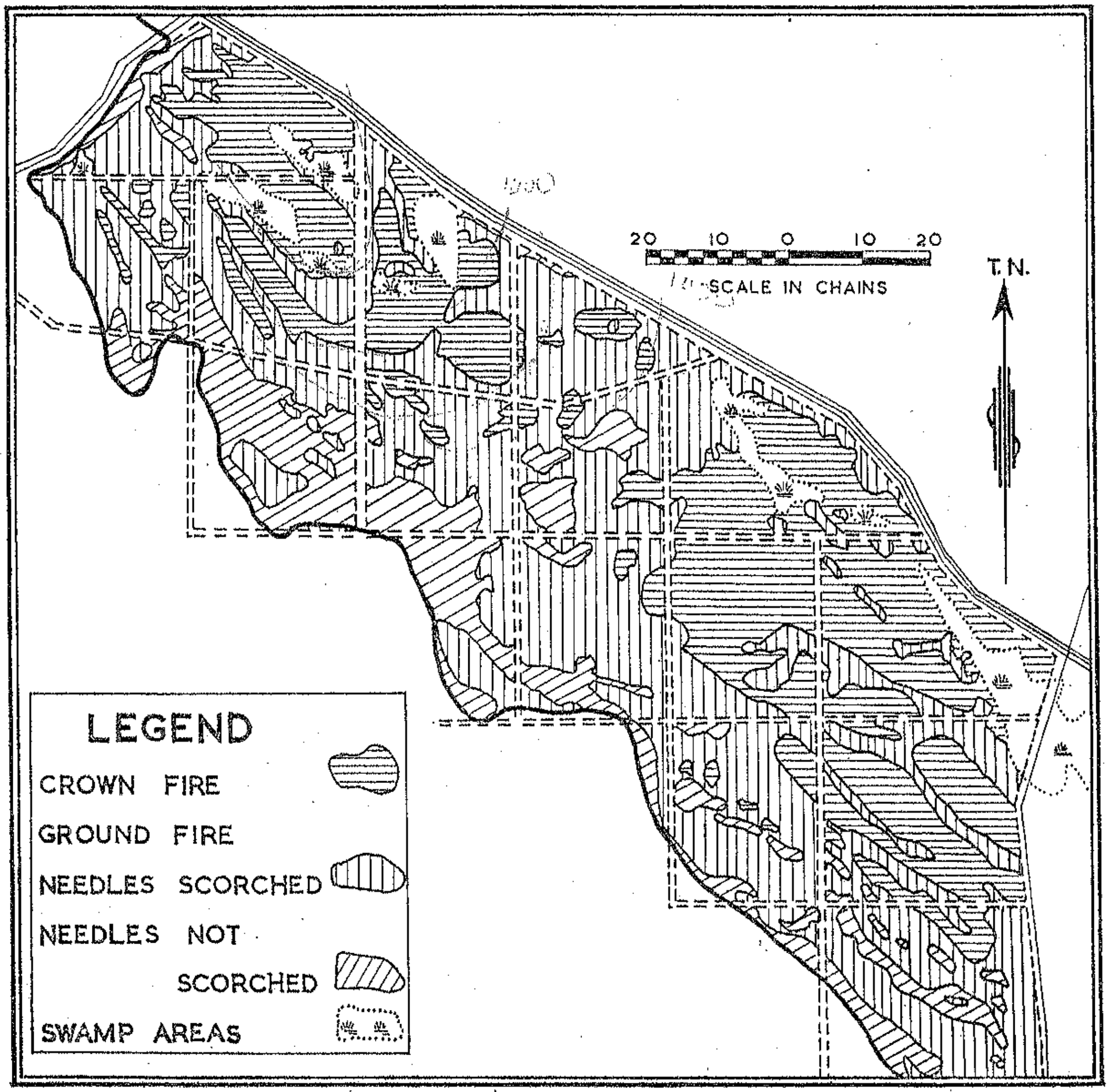
RATE OF SPREAD ANALYSIS OF THE WANDILO FIRE, SHOWING FORWARD PROGRESS, PERIMETER AND AREA SPREAD, FUEL AND METEOROLOGICAL CONDITIONS

Period	*Forward Progress*		*Perimeter Spread*		*Area Spread*		*Meteorological Conditions*				*Fuel Types*	*General Fire Behaviour*
Hours	*Total Chns*	*Inc./hr Chns*	*Total Chns*	*Inc./hr Chns*	*Total Acs*	*Inc./hr Acs*	*Average Wind Velocity*	*Average Screen Temp.*	*Average Relative Humidity*	*Wind Direction*		
							m.p.h.	degrees f.	per cent	degrees		
0825 ..	..	..	..	..	..	..	..	..	..	..	..	Estimated time of origin
0825–1140	16	5	22	7	8	2½	17	87	32	340	Swamp vegetation	Slow burning fire. High fuel moisture contents
1140–1230	77	73	178	186	114	126	20	92	29	330	Open regrowth Euc. forest 30–40 ft	Intense ground fire. Flame height 10–15 ft
1230–1330	119	42	309	131	381	267	21	92	29	320	*P. pinaster* and *P. radiata*	Area of heavy spotting and severe burnout as crown fires
1330–1500	158	26	469	107	900	346	22	92	31	310	*P. radiata* ..	Mainly ground fires with isolated areas of crowning
1500–1530	273	230	675	412	1,547	1,294	23	91	31	310	*P. radiata* ..	Fire storm and extreme spotting resulting in mass ignition up to 110 chains
1530–2040	320	9	810	27	2,415	174	12	85	40	330	Open regrowth Euc. forest and scattered *P. radiata*	Mostly side spread from 1730 hours on the NE. flank
2030–2140	343	23	945	135	3,200	785	26	76	90	280	Regrowth Euc.	Frontal passage at 2040 hours caused whole of NE. front to break away and assume rapid spread forward progress in the vicinity of 1½–2 m.p.h.
2140–2230	370	27	1,160	215	3,383	183	14	68	88	280	Euc. swamp and *P. radiata*	Forward and perimeter spread stopped at 2230 hours after 10 points of rain made fire virtually self-extinguishing

115

APPENDIX III

FIRE SEVERITY MAP OF THE AREA OF PINE PLANTATION BURNT



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APPENDIX II

MAP SHOWING RATE OF FIRE SPEED